TALLINN UNIVERSITY OF TECHNOLOGY
School of Engineering
Department of Mechanical and Industrial Engineering

VALUE OPTIMIZATION MODEL DEVELOPMENT IN FINGER JOINT MANUFACTURING

VÄÄRTUSE OPTIMEERIMISE MUDELI ARENDUS LIIMPUIT SÕRMJÄTKU TEHASES

MASTER THESIS

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Tallinn, 2020

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Mechanical and Industrial Engineering Department

THESIS TASK

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Study programme: MARM06/18 Industrial Engineering and Management

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Thesis topic:

(in English): Value optimization model development in finger joint manufacturing

(in Estonian): Väärtuse optimeerimise mudeli arendus liimpuit sõrmjätku tehases

Thesis main objectives:

1. Create a detailed production model of finger jointing process.
2. Gather simulation data from timber scanner for further studying and analyzes in created production model.
3. Gain a better understanding to measure the efficiency of finger jointing production processes and alike.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Set hypotheses to test by a production model	01.05.2020
2.	Develop a methodology and create the model	12.05.2020
3.	Gather data to input to the model and analyze the results	23.05.2020

Language: EST/ENG **Deadline for submission of thesis:** "25" May 2020 a

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CONTENTS

Preface

The work was carried out by the initiation of the author as production manager of a finger jointed component factory in company Barrus AS. The assisting information and guidance was provided by Director of Manufacturing Andres Linnasaar.

Manufacturing finger jointed components consists of several steps that are all dependent on the specifics of timber dimensions, quality classifications and client requirements. To comprehend all the major factors related to finger joint manufacturing a model is created to analyze the relevant key performance indicators for batches of sawn timber. As raw material is by far the highest cost in timber manufacturing the main emphasize is on using the timber scanner data of different simulation to be inserted into the production model created resulting key performance indicators for further evaluation.

The resulting data is further analyzed using regression model to predicts the most important independent values of timber scanner settings and batch properties. The resulting conclusions and models can be applied to the whole portfolio to increase the profitability, turnover or other KPIs dependent on what is the sales market and production plan situation.

Further testing of different products, qualities and raw material variations can improve understanding the effects of specific independent value on depended KPI values.

Key words: finger joint ; timber ; wood optimization ; manufacturing model ; simulation ; master thesis

List of abbreviations and symbols

CAL – calibrated (wood) / calibration (of wood)

CC – cross-cut / cross-cutting

FJ – Finger Joint

L - length

ST – sawn timber

wavg – weighted average

WE – WoodEye timber scanner

1. Introduction

Using wood as a building material has steadily increased during the last decades. One of the driving factors has been the renewable side of this resource. Modern design, architectural and technical requirements presented to building materials require, among other things the material to be homogenous in both quality and physical properties. For wood this can be enhanced by using selected parts of the natural roundwood logs for applications where stability and specific quality requirements are presented. Also, other parts of the log can be used for applications with lesser requirements. One of the key approaches to achieve such selective utilization of wood is by cross-cutting the timber into specific quality grade blocks and adjoining the obtained blocks back into a solid pieces through the process of finger jointing and gluing. For example, knot free material can be finger jointed together to create raw material for applications requiring higher levels of dimensional stability and aesthetic appearance such as window frames and sashes. Pieces containing knots and other defects can be adjoined together to form material with lesser requirements or for applications where the aesthetics are less important such as structural parts of furniture, framing and pallets.

Timber processing is by nature a heavy industry where the majority of costs associated are of raw material. This fact along with the scarcity of globally available wood requires timber manufacturing companies to seek for ways to improve the yield of timber and to use each specific part of the natural timber for product application with highest value.

However, as the timber value engineering possibilities has become more and more immerse it poses a challenge for large capacity manufacturing plants to understand the cost efficiency of the complicated processes involving hundreds of sub-grades, cross-sections and other parameters to stay competitive.

The aim of this work is to construct a production model to predict the different key performance indicator values associated with finger joint manufacturing along with the economic factors such as profit earned per unit of time. The key input to the model created is from high-tech timber scanning and optimization device WoodEye, which allows to save test batches and then simulate the grading and optimization process by changing individual parameters. The data from simulations (appendices 4-5) is used to investigate the relation between the minimal allowed block lengths for more common products and to analyze economical outcome though the production model created.

Regression analysis is carried out to define the main independent factors for the dependent factory throughput and financial efficiency. A regression equation is created for two product classes based on their cross-sectional dimensions to predict the optimal minimal allowed block length values for future batches of same or similar products.

It was found that the best yielding settings are not necessarily optimal for every situation because as the yield is optimized to the maximum it means that the average length of extra material obtained for cross-cutting process becomes shorter and at some point it starts to inhibit the performance of the factory to the extent that it reduces the resulting economic performance.

Optimal settings for higher volume product combination were found, which can be interpolated to similar product combination in the company portfolio, which can have considerable effect for the overall profitability of the company and allow for improved understandings and decisions in the future sales and portfolio compilation. Further analyzes and simulations of different test batches can improve the accuracy of predictions and conclusions made.

2. Production Process Overview

The process of turning sawn timber into finger jointer material consists of planing / calibrating the rough surfaced timber into smooth planks that can then be graded by optimization scanner and cross-cut into blocks of wood ready to be assembled in finger jointing operations. In finger jointing process the joints are cut, glue applied and blocks pressed together to form solid pieces of finger jointed material that is further left to cure and transported to warehouse or forwarded on another production step such as re-planing and gluing the individual lamellas together to form glulam products.

2.1 General process and layout description

The general process of finger joint manufacturing consists of four main steps of calibrating the sawn timber, scanning and optimization, cross-cutting and finger jointing the material. Based on Barrus company example the layout can further be divided into two part (red line on figure 2.1). First part consists of preparing the raw material for finger jointing process resulting in graded and sorted blocks of wood. The blocks are fed directly to finger jointing machine centers or partially collected to buffer crates to be later in-fed to finger jointing machines. The other part consists of two finger jointing lines with integrated sub-systems of sorting, compilation to packets, finger joint cutting, glue application and pressing.

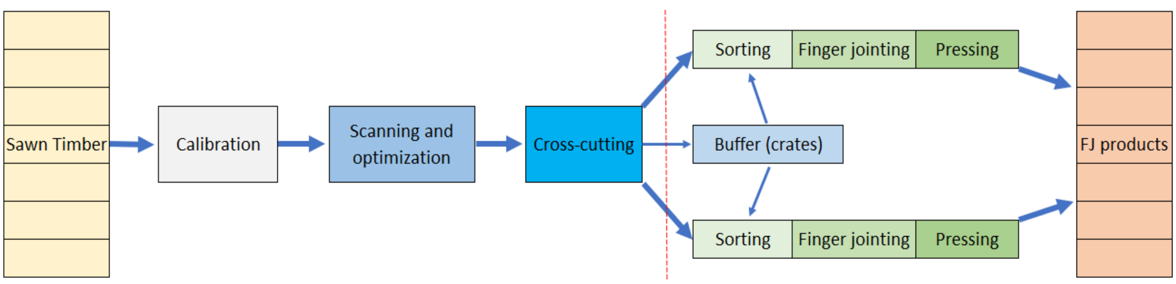

Figure 2.1 General process schema of finger joint production process

The production process of company Barrus has been certified to meet the requirements of FSC and PEFC technical documentation and process. The finger jointing process and ready products has been certified by Danish Window Verification system DVV (Barrus 2020).

2.2 Timber calibration process overview

The starting raw material for finger jointed component factory is sawn timber kiln dried to 12% of moisture content allowing for optimal gluing properties (Eesti Standardikeskus 2014) and is the equilibrium moisture content for most end-use environments (Saarman 1997).

The first step in production process is to dimensionally calibrate the rough surfaced sawn timber into smooth and dimensionally accurate planks. The clean-cut surface allows for more precise results in next production step of scanning and optimization to detect different wood properties. Effective minimal chip removal and high processing speeds are desired (Weinig 2020) for minimal dimensional loss of timber and general production efficiency. The dimensional cross-section of the wood is not further affected in production steps to follow.

The key importance in this step is to provide smooth even surface without any un-calibrated surfaces or cutting tool bites, where shape defects or poor machine set-up can result in sections of plank becoming thinner than the nominal calibration setting are. Deviations described can have an effect on scanning quality and cause shape defects in the finger jointed end-product. The calibration machine used is Weinig Hydromat 2000 which has enough capacity to feed both finger jointing stations (Weinig Hydromat 2000).

2.3 Scanning and optimization process overview

After calibration the planed planks are directly in-fed to WoodEye timber scanner that uses laser measuring to confirm the position and dimensions of the planks scanned (Fredriksson 2011). This allows for the detection of size, shape and surface roughness variations and knot holes in the wood (WoodEye 2020). For each side of the calibrated plank an RGB camera is also used to detect the various knot types, grain patterns, blue stain, resin pockets, pith and other natural wood properties. The properties are measured against the prescribed quality requirements of the products to be produced from a given raw material. These settings include the type and size of the knot, their position in relation to sides and edges of the plank as well as relative position to the direction of end-grain.

The detailed quality requirements applied to the surface layout of the product are standardized as a matrix of specific quality rules (Appendix 1). The specific rules applied are agreed with the client taking into consideration the end-product use, surface treatment and other further processing requirements.

2.3.1 Common grades in batch

The most common production recipe is to grade the timber into three different grades:

Main product (referred to as "A") is usually knot-free material with very limited tolerances for defects and undesired wood features. Used for applications requiring high aesthetical appearance and dimensional stability, such as window and door frame and sashes. An examples of a typical main grade product cross-section can be seen on figures 2.2-2.3.

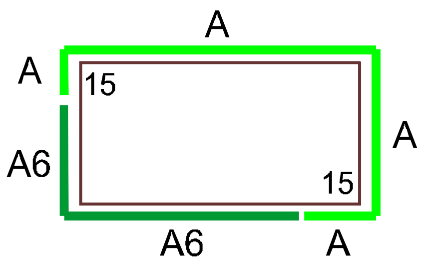

Figure 2.2 An example of grading rules applied for A-type product ("15" representing the extent of the grading area on a specific side in millimeters)

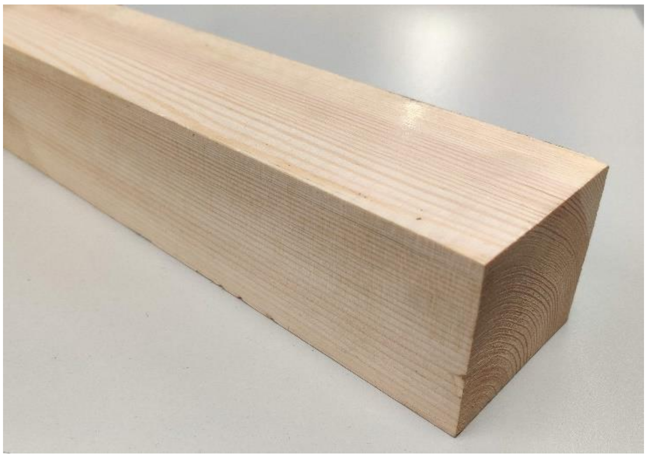

Figure 2.3 An example of an A-grade block, cross-section 61x72mm

Side-product (referred to as "B") consists of limited defects or the defects can occur only on some sides or areas of the surface. Commonly used for inside parts of windows where the possible defects are commonly not visually seen by end user. Typical B-grade product can be seen on figures 2.4-2.5.

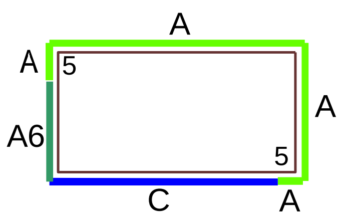

Figure 2.4 An example of grading rules applied for B-type product ("5" representing the extent of the grading area on a specific side in millimeters)

Figure 2.5 An example of a B-grade block, cross-section 58x58mm

Lower grade side-product (referred to as "C") can consist several limited size knots and defects the still allows the end product to be used structurally for applications such as wall framing or support material for construction operations. Example for C-grade product and the grading associated can be seen on figures 2.6-2.7.

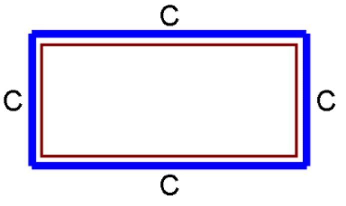

Figure 2.6 An example of grading rules applied for C-type product

Figure 2.7 An example of a C-grade block, cross-section 58x58mm

Reject (referred to as ("R") part of the optimized timber consists of large knots, knot holes, rot, excessive wane and other properties not possible to process in finger jointing operations. Also, the linear parts of the scanned timber where two defects are closer together then 140mm are cut into reject. This is because the available finger jointing technology is not capable to handle pieces shorter than 140mm in length. A selection of reject pieces are illustrated on figure 2.8.

Figure 2.8 An example of reject pieces – end-cuts, undersize, large defects

Based on the scanning results WoodEye optimizes each separate plank for optimal yield and creates a cutting pattern assigned to the specific piece that is then automatically forwarded to the next production step of cross-cutting the calibrated planks into graded blocks of wood.

2.3.2 Value optimization

Optimization system of WoodEye scanner uses two sets of parameters to decide how to distribute the grading possibilities across the scanned planks for optimal end-result.

For each grade a numeric value is assigned that represents its value in relation to the all grades produced. Standard value settings of 1000/400/200 respectively for A, B and C type products are not altered during the study at hand.

Optimization limitation on minimum and maximum lengths allowed for a single block cut are set for each grade. The common maximum length is usually set to 700mm as longer pieces tend to produce shape defects in the finger jointed end products. The standard minimum value for finger jointing machines is 150mm, but this has been enhanced by the company and can be set to as low as 140mm. Lower minimum length allows scanner to locate smaller sections of calibrated planks to be graded to A, B or C grade instead rejecting them to scrap. This improves the overall yield, but shorter average block lengths can inhibit the throughput for finger jointing equipment.

2.4 Cross-cutting process overview

For cross-cutting operation the scanned timber is forwarded by automation into three individual cutting station that use the cutting pattern assigned by WoodEye for each individual plank to be cut into specific grade blocks. Reject parts of the timber are dropped into reject material line that transports the pieces to shredder.

Figure 2.9 Metal containers as buffer room between cross-cutting and finger jointing

Graded pieces for finger jointing operations are dropped on a conveyor belts transporting the material to either of the finger jointing lines or into metal containers that serve the purpose of being a buffer room (figure 2.9). As usually three grades are cut simultaneously at least one of them is directed to the buffer and will be finger jointed later. Usually the grade with lowest yield is forwarded to buffer as emptying the containers is less efficient compared to forwarding the pieces directly to the finger jointing machine via conveyor belts.

2.5 Finger jointing process

For the process of finger-jointing two similar Weinig Turbo-S 1000 machine centers are used. Each unit consists of three sub-processes that form directly related production process: compiling the blocks into in-feed packets, cutting the joints along with applying the glue and pressing the finger jointed blocks into a solid piece. The process is illustrated in appendix 2.

2.4.1 Sorting and compilation

The graded pieces need to be compiled in specific direction as most of the finger jointed products have requirements for which direction should the end-grain be facing relative to the quality of sides designated to the end-product.

To achieve this the blocks are fed on a conveyor belt to compilation table where sorters manually inspect each block and place them side by side ensuring proper alignment of the end-grain (figure 2.10). The secondary task for sorters is to inspect the quality of each piece to verify that the pieces are corresponding to the grading rules and that the automation or grade scanning in the previous parts of the production process has not made an error. If a defect not permitted is found it is possible for sorters to manually saw the defect out using a table saw or if this is not possible then the block is sorted to a lower grade or rejected. The rate of regrading in this phase of the production is 1-2% of blocks due to various reasons described.

Figure 2.10 Turbo-S 1000 compilation table, blocks are fed from left to right

2.4.2 Finger joint cutting and pressing

From this step the automation takes over and pieces are aligned side by side to form a packet of fixed width that is then fed through a series of saws and cutting tools to form the finger joints. Glue is applied to one end of each block. As the work rate of the machine is determined in packets per time unit it means that the throughput volume is greatly dependent on height of the blocks in a packet (Weinig 2018). Usually the pieces are assembled into packets with the wider side of the cross-section being vertical. Another important factor for throughput is the average length of the blocks to be finger jointed. As the width of the packet is fixed mechanically and height of the packet is determined by the product cross-section the only parameter possible to manipulate in the production process is the average length of the blocks by altering the settings for WoodEye scanner optimization software.

Last step of the finger jointing process is feeding the blocks in a linear formation to the press where blocks are pushed together by hydraulics and then cut to length to form the final product. The pressing time varies depending on the cross-section and the length of finger joints and can be the limiting factor in the total production process depending on the length of the finished piece and other parameters described.

The ready products are compiled to a pack by automation and that is later packed and forwarded to ready product stock or to further processing for glue laminated products.

3. Task Specification

3.1 Problem description

Large scale timber joint manufacturing is heavily related to the raw material cost which consists of 75-80% of the total besides the production cost of end-product (Broman 2012). Such is the high-volume based business model meaning that in generalized terms the profit is generated through efficiency and high volume of sales.

Company Barrus has taken many technical solution steps to improve the yield of production. For example, having an integrated sawmill supplying the majority of raw material needed, optimizing sawn timber calibration sizes to the very minimum possible, using extra thin saw blades, minimizing end-cuttings etc. However, one of the most critical factors for yield is the scanning and optimization process of WoodEye scanners as this defines the value of the wood used by grading it into different end-product blocks. The quality specifications are carefully set in accordance with requirements of Barrus` clients. These settings can be improved to some extent but are limited by client requirements and by the optimization of production batch sizes through standardization of portfolio where applicable.

Regarding the minimum and maximum block length values the standard approach up to this point has been to minimize the minimum allowed block lengths and maximize the maximum lengths allowed. As generally the defects like knots and cracks are present relatively closely together the maximum value of block length allowed has little effect on the yield of timber. For the same reason minimizing the minimum value can have significant effect on the yield of sawn timber as it allows the optimization software to extract short sections of timber between not permitted defects into one of the grades designated for a batch at hand. This is standard approach has is utilized by Barrus and its competitors alike (Lillepalu 2015).

The side effect of shortening the minimum allowed lengths is that higher volume of shorter blocks needs to be processed in the finger jointing operations. Because of the technical solution of Turbo-S machines discussed previously, it has a negative effect on the throughput of the finger jointing lines. From the basic observations of the factory set-up and efficiency monitoring software Evocon (Evocon 2020) data it has been concluded by the author that the limiting factor for the factory is usually the finger jointing capacity or the pressing action integrated with it.

Evaluation of production performance can be measured by different performance indicators such as yield, earnings and throughput and as it has been proven by author`s observations they can be partly contradictory. Because of that we need to carefully reason how and what performance indicators we need to assess to judge the outcome and make decisions on the level on production planning, sales strategy and machine parameter set-up.

There for the task set is to create a mathematical model for the production set-up of finger joint manufacturing in company Barrus to better understand the process, its variables and yielding outcomes. The model needs to account for the many different parameters contributing to the end results and especially the WoodEye scanner input. Emphasize is on analyzing the effect of varying the minimum allowed lengths of A, B and C grade products seeking for optimal compromise between the key performance indicators.

The results can lead to more profitable operations strategies for both company Barrus and other finger jointing material producers alike.

3.2 Composing the hypotheses

Based on the previously discussed the following hypotheses to be tested are constructed:

H1 - increasing the overall yield through minimizing the minimum allowed block lengths has an inverse effect on earning per hour and throughput indicators.

H2 – increasing the B and C product minimum allowed length from standard 140mm value has a positive effect on both the throughput and earnings per time unit.

H3 – increasing the A product minimum allowed block lengths from standard 140mm has a strong negative effect on the earning per time unit and overall yield.

4. Methodology

The initial step to test the set hypotheses is to choose appropriate key performance indicators to analyze the batches and parameter to be simulated. Following this a production calculation model is created that provides the possibility to input WoodEye simulation data from varying the minimum block lengths and retrieve the values of key performance indicators. The relation between the input data and resulting performance indicator values will be investigated using regression analysis and observations to form predictions for optimal parameter tendencies that could be used for the future products, batches and simulations to improve the performance of the company.

4.1 Selecting the key performance indicators

The common performance indicators used to evaluate a production efficiency can be divided into production process related indicators and economic indicators. The more common units of measure used for throughput of timber manufacturing are associated with the nature of the individual operation or factory in general. It is not reasonable to consider only one unit of measure as for varying economical and production flow related circumstances may require strategic decisions to compromise between the absolute values of performance indicators.

For linear operation with timber pieces, such as planing / calibration, linear timber scanning and cross-cutting, indicators of length measure produced per time unit are used. The most common specific units being linear meters per minute or hour. Processes involving non-linear operation such as chipping wood or finger jointing are commonly measured in volume per time unit. Most commonly such used measure is cubic meters per hour (Lillepalu 2015).

In finger jointing and construction timber business by far the most common volume unit of measure for both raw material (sawn timber) as well as ready products (finger jointed material, panels, moldings, beams) is cubic meters (FAO 2017).

For this reason unit of m^3 is used to universally describe volume input and output and the key performance indicator for throughput is selected to be m^3/h. Through the production model created it can be calculated for all production steps of finger joint manufacturing.

Commonly used performance indicators to measure manufacturing operations could be divided into two: metrics focusing on throughput and efficiency of production processes and secondly the economical side related indicators of productions costs, sales and gross profit per time unit. In addition, the sub-processes present are possible to measure in secondary performance indicators such for finger jointing manufacturing packets per minute or for calibration linear meters per hour.

Calibration – production is carried on linearly there for the common metric used is linear meters per hour, lm/h.

Scanning and optimization – as the in-feeding is directly from calibration it is also measured in linear meters per minute. This is the step in production process where 75-80% of total costs are decided on. For this reason the substantive key performance indicator is yield of end product(s) from sawn timber. The unit of measure for optimizing process is yield percent.

Cross-cutting saw – production is carried out linearly and measured in linear meters per minute, but alternatively also in cuts made / blocks produced.

