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Abstract

The thesis investigates optical measuring and statistical data processing, and presents a method to understand and reduce sawing variation by examination of sawn timber sizes. Continuous timber size control offers improved opportunities for analysing saw machines or even individual sawblades. The thesis is illustrated with seven saw machine case studies that relate to the development of the technique. Log and cant breakdown is examined in single- and double-arbor circular saws and bandsaws. The first analysis of each saw machine is made in normal production, and the second using a controlled benchmarking test. A total of 44350 logs were sawn in the study.

The behaviour of a saw machine is described using such descriptors as total, within-board and between-board standard deviations, and sawblade bend. Based on observations in benchmarking, an equation $y=\alpha e^{\beta x}\pm R$, where α and β are constants, R the process reproducibility, and x a variable that expresses sawing time and saw load, can be established for each of the saw machine descriptors. An example is the total standard deviation descriptor function $s=0.21e^{0.58x}\pm 0.11$, established for a single-arbor circular saw in a 4-piece saw set-up.

The method will help a sawmill to establish descriptors and equations used to describe the behaviour of their saw machines, to baseline saw machine performance and to compare it to best practices in the industry. The descriptors may be used to establish current, short- or long-term capabilities and characteristics. The method can be used to examine various production conditions and tooling, such as effects of log size, feed speed, and sawing time. Other factors include saw speed, sawblade parameters, operation of setworks and feedworks, and effects of seasons. The results of the study show that sawblade behaviour, feedworks and work piece holding problems, and previous saw machines may be causes of large sawing variation.

Keywords

Sawing variation, lumber size control, sawn timber size, optical measurement, saw machines

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Symbols and Conversions

B	Sawblade bend amplitude (mm)	s_M	Between-segment standard deviation (mm)
C	Capability index of a saw machine	t	Time (h)
D	Dimension or size of a sawn piece or test reference, smallest acceptable green size (mm)	T	Trimmed mean (mm)
F	Feed speed (m/min)	x	Time*Saw load factor (h*m^3/min)
k	Kerf width, tooth tip width (m)	x_i	Individual reading, measurement or observation
L	Length of a cutting path (m)	$\overline{X}$	Mean (mm)
n	Number of readings, measurements, teeth, sawblades, or sample or population size	y	Saw machine descriptor
R	Reproducibility (mm)	Z	Standardised normal random variable
s	Standard deviation (mm)	α	Inherent capability constant
s_T	Total standard deviation (mm)	β	Time-wear constant
s_B	Between-board standard deviation (mm)	μ	Mean of a population (mm)
		σ	Standard deviation of a population (mm)

100 000 cubic metres (m^3) = 42 500 000 board feet
1 cubic metre per minute (m^3/min) = 36 cubic feet per minute
50 metres per minute (m/min) = 165 feet per minute
1 metre (m) = 3.3 feet
25.4 millimetres (mm) = 1 inch
0.1 millimetres (mm) = 0.004 inch
0.01 millimetres (mm) = 0.0004 inch

Contents

1 Introduction

The breakdown of logs to sawn timber is one of the core processes in sawmilling. Each log and its cutting process is unique in nature. Currently, sawmills have no practical real-time methods for analysing saw machine behaviour in the breakdown of wood. Furthermore, many beliefs, whether justified or not, concerning saw machines, sawblades, large or frozen logs and curve sawing, exist in sawmill industry. Although breakdown control of logs and cants is one of the essential factors in sawmill profitability, very few systems for measuring timber size in the primary and resaw breakdown process environment have been developed. The technique presented in this thesis provides a tool that can be use to analyse breakdown processes in sawmills in both the short- and long-term.

The essential information on the properties of a saw machine, of its breakdown process of logs, cants and square cants, is available in the sawn pieces. Thus, emphasis should be on real-time process control of a production system rather than on deviation detection and inspection in later stages of production flow, because manual inspection of timber size does not offer sufficient data on the behaviour of a saw machine. In order to be able to analyse what has happened in a saw machine, one must know the situation before the problem appeared, when it happened, and what were the effects of corrective actions. As long as actions are essentially reactive, relying on practically obsolete data, and the effects of actions are insufficiently recorded, very little can be learned from saw machine behaviour.

According to Dr. W. E. Deming, “We cannot have improvement if we cannot measure it”. The measured data must also be readily available for process control. “The usefulness of quality control measurement-taking is inversely proportional to the time and distance between the point of measurement and the place of data analysis. That is to say, the results of measurement are of no more value to real-time control than their ability to be used for corrective adjustments” (Martin, 1982, p. 33).

Sustainable usage of raw material, its rising cost, and increasing international competition are some of the reasons why sawmills must improve their production practises. It has been shown by Brown (1979, p. 49), and known to sawmill professionals, that a sawmill having a ‘tight machinery’ can saw many millimetres closer to a cumulative target size than a sawmill with ‘looser machinery’. This practise will not only save wood, but also lead to higher earnings for a sawmill. Although this has long been known, lack of available technology has, in most cases, prevented exploitation of smaller target sizes. Capability of breakdown saw machines may have improved through recent advances in instrumentation, sawblade materials, machinery elements, servo controls, and various optimisation and management software tools. However, factual data on the improvement is not available. Williston (1988) presents no fewer than eight different scanning methods for edgers, and even more for trimming and sorting. In breakdown sawing the used technology is log scanning, for turning and position optimisation. The situation has persisted over the last decade of the previous millennium, when most of the work centred on optical quality grading of boards (Kauppinen, 1999, and Åstrand, 1996). In the most basic sawmill process – the breakdown and resaw of logs and cants – the knowledge of produced timber size leaving a saw is based on periodic manual sampling.