Finger jointing – measured in packets per time minute as the machine operation structure is based on adjusting the rate at which the packets move through the machine. The volume of blocks present in a packet has a strong effect on the volume output per time unit of finger jointing machine.

Pressing – measured linearly because blocks are adjoined together length wise. Secondary measure can also be pieces of end-product produced. Throughput depends on the cross-section and length of the resulting piece because of how long the pressing cycle time needs to be and how quickly and what length pieces are fed from previous finger joint cutting operation.

As it is possible to determine the processable timber dimensions in each step involved the one common unit of measure for volume and throughput are $\mathbf{m^3}$ and $\mathbf{m^3/h}$ respectively.

Because of the periodically limited supply and high demand for sawn timber it is important to involve also **yield percentage** as a key performance indicator on how efficiently the resources are utilized in parallel to gross profit earnings and throughput rates.

4.2 Production model description

The aim of the production model is to calculate the set dependent key performance indicators through inputting the independent values of minimum block lengths for each batch of samples tested in the model. The key dependent metrics for each machine center includes the input volume, production time, yield, output volume and throughput. Overall throughput is considered through the time required for the slowest operation and its volume output. Knowing the production costs for each machine (table 4.1) it is possible to calculate the combined production cost for each machine center involved in producing the batch. These costs can be further divided between the grades produced.

Table 4.1 Production costs

Operation	**Resource**	**No of workers involved (3 shifts)**	**Total production cost, €/h**
Calibration	Hydromat 2000-1	3	55
Optimization	WE + Paul CC saws	3	81
Finger jointing 1	Turbo-S 1	15	156
Finger jointing 2	Turbo-S 2	15	156
	Total	**33**	**448**

*in-house logistics costs distributed on operations

Other independent values required to be inserted involve the dimensions and volume of processed timber. Average set-up times and downtime rates are retrieved from production monitoring system Evocon for each machine center.

The general formula to calculate the production time required (4.1) and throughput rate possible (4.2) are described.

$$t = t_{set} + \left(\frac{V}{R}\right) \times (1 + c_{dt})$$

(4.1)

Where, t – production time required, h

t_{set} – set-up time, h

V – volume of finger jointed ready product produced, m^3

R –throughput, m^3/h

c_{dt} – average downtime, %

$$R = \frac{V}{\mathrm{t}}$$

(4.2)

Where,

R – throughput, m^3/h

VFJ – volume of finger jointed ready product produced, m^3

t – production time required, h

More detailed formulation of the formulas (4.1, 4.2) are discussed in following chapters.

4.3 Sample selection

The company portfolio for the production facility considered consists of over 2000 different products (Barrus 2020). The variations include cross-sectional differences, quality grades assigned to the sides, length of the finger joints and different end-product lengths and the density of timber used. The main difference being the cross-sectional size and quality requirements.

The products can be divided by the cross-section into two sub-groups of board-type and stud-type (Nordic Timber, 2015). Board type products are cut mainly from the from sap wood of pine logs and are pieces with thickness of 16-30mm and width of 75-150mm. An example of typical 25x125 sawn timber board on figure 4.1.

Figure 4.1 Typical board-type sawn timber, cross-section 25x125mm

Stud-type raw material is cut from the hear center of log consisting heartwood and have typical dimensions range of 32-75mm for thickness and 100-175mm in width. An example of typical 56x73 stud-type sawn timber on figure 4.2.

Figure 4.2 Typical stud-type sawn timber, cross-section 56x73mm

After calibration the sawn timber is usually cut into blocks of three different grades. The main grade yields about 50-60% of the total sawn timber volume used. Two different side products are usually obtained from which one yields about 10-15% and the lowest grade about 5-10% of the total volume. Depending on raw material used and grades produced about 20-30% of volume is lost as saw dust and rejected sections of wood.

Typical yield change through the process is described in table 4.2.

Table 4.2 Example of yield through the production process

Figure	Sawn timber	Calibration	Optimization	CC saws	FJ	Ready product
Loss in process, m^3		6,30	0,00	9,77	2,39	0,11
Accumulative loss, m^3		6,30	6,30	16,08	18,46	18,57
Volume, m^3	65,00	58,70	58,70	48,92	46,54	46,43
Overall yield, %	100,00%	90,30%	90,30%	75,30%	71,60%	71,40%

Examples of typical grading patterns can be seen on figure 4.3 (corresponding quality matrix in appendix 1).

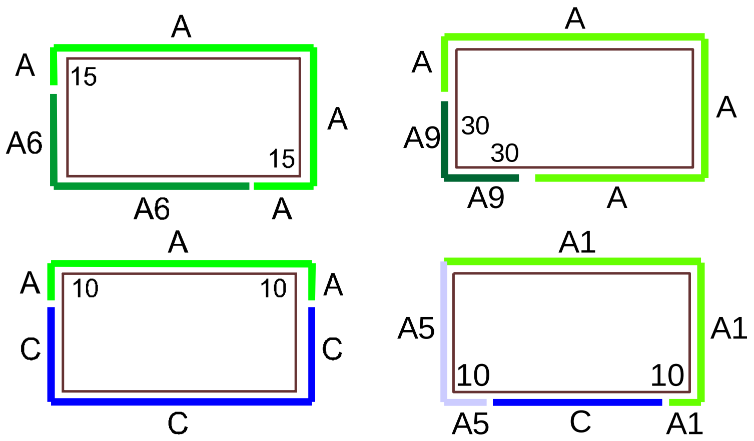

Figure 4.3 Examples of quality grades assigned to the cross-section of products (values inside the cross-section represent the length of a specific grade in millimeters)

For further testing two common cross-sections representing the discussed board-type and stud-type products with typical quality requirements are chosen. These product types have a high annual volume of sales and make it possible to interpolate the obtained data to other similar products in production.

The chosen board-type sawn timber cross-section 25x125mm calibrated to a final dimension of 23x125mm and graded according to the figure 4.4

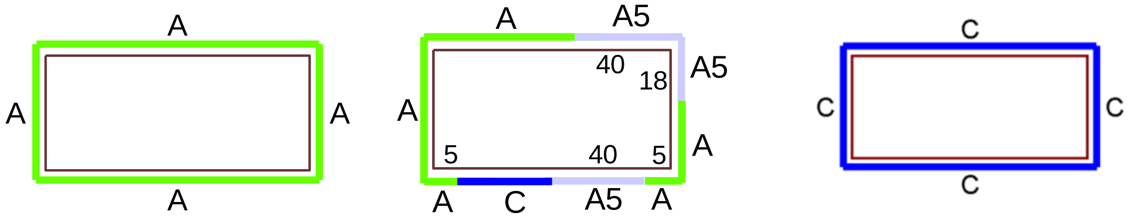

Figure 4.4 Chosen board-type products grading scheme for A, B and C blocks (values inside the cross-section represent the length of a specific grade in millimeters)

For stud-type product a sawn timber cross-section of 49x81mm is selected which is calibrated to the final dimensions of 46x78mm and graded according schemes on figure 4.5.

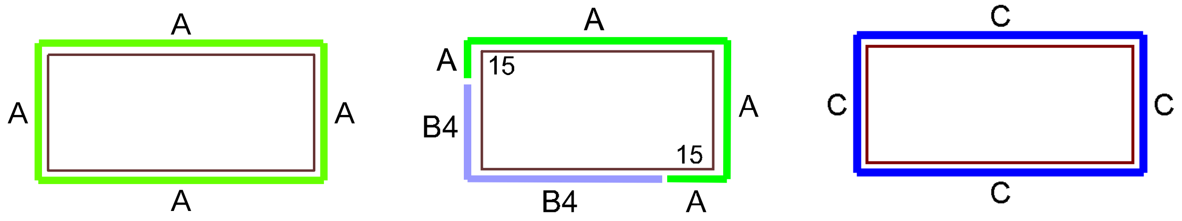

Figure 4.5 Chosen stud-type products grading scheme for A, B and C blocks (values inside the cross-section represent the length of a specific grade in millimeters)

4.4 Sample size selection

The annual volume of finger jointed material produced in considered production unit is around 45 000m^3. Average batch size of sawn timber is usually 65m3 which results in one truck load of 45-50m^3 finger jointed material.

A unit of measure must be set to determine what can be considered a single sample. The unit could be either cubic meters of sawn timber used, blocks cut, linear meters processed or pieces of sawn timber planks worked. The author of the thesis reasons pieces of sawn timber to be appropriate unit of measure to describe a sample as such. This is because a given piece of timber consists of inherit features of the log it was cut from and the blocks derived are likely to share the similar features to some extent (Saarman 1998).

To determine the appropriate sample-size it must be considered how to determine the total population size of the study. As the purpose of the study is to make predictions and conclusions on a general level and beyond the specific batch at hand, the total population is considered infinite.

For the approach on sample size calculation there are several approaches possible. Here two of the possible were considered. First of which presented (4.3) by Green (Green 1991).

$$N = 104 + k \tag{4.3}$$

Where, *N* – sample size for medium to large relationship

k= number of independent variables in a regression analysis

As three independent values of minimum block lengths are altered in analysis it would result in a minimum sample size of 107 pieces of sawn timber for both cross-sections.

Another approach (4.4) to determine a sample size is by Yamane (Yamane 1967)

$$n = \frac{N}{(1 + N \times e^2)} \tag{4.4}$$

Where, *n* – sample size

N – total population

e – margin of error

The equation present by Yamane is decided to be used to determine the further sample size and margins of error.

In table 4.3 are expressing the calculated results for 5% margin of error for both infinite population as well as an average batch size of 65m^3 for each cross-section to be used.

Table 4.3 Sample size calculations

ST thickness, mm	**ST width, mm**	**Avg L, mm**	**Batch size, m^3**	**ST, pcs**	**Margin of error, *e***	**Sample size, *n***
25	125	4,5	65	4622	5,0%	368
25	125	4,5	Infinite	Infinite	5,0%	400
49	81	4,5	65	3639	5,0%	290
49	81	4,5	Infinite	Infinite	5,0%	400

Based on the equation used it can be concluded that for 5% margin of error it is necessary to use 400 pieces of sawn timber as a sample size.

Once the simulation raw data saving began two packs were processed resulting in an even higher number of samples. The following data table represent the actual pieces saved as samples and the derived margins of error for both the batch and infinite analysis based on the chosen sample size calculation.

Table 4.4 Margins of error for obtained sample amount

ST thickness, mm	**ST width, mm**	**Avg L, mm**	**Batch size, m3**	**ST pieces (*N*)**	**Margin of error (*e*)**	**Sample size (*n*)**
25	125	4,5	65	4622	2,9%	958
25	125	4,5	Infinite	Infinite	3,2%	958
49	81	4,5	65	3639	3,8%	480
49	81	4,5	Infinite	Infinite	4,6%	480

It can be concluded (table 4.4) that the actual sample size used will provide a 3,2% margin of error for 25x125 cross-section of sawn timber and a corresponding value of 4,6% for 49x81 cross-section.

4.5 Setting WoodEye simulation parameters

The grading specification used for testing were the same applied to the actual A, B and C products in common circumstances. Other main parameters involved for WoodEye to make the optimization decisions consist of the values assigned to the individual products. Actual sales value ratios were used for all products and kept constant through all the simulations.

The main parameters subject to change involve minimum allowed blocks lengths. As discussed the maximum length allowed has been set to 700mm as this is optimal to keep the end-product shape defects under control and it is very seldom there are sections of wood that are 700mm of same grade in one linear section. The minimum allowed length values were altered and this is the basis for the analysis to follow. As current standard practice the minimum values have been set to 140mm for all products and it is not possible to lower it because of the finger jointing technology limitations and requirements set by the clients of Barrus. Thus, the AS-IS reference settings of minimum allowed block length are 140mm for all grades and products.

4.6 Data analysis

Production model and data analysis is conducted in MS Excel environment and is used for both determining the initial conclusions from production model and also the further regression analysis conducted. For the purposes of this study the functionality of the software was appropriate for both initial data processing and further analysis. MS Excel add-in module of data analysis was used for regression testing.

The retrieved sample data of yields and average block lengths is entered to the production model. Next the key performance indicators were compared and initial conclusions drawn for simulations to follow. The final simulation batches are evaluated by observations and regression analysis dependent on different minimum block lengths of the grades and regression equations derived (4.5)

$$Y_i = \beta_0 + \beta_1 \times X_1 + \beta_2 \times X_2 + \beta_3 \times X_3 + \varepsilon_i \tag{4.5}$$

Where, Yi – dependent variable

β_0 – intercept

β_1 – unknown coefficient for independent variable 1

X_1 – independent variable 1

β_2 – unknown coefficient for independent variable 2

X_2 – independent variable 2

β_3 – unknown coefficient for independent variable 3

X_3 – independent variable 3

ε_i – error term not directly observed in data

Based on the data from production model and regression analysis further samples might be simulated. The optimal minimum length value range is determined by production model key performance indicators output of yield and earning €/h and the sample data from this range is input to the regression analysis to determine the appropriate regression equation to be used for future estimates of minimum length values.

5. Production Model Development

The model developed is based on a single raw material input that can be produced up to three different products and the reject part. The reasoning for making it based on sawn timber input is that in general terms the demand for specific quality timber has proven to be almost always higher than the supply capabilities of the market (FIM 2017). As timber in a form of logs or sawn timber is relatively cheap merchandise compared to its volume, it is not economical to procure from great distances, hence the high local demand for most high capacity manufacturers. Also, in the terms of production planning of logs, sawn timber and kilning capacities the volume measure of m^3 is commonly used in Barrus and other companies in the timber manufacturing sector (Stora Enso 2020).

The production model helps to analyze the most efficient way to use the raw material resources available and how could the production process be optimized to generate highest value or other KPI-s that might be changing in superiority depending on the market situation and ready product sales.

Following sections describe what variables are accounted for in each production step and what underlying modelling logic is considered.

5.1 Calibration process parameters

The calibration process brings the rough sawn timber surface down to smooth and dimensionally accurate material. The cross-sectional dimensions do not change in the following steps of production. Only length changes as the pieces of wood are cross-cut into blocks which are later finger jointed.

The equipment used consists of a an in-feed table and a Weinig Hydromat 2000 four-side planer. The following constants and variables are considered:

Table 5.1 Constant parameters for calibration process (Weinig 2014)

Constant	Value	Unit	Description
Maximum linear speed	6600	lm/h	Maximum possible linear speed setting
Standard efficiency	90%	%	Average efficiency in normal circumstances. Data retrieved from Evocon
Set-up time	20	min	Average set-up time to change calibration dimensions. Data from monitoring software Evocon

Table 5.1 Variable parameters for calibration process (Weinig Hydromat 2014)

Variable	Unit	Description
ST thickness	mm	Used to determine the cross-sectional difference of sawn timber vs calibrated material. A matrix table of efficiency values is used to determine how much the standard efficiency is reduced because of the motor power compared to the wood removed from the original cross-section of sawn timber.
ST width		
CAL thickness		
CAL width		
Cross-section loss	mm^2	Cross-section over $500mm^2$ will have about 2% less efficiency for every 100mm2 increase because of the heavier pieces that are more prone to cause downtime.
Average ST length	m	Pieces shorter than 3,3m on average have a negative effect on the in-feed. Efficiency is reduced using an appropriate matrix table from past testing.
ST on sticks?	Y/N	If sawn timber layers are on individual kilning sticks then the monitoring data has indicated 1% loss in general due to problems related to automatic stick collection.

As calibration is a linearly carried out process the processed linear meters are first calculated (5.1).

$$lm = \left(\frac{V_{ST}}{T_{ST} \times W_{ST}}\right)^{10^6} \times (1 - r_{cal}) \tag{5.1}$$

Where, *lm* – length meters processed, m

V_{ST} – volume of sawn timber, m^3

T_{ST} – thickness of sawn timber, mm

W_{ST} – width of sawn timber, mm

r_{cal} – yield loss from damaged sawn timber pieces

Calibration throughput formula is constructed (5.2)

$$R_{CAL} = \frac{V_{ST} \times Y_{FJ}}{lm/v_{cal} \times (1 + c_{dt})} \tag{5.2}$$

Where, R_{CAL} – rate of throughput from calibration process, m^3/h

V_{ST} – volume of sawn timber, m3

Y_{FJ} – yield of finger jointed ready products from sawn timber

lm – length meters processed, m

v_{CAL} – nominal processing rate of calibration, lm/h

c_{dt} – downtime coefficient

In common circumstances the calibration capacity is not the limiting element in the whole production line set-up.

5.2 Timber scanning and optimization parameters

Scanning the calibrated planks is done in-line with the calibration line and the feed speed is there for equal to the one of calibration. The settings consist of specific quality grades assigned to the product assortment. The standard settings changed and optimized are the value settings and allowed length values for blocks to be cut in each grade (5.3)

For simulations in this study the value parameters are left constant at 1000/400/200, which are also the average earnings ratios of A, B and C grade quality end-products if the allowed block length limitations are the same (table 5.4)

Table 5.3 Variable parameters for scanning and optimization process (WoodEye 2015)

Variables	Value	Unit	Description
Block min/max length	140-700	mm	Key parameter changed in the study

Table 5.4 Constant parameters for scanning and optimization process (WoodEye 2015)

Constant	Value	Unit	Description
A grade value	1000	n/a	Speed at which the blocks are feed into a single row of material
B grade value	400	n/a	Average efficiency in normal circumstances. Data from monitoring software
C grade value	200	n/a	Set-up time to changes the length of the end-stop and adjusting the hydraulic pressure and wait times
Quality requirement	n/a	n/a	Specific quality requirements for each grade produced. Constant optimal settings are selected for each simulation in this study.

5.3 Cross-cutting parameters

Cross-cutting pattern for each plank is retrieved directly from the previous process of scanning the pieces with WoodEye scanner.

Table 5.5 Constant parameters for cross-cutting process (Paul 2006)

Constants	Value	Unit	Description
Max linear speed	5100	lm/ h	Maximum speed setting both by technical specification and testing
Standard efficiency	85	%	Average efficiency in normal circumstances. Data is from monitoring software.
Set-up time	Cal>CC	min	Set-up of calibration machine always takes more time then setting up cross-cutting saws. For that reason no set-up time is calculated for saws.
Saw kerf	2,6	mm	The width of the saw blade
Cycle time	0,15	s	Time for saw to move through the material and back to rest position after the piece has stopped.
Acceleration	0,1	s	Time for piece to start moving on nominal linear speed
Deceleration	0,1	s	Time for piece to slow to a stop from moving at nominal speed
Loading the next board	1	s	Time for a new pcs to enter the machine after the last cut has been made for the previous
no. of saws	3	pcs	Number on identical cross-cutting units
Rejects	3	pcs/m	Average reject section of wood per linear meter

Table 5.6 Variable parameters for cross-cutting process (Paul 2006)

Variables	Unit	Description
Front end-cut	mm	Ends are pre-cut to avoid possible thin crack that WE might not have noticed
Rear end-cut	mm	Ends are pre-cut to avoid possible thin crack that WE might not have noticed
Average block length	mm	Data from WE simulations, value is separate for all three quality classes. Allowing for shorter block lengths translate into more cuts made and time spent on the operation.
Input volume	lm	Determines the total time and depends on WE simulation information

The cross-cutting process throughput is strongly effect by the number of cuts made / average block length cut (table 5.4-5.5) The time needed for a single cut consists of acceleration, deceleration and saw movement times (5.3).

$$t_{cyc} = t_{dec} + t_{saw} + t_{acc}$$

(5.3)

Where, t_{cyc} – time to make one cut cycle, s

t_{dec} – time to decelerate the moving piece of calibrated material, s

t_{saw} – time for the saw blade to do the cut, s

t_{acc} – time to accelerate the piece from stand still, s

Next the throughput formula for cross-cutting saws is constructed (5.4).

$$R_{CC} = \frac{V_{ST} \times Y_{FJ} \times n_{ccs}}{lm \div v_{cc} + \left\{\left[\frac{lm \times 2}{L_{ST}} + \left(\frac{L_{ST} - L_{ec} \times 2}{L_{wavg}} - 1\right) \times \frac{lm}{L_{ST}}\right] \times t_{cyc} + t_{load} \times \frac{lm}{L_{ST}}\right\} \div 3600}$$

(5.4)

Where, R_{CC} – rate of throughput from cross-cutting saws, m^3/h

V_{ST} – volume of sawn timber, m^3

Y_{FJ} – yield of finger jointed ready product from sawn timber

n_{ccs} – number of identical cross-cutting machines used

lm – length meters processed, m

V_{cc} – nominal feeding speed of cross-cutting saws, m/h

L_{ST} – average sawn timber piece length, m

L_{ec} – end-cut length, m

L_{wavg} – weighted average block length cut, m

t_{cyc} – total time to make a cut, s

t_{load} – time to load a new piece into cross-cutting saw, s

5.4 Finger jointing process

The finger jointing process speed is mainly determined by the dimensional size of the blocks (table 5.7) and is measured in packets per minute. The constants to consider are the fixed packet width and standard set-up times and pre-trim cutting to clean the end-surface for finger joint cutting (table 5.8). The common limiting factor in production process, according to both technical data and production monitoring system Evocon, is usually either the packet speed for short average block length or the later pressing action for longer block lengths. For that reason the throughput calculation formulas are constructed for these two sub-sections.

Table 5.7 Variable parameters for finger jointing process (Weinig 2018)

Variables	Value	Unit	Description
Finger joint length	6-10	mm	Ends are pre-cut to avoid possible thin cracks that WE might not have detected during scanning
Average blocks T	46/23	mm	Determines how many pieces fit inside the packet
Average block W	78/123	mm	Determines the height of block packet processed
Average block L*	140-700	mm	Determines the volume of an average packet
Packet cycle time	3-10	packets/ min	The speed setting of the machine.

*The average block length values are retrieved from WoodEye simulation data.

Table 5.8 Constant parameters for finger jointing process (Weinig 2018)

Constants	Value	Unit	Description
Width of the in-feed packet	650	mm	Determines how many blocks in a provided thickness fits inside the in-feed packet. Value of number of blocks is rounded down to whole number
Standard efficiency	85	%	Average efficiency in normal circumstances. Data from monitoring software Evocon
Set-up time, min	40	min	Set-up time to change the settings dimensions, glue application, pressing times etc.
Pre-trim	3	mm	Each end of a blocks is pre-trimmed to form an accurate base for finger joint cutting

5.4.1 Finger joint cutting process

The volume throughput rating of finger jointed material passing through the finger joint forming process is calculated including the ready product losses from length cutting present after pressing action (5.5).

$$R_{FJ} = \left[r_P \times \left\lfloor \frac{W_p}{T_{FJ}} \right\rfloor \times T_{FJ} \times W_{FJ} \times \left(L_{avg} - 2 \times L_t - L_{FJ}\right) \times \left(1 - \frac{k + L_{cl} + L_o}{L_P}\right) \right]^{10^{-9}} \tag{5.5}$$

Where, R_{FJ} – rate of throughput from finger joint cutting, m³/h

r_P – packet cycle rate, packets/h

W_p – width of the in-feed packet, mm

T_{FJ} – thickness of finger jointed product, mm

W_{FJ} – width of finger jointed product, mm

L_{avg} – average length of blocks to be finger jointed, mm

L_t – trim length of block ends, mm

L_{FJ} – length of finger joint, mm

k – sawblade kerf, mm

L_{cl} – loss from cutting the ready product to length, mm

L_o – ready product length oversize, mm

L_p – length of a finished product, mm

5.4.2 Finger joint pressing process

In the process of pressing the finger jointed blocks with glue applied are aligned linearly, pressed together and the resulting piece cut to specified length. The trimming process constants involves some loss of material from end-cutting the pieces to exact length and average set-up times and efficiency ratings (table 5.9). Pressing times vary based on the cross-section of blocks and length of the fingers (table 5.10).

Table 5.9 Constant parameters for pressing process (Weinig 2018)

Constants	Value	Unit	Description
Speed of the aligner	300	m/min	Speed at which the blocks are feed into a single row of material
Standard efficiency	85	%	Average efficiency in normal circumstances. Data from monitoring software
Set-up time	10	min	Set-up time to changes the length of the end-stop and adjusting the hydraulic pressure and wait times
Final trim	10	mm	Average length of material lost in cutting to ready product length specification

Table 5.10 Variable parameters for pressing process (Weinig 2018)

Variables	Value	Unit	Description
Length of the ready product	6-10	mm	Depends on the client order
Pressing time	1,5-5	s	Depends on the cross-section of blocks

Pressing is the final part of the process and one of the two possible limiting factors for overall throughput depending on the average length of the finger jointed blocks. The process can be further divided into two sections of aligning the finger jointed blocks in a row for pressing and the pressing action itself.

The pressing process throughput is calculated by the components of linearly feeding the blocks to pressing section and the time it takes to make the cut and press the obtained pieces together.

First the linear in-feed speed is calculated (5.6). As the alignment conveyor can run up to 300 m/min (table 5.9) it is more than capable to feed the blocks. The actual feeding speed is determined by the linear meters present in the finger jointing packet and the cycle time of it.

$$R_{al} = \left(\left\lfloor\frac{W_P}{T_{FJ}}\right\rfloor \times \left(L_{avg} - 2 \times L_t - L_{FJ}\right) \times r_p\right)^{10^{-3}}$$

(5.6)

Where, R_{al} – rate of finger jointed blocks fed from packet into press, lm/min

W_p – width of the in-feed packet, mm

T_{FJ} – thickness of finger jointed product, mm

L_{avg} – average length of blocks to be finger jointed, mm

L_t – trim length of block ends, mm

L_{FJ} – finger joint length, mm

r_p – packet cycle rate, packets/h

As the pressing segment of finger jointing machine needs separate evaluation the throughput for it is calculated (5.7).

$$R_{pr} = \left(L_P \times T_{FJ} \times W_{FJ}\right)^{10^{-9}} \div \left(\left(\frac{(L_P + k + L_{cl} + L_o)^{10^{-3}}}{R_{al}}\right) \div 60 + \frac{t_c + t_p}{3600}\right)$$

(5.7)

Where, R_{pr} – throughput of pressing operations, m^3/h

L_p – nominal length of a finished product, mm

T_{FJ} – thickness of finger jointed product, mm

W_{FJ} – width of finger jointed product, mm

k – sawblade kerf, mm

L_{cl} – loss from cutting the ready product to length, mm

L_o – ready product length oversize, mm

R_{al} – alignment rate, lm/min

t_c – cutting time in press, s

t_p – pressing time, s

5.5 Composing yield KPI calculations

For calculating the key performance indicator of yields for grades produced it is first calculated the yield loss in calibration process (5.8)

$$Y_{cal} = 1 - \left[(1-r) \times \left(\frac{T_{FJ} \times W_{FJ}}{T_{ST} \times W_{ST}}\right)\right] \times 100\% \tag{5.8}$$

Where, Y_{cal} – yield loss in calibration process, %

r – damaged and/or rejected sawn timber volume before or during calibration process, %

T_{FJ} – thickness of finger jointed product, mm

W_{FJ} – width of finger jointed product, mm

T_{ST} – sawn timber thickness, mm

W_{ST} – sawn timber width, mm

Next the yield loss in finger jointing operations is calculated (5.9).

$$Y_{FJ} = 1 - \left[(1-S_G) \times \frac{2 \times L_t + L_{FJ}}{L_{WavgG}} \times \frac{k + L_{cl} + L_o}{L_p}\right] \times 100\% \tag{5.9}$$

Where, Y_{FJ} – yield loss in finger jointing and pressing process, %

S_G – secondary sorting loss in compilation for grade selected, %

L_t – length of end-trimming before finger joint cutting, mm

L_{FJ} – length of finger joint cut, mm

L_{WavgG} – weighted average length of blocks from WE optimization data, mm

k – sawblade kerf, mm

L_{cl} – loss from cutting the ready product to length, mm

L_o – ready product length oversize, mm

L_p – length of a finished product, mm

During the set-up of the finger jointing machines some pieces are lost and scrapped. Also test sample pieces are withdrawn in regular intervals that are considered scrap later as the cross-sectional dimensions are altered. These losses in yield are dependent on the cross-section of products and time needed for production (5.10).

$$V_x = r_{t0} \times T_{FJ} \times W_{FJ} \times (L_P + k + L_{cl} + L_0) + \frac{T_{FJ} \times W_{FJ} \times (L_P + k + L_{cl} + L_0) \times t}{f}$$

(5.10)

Where, V_x – volume loss from set-up and testing of sample pieces, m^3

r_{t0} – average amount of ready products rejected during set-up, pieces, pcs

T_{FJ} – finger jointed products thickness, mm

W_{FJ} – finger jointed products width, mm

L_p – nominal length of the ready product, mm

k – cut width of sawblade, mm

L_{cl} – length of piece lost by cutting the ready product to specified length, mm

L_o – average ready product length oversize, mm

t – production time of finger jointing machine, h

f – average period for taking a test piece to verify finger joint quality, h

For overall yield of a specific grade produced all the previously derived losses are taken into consideration (5.11).

$$Y_g = \frac{\left[V_{STg} \times (1 - Y_{cal}) \times Y_G \times \left(1 - Y_{FJ}\right)\right] - V_x}{V_{ST}} \times 100\%$$

(5.11)

Where, Y_g – yield of grade selected, %

V_{stg} – total volume of sawn timber used for particular grade, m^3

Y_{cal} – yield loss in calibration process, %

Y_G – yield of grade selected from WE simulation, %

Y_{FJ} – yield loss in finger jointing and pressing process, %

V_x – volume loss from set-up and testing of sample pieces, m^3

For calculations of total ready product yielding from raw material all individual yields of grades produced are added (5.12).

$$Y = Y_{gA} + Y_{gB} + Y_{gC}$$

(5.12)

Where, Y – overall yield of simulation, %

Y_{gA} – yield of A grade, %

Y_{gB} – yield of B grade, %

Y_{gC} – yield of C grade, %

For both of the calculations (5.11-5.12) the end-cuttings and saw kerfs of calibrated planks in cross-cutting operations is not expressed as this volume is already calculated as reject by WoodEye Simulations and not present in the grade yield values obtained from simulation software.

Once the yield values for specific grades produced are calculated it is possible to estimate the effective finger jointed ready product output volume (5.13-5.16) and the volume difference of saw dust, damaged pieces, test pieces etc. are considered as rejects (5.17).

$$V_A = V_{ST} \times Y_A \tag{5.13}$$

Where, V_A - volume of A-grade finger jointed ready product

V_{ST} - volume of sawn timber used

Y_A – yield of A-grade finger jointed material from sawn timber

$$V_B = V_{ST} \times Y_B \tag{5.14}$$

Where, V_B - volume of B-grade finger jointed ready product

V_{ST} - volume of sawn timber used

Y_B – yield of B-grade finger jointed material from sawn timber

$$V_C = V_{ST} \times Y_C \tag{5.15}$$

Where, V_C - volume of C-grade finger jointed ready product

V_{ST} - volume of sawn timber used

Y_C – yield of C-grade finger jointed material from sawn timber

$$V_{FJ} = V_{ST} \times Y_{FJ} \tag{5.16}$$

Where, V_{FJ} – total volume of finger jointed ready products

V_{ST} - volume of sawn timber used

Y_{FJ} – yield of A-grade finger jointed material from sawn timber

$$V_R = V_{ST} - V_{FJ} \tag{5.17}$$

Where, V_R - volume of A-grade finger jointed ready product

V_{ST} - volume of sawn timber used

V_{FJ} - total volume of finger jointed ready products

The detailed volume of grades produced is needed for later calculations on earnings.

5.7 Composing throughput KPI calculations

The approach used to calculated the throughput uses the average production times of the two finger jointing machines that are used simultaneously. If one machine finishes the production earlier it effectively start to set-up for a next batch and thus the average time spent on a batch for 2 finger jointing machines is appropriate for time factor in throughput formula presented (figure 5.11).

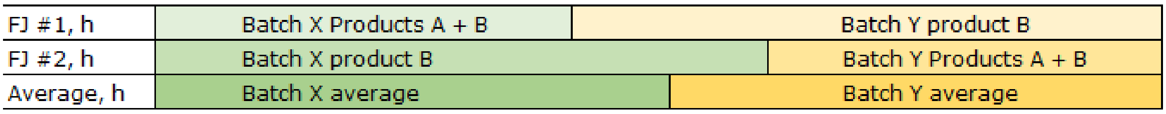

Figure 5.11 Illustration of total production time used for two finger jointing machines

There for the production time calculation is formulated as an average of two finger jointing machines (5.18)

$$t = \frac{t_1 + t_2}{2} \tag{5.18}$$

Where, t – total production time, h

t_1 – production time for finger jointing machine #1, h

t_2 - production time for finger jointing machine #2, h

To determine the limiting factor for production of each product the corresponding values of R_{FJ} and R_{pr} are calculated and the limiting factor determined (5.19).

$$R = min\{R_{CAL}; R_{CC}; R_{FJ}; R_{pr}\}$$

(5.19)

Where, R – overall throughput of one finger jointing line, m^3/h

R_{CAL} – rate of throughput from calibration process, m^3/h

R_{CC} – rate of throughput from cross-cutting saws, m^3/h

R_{FJ} – finger joint cutting throughput, m^3/h

R_{pr} - pressing throughput, m^3/h

The approach of determining the minimal throughput value is used for calculations in all simulations to follow. Production time required for each of the machines is constructed the same (5.20).

$$t_{FJ} = t_{set} + \frac{V_{FJ}}{R} \times (1 - c_{dt})$$

(5.20)

Where, t_{FJ} – production time for finger jointing operation of one machine, h

t_{set} – average set-up time for finger jointing machine, h

V_{FJ} – volume of finger jointed ready product, m^3

R – throughput of finger jointing machine, m^3/h

C_{dt} – coefficient of average downtime, %

5.8 Composing economical KPI calculations

For economic KPI earnings per hour was selected. For that the components of sales value generated and costs associated are calculated (5.21)

$$S_t = P_A \times V_A + P_B \times V_B + P_C \times V_C + P_R \times V_R$$

(5.21)

Where, S_t – total sales value, €

P_A – A grade ready product sales price, €/m^3

V_A – volume of A grade ready product, m^3

P_B - B grade ready product sales price, €/m^3

V_B - volume of B grade ready product, m^3

P_C - C grade product sales price, €/m^3

V_C - volume of C grade ready product, m^3

P_R - C grade product sales price, €/m^3

V_R - volume of C grade ready product, m^3

Next the total raw material cost in a form of sawn timber is calculated (5.22).

$$C_{ST} = P_{ST} \times V_{ST} \tag{5.22}$$

Where, C_{ST} – cost of sawn timber, €

P_{ST} – sawn timber cost, €/m^3

V_{ST} – volume of sawn timber used, m^3

Total production costs involved for first part of the production step of calibration, scanning and cross-cutting by having the production time as the average of finger jointing machines. For finger jointing machines the costs are calculated separately because production times and costs associated vary (5.23).

$$C_P = (C_{PC} + C_{PWE} + C_{PCC}) \times [(C_{PC} + C_{PWE} + C_{PCC}) \times t + C_{T1} \times t_{T1} + C_{T2} \times t_{T2}] \tag{5.23}$$

Where, C_P – Total production cost, €

C_{PC} – production costs of calibration process, €/h

C_{PWE} – production costs of WoodEye scanner, €/h

C_{PCC} – production costs of cross-cutting saws, €/h

C_{PT1} – production costs of finger jointing machine #1, €/h

C_{PT2} - production costs of finger jointing machine #2, €/h

t – total production time, h

t_1 – production time for finger jointing machine #1, h

C_{T1} – production costs of finger jointing machine #1, €/h

t_2 - production time for finger jointing machine #2, h

C_{P2} - production costs of finger jointing machine #2, €/h

After having all the individual components available the earnings per hour KPI is calculated (5.24)

$$E = \frac{S_t - C_{ST} - C_p}{t} \tag{5.24}$$

Where, E – earning per hour, €/h

S_t – total turnover from sales, €

C_{ST} – cost of sawn timber, €

C_P – Total production cost, €

t – total production time, h

6. Initial Simulations

For this study two sawn timber cross-sections were chosen to represent the usual board-type products and the even sided stud-type product. For both of the chosen cross-sections three typical product grades were assigned, represented as A for main product and B and C for side-products.

Table 6.1 Sample size and volume

Cross-section, mm	**Cross-section type**	**Samples, boards**	**Average ST length, mm**	**Volume, m^3**	**Linear meters**
25x125	Board	958	4551	13,47	4311
49x81	Stud	460	4725	8,76	2208

The samples were of commonly used pine (*Pinus Sylvestris*) sawn timber quality level SF+V grade (Nordic Timber 2015) and average moisture content at 12%. The detailed data of sample pieces was saved during normal production operations (table 6.1). The data consists dimensions and wood feature possible for WoodEye scanner to detect. The data of saved sample pieces can be graded under many different simulation parameters and values. For the following simulations the grading patterns described in chapter 4.1 were used.

For initial simulations the standard minimum block length settings of 140mm were used for all products to set the base line referred to as “AS IS”. For comparative simulations the settings are changed by 60mm increments. For A products the settings are changed up to 200mm and for B and C grades up to 380mm. In total 50 initial simulation were conducted for both cross-sections chosen.

6.1 Initial simulation of board-type products

The results obtained for board type products are described in the following table (6.2) by color coding the selected KPI change from AS IS settings and ordered by earning per hour values.

Table 6.2 Initial simulation data of board-type products, ordered by change in earnings per hour

Sim no	L_{min}, mm			FJ yield			KPI			KPI change		
	A	B	C	A	B	C	FJ yield	FJ m³/h	€/h	FJ yield	FJ m³/h	€/h
BI50	200	380	380	55,3%	4,2%	6,7%	66,2%	8,77	599	-6,0%	7,0%	-3,9%
BI32	200	200	200	53,9%	11,2%	5,7%	70,8%	8,59	607	-1,4%	4,8%	-2,7%
BI46	200	380	140	55,2%	4,4%	13,9%	73,6%	8,56	608	1,3%	4,4%	-2,5%
BI16	140	320	140	58,0%	3,9%	10,3%	72,3%	8,34	610	0,1%	1,8%	-2,1%
BI38	200	260	260	54,1%	8,9%	6,3%	69,3%	8,85	611	-2,9%	8,0%	-2,1%
BI49	200	380	320	54,9%	5,0%	8,1%	68,0%	8,91	612	-4,3%	8,7%	-1,7%
BI25	140	380	380	57,9%	3,7%	4,5%	66,1%	8,39	613	-6,1%	2,3%	-1,6%
BI41	200	320	140	55,2%	5,9%	12,3%	73,4%	8,63	614	1,2%	5,3%	-1,5%
BI45	200	320	380	54,9%	6,8%	5,1%	66,8%	8,81	616	-5,4%	7,4%	-1,2%
BI24	140	380	320	57,9%	3,5%	6,0%	67,4%	8,47	618	-4,8%	3,3%	-0,9%
BI26	200	140	140	55,1%	13,2%	4,4%	72,7%	8,26	618	0,5%	0,8%	-0,9%
BI47	200	380	200	55,2%	4,4%	12,1%	71,6%	8,71	618	-0,6%	6,2%	-0,8%
BI11	140	260	140	58,1%	5,4%	8,8%	72,3%	8,40	619	0,1%	2,5%	-0,8%
BI21	140	380	140	58,2%	3,5%	11,4%	73,1%	8,34	619	0,8%	1,8%	-0,7%
BI22	140	380	200	58,1%	2,9%	9,5%	70,6%	8,45	619	-1,7%	3,0%	-0,7%
BI20	140	320	380	57,8%	4,9%	3,7%	66,5%	8,38	620	-5,7%	2,2%	-0,6%
BI23	140	380	260	58,1%	3,1%	7,6%	68,8%	8,53	620	-3,4%	4,0%	-0,5%
BI6	140	200	140	58,1%	7,0%	6,9%	72,1%	8,37	621	-0,1%	2,1%	-0,4%
BI44	200	320	320	54,9%	6,7%	6,4%	68,0%	8,88	621	-4,2%	8,4%	-0,4%
BI48	200	380	260	55,5%	4,3%	9,9%	69,7%	8,80	622	-2,5%	7,3%	-0,3%
BI2	140	140	200	58,0%	9,7%	3,3%	71,0%	8,22	622	-1,2%	0,2%	-0,2%
BI5	140	140	380	58,0%	9,8%	1,8%	69,5%	8,17	623	-2,7%	-0,3%	0,0%
BI17	140	320	200	58,1%	4,0%	8,3%	70,4%	8,50	623	-1,8%	3,6%	0,0%
AS IS	140	140	140	58,4%	9,7%	4,2%	72,2%	8,20	623	0,0%	0,0%	0,0%
BI19	140	320	320	57,8%	4,9%	4,9%	67,6%	8,45	624	-4,7%	3,1%	0,1%
BI4	140	140	320	58,0%	9,8%	2,2%	69,9%	8,19	624	-2,3%	0,0%	0,1%
BI15	140	260	380	57,6%	6,6%	3,1%	67,3%	8,38	625	-5,0%	2,2%	0,2%
BI3	140	140	260	58,0%	9,7%	2,6%	70,3%	8,21	625	-1,9%	0,1%	0,2%
BI27	200	140	200	55,1%	13,3%	3,4%	71,8%	8,28	625	-0,5%	1,0%	0,2%
BI36	200	260	140	55,3%	8,2%	10,0%	73,4%	8,73	625	1,2%	6,5%	0,3%
BI43	200	320	260	55,0%	6,4%	8,2%	69,6%	8,93	626	-2,6%	8,9%	0,4%
BI42	200	320	200	55,3%	5,8%	10,3%	71,4%	8,79	626	-0,8%	7,2%	0,5%
BI18	140	320	260	57,9%	4,6%	6,2%	68,8%	8,50	627	-3,5%	3,7%	0,5%
BI40	200	260	380	54,9%	8,8%	4,0%	67,7%	8,77	628	-4,6%	7,0%	0,7%
BI29	200	140	320	55,1%	13,2%	2,4%	70,7%	8,28	629	-1,5%	1,1%	0,9%
BI12	140	260	200	58,0%	5,8%	6,5%	70,3%	8,49	630	-1,9%	3,5%	1,0%
BI10	140	200	380	57,8%	8,1%	2,4%	68,3%	8,31	630	-4,0%	1,4%	1,0%
BI30	200	140	380	55,2%	13,3%	2,0%	70,4%	8,26	630	-1,8%	0,8%	1,1%
BI9	140	200	320	57,8%	8,0%	3,1%	68,9%	8,35	632	-3,3%	1,9%	1,4%
BI7	140	200	200	57,9%	7,8%	4,9%	70,5%	8,40	632	-1,7%	2,5%	1,4%
BI8	140	200	260	57,8%	7,9%	3,8%	69,6%	8,20	634	-2,7%	0,0%	1,7%
									Color coding	-10,0%	AS IS	10,0%

Table 6.2 Initial simulation data of board-type products, ordered by change in earnings per hour

Table 6.2 continued

Sim no	L_{min}, mm			FJ yield			KPI			KPI change		
	A	B	C	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
BI37	200	260	200	55,0%	8,4%	7,7%	71,2%	8,91	634	-1,1%	8,7%	1,7%
BI35	200	200	380	55,0%	10,9%	3,1%	68,9%	8,58	635	-3,3%	4,7%	1,9%
BI13	140	260	260	58,2%	5,7%	5,0%	69,0%	8,43	635	-3,3%	2,9%	1,9%
BI28	200	140	260	55,4%	13,4%	2,6%	71,4%	8,28	636	-0,8%	1,0%	2,0%
BI34	200	200	320	54,9%	10,9%	3,7%	69,6%	8,61	637	-2,7%	5,0%	2,2%
BI14	140	260	320	58,2%	6,3%	3,8%	68,3%	8,41	638	-3,9%	2,6%	2,3%
BI39	200	260	320	55,2%	8,8%	4,8%	68,8%	8,82	639	-3,4%	7,6%	2,5%
BI31	200	200	140	55,7%	10,4%	7,2%	73,4%	8,66	639	1,1%	5,6%	2,5%
BI33	200	200	260	55,3%	10,6%	4,3%	70,3%	8,65	643	-2,0%	5,5%	3,2%
									Color coding	-10,0%	AS IS	10,0%

From the initial test of board-type products it appears that increasing the minimum length of blocks increases the throughput significantly and earnings by a small margin of 1-2%. In most of the simulations the added production rate comes at the cost of notably lower yield.