One might ask why there are no real-time measuring devices applied on a large scale in log and cant breakdown processes if it is so important? Perhaps it is simply that the measuring environment in breakdown processes is demanding. The latest developments in electronics and software have provided the technologies that are applicable in this environment.

1.1 Purpose of the Thesis

The principal objective of this thesis is the development of a method, which can be used to investigate sawing processes in primary and secondary breakdown saws for the purpose of reducing sawing variation. There exists a straight relationship between sawing variation – sawing allowance – recovery – profit for the sawn products. When sawing variation is under control in various production conditions, it is possible to use smaller sawing allowances, and thus increase recovery and sawmill profitability. For these reasons a technique for analysing performance of breakdown saw machines is developed.

The main differences between manual inspection and computerised optical control in wood breakdown are the sampling frequency and the quantity of readings. A softwood sawmill cuts hundreds of logs per hour and a few pieces of timber are measured manually from time to time. An optical measuring device, installed immediately after a breakdown saw machine, measures all pieces. The difference in data collection between manual inspection and optical control may be in the order of one to several million readings. Although optical data collection is chosen for this thesis, the readings used as the basis of calculations may be produced with any feasible measuring technology.

Assessment of accuracy, precision, and reproducibility of a saw machine can be made by examining a large number of readings from a large number of sawn boards. An adjustment to correct lack of process accuracy is simpler than a larger investigation required to understand and correct problems of standard deviation, or large or inconsistent variation. Reproducibility of a sawing machine may be assessed in the long term. When a saw holds the target size consistently, and the precision, expressed by the standard deviation, has consistently small variability for given log sizes, feed speeds, species and seasons, so that a saw operator can predict the outcome, the saw machine demonstrates consistent reproducibility. Better understanding of these factors and saw machine behaviour can be gained through extensive size analysis. The modern rough board size measuring devices provide data in such quantities that more versatile analysis and control of saw machines by traditional and new statistical descriptors is possible.

This thesis provides a technique that can be used to examine and analyse performance of saw machines using numeric and graphic descriptors. Controlled benchmarking tests are used to establish a mathematical model to describe features of saw machines, such as standard deviations. The usefulness and potential of the developed method is examined with three variables, feed speed, log size and sawing time. Besides the effects of these variables, other factors, such as sawblade geometry and saw speed are kept constant.

The thesis is illustrated with seven saw machine case studies that relate to the development of the technique. Each saw machine is examined both in normal production and in a benchmarking test.

1.2 Outline of the Thesis

Because this study deals with two different engineering branches, wood processing in sawmills and measuring techniques, an introduction to these two branches is presented. Basics of optical and manual measurement, verification of the used device, and principles of statistics, together with the definition of new and current saw machine descriptors, are introduced in separate chapters. Measurement and results of normal production and control tests, benchmarking, are presented for seven different saw machines and sawing processes. The saw machine descriptors are evaluated in the light of results and a discussion on economic importance is presented.

Chapter 2 describes concepts of accuracy and precision of saw machines as well as causes of sawing variation. It provides also an introduction to concepts of target size and variation in wood. Chapter 3 presents the various aspects of manual measurement, and Chapter 4 the current control methods used in breakdown sawing. Chapter 5 provides a detailed description of the optical measuring technology used in this thesis, the concepts of accuracy and precision of a measuring device, and the method of verification and the verification results of the used measuring device. In this chapter the part describing the optical technology is rather extensive. This is done on purpose because the principles of the optical measuring technology are not commonly known in the sawmill industry, and understanding of the developed analysis method requires some basic knowledge of this technology. Chapter 6 provides the basics of statistical quality control necessary in breakdown saw control. The chapter additionally presents the traditional and the new numerical and graphic process descriptors required in describing and analysing recorded data, as well as their definitions. Chapter 7 presents the log breakdown tests and Chapter 8 the cant resaw tests in normal production and benchmarking. The tests in Chapters 7 and 8 provide data to help in understanding the behaviour of the descriptors in different sawing processes. Chapter 9 discusses certain economic implications of the method, and Chapter 10 presents the final discussion and conclusions of this study.

Appendix A describes the examined saw machines and production lines. Appendix A presents also use of graphic descriptors in examination of observed irregularities. Appendix B presents results of two tests made on precision and accuracy of manual measurement. Appendix C presents the effect of trim percentage and segment quantity on segment means. Appendix D presents a sample of optical data and segment means.

1.3 Research Plan

New technologies offer new opportunities also for traditional areas of industry. Size control in breakdown process in sawmills is one such technology. A device with parallax free optics was selected as the optical system for data collection. Parallax free optics makes possible recording of size of cants and boards whose distance to a measuring device varies when the pieces exit from a saw. Such optics also allows recording of size on curved surfaces, such as size of log cants. Wood enters a measuring zone in many shapes and colours. Therefore, effective edge detection algorithms are required, and the accuracy of a measuring device must be proven in sawmill conditions.