Initial observations indicate that increasing the B and C product minimum allowed length over 320mm has a strong negative effect on the yield which is not compensated by the higher throughput rate achieved as the earnings per hour decline as well.

The combined yield becomes maximized once the C-grade material is allowed to be lower than A and B product minimum length values. This was expected because now the shorter segments of wood are all cut to C-grade plus some extra around the defects that would have been graded to A-grade before.

6.2 Initial simulations of stud-type products

For stud-type products the same 50 combinations of allowed minimum lengths were simulated. The results obtained are described in table 6.3 by color coding the change in key performance indicators from AS IS settings and ordered by earning per hour value.

Table 6.3 Initial simulation data of stud-type products, ordered by change in earnings per hour

Sim no	L_{min}, mm			FJ yield			KPI			KPI change		
	A	B	C	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
SI26	200	140	140	47,2%	16,0%	9,4%	72,6%	7,71	512	1,0%	1,0%	-3,8%
SI31	200	200	140	47,0%	13,1%	12,8%	73,0%	8,12	530	1,3%	6,4%	-0,6%
AS IS	140	140	140	50,5%	11,7%	9,4%	71,7%	7,63	533	0,0%	0,0%	0,0%
SI46	200	380	140	47,2%	5,1%	22,0%	74,3%	8,30	535	2,6%	8,8%	0,5%
SI27	200	140	200	47,1%	16,0%	6,7%	69,7%	7,87	536	-1,9%	3,1%	0,6%
SI41	200	320	140	47,1%	7,6%	19,2%	74,0%	8,32	536	2,3%	9,0%	0,7%
SI36	200	260	140	47,2%	10,0%	16,5%	73,8%	8,31	541	2,2%	9,0%	1,5%
SI28	200	140	260	47,1%	16,1%	4,9%	68,0%	7,91	548	-3,6%	3,7%	2,9%
SI6	140	200	140	50,5%	9,2%	12,4%	72,1%	7,86	549	0,4%	3,1%	3,1%
SI29	200	140	320	47,1%	16,1%	3,9%	67,1%	7,90	551	-4,6%	3,6%	3,5%
SI30	200	140	380	47,1%	16,2%	3,2%	66,6%	7,89	553	-5,1%	3,4%	3,8%
SI11	140	260	140	50,6%	6,7%	15,2%	72,5%	7,90	554	0,8%	3,6%	4,0%
SI21	140	380	140	50,6%	3,7%	18,5%	72,9%	7,91	554	1,2%	3,7%	4,1%
SI16	140	320	140	50,6%	5,2%	16,9%	72,7%	7,91	555	1,1%	3,7%	4,1%
SI2	140	140	200	50,5%	11,8%	6,7%	68,9%	7,77	556	-2,7%	1,9%	4,5%
SI32	200	200	200	47,0%	13,1%	9,9%	70,1%	8,42	558	-1,6%	10,4%	4,9%
SI47	200	380	200	47,2%	5,1%	19,4%	71,7%	8,57	559	0,0%	12,3%	5,0%
SI42	200	320	200	47,1%	7,6%	16,4%	71,2%	8,61	563	-0,5%	12,9%	5,7%
SI37	200	260	200	47,1%	10,1%	13,7%	70,8%	8,63	564	-0,9%	13,1%	5,8%
SI3	140	140	260	50,4%	11,9%	4,9%	67,2%	7,79	566	-4,4%	2,2%	6,2%
SI50	200	380	380	46,9%	5,9%	13,7%	66,4%	8,88	567	-5,2%	16,4%	6,5%
SI48	200	380	260	47,1%	5,2%	17,3%	69,7%	8,71	568	-2,0%	14,2%	6,6%
SI4	140	140	320	50,4%	12,0%	3,7%	66,2%	7,77	568	-5,5%	1,9%	6,7%
SI49	200	380	320	47,0%	5,6%	15,4%	68,0%	8,81	570	-3,7%	15,5%	7,0%
SI5	140	140	380	50,5%	12,1%	2,9%	65,5%	7,75	570	-6,1%	1,6%	7,0%
SI33	200	200	260	47,0%	13,2%	7,9%	68,2%	8,46	570	-3,5%	10,9%	7,0%
SI45	200	320	380	46,9%	8,2%	10,8%	65,9%	8,94	572	-5,8%	17,1%	7,5%
SI34	200	200	320	47,0%	13,4%	6,5%	66,9%	8,44	573	-4,8%	10,6%	7,6%
SI43	200	320	260	47,0%	7,9%	14,2%	69,1%	8,78	573	-2,6%	15,2%	7,6%
SI35	200	200	380	47,0%	13,4%	5,6%	66,0%	8,42	574	-5,7%	10,4%	7,7%
SI7	140	200	200	50,4%	9,3%	9,3%	69,1%	8,12	574	-2,6%	6,4%	7,8%
SI44	200	320	320	46,9%	8,2%	12,3%	67,4%	8,88	575	-4,3%	16,5%	7,9%
SI38	200	260	260	47,0%	10,3%	11,3%	68,6%	8,81	576	-3,0%	15,5%	8,1%
SI40	200	260	380	46,9%	10,6%	8,3%	65,8%	8,84	576	-5,9%	15,8%	8,1%
SI39	200	260	320	46,9%	10,5%	9,7%	67,1%	8,87	577	-4,6%	16,3%	8,3%
SI22	140	380	200	50,6%	3,8%	15,6%	70,0%	8,18	579	-1,7%	7,3%	8,8%
SI12	140	260	200	50,5%	6,9%	12,1%	69,5%	8,20	580	-2,1%	7,6%	8,9%
SI17	140	320	200	50,6%	5,2%	13,9%	69,7%	8,20	581	-2,0%	7,5%	9,0%
SI8	140	200	260	50,4%	9,5%	7,2%	67,1%	8,14	584	-4,6%	6,7%	9,6%
SI9	140	200	320	50,4%	9,6%	5,7%	65,7%	8,11	585	-6,0%	6,4%	9,9%
SI10	140	200	380	50,4%	9,8%	4,6%	64,7%	8,08	587	-6,9%	6,0%	10,1%
SI23	140	380	260	50,6%	4,0%	13,3%	67,8%	8,33	588	-3,9%	9,2%	10,4%
SI25	140	380	380	50,4%	4,5%	9,9%	64,8%	8,45	589	-6,8%	10,8%	10,6%
SI13	140	260	260	50,4%	7,2%	9,7%	67,3%	8,33	589	-4,3%	9,3%	10,6%
SI15	140	260	380	50,3%	7,8%	6,7%	64,7%	8,27	590	-6,9%	8,4%	10,7%
SI18	140	320	260	50,5%	5,6%	11,4%	67,5%	8,36	590	-4,1%	9,6%	10,7%
SI24	140	380	320	50,4%	4,3%	11,4%	66,2%	8,41	590	-5,5%	10,3%	10,8%
SI14	140	260	320	50,3%	7,6%	7,9%	65,8%	8,30	591	-5,9%	8,8%	10,9%
SI20	140	320	380	50,3%	6,1%	8,3%	64,7%	8,37	591	-7,0%	9,8%	11,0%
SI19	140	320	320	50,4%	6,0%	9,5%	65,8%	8,41	592	-5,8%	10,3%	11,2%
								Color coding		-10,0%	AS IS	10,0%

From the initial observations it is possible to see that the possible increase in earnings is significantly compared to board-type products. The AS IS setting of 140mm minimum lengths has one of the poorest KPI results from all of 50 simulations. However the better earnings and throughput performance reduce the yield significantly. The positive is that best performing simulations still allow for 140mm length for A-grade products there for the reduction in yield evident for lower grades.

The base line settings of 140mm minimum lengths proved to have one of the best yield indicators. Only surpassed by the settings where A product minimum value is above the minimum value of C grade (samples SI26, SI31), which however translate into less earnings due to the lower value of C-products.

6.3 Interpretation of initial simulations

For both sets of simulations it could be concluded that lengthening the average block length does improve throughput considerably. Difference seems to be that for board-type products the improvement was considerably evident once the A-grade minimum length was increased to 200mm. For stud-types the throughput increase was even higher and the results show it can be attained by increasing the length of B- and C-grade products only. With the increase in minimum lengths the yield is expected to drop, but for stud-type products the loss can be largely from B- and C-grades. This seems to also translate into difference in expected earnings increases where stud-type products can perform significantly better because the lost yield and gained throughput can be at the expense of less valuable grades.

As discussed earlier the available raw material of timber can be scarce at times and thus it is not reasonable to impair the yield too much for increase in productions speed if it does not translate into much different overall earnings because of the lost raw material value. For better illustration purposes the average sales values and volumes of each product are represented in figure 6.1.

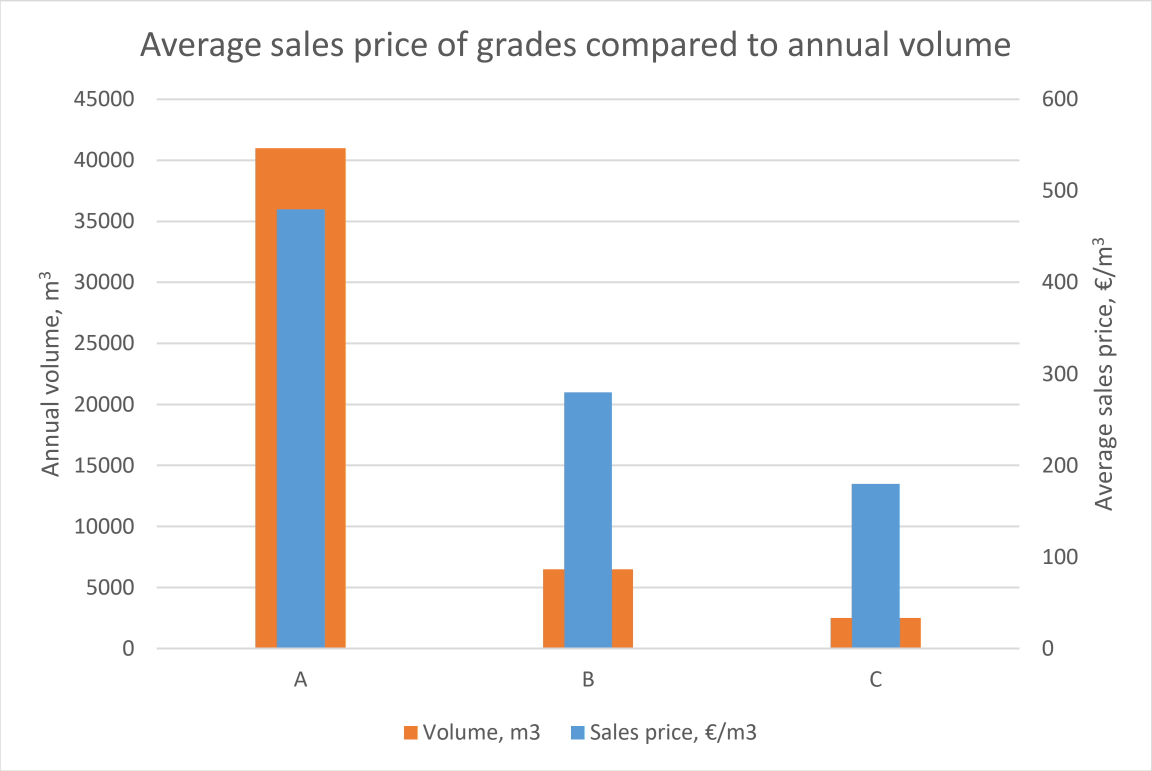

Figure 6.1 Graph comparison of average sales value and volume produced annually

Considering the KPI of earnings it can be concluded that the increase in yield through keeping the allowed block lengths of B and C products at minimum does not cover the cots associated with slower production rates.

Therefor the H1 is confirmed that the highest yield settings tend to have an adverse effect on other KPIs. For further analysis additional simulations are conducted.

7. Detailed Simulations

For the additional simulations the increment of length change will be 30mm for more detailed data to be later regression analyzed. The A-grade products will be tested for 140 and 170mm minimum length settings as the initial simulation indicated that further increase would not benefit the earnings because of the lost yield of most valuable product. For B- and C-grade minimum values the limit will be set to 290mm as this was proved to be the range where yield vales were still acceptable. For these combination an additional 63 simulation are conducted for a total sum of 113 simulations (appendices 4-5) in both cross-sections. For following analysis the data points from initial simulations are merged with additional ones to form all combinations of minimum lengths possible for a total of 72 simulations.

7.1 Combined simulation of board-type products

The combined data points of board-type products indicate similar results as initial testing with KPI vales being more uniform for better interpretation (table 7.1).

Table 7.1 Combined simulation data of board-type products

Sim no	L_{min}, mm			FJ yield			KPI			KPI change		
	A	B	C	A	B	C	FJ yield	FJ m³/h	€/h	FJ yield	FJ m³/h	€/h
BM25	140	290	230	57,9%	5,1%	4,1%	67,2%	8,34	615	-5,1%	1,7%	-1,4%
BM22	140	290	140	58,1%	4,6%	9,6%	72,4%	8,37	616	0,2%	2,2%	-1,1%
BM28	170	140	140	56,7%	11,3%	4,4%	72,4%	8,24	618	0,1%	0,5%	-0,8%
BI11	140	260	140	58,1%	5,4%	8,8%	72,3%	8,40	619	0,1%	2,5%	-0,8%
BM13	140	230	140	58,1%	6,2%	7,9%	72,2%	8,42	620	0,0%	2,8%	-0,5%
BM1	140	140	170	58,0%	9,7%	3,8%	71,5%	8,22	620	-0,7%	0,2%	-0,5%
BI6	140	200	140	58,1%	7,0%	6,9%	72,1%	8,37	621	-0,1%	2,1%	-0,4%
BM4	140	170	140	58,0%	8,6%	5,4%	72,0%	8,30	621	-0,2%	1,3%	-0,3%
BI2	140	140	200	58,0%	9,7%	3,3%	71,0%	8,22	622	-1,2%	0,2%	-0,2%
BM23	140	290	170	58,1%	4,6%	8,7%	71,4%	8,46	622	-0,8%	3,2%	-0,2%
BM52	170	260	140	56,8%	6,6%	9,4%	72,8%	8,55	623	0,5%	4,3%	-0,1%
AS IS	140	140	140	58,4%	9,7%	4,2%	72,2%	8,20	623	0,0%	0,0%	0,0%
BM2	140	140	230	58,0%	9,8%	2,9%	70,6%	8,21	623	-1,6%	0,2%	0,0%
BM58	170	290	140	57,0%	5,7%	10,4%	73,0%	8,52	624	0,8%	3,9%	0,1%
BM29	170	140	170	56,7%	11,3%	3,8%	71,9%	8,26	624	-0,4%	0,7%	0,1%
BM46	170	230	140	56,8%	7,5%	8,3%	72,6%	8,58	624	0,4%	4,7%	0,1%
BM19	140	260	170	58,1%	5,4%	7,9%	71,3%	8,48	624	-0,9%	3,5%	0,2%
BI3	140	140	260	58,0%	9,7%	2,6%	70,3%	8,21	625	-1,9%	0,1%	0,2%
									Color coding	-10,0%	AS IS	10,0%

Table 7.1 continued

Sim no	Lmin, mm			FJ yield			KPI			KPI change		
	A	B	C	A	B	C	FJ yield	FJ m³/h	€/h	FJ yield	FJ m³/h	€/h
BM3	140	140	290	58,0%	9,7%	2,4%	70,1%	8,20	625	-2,1%	0,1%	0,2%
BM24	140	290	200	58,1%	4,6%	7,6%	70,4%	8,51	626	-1,9%	3,8%	0,4%
BM30	170	140	200	56,7%	11,4%	3,4%	71,4%	8,26	626	-0,8%	0,7%	0,4%
BM34	170	170	140	56,7%	10,1%	5,6%	72,4%	8,43	626	0,2%	2,8%	0,4%
BM59	170	290	170	56,8%	5,7%	9,5%	71,9%	8,60	626	-0,3%	5,0%	0,5%
BM5	140	170	170	58,0%	8,7%	4,6%	71,3%	8,32	626	-0,9%	1,4%	0,5%
BM14	140	230	170	58,1%	6,2%	6,9%	71,2%	8,45	627	-1,0%	3,0%	0,5%
BM40	170	200	140	56,9%	8,5%	7,2%	72,6%	8,55	627	0,4%	4,3%	0,6%
BM31	170	140	230	56,7%	11,4%	2,9%	71,0%	8,26	627	-1,2%	0,7%	0,6%
BM27	140	290	290	57,9%	5,5%	4,9%	68,2%	8,46	628	-4,0%	3,1%	0,8%
BM53	170	260	170	56,8%	6,6%	8,5%	71,8%	8,64	629	-0,4%	5,4%	0,8%
BM32	170	140	260	56,7%	11,4%	2,6%	70,7%	8,25	629	-1,5%	0,7%	0,8%
BM10	140	200	170	57,9%	7,7%	5,7%	71,3%	8,40	629	-0,9%	2,5%	0,9%
BM6	140	170	200	57,9%	8,8%	4,0%	70,7%	8,32	629	-1,6%	1,5%	0,9%
BM26	140	290	260	57,9%	5,3%	5,6%	68,8%	8,48	629	-3,4%	3,4%	0,9%
BM33	170	140	290	56,7%	11,4%	2,4%	70,5%	8,25	629	-1,7%	0,7%	0,9%
BI12	140	260	200	58,0%	5,8%	6,5%	70,3%	8,49	630	-1,9%	3,5%	1,0%
BM60	170	290	200	56,8%	5,6%	8,4%	70,8%	8,68	630	-1,4%	5,9%	1,0%
BM21	140	260	290	57,8%	6,2%	4,4%	68,5%	8,43	630	-3,8%	2,9%	1,1%
BM35	170	170	170	56,7%	10,2%	4,9%	71,7%	8,44	631	-0,5%	2,9%	1,2%
BM47	170	230	170	56,8%	7,5%	7,4%	71,7%	8,64	631	-0,6%	5,3%	1,2%
BM9	140	170	290	57,9%	8,9%	2,7%	69,5%	8,29	631	-2,7%	1,2%	1,2%
BM20	140	260	230	57,9%	6,0%	5,7%	69,6%	8,47	631	-2,6%	3,4%	1,2%
BM63	170	290	290	56,5%	6,6%	5,5%	68,6%	8,66	631	-3,7%	5,7%	1,2%
BM8	140	170	260	57,9%	8,8%	3,1%	69,8%	8,30	631	-2,4%	1,3%	1,2%
BM7	140	170	230	57,9%	8,9%	3,4%	70,3%	8,31	631	-2,0%	1,4%	1,3%
BM15	140	230	200	57,9%	6,8%	5,7%	70,4%	8,45	632	-1,8%	3,1%	1,3%
BM61	170	290	230	56,6%	6,1%	7,2%	69,9%	8,71	632	-2,3%	6,2%	1,3%
BM62	170	290	260	56,6%	6,3%	6,3%	69,2%	8,69	632	-3,0%	6,0%	1,4%
BI7	140	200	200	57,9%	7,8%	4,9%	70,5%	8,40	632	-1,7%	2,5%	1,4%
BM18	140	230	290	57,8%	7,1%	3,9%	68,8%	8,41	633	-3,4%	2,6%	1,5%
BM16	140	230	230	57,9%	6,9%	4,9%	69,7%	8,44	633	-2,5%	3,0%	1,5%
BM41	170	200	170	56,6%	9,0%	6,0%	71,7%	8,58	633	-0,5%	4,7%	1,5%
BM12	140	200	290	57,8%	8,0%	3,4%	69,2%	8,37	633	-3,1%	2,1%	1,6%
BM36	170	170	200	56,7%	10,2%	4,2%	71,0%	8,44	633	-1,2%	2,9%	1,6%
BM17	140	230	260	57,8%	7,0%	4,3%	69,2%	8,43	633	-3,0%	2,8%	1,6%
BM57	170	260	290	56,5%	7,3%	4,9%	68,7%	8,63	633	-3,5%	5,2%	1,6%
BM11	140	200	230	57,9%	7,9%	4,2%	70,0%	8,39	633	-2,2%	2,4%	1,6%
BM54	170	260	200	56,7%	6,9%	7,1%	70,7%	8,68	633	-1,5%	5,9%	1,6%
BI8	140	200	260	57,8%	7,9%	3,8%	69,6%	8,20	634	-2,7%	0,0%	1,7%
BM55	170	260	230	56,6%	7,1%	6,2%	69,9%	8,67	634	-2,3%	5,7%	1,7%
BM56	170	260	260	56,6%	7,3%	5,4%	69,3%	8,64	634	-3,0%	5,5%	1,8%
BM37	170	170	230	56,6%	10,3%	3,6%	70,5%	8,42	635	-1,7%	2,8%	1,8%
BI13	140	260	260	58,2%	5,7%	5,0%	69,0%	8,43	635	-3,3%	2,9%	1,9%
BM39	170	170	290	56,6%	10,3%	2,9%	69,8%	8,41	635	-2,4%	2,6%	1,9%
BM38	170	170	260	56,6%	10,3%	3,2%	70,2%	8,42	636	-2,1%	2,7%	2,0%
BM48	170	230	200	56,6%	8,0%	6,1%	70,8%	8,64	636	-1,5%	5,4%	2,0%
BM51	170	230	290	56,5%	8,3%	4,2%	69,0%	8,59	636	-3,2%	4,8%	2,0%
BM42	170	200	200	56,6%	9,1%	5,1%	70,9%	8,58	636	-1,4%	4,6%	2,0%
BM50	170	230	260	56,6%	8,2%	4,7%	69,5%	8,61	637	-2,7%	5,0%	2,1%
BM49	170	230	230	56,6%	8,2%	5,3%	70,0%	8,62	637	-2,2%	5,2%	2,1%
BM45	170	200	290	56,6%	9,3%	3,6%	69,4%	8,54	637	-2,8%	4,2%	2,3%
BM43	170	200	230	56,6%	9,2%	4,5%	70,3%	8,57	638	-2,0%	4,5%	2,3%
BM44	170	200	260	56,6%	9,2%	4,1%	69,9%	8,56	640	-2,3%	4,4%	2,6%
									Color coding	-10,0%	AS IS	10,0%

For more detailed understanding of the results a regression analysis is conducted for dependent values of yield, throughput and earnings while having minimum block length values as independent variables for all tests. The results are combined in table 7.2, while the full testing data is available in appendix 4.

Table 7.2 Summary of regression analysis for board-type products KPI-s

KPI	Multiple R	R^2	Adjusted R^2		Coefficient	t Stat	P-value
Yield	0,9356	0,8753	0,8698	I/C	0,7428	115,4729	0,0000
				A	0,0001	4,0795	0,0001
				B	-0,0001	-5,7717	0,0000
				C	-0,0002	-20,6678	0,0000
FJ m^3/h	0,8960	0,8028	0,7941	I/C	7,1900	76,6823	0,0000
				A	0,0052	9,9887	0,0000
				B	0,0020	13,3056	0,0000
				C	0,0000	0,2124	0,8325
€/h	0,7074	0,5004	0,4783	I/C	593,0439	103,9817	0,0000
				A	0,1362	4,2821	0,0001
				B	0,0038	0,4093	0,6836
				C	0,0656	7,0428	0,0000

By looking at the adjusted R-values (table 7.2) we can see that all the performance indicators have strong relation with minimum allowed block lengths. Because of having multiple independent values in the form on block length for three grades, it is most appropriate to evaluate the adjusted R^2 values. It can be noted that the yield has the strongest relation to block lengths while earnings per hour have a medium effect of only adjusted R^2=0,478 indicating that only 47,8% of the variance in earnings can be explained by the minimum block lengths.

The P-values for are generally well below the required P=0,05 value, but not so for throughput of C-grade and earnings of B-grade.

The regression coefficients indicate if a particular KPI value should increase or decrease when minimum block lengths are changed. Increasing the length of B- and C-grade products seems to have a negative effect on overall yield. The t Stat value of C-grade being almost four times different from that of B-grade indicates the considerably larger effect. This is expected because when increasing the minimum C-grade block length it effectively forbids the optimization software to salvage the short sections of wood that are not appropriate for higher grades.

Based on the results the predictive regression equations are formulated (7.1-7.3)

$$Y_Y = 0{,}7428 + 1{,}46^{10^{-6}} \times L_{minA} - 6{,}06^{10^{-5}} \times L_{minB} - 2{,}17^{10^{-6}} \times L_{minC} \tag{7.1}$$

Where, Y_Y – overall yield of finger jointed material from sawn timber

L_{minA} – minimum allowed A-grade block length, mm

L_{minB} – minimum allowed B-grade block length, mm

L_{minC} – minimum allowed C-grade block length, mm

$$Y_R = 7{,}1900 + 5{,}22^{10^{-5}} \times L_{minA} + 2{,}04^{10^{-5}} \times L_{minB} + 3{,}2^{10^{-5}} \times L_{minC} \tag{7.2}$$

Where, Y_R – overall yield of finger jointed material from sawn timber

L_{minA} – minimum allowed A-grade block length, mm

L_{minB} – minimum allowed B-grade block length, mm

L_{minC} – minimum allowed C-grade block length, mm

$$Y_E = 593{,}0439 - 1{,}362^{10^{-3}} \times L_{minA} - 3{,}81^{10^{-3}} \times L_{minB} - 6{,}57^{10^{-4}} \times L_{minC} \tag{7.3}$$

Where, Y_E – *overall yield of finger jointed material from sawn timber*

L_{minA} – minimum allowed A-grade block length, mm

L_{minB} – minimum allowed B-grade block length, mm

L_{minC} – minimum allowed C-grade block length, mm

7.2 Combined simulation of stud-type products

In identical methodology to board-type products a combined simulation data table for stud-type cross-section is formed (table 7.3).

Table 7.3 Combined simulation data of stud-type products

Sim no	L_{min}, mm			FJ yield			KPI			KPI change		
	A	B	C	A	B	C	FJ yield	FJ m³/h	€/h	ABC	FJ m³/h	€/h
SM28	170	140	140	49,0%	13,6%	9,5%	72,0%	7,68	525	0,4%	0,6%	-1,4%
AS IS	140	140	140	50,5%	11,7%	9,4%	71,7%	7,63	533	0,0%	0,0%	0,0%
SM34	170	170	140	49,0%	12,2%	11,1%	72,3%	7,90	536	0,7%	3,6%	0,6%
SM29	170	140	170	49,0%	13,6%	7,9%	70,5%	7,78	541	-1,1%	1,9%	1,6%
SM4	140	170	140	50,5%	10,5%	10,9%	71,9%	7,80	542	0,2%	2,2%	1,7%
SM40	170	200	140	49,0%	10,9%	12,7%	72,6%	8,04	543	0,9%	5,4%	2,0%
SM46	170	230	140	49,0%	9,4%	14,4%	72,8%	8,07	547	1,2%	5,8%	2,7%
SI6	140	200	140	50,5%	9,2%	12,4%	72,1%	7,86	549	0,4%	3,1%	3,1%
SM52	170	260	140	49,0%	8,1%	15,9%	73,1%	8,10	549	1,4%	6,1%	3,1%
SM58	170	290	140	49,1%	7,1%	17,1%	73,3%	8,10	549	1,6%	6,1%	3,2%
SM30	170	140	200	49,0%	13,6%	6,7%	69,3%	7,83	551	-2,4%	2,6%	3,4%
SM13	140	230	140	50,6%	7,8%	13,9%	72,3%	7,88	552	0,6%	3,3%	3,6%
SM35	170	170	170	49,0%	12,2%	9,5%	70,7%	8,03	553	-0,9%	5,3%	3,8%
SI11	140	260	140	50,6%	6,7%	15,2%	72,5%	7,90	554	0,8%	3,6%	4,0%
SM1	140	140	170	50,8%	11,8%	7,7%	70,3%	7,72	554	-1,3%	1,2%	4,1%
SM22	140	290	140	50,6%	5,8%	16,1%	72,6%	7,91	555	1,0%	3,7%	4,2%
SM31	170	140	230	49,0%	13,6%	5,7%	68,3%	7,85	556	-3,3%	2,9%	4,4%
SI2	140	140	200	50,5%	11,8%	6,7%	68,9%	7,77	556	-2,7%	1,9%	4,5%
SM5	140	170	170	50,5%	10,5%	9,3%	70,3%	7,92	557	-1,4%	3,8%	4,6%
SM41	170	200	170	49,0%	10,9%	11,1%	71,0%	8,23	560	-0,7%	7,9%	5,2%
SM32	170	140	260	49,0%	13,7%	4,9%	67,6%	7,86	561	-4,1%	3,0%	5,3%
SM2	140	140	230	50,4%	11,8%	5,7%	68,0%	7,79	562	-3,7%	2,1%	5,5%
SM36	170	170	200	49,0%	12,3%	8,1%	69,4%	8,09	563	-2,3%	6,1%	5,8%
SM10	140	200	170	50,5%	9,2%	10,8%	70,5%	8,04	564	-1,2%	5,4%	5,9%
SM47	170	230	170	49,0%	9,5%	12,7%	71,2%	8,27	564	-0,4%	8,4%	6,0%
SI3	140	140	260	50,4%	11,9%	4,9%	67,2%	7,79	566	-4,4%	2,2%	6,2%
SM53	170	260	170	49,1%	8,0%	14,5%	71,5%	8,27	566	-0,1%	8,4%	6,2%
SM59	170	290	170	49,1%	7,0%	15,6%	71,7%	8,26	566	0,1%	8,3%	6,2%
SM6	140	170	200	50,4%	10,6%	7,9%	68,9%	7,97	567	-2,7%	4,5%	6,5%
SM3	140	140	290	50,4%	12,0%	4,1%	66,6%	7,78	568	-5,1%	2,0%	6,6%
SM14	140	230	170	50,5%	8,0%	12,2%	70,7%	8,07	568	-1,0%	5,8%	6,6%
SM37	170	170	230	49,0%	12,3%	7,1%	68,4%	8,13	570	-3,3%	6,5%	7,0%
SM19	140	260	170	50,6%	6,6%	13,6%	70,9%	8,07	570	-0,8%	5,8%	7,0%
SM33	170	140	290	49,4%	13,9%	3,8%	67,0%	7,83	571	-4,6%	2,6%	7,2%
SM42	170	200	200	48,9%	10,9%	9,7%	69,6%	8,33	571	-2,1%	9,2%	7,2%
SM7	140	170	230	50,4%	10,6%	6,9%	67,9%	8,00	573	-3,7%	4,9%	7,6%
SM23	140	290	170	50,8%	5,8%	14,5%	71,1%	8,07	574	-0,6%	5,9%	7,8%
SI7	140	200	200	50,4%	9,3%	9,3%	69,1%	8,12	574	-2,6%	6,4%	7,8%
SM38	170	170	260	49,0%	12,3%	6,2%	67,5%	8,14	574	-4,1%	6,7%	7,8%
SM43	170	200	230	48,9%	11,0%	8,6%	68,5%	8,35	576	-3,1%	9,5%	8,2%
SM54	170	260	200	49,0%	8,2%	12,9%	70,2%	8,40	577	-1,5%	10,2%	8,2%
SM39	170	170	290	49,0%	12,3%	5,4%	66,8%	8,13	577	-4,9%	6,6%	8,3%
SM60	170	290	200	49,0%	7,2%	14,0%	70,3%	8,41	578	-1,4%	10,2%	8,4%
SM48	170	230	200	49,1%	9,4%	11,4%	69,9%	8,39	578	-1,7%	10,0%	8,5%
SM15	140	230	200	50,5%	8,1%	10,8%	69,3%	8,20	578	-2,3%	7,5%	8,5%
SM9	140	170	290	50,4%	10,7%	5,2%	66,3%	8,00	580	-5,3%	4,9%	8,8%
SI12	140	260	200	50,5%	6,9%	12,1%	69,5%	8,20	580	-2,1%	7,6%	8,9%
SM44	170	200	260	48,9%	11,1%	7,7%	67,6%	8,36	580	-4,0%	9,7%	8,9%
									Color coding	-10,0%	AS IS	10,0%

Table 7.3 Combined simulation data of stud-type products

Table 7.3 continued

Sim no	L_{min}, mm			FJ yield			KPI			KPI change		
	A	B	C	A	B	C	FJ yield	FJ m^3/h	€/h	ABC	FJ m^3/h	€/h
SM24	140	290	200	50,6%	6,0%	13,0%	69,6%	8,21	581	-2,1%	7,6%	9,1%
SM45	170	200	290	48,9%	11,2%	6,7%	66,8%	8,34	582	-4,8%	9,4%	9,2%
SM8	140	170	260	50,6%	10,7%	5,6%	67,0%	7,99	582	-4,7%	4,8%	9,3%
SM55	170	260	230	49,0%	8,3%	11,8%	69,0%	8,49	582	-2,6%	11,4%	9,3%
SM61	170	290	230	49,0%	7,3%	12,9%	69,2%	8,49	582	-2,5%	11,3%	9,3%
SI8	140	200	260	50,4%	9,5%	7,2%	67,1%	8,14	584	-4,6%	6,7%	9,6%
SM16	140	230	230	50,4%	8,2%	9,6%	68,2%	8,25	584	-3,4%	8,2%	9,6%
SM12	140	200	290	50,4%	9,6%	6,3%	66,3%	8,13	585	-5,4%	6,5%	9,8%
SM20	140	260	230	50,5%	7,0%	10,9%	68,4%	8,29	585	-3,3%	8,7%	9,9%
SM51	170	230	290	48,9%	9,9%	8,1%	66,9%	8,48	586	-4,7%	11,2%	10,0%
SM11	140	200	230	50,7%	9,4%	8,1%	68,1%	8,13	586	-3,5%	6,6%	10,0%
SM62	170	290	260	48,9%	7,5%	11,7%	68,2%	8,57	586	-3,5%	12,3%	10,1%
SM25	140	290	230	50,5%	6,2%	11,8%	68,5%	8,30	587	-3,2%	8,8%	10,1%
SM17	140	230	260	50,4%	8,3%	8,4%	67,2%	8,25	588	-4,5%	8,1%	10,4%
SM18	140	230	290	50,4%	8,5%	7,5%	66,4%	8,23	588	-5,3%	7,9%	10,5%
SI13	140	260	260	50,4%	7,2%	9,7%	67,3%	8,33	589	-4,3%	9,3%	10,6%
SM21	140	260	290	50,4%	7,4%	8,7%	66,5%	8,32	590	-5,1%	9,1%	10,8%
SM49	170	230	230	49,8%	8,4%	10,4%	68,5%	8,43	590	-3,1%	10,5%	10,8%
SM26	140	290	260	50,5%	6,3%	10,6%	67,4%	8,36	590	-4,2%	9,6%	10,8%
SM27	140	290	290	50,4%	6,5%	9,5%	66,5%	8,39	592	-5,2%	9,9%	11,2%
SM56	170	260	260	49,3%	8,5%	10,2%	68,0%	8,57	593	-3,6%	12,4%	11,4%
SM57	170	260	290	49,4%	8,2%	9,3%	66,9%	8,54	595	-4,7%	12,0%	11,8%
SM63	170	290	290	49,3%	7,7%	10,2%	67,2%	8,63	596	-4,5%	13,1%	12,0%
SM50	170	230	260	49,7%	9,2%	8,8%	67,6%	8,45	597	-4,0%	10,8%	12,1%
							Color coding			-10,0%	AS IS	10,0%

A regression analyzes were carried out for the three key performance indicators as dependable values and minimum allowed block lengths as independent variables and results compiled in table 7.4.

Table 7.4 Summary of regression analysis for stud-type products KPI-s

KPI	Multiple R	R^2	Adjusted R^2		Coefficient	t Stat	P-value
Yield	0,9893	0,9787	0,9777	I/C	0,7369	173,6255	0,0000
				A	0,0002	7,3159	0,0000
				B	0,0000	6,9702	0,0000
				C	-0,0004	-54,9248	0,0000
FJ m^3/h	0,9090	0,8262	0,8185	I/C	6,0808	41,1225	0,0000
				A	0,0056	6,7586	0,0000
				B	0,0034	14,1882	0,0000
				C	0,0021	8,7352	0,0000
€/h	0,9289	0,8629	0,8569	I/C	497,5097	55,5243	0,0000
				A	-0,1059	-2,1205	0,0376
				B	0,1594	10,9015	0,0000
				C	0,2553	17,4550	0,0000

The adjusted R^2 value indicates an even higher value for stud-type products. 97,9% of the variance in yield results can be explained by the changes in block lengths. The corresponding values for throughput and earnings can be considered strong. Especially so the earnings being at 86,3% value compared to 47,8% of board-type products (table 7.2).

A notable difference in coefficients is that of block length on throughput. While board-type products throughput had little to no effect from C-grade minimum length variations, for stud-type products the positive effect is notable for from all grades. That is also evident from *t Stat* figures where all grades have a comparable value while for board-types the C-grade minimum block length value *t Stat* was close to zero. The *P*-values for all performance indicators and block grades are well below the P=0,05 value indicating that the coefficients are reasonably reliable.

Based on the results the predictive regression equations are formulated (7.4-7.6)

$$Y_Y = 0{,}73686 + 1{,}731^{10^{-6}} \times L_{minA} + 4{,}83^{10^{-5}} \times L_{minB} - 3{,}805^{10^{-6}} \times L_{minC} \tag{7.4}$$

Where, Y_Y – overall yield of finger jointed material from sawn timber

L_{minA} – minimum allowed A-grade block length, mm

L_{minB} – minimum allowed B-grade block length, mm

L_{minC} – minimum allowed C-grade block length, mm

$$Y_R = 6{,}08084 + 5{,}572^{10^{-5}} \times L_{minA} + 3{,}424^{10^{-5}} \times L_{minB} + 2{,}108^{10^{-5}} \times L_{minC} + \varepsilon_i \tag{7.5}$$

Where, Y_R – overall yield of finger jointed material from sawn timber

L_{minA} – minimum allowed A-grade block length, mm

L_{minB} – minimum allowed B-grade block length, mm

L_{minC} – minimum allowed C-grade block length, mm

$$Y_E = 497{,}50972 - 1{,}059^{10^{-3}} \times L_{minA} - 1{,}594^{10^{-3}} \times L_{minB} - 2{,}553^{10^{-3}} \tag{7.6}$$

Where, Y_E – *overall yield of finger jointed material from sawn timber*

L_{minA} – minimum allowed A-grade block length, mm

L_{minB} – minimum allowed B-grade block length, mm

L_{minC} – minimum allowed C-grade block length, mm

8. Interpreting the Data

After both initial observations of the simulation data retrieved from the production model and conducting regression analyzes it is possible to make conclusions. The most evident connections proved to be between the increase in average block length and throughput. This can be explained by finger jointing process logic where packets of fixed width are compiled in a single layer of blocks width a fixed height resulting from the dimensions of product. As the cycle rate of packets is limited the only possible way to increase the volume throughput is by increasing the average length of the blocks. The difference in effective packet height can be substantial as it was for the cross-sections tested – 46x78mm and 23x123mm. The difference in packet height being 55mm. This translates into a 37% difference that would need to be overcome by increasing the average length of the block by equal proportion, which in consequence would result in a substantial loss of yield. This explains why the stud-type product reacted considerably better to increase in minimum block length in regards to throughput. The board-type had less of an effect because of the higher volume in linear meters in a packet which makes the pressing section the limiting factor. This is evident from figures 8.1-8.2.

The yield proved to be more easily negatively affected for stud-type products, but the substantial increase in throughput improved the expected earning up to 10%. From regression analysis (table 7.2) it can be concluded that increasing the C-product length for studs can gain significant improvements in throughput. This could be an economically reasonable solutions to lose some yield in a form of less C-grade, but gain a considerable effect on production rates and earnings. The board-type product throughput proved to be less reactive to the lengthening of C-grade product minimum allowed length and there for did not gain much earnings per hour either. Both types have good throughput related reaction to B-grade length changes, but as the B-grade is more expensive it is less efficient way to increase the earnings.

Yield indicated an expected strong relation to minimum block lengths. As the yield consists of different grades of material with very different sales value it is not reasonable to use it as a primary key performance indicator. It could be effectively used as an additional measure to decide on different scenarios where the earning and throughput indicators could be similar and the option with most effective raw material usage should be desirable.

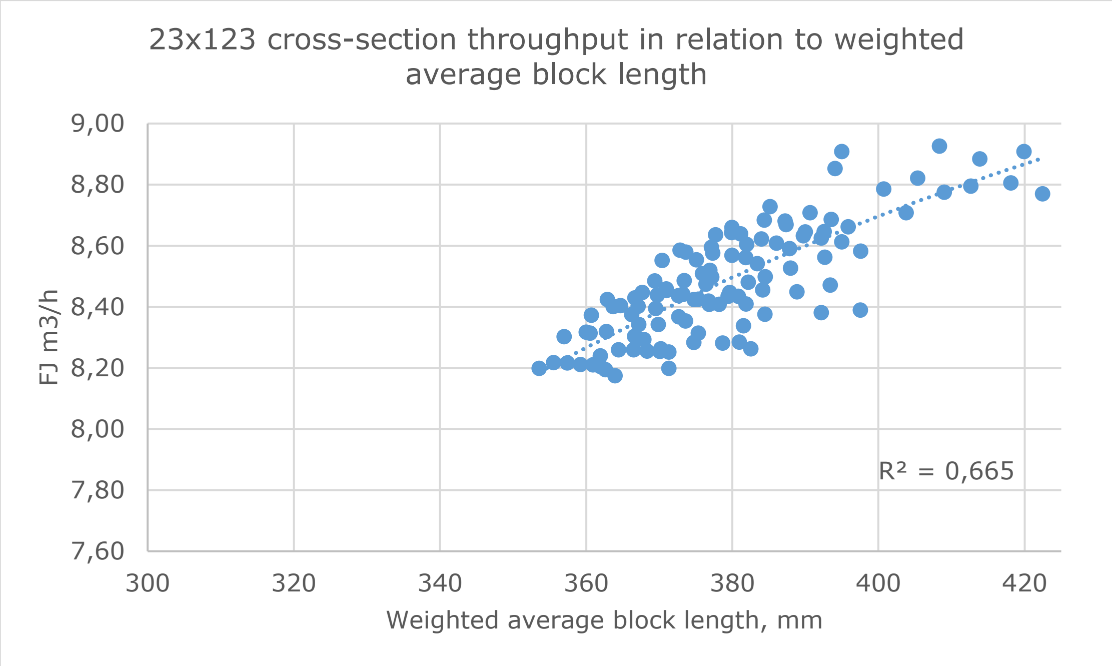

Figure 8.1 Scatter plot of board-type products earnings per hour and weighted average block length

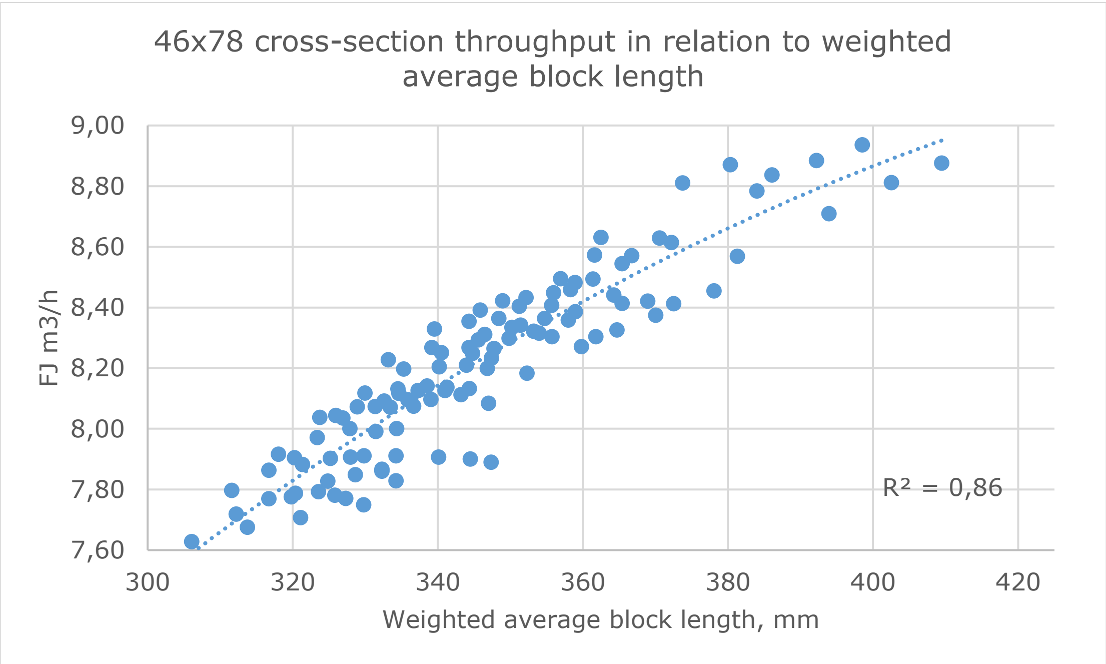

Figure 8.2 Scatter plot of stud-type products earnings per hour and weighted average block length

9. Summary

The process of finger joint manufacturing is one of the keyways to add value to the wood. Doing it efficiently is a matter of carefully planning raw material and production process along with its parameters. The thesis focused on the scanning and optimization process parameters of blocks length cut for the finger jointing process. A production model was constructed to input the optimization simulation info for better understanding of how minimum allowed block lengths affect they key performance indicators.