The traditional saw process descriptors based on manual measurement are (Brown, 1982, p. 132-133):

- Mean
- Within-board standard deviation s_W

- Between-board standard deviation s_B
- Total standard deviation as $\sqrt{s_W^2 + s_B^2}$.

Due to limited number of samples and readings, these descriptors provide rather limited information on mean and total and between-board standard deviations of a process during production. The value of these descriptors depends entirely on the number of sampled boards and the sampling frequency. Real-time detection and a cause-effect analysis of a shift in process mean, or increase or decrease in standard deviations, is difficult using manual measurement.

Optical measuring provides hundreds of readings for the length of each sawn board and makes possible the use of new numeric and graphic process descriptors, such as within-board standard deviation for individual boards, between-segment standard deviation and sawblade bend, Chapter 6.6. These new descriptors are discussed extensively in this study. Saw machine cases show that the usefulness of each descriptor depends on the problem at hand, and that in general the descriptors will uncover phenomena the detection of which has previously been difficult or impossible.

The studied saw machines are selected to represent three modern types of saw machine used in softwood industry, single- and double-arbor circular saws and bandsaws. Sawing processes, both in log breakdown and cant resaw, are examined. The production line layouts, with measuring device locations, are presented in Appendix A. Table 1.1 describes the seven measuring locations where size data of various products is recorded.

Table 1.1. *Types of pieces measured in various process stages in different saw machines.*

	Process and Measured pieces	
Saw machine type	Log breakdown	Cant resaw
Single-arbor circular saw, Type A		Centrepieces and flitches
Single-arbor circular saw, Type B	Log cant and flitches	Centrepieces and flitches
Double-arbor circular saw	Square cant	Centrepieces
Bandsaw	Log cant	Centrepieces

The saw machines are examined both in normal production and in benchmarking tests. The former is necessary for establishing a basic understanding of the sawing processes and the descriptors of the method. Benchmarking is performed to establish a control reference for normal production and to calculate the constants for the descriptor equations. Sampling during normal production gives descriptors both for the current situation at a specific point of time and long-term trend data over a recording period. Benchmarking reveals production descriptors over a short-term, between sawblade changes. When benchmarking is repeated periodically over a period, it will also reveal accurate short- and long-term behaviour of a saw machine.

Table 1.2. *Number of measured pieces in normal production.*

Saw machine type	Number of measured pieces Log breakdown	 Cant resaw
Single-arbor circular saw, Type A		12100
Single-arbor circular saw, Type B	3900	7050
Double-arbor circular saw	1550	5550
Bandsaw	1950	5750

Normal production data was collected periodically during regular production. In each sawmill, the data collection was repeated twenty to thirty times and it covered a period of two to six months. The numbers of pieces measured in this study are presented in Table 1.2. The production details, such as log and cant sizes, and feed speeds were provided by saw operators on duty. Because saw operators have rotating duties, they usually do not have accurate knowledge of sawblade changes, and thus of sawing time with individual sawblades. The recorded, normal production data represents the typical production of each sawmill. Set-ups used by different sawmills vary depending on their production demands, as seen in Table 1.3.

Table 1.3. *Set-ups and sawblades in saw machines in normal production.*

Saw machine type	Process and Set-up Log breakdown	 Cant resaw
Single-arbor circular saw, Type A		4-, 5-, 6- and 8-piece set-ups Sawblade: Toijalan Koneterä, Sandvik
Single-arbor circular saw, Type B	Log cant with 2 flitches Sawblade: TTT Technology	4-, 6-, 7- and 8-piece set-ups Sawblade: Toijalan Koneterä
Double-arbor circular saw	Square cant with 2 or 4 sideboards Sawblade: Kanefusa	2-, 3-, 4- or 5-piece set-ups with 2 or 4 sideboards Sawblade: Kanefusa
Bandsaw	Log cant with 2 flitches Sawblade: Uddeholm	2-, 3- and 4-piece set-ups Sawblade: Uddeholm and Sandvik

Benchmarking deals with scientific examination of variables in specific process environment. Similar methodology has been used and proposed by Juvonen (1974, p. 119) in his research of sawing variation in frame saws and edgers. The benchmarking details are selected to chart the most important factors influencing a saw machine. These include log and cant size, feed speed, and sawblade wear, expressed as sawing time. Thus, logs are selected to represent small, middle, and large size logs, and the feed speeds to represent slow, normal, and fast speeds, as can be seen in Table 1.4. Sawing time with the used sawblades is the third factor. Benchmarking takes place within a period between sawblade changes, under normal production conditions. The sawn pieces are processed in the mill, as is the case with all sawn goods.