The hypotheses set were confirmed that increasing the minimum allowed block length improves the throughput of the finger jointing process. However, this was true only to a certain level where further lengthening of average block length decreased the yield from sawn timber to a point it started to inhibit the key performance indicator of earnings per hour. Furthermore, the sales value and volume of products cut has a strong effect on to which extent lengthening the minimum allowed block value is economically reasonable. For main products tested it was concluded that it is not reasonable to impair the yield in order to gain extra throughput, as the sales value was high enough to justify the slower production rates. For less valuable side-products it was proved to be a viable option for better earnings per time unit, especially so for stud-type cross sections. The described effects were more evident for products with relatively low values in thickness and width. This is explained by the finger jointing technology used where throughput is determined by the volume of blocks it is possible to compile in a single row for a fixed width of the packet.

As two of the more common type of product cross-section were used for simulation it is possible to make some general suggestion for the production process to be more efficient. The minimum allowed length of the main products should be kept at relatively close to the minimum possible setting to ensure the best possible yield of highly valuable products. Only for board-type cross-sections it could be considered to rise up to 30mm. For all side-products it proved efficient to increase the minimum allowed lengths from 140mm to the range of 200-260mm.

For board-type products the optimal settings in block lengths, without losing too much main product yield, proved to only increase the earnings per hour 1-2%. For stud-type products the corresponding figure was more prominent being around 5-10%. Therefor the focus in optimization should be pointed to studying the stud-type product portfolio by saving more simulation data, testing different grading settings and modifying the allowed block lengths.

The approach of further simulating the optimization data of timber scanner can be used in other manufacturing segment using similar system to optimize the production process at a wider level then what WoodEye, for example, can do on its own right. The models and methods used could be integrated to an ERP system in the future for faster analyzes.

In practical business situations the finding must also be compared with the overall production flow and sales orders as for some situation a higher yielding side-product result might be preferred for compiled sales orders where the ratios of different products are pre-described and the overall more efficient approach to fulfil them might be producing semi-optimally during the production process.

The found data can support the sales and production planning and the developed production model used to further study the topic and introduce other variables such different optimization settings for different suppliers or timber qualities.

10. Kokkuvõte

Puidu sõrmjätkamine on üks peamisi viise andmaks selle suuremat lisandväärtust. Tegemaks seda tööstuslikult ja efektiivselt on tarvis hoolikalt planeerida puidutöötlemise kõiki etappe ja nende parameetreid. Antud uurimus keskendub puidu skaneerimise ja optimeerimise protsessi tõhustamisele, kus tehakse otsuseid kuidas ja millisteks osadeks saematerjal lõigata, et saadud erinevaid kvaliteete siis hiljem liita sõrmjätkamise teel. Selle saavutamiseks töötati välja arvutuslik tootmismudel, mille üheks olulisemaks sisendiks on optimeerimisprotsessi tulemus. Loodud mudel aitab paremini mõista optimeerimises saadud tulemuste tegelikku mõju tootmisprotsessi lõppnäitajatele.

Seatud hüpoteesid leidsid kinnitust, et suurendades optimeerimistarkvaras lubatud minimaalset klotside pikkust on tulemuseks kõrgem tootmisefektiivsus. Küll aga pidas see paika teatud pikkustasemeni, millest edasine klotside pikendamine hakkas vähendama partii väljatulekut sedavõrd, et see hakkas negatiivselt mõjutama tootmisajas teenitud raha mõõdikut. Samuti on oluline roll partii mahul ja toodetavate toodete konkreetses hinnas, mille arvelt väljatuleku kadu ja tootluskasv tulevad. Testitud põhitoodete põhjal võib järeldada, et nende minimaalset lubatud klotsipikkust ei ole enamasti mõistlik suurendada, kuna nende üldine osakaal ja väärtus on partiis piisavalt kõrged, et õigustada pisut aeglasemat tootmiskiirust. Vähem väärtuslike kõrvaltoodete puhul oli keskmise klotsipikkuse suurendamine arvestatav lahendus saavutamaks paremat kasumi tootlust ajaühikus, seda eriti pruss-tüüpi ristlõigetega toodetel.

Kirjeldatud positiivne mõjutootlusele oli eriti tugev ristlõigetel, mille küljepikkuste väärtused on suhteliselt madalad. See on seletatav sõrmjätkuliinide tööpõhimõttega, kus fikseeritud laiusega sahtlitesse saab paigutada ainult teatud hulga klotse ning sahtlite liikumiskiirus on piiratud.

Kuna simulatsioonides ja tootmismudelis testiti kahte enam levinud ristlõiget on võimalik saadud tulemusi ja järeldusi üle kanda ka teistele sarnaste mõõtmete ja kvaliteediga toodetele. Põhitoodete lubatud minimaalne klotsipikkus tuleks hoida suhteliselt madalana, sest vastasel juhul kaotatakse tootlust kalli ja suuremahulise tootegrupi arvelt. Laud-tüüpi ristlõikega toodetel võib kaaluda selle väärtuse tõstmis umbes 30mm võrra. Kõrvaltoodete puhul näitasid tulemused positiivset mõju kui nende minimaalseid klotsipikkusi suurendada isegi 200-260mm-ni.

Laud-tüüpi toodete testimisel ilmnes, et optimaalseimad testitud klotsipikkuse seaded tõstsid kasumitootlust kõigest 1-2%. Pruss-tüüpi toodetel ulatus sama näitaja 5-10%. Senisest enam tähelepanu peaks pöörama just selliste toodete optimeerimisele, täiendavate simulatsioonide salvestamisele ja tootmisportfelli täiustamisse.

Kasutatud probleemikäsitlus, mille käigus simuleeritakse tooraine optimeerimisest tulenevat tegelikku mõju kogu tootmisprotsessil võib saada edukalt kasutada ka teistes analoogsetes tootmisettevõtetes. Tulevikus võib loodud mudeli ja lähenemise integreerida ettevõtte ERP süsteemi koos optimeerimisseadmega, et tagada simulatsioonide kiirem ja mahukam teostamine.

Tootmisettevõtte igapäeva olukordades tuleb võtta arvesse ka tootmisvoost ja klienditellimuste iseärasustest tulenevaid piiranguid, millest tulenevalt võibki kõige kasumlikum ja efektiivsem lahendus olla toota lühemaid klotse kui toorainet napib või kui on kindlad tellimused kõrvaltootele, mille maht on vaja täis saada või mille väärtus on piisav õigustamaks madalamat tootmisefektiivsust.

Uurimuse tulemused on rakendatavad müügitehingute kalkuleerimisel ja tootmise planeerimises. Loodud tootmismudelit on võimalik kasutada edasisteks uuringuteks ning võimalik kaasata täiendavad muutujaid nagu erinev tooraine, optimeerimisseadete muutmine, partiipikkused ja toodete erinev järgnevus.

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12. Appendices

Appendix 1 Barrus` quality matrix

Appendix 2 – Process scheme of finger jointing

Appendix 3 – Process scheme of calibration, scanning and cross-cutting

Appendix 4 – Board-type material simulation results

Appendix 5 – Stud-type material simulation results

Appendix 6 – Barrus quality matrix

Appendix 1 Barrus quality matrix

Nr: 2.04.003 | *Versioon*: 7 | *Kinnitatud*: 26.03.2020
Dokumendi tase: Eeskirjad | *Valdkond*: kompo tootmine
Juhendi tüüp: [JuhendiTyyp] | *Seadme nimi*: Üld/muu
Sihtgrupp: Kompo tootmistöötaja | *Vastutaja*: Vahetuse juht; Vahetuse meister
***Nimi*: Kvaliteedimaatriks töötajale**

	Terve oks	Must oks	Lõhe	Vaigupesa	Säsi	Säsitäpid	Poomkant/ koor/ nurgakildumine	Auk	Alamõõt	Sinine
A0	Pole lubatud	Pole lubatud	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	Pole lubatud	Pole lubatud	0,5	Pole lubatud
A-ots	Pole lubatud	Pole lubatud	Kõik	3	Kõik	Kõik	4	Pole lubatud	1	Pole lubatud
A	Pole lubatud	Pole lubatud	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	3	Pole lubatud	1	Pole lubatud
A1	6x15	Pole lubatud	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	4	Pole lubatud	1	Pole lubatud
A2	Pole lubatud	Pole lubatud	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	4	Pole lubatud	1	Kõik
A4	15x30	15x15	1	5	Kõik	Kõik	10	Pole lubatud	1	Pole lubatud
A5	15x30	10X12	0,3	2	Pole lubatud	Kõik	4	Pole lubatud	1	Pole lubatud
A6	3x3	3x3	1	4	Kõik	Kõik	4	Pole lubatud	1	Pole lubatud
A7	20x20	8x8	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	Pole lubatud	Pole lubatud	1	Pole lubatud
A8	3x3	3x3	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	10	Pole lubatud	5	Pole lubatud
B	20x30	8x10	0,2	Kõik	Kõik	Kõik	4	Pole lubatud	2	Pole lubatud
B1	20x35	3x3	0,2	4	Kõik	Kõik	4	Pole lubatud	2	Pole lubatud
B2	30x40	10x15	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	Kõik	Pole lubatud	2	Kõik
B3	30x50	3x3	Pole lubatud	Pole lubatud	Pole lubatud	Kõik	Kõik	Pole lubatud	2	Kõik
B4	30x50	15x25	4	Kõik	Kõik	Kõik	5	Pole lubatud	2	Kõik
C	30x50	20x30	4	Kõik	Kõik	Kõik	Kõik	5x5	3	Kõik
C1	35x60	15x30	Kõik	Kõik	Kõik	Kõik	5	5x5	3	Kõik
C2	Kõik	15x30	4	Kõik	Kõik	Kõik	Kõik	5x5	3	Pole lubatud
D	Kõik	20x40	Kõik	Kõik	Kõik	Kõik	Kõik	20x20	4	Kõik
Kasutame vaid Dovista toodetel										
A9	15x30	10x20	0,4	Pole lubatud	Pole lubatud	Pole lubatud	1,5	Pole lubatud	0,5	Pole lubatud
C4	30x40	25x35	0,5	Kõik	Pole lubatud	Pole lubatud	1,5	5x5	0,5	Pole lubatud
C3	30x40	25x35	4	Kõik	Pole lubatud	Kõik	1,5	5x5	0,5	Pole lubatud
Dov-ot	Pole lubatud	Pole lubatud	Kõik	Kõik	Pole lubatud	Kõik	Pole lubatud	Pole lubatud	1	Pole lubatud
C5	45x55	20x40	0,5	Kõik	Kõik	Kõik	1,5	5x5	0,5	Pole lubatud
	Terve oks	Must oks	Lõhe	Vaigupesa	Säsi	Säsitäpid	Poomkant/ koor/ nurgakildumine	Auk	Alamõõt	Sinine

Tabelis olevad väärtused on vormis "Laius x Pikkus".
Defekt on liiga suur, kui mõlemad väärtused on ületatud.
Alamõõdu väärtused ei kehti limitavatele pindadele. Sõrmjätkamisel liimitaval pinnal max 0,5 ja lamineerimisel keelatud.

Figure 1.1 Barrus standard quality matrix and defect tolerances

Appendix 2 Process scheme of finger jointing

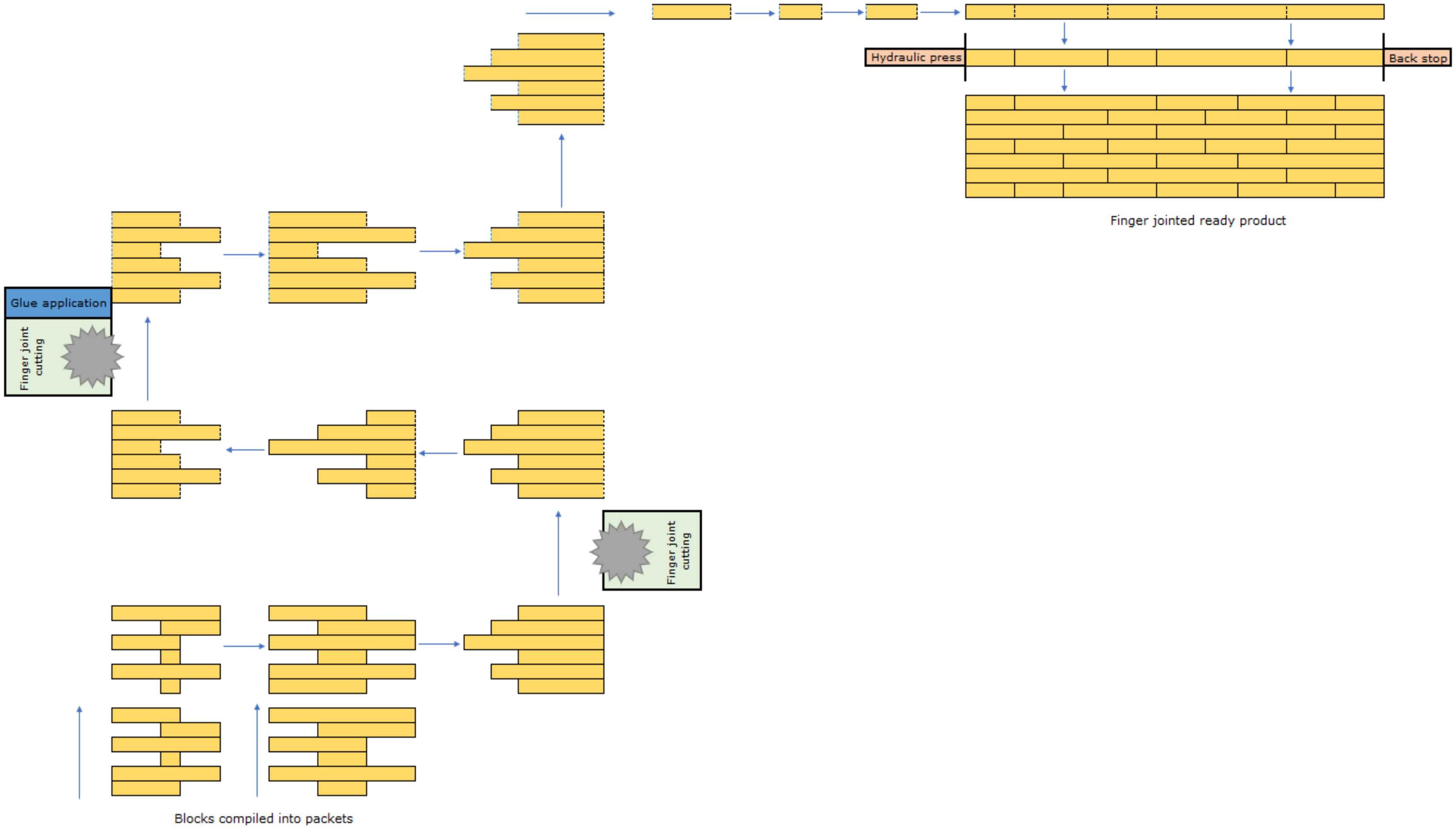

Figure 2.1 Finger jointing process scheme based on Weinig Turbo-S

Appendix 3 Process scheme of calibration, scanning and cross-cutting

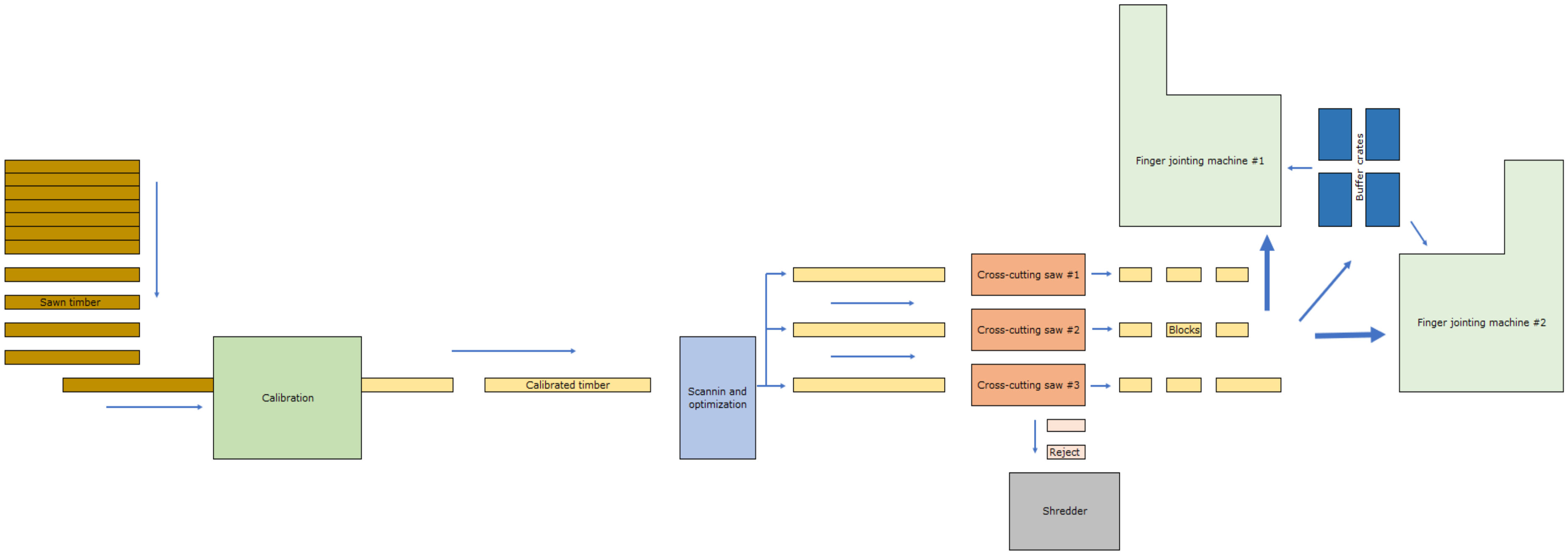

Figure 3.1 Production process scheme of calibration, scanning and cross-cutting

Appendix 4 Board-type material simulation results

Table 4.1 Simulation results of 23x123 products, ordered by minimum block length values

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
AS IS	140	140	140	388	218	200	354	67,4%	11,4%	4,9%	83,8%	58,4%	9,7%	4,2%	72,2%	8,20	623	0,0%	0,0%	0,0%
BM1	140	140	170	387	217	231	356	67,0%	11,4%	4,5%	82,9%	58,0%	9,7%	3,8%	71,5%	8,22	620	-0,7%	0,2%	-0,5%
BI2	140	140	200	387	216	260	357	67,0%	11,5%	3,9%	82,3%	58,0%	9,7%	3,3%	71,0%	8,22	622	-1,2%	0,2%	-0,2%
BM2	140	140	230	387	216	291	359	67,0%	11,5%	3,3%	81,8%	58,0%	9,8%	2,9%	70,6%	8,21	623	-1,6%	0,2%	0,0%
BI3	140	140	260	387	217	324	361	67,0%	11,5%	3,0%	81,4%	58,0%	9,7%	2,6%	70,3%	8,21	625	-1,9%	0,1%	0,2%
BM3	140	140	290	387	217	353	362	67,0%	11,5%	2,7%	81,2%	58,0%	9,7%	2,4%	70,1%	8,20	625	-2,1%	0,1%	0,2%
BI4	140	140	320	387	216	381	363	67,0%	11,5%	2,5%	80,9%	58,0%	9,8%	2,2%	69,9%	8,19	624	-2,3%	0,0%	0,1%
BI5	140	140	380	387	216	441	364	67,0%	11,5%	2,0%	80,5%	58,0%	9,8%	1,8%	69,5%	8,17	623	-2,7%	-0,3%	0,0%
BM4	140	170	140	388	248	207	357	67,0%	10,0%	6,4%	83,4%	58,0%	8,6%	5,4%	72,0%	8,30	621	-0,2%	1,3%	-0,3%
BM5	140	170	170	387	246	236	360	67,0%	10,2%	5,4%	82,6%	58,0%	8,7%	4,6%	71,3%	8,32	626	-0,9%	1,4%	0,5%
BM6	140	170	200	387	245	267	363	66,9%	10,3%	4,6%	81,8%	57,9%	8,8%	4,0%	70,7%	8,32	629	-1,6%	1,5%	0,9%
BM7	140	170	230	387	244	299	361	66,9%	10,5%	3,9%	81,3%	57,9%	8,9%	3,4%	70,3%	8,31	631	-2,0%	1,4%	1,3%
BM8	140	170	260	387	245	329	367	66,9%	10,3%	3,5%	80,8%	57,9%	8,8%	3,1%	69,8%	8,30	631	-2,4%	1,3%	1,2%
BM9	140	170	290	387	245	359	368	66,9%	10,4%	3,1%	80,4%	57,9%	8,9%	2,7%	69,5%	8,29	631	-2,7%	1,2%	1,2%
BI6	140	200	140	388	287	208	361	67,2%	8,2%	8,2%	83,5%	58,1%	7,0%	6,9%	72,1%	8,37	621	-0,1%	2,1%	-0,4%
BM10	140	200	170	387	276	243	364	66,9%	8,9%	6,6%	82,5%	57,9%	7,7%	5,7%	71,3%	8,40	629	-0,9%	2,5%	0,9%
BI7	140	200	200	387	275	275	367	66,9%	9,1%	5,6%	81,6%	57,9%	7,8%	4,9%	70,5%	8,40	632	-1,7%	2,5%	1,4%
BM11	140	200	230	387	274	308	370	66,8%	9,2%	4,9%	80,9%	57,9%	7,9%	4,2%	70,0%	8,39	633	-2,2%	2,4%	1,6%
BI8	140	200	260	387	273	336	371	66,8%	9,2%	4,4%	80,4%	57,8%	7,9%	3,8%	69,6%	8,20	634	-2,7%	0,0%	1,7%
BM12	140	200	290	387	273	365	373	66,8%	9,3%	3,9%	80,0%	57,8%	8,0%	3,4%	69,2%	8,37	633	-3,1%	2,1%	1,6%
BI9	140	200	320	387	272	391	374	66,8%	9,3%	3,5%	79,6%	57,8%	8,0%	3,1%	68,9%	8,35	632	-3,3%	1,9%	1,4%
BI10	140	200	380	387	272	451	375	66,8%	9,4%	2,7%	78,9%	57,8%	8,1%	2,4%	68,3%	8,31	630	-4,0%	1,4%	1,0%
BM13	140	230	140	388	317	215	363	67,2%	7,1%	9,3%	83,6%	58,1%	6,2%	7,9%	72,2%	8,42	620	0,0%	2,8%	-0,5%
BM14	140	230	170	388	317	242	368	67,1%	7,1%	8,1%	82,4%	58,1%	6,2%	6,9%	71,2%	8,45	627	-1,0%	3,0%	0,5%
BM15	140	230	200	387	306	278	371	66,9%	7,8%	6,7%	81,4%	57,9%	6,8%	5,7%	70,4%	8,45	632	-1,8%	3,1%	1,3%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 4.1 Board-type material simulation results

Table 4.1 Simulation results of 23x123 products, ordered by minimum block length values

Table 4.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
BM16	140	230	230	387	304	308	373	66,8%	8,0%	5,7%	80,6%	57,9%	6,9%	4,9%	69,7%	8,44	633	-2,5%	3,0%	1,5%
BM17	140	230	260	387	303	335	375	66,8%	8,2%	5,0%	80,0%	57,8%	7,0%	4,3%	69,2%	8,43	633	-3,0%	2,8%	1,6%
BM18	140	230	290	387	302	362	377	66,8%	8,3%	4,4%	79,5%	57,8%	7,1%	3,9%	68,8%	8,41	633	-3,4%	2,6%	1,5%
BI11	140	260	140	388	347	222	365	67,2%	6,2%	10,4%	83,7%	58,1%	5,4%	8,8%	72,3%	8,40	619	0,1%	2,5%	-0,8%
BM19	140	260	170	388	347	248	369	67,1%	6,2%	9,2%	82,5%	58,1%	5,4%	7,9%	71,3%	8,48	624	-0,9%	3,5%	0,2%
BI12	140	260	200	387	337	282	373	67,0%	6,7%	7,6%	81,2%	58,0%	5,8%	6,5%	70,3%	8,49	630	-1,9%	3,5%	1,0%
BM20	140	260	230	387	335	311	376	66,9%	6,9%	6,6%	80,4%	57,9%	6,0%	5,7%	69,6%	8,47	631	-2,6%	3,4%	1,2%
BI13	140	260	260	387	335	339	379	67,3%	6,6%	5,7%	79,6%	58,2%	5,7%	5,0%	69,0%	8,43	635	-3,3%	2,9%	1,9%
BM21	140	260	290	387	332	364	381	66,8%	7,2%	5,1%	79,1%	57,8%	6,2%	4,4%	68,5%	8,43	630	-3,8%	2,9%	1,1%
BI14	140	260	320	387	331	388	382	67,2%	7,3%	4,4%	78,9%	58,2%	6,3%	3,8%	68,3%	8,41	638	-3,9%	2,6%	2,3%
BI15	140	260	380	387	330	452	384	66,6%	7,6%	3,5%	77,6%	57,6%	6,6%	3,1%	67,3%	8,38	625	-5,0%	2,2%	0,2%
BM22	140	290	140	389	375	229	366	67,2%	5,3%	11,3%	83,8%	58,1%	4,6%	9,6%	72,4%	8,37	616	0,2%	2,2%	-1,1%
BM23	140	290	170	388	375	254	371	67,1%	5,3%	10,1%	82,6%	58,1%	4,6%	8,7%	71,4%	8,46	622	-0,8%	3,2%	-0,2%
BM24	140	290	200	388	374	282	376	67,1%	5,3%	8,9%	81,3%	58,1%	4,6%	7,6%	70,4%	8,51	626	-1,9%	3,8%	0,4%
BM25	140	290	230	388	365	314	382	66,9%	5,9%	4,7%	77,6%	57,9%	5,1%	4,1%	67,2%	8,34	615	-5,1%	1,7%	-1,4%
BM26	140	290	260	388	362	342	382	66,9%	6,1%	6,5%	79,5%	57,9%	5,3%	5,6%	68,8%	8,48	629	-3,4%	3,4%	0,9%
BM27	140	290	290	388	360	369	384	66,8%	6,3%	5,6%	78,8%	57,9%	5,5%	4,9%	68,2%	8,46	628	-4,0%	3,1%	0,8%
BI16	140	320	140	388	403	236	367	67,0%	4,5%	12,1%	83,6%	58,0%	3,9%	10,3%	72,3%	8,34	610	0,1%	1,8%	-2,1%
BI17	140	320	200	388	402	288	377	67,2%	4,6%	9,7%	81,4%	58,1%	4,0%	8,3%	70,4%	8,50	623	-1,8%	3,6%	0,0%
BI18	140	320	260	388	392	346	385	66,9%	5,3%	7,2%	79,4%	57,9%	4,6%	6,2%	68,8%	8,50	627	-3,5%	3,7%	0,5%
BI19	140	320	320	388	391	396	389	66,8%	5,6%	5,6%	78,0%	57,8%	4,9%	4,9%	67,6%	8,45	624	-4,7%	3,1%	0,1%
BI20	140	320	380	388	390	456	392	66,8%	5,7%	4,3%	76,7%	57,8%	4,9%	3,7%	66,5%	8,38	620	-5,7%	2,2%	-0,6%
BI21	140	380	140	389	461	248	370	67,2%	4,0%	13,3%	84,5%	58,2%	3,5%	11,4%	73,1%	8,34	619	0,8%	1,8%	-0,7%
BI22	140	380	200	389	460	300	380	67,2%	3,4%	11,0%	81,5%	58,1%	2,9%	9,5%	70,6%	8,45	619	-1,7%	3,0%	-0,7%
BI23	140	380	260	389	459	352	388	67,1%	3,5%	8,8%	79,4%	58,1%	3,1%	7,6%	68,8%	8,53	620	-3,4%	4,0%	-0,5%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 4.2 Board-type material simulation results

Table 4.1 Simulation results of 23x123 products, ordered by minimum block length values

Table 4.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
BI24	140	380	320	389	452	405	393	66,9%	4,0%	6,9%	77,8%	57,9%	3,5%	6,0%	67,4%	8,47	618	-4,8%	3,3%	-0,9%
BI25	140	380	380	389	450	464	398	66,9%	4,2%	5,2%	76,3%	57,9%	3,7%	4,5%	66,1%	8,39	613	-6,1%	2,3%	-1,6%
BM28	170	140	140	403	223	198	362	65,5%	13,2%	5,2%	83,9%	56,7%	11,3%	4,4%	72,4%	8,24	618	0,1%	0,5%	-0,8%
BM29	170	140	170	403	223	230	364	65,5%	13,3%	4,5%	83,3%	56,7%	11,3%	3,8%	71,9%	8,26	624	-0,4%	0,7%	0,1%
BM30	170	140	200	402	222	260	366	65,4%	13,4%	3,9%	82,7%	56,7%	11,4%	3,4%	71,4%	8,26	626	-0,8%	0,7%	0,4%
BM31	170	140	230	402	222	291	368	65,4%	13,4%	3,4%	82,2%	56,7%	11,4%	2,9%	71,0%	8,26	627	-1,2%	0,7%	0,6%
BM32	170	140	260	402	223	322	370	65,4%	13,4%	3,0%	81,8%	56,7%	11,4%	2,6%	70,7%	8,25	629	-1,5%	0,7%	0,8%
BM33	170	140	290	402	223	352	371	65,4%	13,3%	2,8%	81,6%	56,7%	11,4%	2,4%	70,5%	8,25	629	-1,7%	0,7%	0,9%
BM34	170	170	140	403	253	209	367	65,5%	11,8%	6,6%	83,8%	56,7%	10,1%	5,6%	72,4%	8,43	626	0,2%	2,8%	0,4%
BM35	170	170	170	403	251	237	370	65,4%	11,9%	5,7%	83,0%	56,7%	10,2%	4,9%	71,7%	8,44	631	-0,5%	2,9%	1,2%
BM36	170	170	200	403	250	269	373	65,4%	11,9%	4,9%	82,2%	56,7%	10,2%	4,2%	71,0%	8,44	633	-1,2%	2,9%	1,6%
BM37	170	170	230	402	250	299	375	65,4%	12,0%	4,2%	81,5%	56,6%	10,3%	3,6%	70,5%	8,42	635	-1,7%	2,8%	1,8%
BM38	170	170	260	403	251	329	377	65,4%	12,0%	3,7%	81,1%	56,6%	10,3%	3,2%	70,2%	8,42	636	-2,1%	2,7%	2,0%
BM39	170	170	290	403	251	360	378	65,4%	12,0%	3,3%	80,7%	56,6%	10,3%	2,9%	69,8%	8,41	635	-2,4%	2,6%	1,9%
BM40	170	200	140	403	289	211	370	65,6%	9,8%	8,5%	84,0%	56,9%	8,5%	7,2%	72,6%	8,55	627	0,4%	4,3%	0,6%
BM41	170	200	170	402	281	245	374	65,4%	10,5%	7,1%	82,9%	56,6%	9,0%	6,0%	71,7%	8,58	633	-0,5%	4,7%	1,5%
BM42	170	200	200	402	279	276	377	65,3%	10,6%	6,0%	81,9%	56,6%	9,1%	5,1%	70,9%	8,58	636	-1,4%	4,6%	2,0%
BM43	170	200	230	402	279	309	380	65,3%	10,7%	5,2%	81,2%	56,6%	9,2%	4,5%	70,3%	8,57	638	-2,0%	4,5%	2,3%
BM44	170	200	260	402	279	335	382	65,4%	10,7%	4,7%	80,8%	56,6%	9,2%	4,1%	69,9%	8,56	640	-2,3%	4,4%	2,6%
BM45	170	200	290	402	278	364	383	65,3%	10,8%	4,1%	80,2%	56,6%	9,3%	3,6%	69,4%	8,54	637	-2,8%	4,2%	2,3%
BM46	170	230	140	403	318	219	373	65,5%	8,7%	9,8%	84,0%	56,8%	7,5%	8,3%	72,6%	8,58	624	0,4%	4,7%	0,1%
BM47	170	230	170	403	318	245	378	65,5%	8,7%	8,6%	82,8%	56,8%	7,5%	7,4%	71,7%	8,64	631	-0,6%	5,3%	1,2%
BM48	170	230	200	402	310	280	381	65,3%	9,3%	7,1%	81,7%	56,6%	8,0%	6,1%	70,8%	8,64	636	-1,5%	5,4%	2,0%
BM49	170	230	230	402	307	310	384	65,3%	9,4%	6,1%	80,8%	56,6%	8,2%	5,3%	70,0%	8,62	637	-2,2%	5,2%	2,1%
BM50	170	230	260	402	307	336	386	65,3%	9,5%	5,5%	80,2%	56,6%	8,2%	4,7%	69,5%	8,61	637	-2,7%	5,0%	2,1%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 4.3 Board-type material simulation results

Table 4.1 Simulation results of 23x123 products, ordered by minimum block length values

Table 4.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
BM51	170	230	290	402	306	363	388	65,2%	9,6%	4,8%	79,7%	56,5%	8,3%	4,2%	69,0%	8,59	636	-3,2%	4,8%	2,0%
BM52	170	260	140	403	347	227	375	65,5%	7,6%	11,0%	84,1%	56,8%	6,6%	9,4%	72,8%	8,55	623	0,5%	4,3%	-0,1%
BM53	170	260	170	403	347	253	380	65,5%	7,6%	9,9%	82,9%	56,8%	6,6%	8,5%	71,8%	8,64	629	-0,4%	5,4%	0,8%
BM54	170	260	200	402	340	286	384	65,4%	8,0%	8,3%	81,6%	56,7%	6,9%	7,1%	70,7%	8,68	633	-1,5%	5,9%	1,6%
BM55	170	260	230	402	337	314	387	65,3%	8,2%	7,2%	80,7%	56,6%	7,1%	6,2%	69,9%	8,67	634	-2,3%	5,7%	1,7%
BM56	170	260	260	401	335	343	390	65,3%	8,4%	6,2%	79,9%	56,6%	7,3%	5,4%	69,3%	8,64	634	-3,0%	5,5%	1,8%
BM57	170	260	290	401	335	370	392	65,2%	8,4%	5,6%	79,3%	56,5%	7,3%	4,9%	68,7%	8,63	633	-3,5%	5,2%	1,6%
BM58	170	290	140	403	375	236	377	65,7%	6,5%	12,2%	84,4%	57,0%	5,7%	10,4%	73,0%	8,52	624	0,8%	3,9%	0,1%
BM59	170	290	170	403	376	260	382	65,5%	6,5%	11,0%	83,1%	56,8%	5,7%	9,5%	71,9%	8,60	626	-0,3%	5,0%	0,5%
BM60	170	290	200	403	375	288	387	65,5%	6,5%	9,7%	81,7%	56,8%	5,6%	8,4%	70,8%	8,68	630	-1,4%	5,9%	1,0%
BM61	170	290	230	402	367	320	391	65,4%	7,0%	8,3%	80,7%	56,6%	6,1%	7,2%	69,9%	8,71	632	-2,3%	6,2%	1,3%
BM62	170	290	260	402	364	348	394	65,3%	7,3%	7,3%	79,8%	56,6%	6,3%	6,3%	69,2%	8,69	632	-3,0%	6,0%	1,4%
BM63	170	290	290	402	361	376	396	65,2%	7,5%	6,3%	79,1%	56,5%	6,6%	5,5%	68,6%	8,66	631	-3,7%	5,7%	1,2%
BI26	200	140	140	419	230	198	370	63,6%	15,5%	5,2%	84,2%	55,1%	13,2%	4,4%	72,7%	8,26	618	0,5%	0,8%	-0,9%
BI27	200	140	200	418	228	259	375	63,5%	15,6%	3,9%	83,0%	55,1%	13,3%	3,4%	71,8%	8,28	625	-0,5%	1,0%	0,2%
BI28	200	140	260	418	229	322	379	63,9%	15,7%	3,0%	82,6%	55,4%	13,4%	2,6%	71,4%	8,28	636	-0,8%	1,0%	2,0%
BI29	200	140	320	418	229	385	381	63,5%	15,5%	2,8%	81,8%	55,1%	13,2%	2,4%	70,7%	8,28	629	-1,5%	1,1%	0,9%
BI30	200	140	380	418	229	445	383	63,6%	15,6%	2,2%	81,4%	55,2%	13,3%	2,0%	70,4%	8,26	630	-1,8%	0,8%	1,1%
BI31	200	200	140	418	291	215	380	64,2%	12,0%	8,5%	84,8%	55,7%	10,4%	7,2%	73,4%	8,66	639	1,1%	5,6%	2,5%
BI32	200	200	200	407	285	281	377	62,2%	13,0%	6,6%	81,8%	53,9%	11,2%	5,7%	70,8%	8,59	607	-1,4%	4,8%	-2,7%
BI33	200	200	260	418	284	338	393	63,8%	12,3%	5,0%	81,1%	55,3%	10,6%	4,3%	70,3%	8,65	643	-2,0%	5,5%	3,2%
BI34	200	200	320	418	282	394	395	63,3%	12,7%	4,2%	80,2%	54,9%	10,9%	3,7%	69,6%	8,61	637	-2,7%	5,0%	2,2%
BI35	200	200	380	418	282	451	398	63,3%	12,6%	3,6%	79,5%	55,0%	10,9%	3,1%	68,9%	8,58	635	-3,3%	4,7%	1,9%
BI36	200	260	140	419	347	234	385	63,7%	9,4%	11,7%	84,8%	55,3%	8,2%	10,0%	73,4%	8,73	625	1,2%	6,5%	0,3%
BI37	200	260	200	417	342	292	395	63,4%	9,7%	8,9%	82,1%	55,0%	8,4%	7,7%	71,2%	8,91	634	-1,1%	8,7%	1,7%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 4.4 Board-type material simulation results

Table 4.1 Simulation results of 23x123 products, ordered by minimum block length values

Table 4.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
BI38	200	260	260	408	340	350	394	62,4%	10,3%	7,2%	79,9%	54,1%	8,9%	6,3%	69,3%	8,85	611	-2,9%	8,0%	-2,1%
BI39	200	260	320	417	338	400	405	63,6%	10,2%	5,5%	79,3%	55,2%	8,8%	4,8%	68,8%	8,82	639	-3,4%	7,6%	2,5%
BI40	200	260	380	417	337	460	409	63,3%	10,1%	4,6%	78,0%	54,9%	8,8%	4,0%	67,7%	8,77	628	-4,6%	7,0%	0,7%
BI41	200	320	140	419	405	254	390	63,6%	6,8%	14,4%	84,8%	55,2%	5,9%	12,3%	73,4%	8,63	614	1,2%	5,3%	-1,5%
BI42	200	320	200	419	405	303	401	63,7%	6,7%	12,0%	82,3%	55,3%	5,8%	10,3%	71,4%	8,79	626	-0,8%	7,2%	0,5%
BI43	200	320	260	417	395	357	408	63,4%	7,4%	9,4%	80,1%	55,0%	6,4%	8,2%	69,6%	8,93	626	-2,6%	8,9%	0,4%
BI44	200	320	320	417	392	410	414	63,2%	7,7%	7,4%	78,3%	54,9%	6,7%	6,4%	68,0%	8,88	621	-4,2%	8,4%	-0,4%
BI45	200	320	380	417	392	464	418	63,2%	7,8%	5,8%	76,9%	54,9%	6,8%	5,1%	66,8%	8,81	616	-5,4%	7,4%	-1,2%
BI46	200	380	140	419	461	269	393	63,6%	5,1%	16,2%	84,9%	55,2%	4,4%	13,9%	73,6%	8,56	608	1,3%	4,4%	-2,5%
BI47	200	380	200	419	460	316	404	63,6%	5,0%	13,9%	82,5%	55,2%	4,4%	12,1%	71,6%	8,71	618	-0,6%	6,2%	-0,8%
BI48	200	380	260	418	460	361	413	63,9%	4,9%	11,4%	80,3%	55,5%	4,3%	9,9%	69,7%	8,80	622	-2,5%	7,3%	-0,3%
BI49	200	380	320	418	451	416	420	63,3%	5,7%	9,2%	78,2%	54,9%	5,0%	8,1%	68,0%	8,91	612	-4,3%	8,7%	-1,7%
BI50	200	380	380	414	453	470	422	63,8%	4,8%	7,7%	76,2%	55,3%	4,2%	6,7%	66,2%	8,77	599	-6,0%	7,0%	-3,9%
																	Color coding	-10,0%	AS IS	10,0%

Table 5.1 Simulation results of 46x78 products, ordered by minimum block length values