Table 1.4. *Log and cant sizes, feed speeds, duration of test and number of sawn logs in benchmarking.*

	Process and Parameters	
Saw machine type	Log breakdown	Cant resaw
Single-arbor circular saw, Type A		Cant size: 110, 145, 175mm Feed speed: 40, 60, 85m/min Test period: 14 hours Sawn logs: 750
Single-arbor circular saw, Type B	Log size: 200, 265, 295mm Feed speed: 35, 50, 70m/min Test period: 9 hours Sawn logs: 800	Cant size: 100, 150, 195mm Feed speed: 35, 50, 70m/min Test period: 9 hours Sawn logs: 800
Double-arbor circular saw	Log size: 196, 225, 265mm Feed speed: 40, 60, 85m/min Test period: 9 hours Sawn logs: 1100	Cant size: 110, 150, 200mm Feed speed: 40, 60, 85m/min Test period: 9 hours Sawn logs: 950
Bandsaw	Log size: 170, 230, 285mm Feed speed: 40, 65, 90m/min Test period: 9 hours Sawn logs: 1050	Cant size: 100, 150, 200mm Feed speed: 40, 65, 90m/min Test period: 9 hours Sawn logs: 1050

In benchmarking flitches or sideboards are sawn in log breakdown so that the measured cant faces are sawn. The requirement for the cant resaw was a 4-piece set-up in all cant sizes, and in case of the double-arbor circular saw also sideboards in the 4-piece set-up. Due to cant size and pattern fit, one sawmill could not comply with this in one cant size, Table 1.5.

Table 1.5. *Saw machine set-ups in benchmarking.*

	Process and Set-up	
Saw machine type	Log breakdown	Cant resaw
Single-arbor circular saw, Type A		4- and 6- set-ups Sawblade: Sandvik
Single-arbor circular saw, Type B	Log cant with 2 flitches Sawblade: TTT Technology	4-piece set-up Sawblade: Toijalan Koneterä
Double-arbor circular saw	Square cant with 2 or 4 sideboards Sawblade: Böhler-Miller	4-piece set-up with 2 or 4 sideboards Sawblade: Böhler-Miller
Bandsaws	Log cant with 2 flitches Sawblade: Uddeholm	4-piece set-up Sawblade: Uddeholm in saw 1 and 3 and Sandvik in saw 2

2 Saw Machines and Sawn Timber

This chapter introduces the concepts of saw machine accuracy and precision, and the cause-effect relationships that have an effect on sawing variation. This chapter further provides an introduction to target size and sawn timber attributes.

2.1 Accuracy and Precision of Saw Machines

There is a difference between the accuracy and the precision of a saw machine. The accuracy relates to the capability of a saw to hit a target size. The precision relates to the degree of a saw's standard deviation. A third factor is reproducibility, which refers to the consistency of a saw machine to produce repeatedly similar patterns of variation, as discussed in Chapter 6.6.7. Where repeated readings show erratic patterns of variation, the operation of a saw machine is not consistent and not reproducible. When accuracy and precision are under control, a system will demonstrate consistent reproducibility.

The accuracy of a saw machine refers to the uniformity of sawn sizes around a target size so that, on average, the target size is realised. When individual sizes spread on both sides of a target size in almost equal proportion, a saw machine is said to be accurate. Accuracy can be improved by set-up adjustment.

Precision of a saw machine refers to the degree of variation of sizes, the standard deviation. Sizes may be off target but still considered precise if dispersion is minimal. An efficient saw machine should be able to produce an output with as little variability as possible. Precision reflects the structural inaccuracy of machinery and is an inherent characteristic of a saw machine, which usually cannot be improved by set-up adjustment.

Assessment of accuracy, precision, and reproducibility should be made by examining a large number of readings rather than individual readings. Adjustment decisions to be made in a process, based on one individual reading, may give an undesirable outcome, owing to lack of information about process accuracy and precision. An adjustment to correct lack of process accuracy is simpler than a larger investigation required to understand or correct problems of standard deviation, or large or inconsistent variation. Reproducibility of a sawing machine is assessed in the long term. When a saw holds the target size consistently, and the precision, expressed by the standard deviation, has consistently small variability for given log sizes, feed speeds, species and seasons, so that a saw operator can predict the outcome, the saw machine demonstrates consistent reproducibility.

The sawmill industry uses expressions of within-board and between-board standard deviation to describe the precision of a sawing process. Within-board deviation is sometimes claimed to represent surface roughness arising from sawing variation in a cut (Warren, 1973, p. 1-2). Between-board deviation is currently understood to represent the variation in operation of saw setworks.

2.2 Reports on Accuracy and Precision

Danielson and Schajer (1993) studied the effects of three adverse factors on accuracy in otherwise normal circular saw operation. Factors included blade tensioning, guide cooling, and rigidity, which varied in quality. The study revealed clear evidence on the effects of the test factors. Each factor reduced accuracy but combinations of factors were far more detrimental than an individual factor acting alone. Manual measurements taken at twelve equally spaced locations along the boards demonstrated that, in the worst case, the top to butt thickness difference was 2.8mm, whereas in a normal case the difference was practically zero (Danielson and Schajer, 1993, p. 134-136). Guide looseness was found to degrade sawing performance most. The authors conclude that if size varies excessively along the length of sawn timber, with varying thick and thin areas, the likely cause is guide movement. According to Williston (1988, p. 93), a specification bandmill, properly aligned, will cut to an accuracy of plus or minus 0.4mm.