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m³/h	€/h	FJ yield	FJ m³/h	€/h
AS IS	140	140	140	349	220	188	306	58,6%	13,8%	11,2%	83,6%	50,5%	11,7%	9,4%	71,7%	7,63	533	0,0%	0,0%	0,0%
SM1	140	140	170	349	219	217	312	59,0%	13,9%	9,1%	82,0%	50,8%	11,8%	7,7%	70,3%	7,72	554	-1,3%	1,2%	4,1%
SI2	140	140	200	349	218	250	317	58,6%	13,9%	7,8%	80,3%	50,5%	11,8%	6,7%	68,9%	7,77	556	-2,7%	1,9%	4,5%
SM2	140	140	230	349	218	284	320	58,6%	14,0%	6,6%	79,1%	50,4%	11,8%	5,7%	68,0%	7,79	562	-3,7%	2,1%	5,5%
SI3	140	140	260	349	219	321	324	58,6%	14,0%	5,6%	78,2%	50,4%	11,9%	4,9%	67,2%	7,79	566	-4,4%	2,2%	6,2%
SM3	140	140	290	349	219	359	326	58,6%	14,1%	4,8%	77,5%	50,4%	12,0%	4,1%	66,6%	7,78	568	-5,1%	2,0%	6,6%
SI4	140	140	320	349	219	390	327	58,6%	14,2%	4,2%	77,0%	50,4%	12,0%	3,7%	66,2%	7,77	568	-5,5%	1,9%	6,7%
SI5	140	140	380	349	221	458	330	58,6%	14,3%	3,4%	76,2%	50,5%	12,1%	2,9%	65,5%	7,75	570	-6,1%	1,6%	7,0%
SM4	140	170	140	349	252	198	312	58,6%	12,2%	13,0%	83,8%	50,5%	10,5%	10,9%	71,9%	7,80	542	0,2%	2,2%	1,7%
SM5	140	170	170	349	250	228	318	58,6%	12,3%	10,9%	81,8%	50,5%	10,5%	9,3%	70,3%	7,92	557	-1,4%	3,8%	4,6%
SM6	140	170	200	349	249	261	323	58,6%	12,3%	9,3%	80,2%	50,4%	10,6%	7,9%	68,9%	7,97	567	-2,7%	4,5%	6,5%
SM7	140	170	230	349	249	296	328	58,5%	12,4%	8,0%	79,0%	50,4%	10,6%	6,9%	67,9%	8,00	573	-3,7%	4,9%	7,6%
SM8	140	170	260	349	250	329	331	58,8%	12,5%	6,5%	77,8%	50,6%	10,7%	5,6%	67,0%	7,99	582	-4,7%	4,8%	9,3%
SM9	140	170	290	349	251	364	334	58,6%	12,5%	6,0%	77,0%	50,4%	10,7%	5,2%	66,3%	8,00	580	-5,3%	4,9%	8,8%
SI6	140	200	140	349	282	212	317	58,6%	10,7%	14,6%	84,0%	50,5%	9,2%	12,4%	72,1%	7,86	549	0,4%	3,1%	3,1%
SM10	140	200	170	349	280	244	324	58,6%	10,7%	12,6%	81,9%	50,5%	9,2%	10,8%	70,5%	8,04	564	-1,2%	5,4%	5,9%
SI7	140	200	200	349	280	279	330	58,6%	10,8%	10,9%	80,2%	50,4%	9,3%	9,3%	69,1%	8,12	574	-2,6%	6,4%	7,8%
SM11	140	200	230	349	278	310	335	58,8%	11,0%	9,3%	79,1%	50,7%	9,4%	8,1%	68,1%	8,13	586	-3,5%	6,6%	10,0%
SI8	140	200	260	349	279	344	339	58,5%	11,0%	8,3%	77,8%	50,4%	9,5%	7,2%	67,1%	8,14	584	-4,6%	6,7%	9,6%
SM12	140	200	290	349	279	373	341	58,5%	11,1%	7,3%	76,9%	50,4%	9,6%	6,3%	66,3%	8,13	585	-5,4%	6,5%	9,8%
SI9	140	200	320	349	279	402	343	58,5%	11,2%	6,5%	76,2%	50,4%	9,6%	5,7%	65,7%	8,11	585	-6,0%	6,4%	9,9%
SI10	140	200	380	349	281	470	347	58,5%	11,4%	5,2%	75,1%	50,4%	9,8%	4,6%	64,7%	8,08	587	-6,9%	6,0%	10,1%
SM13	140	230	140	350	316	223	321	58,7%	9,0%	16,4%	84,1%	50,6%	7,8%	13,9%	72,3%	7,88	552	0,6%	3,3%	3,6%
SM14	140	230	170	349	311	257	329	58,6%	9,3%	14,2%	82,1%	50,5%	8,0%	12,2%	70,7%	8,07	568	-1,0%	5,8%	6,6%
SM15	140	230	200	349	310	289	335	58,6%	9,4%	12,5%	80,4%	50,5%	8,1%	10,8%	69,3%	8,20	578	-2,3%	7,5%	8,5%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 5.1 Stud-type material simulation results

Table 5.1 Simulation results of 46x78 products, ordered by minimum block length values

Table 5.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
SM16	140	230	230	349	309	321	341	58,6%	9,4%	11,1%	79,1%	50,4%	8,2%	9,6%	68,2%	8,25	584	-3,4%	8,2%	9,6%
SM17	140	230	260	349	309	353	345	58,5%	9,7%	9,7%	77,9%	50,4%	8,3%	8,4%	67,2%	8,25	588	-4,5%	8,1%	10,4%
SM18	140	230	290	349	308	380	347	58,5%	9,8%	8,6%	76,9%	50,4%	8,5%	7,5%	66,4%	8,23	588	-5,3%	7,9%	10,5%
SI11	140	260	140	350	345	235	325	58,7%	7,8%	17,8%	84,3%	50,6%	6,7%	15,2%	72,5%	7,90	554	0,8%	3,6%	4,0%
SM19	140	260	170	350	343	268	333	58,7%	7,7%	15,9%	82,3%	50,6%	6,6%	13,6%	70,9%	8,07	570	-0,8%	5,8%	7,0%
SI12	140	260	200	350	339	301	340	58,6%	8,0%	14,0%	80,6%	50,5%	6,9%	12,1%	69,5%	8,20	580	-2,1%	7,6%	8,9%
SM20	140	260	230	350	337	332	346	58,6%	8,1%	12,6%	79,3%	50,5%	7,0%	10,9%	68,4%	8,29	585	-3,3%	8,7%	9,9%
SI13	140	260	260	350	338	362	350	58,6%	8,3%	11,1%	78,0%	50,4%	7,2%	9,7%	67,3%	8,33	589	-4,3%	9,3%	10,6%
SM21	140	260	290	350	336	390	353	58,5%	8,5%	10,0%	77,1%	50,4%	7,4%	8,7%	66,5%	8,32	590	-5,1%	9,1%	10,8%
SI14	140	260	320	350	336	415	356	58,4%	8,8%	9,0%	76,2%	50,3%	7,6%	7,9%	65,8%	8,30	591	-5,9%	8,8%	10,9%
SI15	140	260	380	349	338	466	360	58,4%	9,0%	7,6%	75,0%	50,3%	7,8%	6,7%	64,7%	8,27	590	-6,9%	8,4%	10,7%
SM22	140	290	140	350	370	244	328	58,8%	6,7%	18,9%	84,4%	50,6%	5,8%	16,1%	72,6%	7,91	555	1,0%	3,7%	4,2%
SM23	140	290	170	350	367	277	337	59,0%	6,6%	16,9%	82,5%	50,8%	5,8%	14,5%	71,1%	8,07	574	-0,6%	5,9%	7,8%
SM24	140	290	200	350	365	311	344	58,7%	7,0%	15,0%	80,7%	50,6%	6,0%	13,0%	69,6%	8,21	581	-2,1%	7,6%	9,1%
SM25	140	290	230	350	364	342	350	58,6%	7,1%	13,6%	79,3%	50,5%	6,2%	11,8%	68,5%	8,30	587	-3,2%	8,8%	10,1%
SM26	140	290	260	350	364	371	355	58,6%	7,3%	12,2%	78,1%	50,5%	6,3%	10,6%	67,4%	8,36	590	-4,2%	9,6%	10,8%
SM27	140	290	290	350	365	400	359	58,5%	7,5%	10,9%	77,0%	50,4%	6,5%	9,5%	66,5%	8,39	592	-5,2%	9,9%	11,2%
SI16	140	320	140	350	390	252	330	58,7%	6,0%	19,7%	84,5%	50,6%	5,2%	16,9%	72,7%	7,91	555	1,1%	3,7%	4,1%
SI17	140	320	200	350	390	319	347	58,7%	6,0%	16,0%	80,8%	50,6%	5,2%	13,9%	69,7%	8,20	581	-2,0%	7,5%	9,0%
SI18	140	320	260	350	387	378	358	58,6%	6,5%	13,2%	78,2%	50,5%	5,6%	11,4%	67,5%	8,36	590	-4,1%	9,6%	10,7%
SI19	140	320	320	351	389	429	365	58,5%	6,9%	10,9%	76,2%	50,4%	6,0%	9,5%	65,8%	8,41	592	-5,8%	10,3%	11,2%
SI20	140	320	380	351	390	474	370	58,4%	7,0%	9,5%	74,8%	50,3%	6,1%	8,3%	64,7%	8,37	591	-7,0%	9,8%	11,0%
SI21	140	380	140	350	441	270	334	58,8%	4,3%	21,6%	84,6%	50,6%	3,7%	18,5%	72,9%	7,91	554	1,2%	3,7%	4,1%
SI22	140	380	200	351	441	337	352	58,7%	4,3%	18,0%	81,1%	50,6%	3,8%	15,6%	70,0%	8,18	579	-1,7%	7,3%	8,8%
SI23	140	380	260	351	442	394	365	58,7%	4,5%	15,2%	78,4%	50,6%	4,0%	13,3%	67,8%	8,33	588	-3,9%	9,2%	10,4%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 5.2 Stud-type material simulation results

Table 5.1 Simulation results of 46x78 products, ordered by minimum block length values

Table 5.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m³/h	€/h	FJ yield	FJ m³/h	€/h
SI24	140	380	320	352	444	440	373	58,6%	4,9%	13,1%	76,5%	50,4%	4,3%	11,4%	66,2%	8,41	590	-5,5%	10,3%	10,8%
SI25	140	380	380	352	443	485	378	58,5%	5,2%	11,3%	75,0%	50,4%	4,5%	9,9%	64,8%	8,45	589	-6,8%	10,8%	10,6%
SM28	170	140	140	364	223	187	314	56,8%	16,0%	11,2%	84,0%	49,0%	13,6%	9,5%	72,0%	7,68	525	0,4%	0,6%	-1,4%
SM29	170	140	170	364	222	217	320	56,8%	16,0%	9,3%	82,1%	49,0%	13,6%	7,9%	70,5%	7,78	541	-1,1%	1,9%	1,6%
SM30	170	140	200	364	222	249	325	56,8%	16,0%	7,8%	80,6%	49,0%	13,6%	6,7%	69,3%	7,83	551	-2,4%	2,6%	3,4%
SM31	170	140	230	364	221	283	329	56,8%	16,1%	6,6%	79,5%	49,0%	13,6%	5,7%	68,3%	7,85	556	-3,3%	2,9%	4,4%
SM32	170	140	260	365	223	321	332	56,8%	16,1%	5,6%	78,5%	49,0%	13,7%	4,9%	67,6%	7,86	561	-4,1%	3,0%	5,3%
SM33	170	140	290	364	223	355	334	57,2%	16,3%	4,4%	77,9%	49,4%	13,9%	3,8%	67,0%	7,83	571	-4,6%	2,6%	7,2%
SM34	170	170	140	365	255	199	320	56,8%	14,2%	13,1%	84,2%	49,0%	12,2%	11,1%	72,3%	7,90	536	0,7%	3,6%	0,6%
SM35	170	170	170	365	253	230	327	56,8%	14,3%	11,1%	82,2%	49,0%	12,2%	9,5%	70,7%	8,03	553	-0,9%	5,3%	3,8%
SM36	170	170	200	365	253	262	333	56,8%	14,4%	9,4%	80,6%	49,0%	12,3%	8,1%	69,4%	8,09	563	-2,3%	6,1%	5,8%
SM37	170	170	230	365	253	296	337	56,8%	14,4%	8,3%	79,4%	49,0%	12,3%	7,1%	68,4%	8,13	570	-3,3%	6,5%	7,0%
SM38	170	170	260	365	254	330	341	56,8%	14,4%	7,2%	78,4%	49,0%	12,3%	6,2%	67,5%	8,14	574	-4,1%	6,7%	7,8%
SM39	170	170	290	365	255	365	344	56,8%	14,4%	6,3%	77,5%	49,0%	12,3%	5,4%	66,8%	8,13	577	-4,9%	6,6%	8,3%
SM40	170	200	140	364	284	216	326	56,8%	12,7%	15,0%	84,4%	49,0%	10,9%	12,7%	72,6%	8,04	543	0,9%	5,4%	2,0%
SM41	170	200	170	364	282	248	333	56,8%	12,7%	13,0%	82,4%	49,0%	10,9%	11,1%	71,0%	8,23	560	-0,7%	7,9%	5,2%
SM42	170	200	200	364	281	282	340	56,7%	12,7%	11,3%	80,7%	48,9%	10,9%	9,7%	69,6%	8,33	571	-2,1%	9,2%	7,2%
SM43	170	200	230	364	281	314	344	56,7%	12,8%	10,0%	79,5%	48,9%	11,0%	8,6%	68,5%	8,35	576	-3,1%	9,5%	8,2%
SM44	170	200	260	364	281	346	348	56,7%	12,9%	8,8%	78,4%	48,9%	11,1%	7,7%	67,6%	8,36	580	-4,0%	9,7%	8,9%
SM45	170	200	290	364	281	377	351	56,7%	13,0%	7,7%	77,4%	48,9%	11,2%	6,7%	66,8%	8,34	582	-4,8%	9,4%	9,2%
SM46	170	230	140	365	317	228	331	56,9%	10,8%	17,0%	84,6%	49,0%	9,4%	14,4%	72,8%	8,07	547	1,2%	5,8%	2,7%
SM47	170	230	170	364	313	263	339	56,8%	11,0%	14,8%	82,7%	49,0%	9,5%	12,7%	71,2%	8,27	564	-0,4%	8,4%	6,0%
SM48	170	230	200	364	311	295	346	56,9%	10,9%	13,2%	81,1%	49,1%	9,4%	11,4%	69,9%	8,39	578	-1,7%	10,0%	8,5%
SM49	170	230	230	364	313	325	352	57,7%	9,7%	12,0%	79,4%	49,8%	8,4%	10,4%	68,5%	8,43	590	-3,1%	10,5%	10,8%
SM50	170	230	260	364	312	354	356	57,6%	10,6%	10,1%	78,3%	49,7%	9,2%	8,8%	67,6%	8,45	597	-4,0%	10,8%	12,1%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 5.3 Stud-type material simulation results

Table 5.1 Simulation results of 46x78 products, ordered by minimum block length values

Table 5.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m³/h	€/h	FJ yield	FJ m³/h	€/h
SM51	170	230	290	364	311	385	359	56,7%	11,4%	9,4%	77,5%	48,9%	9,9%	8,1%	66,9%	8,48	586	-4,7%	11,2%	10,0%
SM52	170	260	140	365	345	243	336	56,9%	9,3%	18,6%	84,8%	49,0%	8,1%	15,9%	73,1%	8,10	549	1,4%	6,1%	3,1%
SM53	170	260	170	365	344	275	344	56,9%	9,2%	16,8%	82,9%	49,1%	8,0%	14,5%	71,5%	8,27	566	-0,1%	8,4%	6,2%
SM54	170	260	200	365	340	308	351	56,8%	9,5%	15,0%	81,3%	49,0%	8,2%	12,9%	70,2%	8,40	577	-1,5%	10,2%	8,2%
SM55	170	260	230	365	339	338	357	56,8%	9,6%	13,6%	79,9%	49,0%	8,3%	11,8%	69,0%	8,49	582	-2,6%	11,4%	9,3%
SM56	170	260	260	365	340	365	362	57,1%	9,9%	11,8%	78,7%	49,3%	8,5%	10,2%	68,0%	8,57	593	-3,6%	12,4%	11,4%
SM57	170	260	290	365	340	392	365	57,3%	9,4%	10,7%	77,4%	49,4%	8,2%	9,3%	66,9%	8,54	595	-4,7%	12,0%	11,8%
SM58	170	290	140	365	370	252	339	56,9%	8,1%	20,0%	85,0%	49,1%	7,1%	17,1%	73,3%	8,10	549	1,6%	6,1%	3,2%
SM59	170	290	170	365	368	284	348	56,9%	8,1%	18,2%	83,1%	49,1%	7,0%	15,6%	71,7%	8,26	566	0,1%	8,3%	6,2%
SM60	170	290	200	365	365	318	356	56,8%	8,3%	16,2%	81,4%	49,0%	7,2%	14,0%	70,3%	8,41	578	-1,4%	10,2%	8,4%
SM61	170	290	230	365	364	347	361	56,8%	8,4%	14,9%	80,1%	49,0%	7,3%	12,9%	69,2%	8,49	582	-2,5%	11,3%	9,3%
SM62	170	290	260	365	365	375	367	56,7%	8,6%	13,5%	78,8%	48,9%	7,5%	11,7%	68,2%	8,57	586	-3,5%	12,3%	10,1%
SM63	170	290	290	365	366	402	371	57,1%	8,9%	11,7%	77,7%	49,3%	7,7%	10,2%	67,2%	8,63	596	-4,5%	13,1%	12,0%
SI26	200	140	140	381	228	185	321	54,6%	18,8%	11,2%	84,6%	47,2%	16,0%	9,4%	72,6%	7,71	512	1,0%	1,0%	-3,8%
SI27	200	140	200	381	226	247	332	54,5%	18,8%	7,8%	81,1%	47,1%	16,0%	6,7%	69,7%	7,87	536	-1,9%	3,1%	0,6%
SI28	200	140	260	381	227	320	340	54,5%	18,9%	5,7%	79,0%	47,1%	16,1%	4,9%	68,0%	7,91	548	-3,6%	3,7%	2,9%
SI29	200	140	320	381	229	390	344	54,5%	19,0%	4,4%	77,9%	47,1%	16,1%	3,9%	67,1%	7,90	551	-4,6%	3,6%	3,5%
SI30	200	140	380	381	230	455	347	54,5%	19,1%	3,7%	77,3%	47,1%	16,2%	3,2%	66,6%	7,89	553	-5,1%	3,4%	3,8%
SI31	200	200	140	381	285	217	335	54,5%	15,3%	15,1%	84,8%	47,0%	13,1%	12,8%	73,0%	8,12	530	1,3%	6,4%	-0,6%
SI32	200	200	200	381	284	285	349	54,5%	15,3%	11,5%	81,2%	47,0%	13,1%	9,9%	70,1%	8,42	558	-1,6%	10,4%	4,9%
SI33	200	200	260	381	284	349	358	54,4%	15,4%	9,1%	78,9%	47,0%	13,2%	7,9%	68,2%	8,46	570	-3,5%	10,9%	7,0%
SI34	200	200	320	381	285	408	364	54,4%	15,5%	7,5%	77,4%	47,0%	13,4%	6,5%	66,9%	8,44	573	-4,8%	10,6%	7,6%
SI35	200	200	380	381	286	472	369	54,4%	15,6%	6,4%	76,3%	47,0%	13,4%	5,6%	66,0%	8,42	574	-5,7%	10,4%	7,7%
SI36	200	260	140	381	344	249	346	54,7%	11,6%	19,4%	85,6%	47,2%	10,0%	16,5%	73,8%	8,31	541	2,2%	9,0%	1,5%
SI37	200	260	200	381	340	314	363	54,5%	11,6%	15,8%	81,9%	47,1%	10,1%	13,7%	70,8%	8,63	564	-0,9%	13,1%	5,8%
																	Color coding	-10,0%	AS IS	10,0%

Appendix 5.4 Stud-type material simulation results

Table 5.1 Simulation results of 46x78 products, ordered by minimum block length values

Table 5.1 continued

Sim no	L_{min}, mm			Block L_{avg}, mm				WE yield				FJ yield			KPI			KPI change		
	A	B	C	A	B	C	L_{wavg}	A	B	C	Total	A	B	C	FJ yield	FJ m^3/h	€/h	FJ yield	FJ m^3/h	€/h
SI38	200	260	260	381	341	372	374	54,4%	11,9%	13,0%	79,3%	47,0%	10,3%	11,3%	68,6%	8,81	576	-3,0%	15,5%	8,1%
SI39	200	260	320	381	341	420	380	54,3%	12,1%	11,1%	77,5%	46,9%	10,5%	9,7%	67,1%	8,87	577	-4,6%	16,3%	8,3%
SI40	200	260	380	381	342	472	386	54,3%	12,2%	9,5%	76,0%	46,9%	10,6%	8,3%	65,8%	8,84	576	-5,9%	15,8%	8,1%
SI41	200	320	140	382	389	273	354	54,5%	8,8%	22,4%	85,7%	47,1%	7,6%	19,2%	74,0%	8,32	536	2,3%	9,0%	0,7%
SI42	200	320	200	382	389	337	372	54,5%	8,7%	19,0%	82,2%	47,1%	7,6%	16,4%	71,2%	8,61	563	-0,5%	12,9%	5,7%
SI43	200	320	260	382	387	390	384	54,4%	9,1%	16,3%	79,8%	47,0%	7,9%	14,2%	69,1%	8,78	573	-2,6%	15,2%	7,6%
SI44	200	320	320	382	389	435	392	54,3%	9,4%	14,0%	77,7%	46,9%	8,2%	12,3%	67,4%	8,88	575	-4,3%	16,5%	7,9%
SI45	200	320	380	381	391	479	399	54,3%	9,4%	12,3%	76,0%	46,9%	8,2%	10,8%	65,9%	8,94	572	-5,8%	17,1%	7,5%
SI46	200	380	140	382	439	301	362	54,6%	5,8%	25,5%	85,9%	47,2%	5,1%	22,0%	74,3%	8,30	535	2,6%	8,8%	0,5%
SI47	200	380	200	382	441	364	381	54,6%	5,8%	22,4%	82,7%	47,2%	5,1%	19,4%	71,7%	8,57	559	0,0%	12,3%	5,0%
SI48	200	380	260	383	442	411	394	54,6%	5,9%	19,9%	80,4%	47,1%	5,2%	17,3%	69,7%	8,71	568	-2,0%	14,2%	6,6%
SI49	200	380	320	382	442	451	403	54,4%	6,4%	17,6%	78,4%	47,0%	5,6%	15,4%	68,0%	8,81	570	-3,7%	15,5%	7,0%
SI50	200	380	380	382	442	491	409	54,3%	6,7%	15,6%	76,6%	46,9%	5,9%	13,7%	66,4%	8,88	567	-5,2%	16,4%	6,5%
																	Color coding	-10,0%	AS IS	10,0%