Szymani (1999, p. 1) reports that the total sawing variation of an optimal sawing system can be 0.15mm or less. Heiskanen and Paajanen (1997) studied the precision of a group of different saw machines and conclude that, in the case of circular saws, the within-board standard deviation in small log boards is 0.2mm, and the standard deviation of flitches is from 0.5mm to 0.6mm. In larger log sizes, the values are from 0.1mm to 0.7mm for boards, and from 0.3mm to 0.9mm for flitches, respectively. While no significant difference is noted between band and circular saws, the authors note differences from sawmill to sawmill with otherwise similar machinery. Probable causes for the differences include different tooling, and filer and maintenance practices.

Sawing variation of pine and spruce boards from approximately 800 cants were studied by Virtanen et al. (1997, p. 39 and p. 46) in resaw. Cants were sawn either in a curve sawing circular saw or in a skew optimiser circular saw. The green within-board standard deviation of pine boards varied from 0.09mm to 0.41mm. Spruce sizes were measured after drying to 16% moisture. The standard deviation of spruce boards varied from 0.32mm to 0.73mm. The authors conclude that the forces required in curve sawing reduced process precision so much that it was inferior to skew optimiser saw.

Steele et al. (1996, p. 57) indicate that in a new hardwood bandsaw, a total one-standard-deviation variation value of 0.75mm should be achievable. In their study of 266 saw machines of six different types in hardwood mills, Steele et al. (1992, p. 34) conclude that sawing variation produced by a saw machine was largely independent of the thickness of sawn timber. The authors further conclude that kerf width and within-board sawing variations are closely related, because sawblade flutter is one cause of the within-board variation. The second cause of within-board variation is the failure of feedworks to hold the work piece steady during sawing. They further conclude that between-board variation is generally a measure of setworks precision in a saw machine.

Usenius et al. (1983, p. 3 and p. 59) investigated standard deviation in certain chipper canters, circular saws and bandsaws. The within-board standard deviation of heartwood timber varied from 0.2mm to 0.5mm. The precision was equal in band and circular saws.

Criticism of the results of precision measurement are present in sawmill literature, including Brown (1979, p. 54, and 1982, p. 120), Usenius (1976, p. iii), Usenius et al. (1983, p. 18 and 24), Williston (1985, p. 298), Wade et al. (1992, p. 26) and Heiskanen and Paajanen (1997, p. 59). The reason for scepticism is that researchers cannot obtain reliable measuring data in sufficient quantities for their analyses. Manual measurement is too slow and cumbersome for extensive research purposes. Moreover, it seems that in spite of the technological advances made during the last twenty years, either the behaviour (standard deviation) of saw machines has not improved, or the improvement cannot be recorded properly.

Table 2.1. *Summary of total standard deviations reported in literature.*

	Average total standard deviation (mm)	Minimum total standard deviation (mm)	Maximum total standard deviation (mm)
Single saw machines			
Bandsaw	1.09	0.74	1.52
Circular saws of all types (single- and double-arbor)	0.58	0.20	0.81
Combination saw machines			
Bandsaw + profile arbor	0.25	0.20	0.30
Bandsaw + circular saw	0.57	0.50	0.70
Chipper canter + circular saw	0.41	0.29	0.53
Chipper canter + bandsaw	0.60	0.46	0.74

Because data in the literature is not accurate, missing most test details, only an indicative summary of the precision studies can be presented, as in Table 2.1. The results from the hardwood headrigs (Steele et al., 1992, p. 34) are not listed because headrig-sawing practice differs greatly from Nordic softwood mill practises. The other hardwood mill results can be found in the summary, because their practises are approximately similar with softwood mills.

2.3 Sawing Variation

Variability is inevitable within any process. Variations are due to two types of causes: random, common causes and special, assignable causes. Common causes cannot be easily identified individually but they set the limits of precision in a process, whilst special causes reflect specific changes which either occur or are introduced. Size differences seen on each piece of timber when it leaves a saw are a result of variations in raw material, cutting parameters, and the operation of setworks and feedworks, as can be seen in Figure 2.1. Changes or incorrectness in any of these factors will add to sawing variation, and will be seen in standard deviation, mean, or shape of a sawn board. Winter sawing will further enhance the effects of elements that operate inadequately in a saw machine.

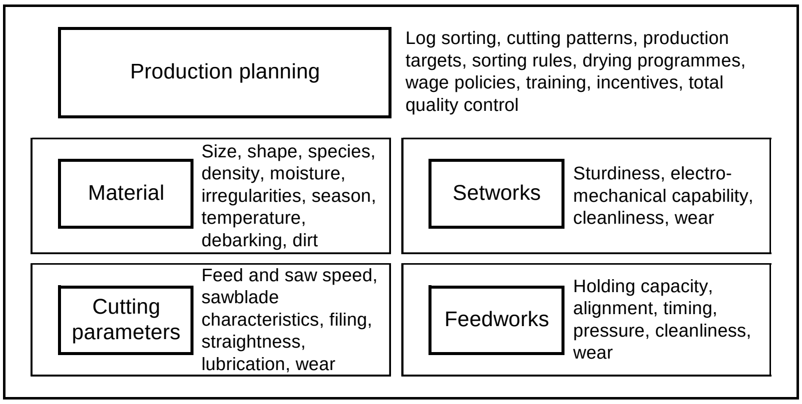


Figure 2.1. *Sawing environment and factors having an effect on sawing result.*

Wood is a natural material and one can control its features only to a limited extent (Markgren and Lycken, 2001, p. 6-7). Because wood and sawblade interact strongly in a cutting process, the general and local natural variations present in wood have a significant effect on the cutting result. When reliable quality control or accurate process analysis is required, the large natural variation is a cause of both frequent and large sample sizes. Variation in raw material has an effect on the standard deviation of sawn boards, as in Table 2.2. In an aligned saw machine, wood quality as such should not have an effect on sawing accuracy, because the sawblades should be cutting straight.

Table 2.2. *Raw material effects on sawing accuracy and precision.*

Cause	Effect	Accuracy	Precision
Size and shape	Affect saw load, standard deviation and sawblade bend		***
Density and density variations	Affect saw load, standard deviation, and sawblade bend		**
Moisture	Increase may cause decrease in standard deviation and sawblade bend		**
Frozen wood	Freezing may cause increase in standard deviation and sawblade bend		***
Tensioned wood	Tensioned wood pinches a sawblade in a non-symmetrical way after it has been cut. May cause increase in standard deviation and sawblade bend		*
Foreign particles	Dirt, stones and bits of metal break or dull sawblades causing increase in standard deviation and sawblade bend		**

Cutting parameters are a combination of the sawblade features and the cutting parameters, including feed and saw speed, sawblade material, thickness and sharpening details, and the elasticity of the machinery at the time of sawing. The cutting parameters are the most significant factors affecting cutting precision. An efficiently operated and maintained cutting process will keep a sawblade under optimum control, and the sawn pieces will be uniform with acceptable surface roughness. Overfeeding may cause sawblade instability due to load strain, and underfeeding may show instability due to resonance vibration. The effects of incorrect cutting parameters are presented in Table 2.3.

Table 2.3. *Cutting parameter effects on sawing shape, accuracy, and precision.*

Cause	Effect	Accuracy or shape	Precision
Feed speed	Over- or under feeding may cause sawblade bend		**
Saw speed	Over- or under feeding may cause sawblade bend		**
Sawblade dullness	Increase in standard deviation and sawblade bend		***
Saws not level or tensioned correctly, or unbalanced, bent	Increase in standard deviation and sawblade bend		**
Tooth face, side, or top angle or clearances not correct or not consistent	Increase in standard deviation and sawblade bend		*
Overfeeding, gullets load up, guide pressure, improperly positioned or functioning saw guides or guide supports	Increase in standard deviation and sawblade bend	*	*
Chipped or broken teeth, solder protruding into cutting circle	Rough surface. Increase in standard deviation and sawblade bend	*	**
Sawblade overheating, loss of tension, loss of coolant	Increase in standard deviation and sawblade bend		**
Incorrect sawing, axial run-out, run-out in a fixed flange, run-out of spacers, worn guides	Wedge. Upper edge size differs from bottom edge size. Increase in standard deviation and sawblade bend	*	*
Out of balance arbor, loose chipper knives	Size errors and marks on chipped surfaces		*
Foreign particles between sawblade guides	Sudden shift in process mean, adjustment failures	*	

Dening (1993, p. 65) mentions that in bandsaws, the within-board sawing variation is a good indicator of a saw's performance. A relationship between bandsaw blade strain and within-board sawing variation at different feed speeds can be calculated for each mill. This relationship depends on sawing conditions, filing parameters, and density of the wood. For the best accuracy, the strain should be sufficient to ensure minimum deflection under load Williston (1988, p. 332). The distance between guides and closeness to the cutting play a role in blade stability. If the depth of tooth cut and feed speed are not properly managed, it may happen that sawdust fills gullets and begins to spill over into the space created by side clearance, heating the sawblade by friction and causing snake.

The larger a circular sawblade is in diameter, the more flexible it becomes, compromising the sawing accuracy. In circular saws that rotate in the direction of feed, self-feeding of the piece sometimes occurs. Such overfeeding can cause increase in sawing variation. Improperly positioned or functioning guides or guide supports are another source of sawing variation in circular saws.

Setworks is a combination of position servo controllers, guides, collars, and other activities and components that are required to achieve a correct set-up for cutting. The purpose of the setworks is to position the sawblades or cutting heads precisely at the target size position. Accuracy of saw setworks is necessary for all types of saw machines. Incorrect operation of saw setworks will lead to wrong target size, as in Table 2.4. Consistently wrong target sizes can be corrected by adjustment or a new set-up. Inconsistent changes are an indication that setworks machinery has mechanical or electrical problems that should be remedied forthwith.

Table 2.4. *Setworks effects on sawing accuracy and precision.*

Cause	Effect	Accuracy	Precision
Incorrect or non-repeatable setworks operation	Incorrect size	***	
Over- or under-adjustment	Incorrect size	**	
Carelessness in set-up	Incorrect size	**	
Looseness or inaccuracy in setworks machinery	Erratic size. Increase in standard deviation	*	*
Failure in facilities or automatic controls	Incorrect size	*	
Software programme problem	Incorrect size	*	

Effects of undesired saw setworks operation are seen in the capability of setworks to produce repeatedly and accurately target size boards. By Bramhall and McIntyre (1973, p. 29) the setworks operation is usually seen in the between-board standard deviation.

For the purpose of deciding the breakdown cutting pattern and position, each log is measured before sawing. Incorrect measuring leads to erroneous top diameter and shape data, and thus wrong cutting pattern, or wrong turning position. Incorrect centring and transport of logs will lead to a shift in sawing location and reduced wood recovery in the form of shorter boards and wane. For accurate cutting, logs and cants must to be fed smoothly, firmly, and straight prior to entering and leaving the cutting zone. A correctly designed transport mechanism requires a feed and press roll system that can manage the weight and length of logs and cants running through the machines. Misalignment and wear of feed, press, out-feed, or guide rolls are typical causes of improper operation. According to Liusvaara (1986, p. 73), a sideways sway of 0.5mm in in-feed may cause a sideways reaction in a circular saw that is 3 to 4 times larger.

If a saw machine is not parallel with the production line, bending of the sawblades will cause problems of accuracy and precision. Alignment problems are probable when:

- Sawing accuracy and precision is substandard
- Sawblades wear down fast
- Sawblade costs increase
- Log movement is uneven
- Chipper canter wrenches work pieces
- Sawn surface is rough
- Lumber recovery factor deteriorates.

According to Lehmann (2000a, pp. 215-216), approximately 50% of all sawmills experience an alignment problem and only 25% of those carry out regular alignment checks. Sawblades are the weakest and most vulnerable part of a saw machine, and thus cannot take the abuse of the sideways movement of the wood. When the wood is not controlled, it may lean against the sawblades. Thus, the objectives of alignment are to:

- Provide consistent support to the wood
- Ensure a smooth transition of control from one part of the feed system to the next
- Prevent the wood from rolling sideways onto the sawblades
- Prevent the wood from bending the sawblades (a contradiction with curve sawing)
- Prevent the wood from moving sideways onto the sawblades.

Table 2.5. *Feedworks effects on sawing shape, accuracy, and precision.*

Cause	Effect	Shape or Accuracy	Precision
Improper feedworks / arbor alignment	Creates sideways forces and causes sawblade bend and taper	***	*
Looseness in feedworks, unreliable holding, incorrect transport	Erratic size, flare, hook, taper, parallel size errors	**	**
Feed, press or out-feed rolls misaligned or worn	Parallel size errors	*	
Positioning or cutting forces cause deflection or rotation	Erratic size	**	
Failure in software programme, facilities or automatic control, over- or under-adjustment	Parallel size errors	*	
Improper saw line alignment, chipper line not parallel with saw line	Edge-to-edge taper	**	
Guides out of alignment and/or not parallel to feed	Parallel size errors	*	*
Improper saw alignment, arbors out of alignment and/or not perpendicular to feed	Wedge	*	
Incorrect size determination, size too small for cutting pattern	Thin top cant. Slab on flitches. Short flitches. Top-end cant size is thinner than expected.	*	
Incorrect turning, orienting, centring or transport	One sided thinness of cant, or slab on flitch, or short flitch.	*	

Feedworks is a combination of log and cant optimisation measurement and handling mechanisms, conveyors, chains, centring and curve sawing devices, end-dogs, infeed-, press-, outfeed- and holding rolls, guide plates and other mechanisms to move a log through a saw machine in a steady and controlled manner. A properly aligned and operating feedworks should correctly turn, centre, offset, and feed the logs in a process. Incorrect action of feedworks is most frequently seen in the shift of process mean, accuracy, and in the geometric shape of sawn boards, as in Table 2.5.

Alignment problems cause errors most frequently in accuracy and geometric shape. The purpose of feedworks is not only to feed logs smoothly into a saw, but also to keep vibration of wood to a minimum. The wear of feedworks elements is one cause of increase in vibration. The vertical feed rolls tend to wear in the middle and the horizontal rolls and guide plates in the lower parts. Moreover, varying holding capability causes vibration. Accuracy errors are generally parallel in flitches, because the effect concentrates on the outer boards. Parallel accuracy errors may also be caused by erratic setworks operation.

Analysis and search for causes of variation, along the outlines in Tables 2.2 to 2.5, can be presented in and assisted by a cause and effect diagram, as presented in Figure 2.2.

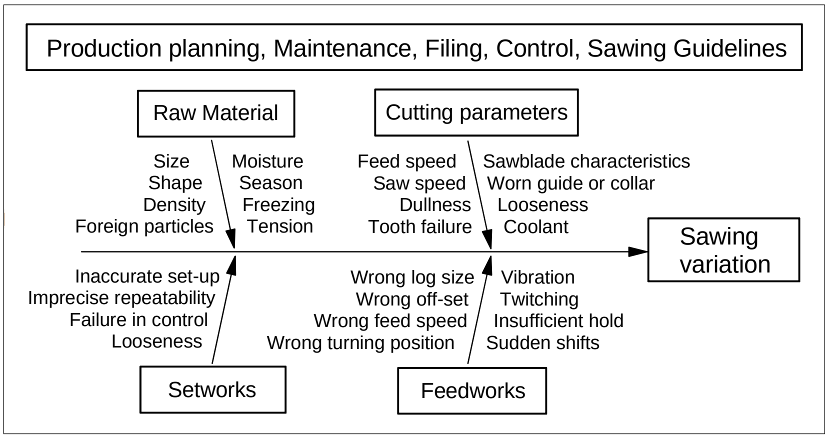


Figure 2.2. *Cause and effect diagram for sawing variation.*

The principal effects of the four factors, raw material, cutting parameters, setworks, and feedworks on sawing quality can roughly be summarised as follows:

- Standard deviation is affected by raw material and cutting parameters
- Standard deviation is affected by setworks in changing set-ups
- Accuracy is affected by setworks and feedworks
- Sawblade bend is caused by cutting parameters
- Geometric shape is caused by feedworks.

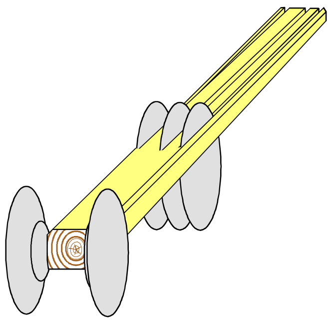


Figure 2.3. *Size variations are effected by both chipper canter and successive sawblades.*

In a saw machine analysis, the fact that sawn faces are produced by different sawblades, or by antecedent saw machines that are at some distance, must be taken into consideration, as in Figure 2.3 and Appendix A. In multiple saw systems, each board and surface must be considered separately according to the saw machine that cuts it.

2.4 Target Size

Sawmills think target size as a combination of series of allowances that are needed to produce the final size that is required by a customer. A customer may need a planing allowance to remove any surface irregularities. The 'planing allowance + final, dry-dressed size' is a sawmill's final sales target size, Figure 2.4. In order to be able to produce this, a sawmill has to calculate and control their shrinkage in drying. Shrinkage depends on drying process, species, moisture content, and from which part of a log and in which orientation timber has been sawn. Besides shrinkage, distortion of timber is a significant quality factor. Distortion of timber has many causes, but it is commonly driven by a change in moisture content and internal residual stresses within wood that are released in a sawing process. Perstorper (1994, p. Ia-1) demonstrates that warp, and twist in particular, is the most significant problem relating to timber quality. Warp leads in certain cases to wastage levels of 30% to 40% at a building site during the assembly stage.

From the point of saw set-up, each saw machine, and sawblade, behaves differently during sawing process. The same saws behave differently depending on log size, species, seasons, number and type of knots, and maintenance of machines and sawblades. These variables are the cause of sawing variation.

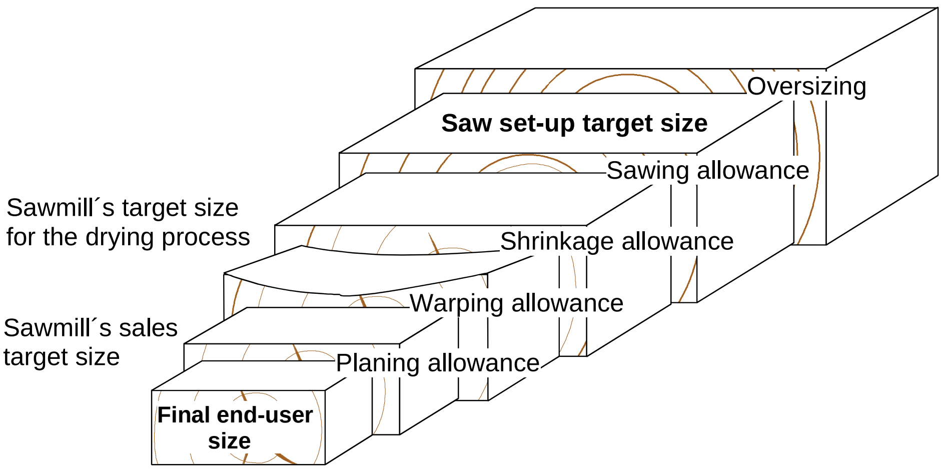


Figure 2.4. *Allowances that determine the saw set-up target size and potential oversizing.*

Any additional thickness in excess of a target size is considered oversizing. This should not be necessary, but it is almost universally practised. Stern et al. (1979, p. 2) found in their study of 600 softwood sawmills that oversizing from 0.0mm to 7.3mm took place, with a mean of 2.0mm. They conclude that almost all sawmills could benefit from closer control of sawing variation.

The determination of the smallest allowed green size for a particular sawing position can be expressed as

$$D_{\mathrm{Min}} = \frac{F_{\mathrm{E}} + P_{\mathrm{A}} + W_{\mathrm{A}}}{\left(1 - \frac{Sh}{100}\right)} \qquad (2.1)$$

where D_{Min} is the smallest sawn acceptable green size,
F_E is the final customer size,
P_A is the plainer allowance,
W_A is the warping allowance, and
Sh is the percent of shrinkage.

The parameters in Equation 2.1 are either facts or estimates based on management decisions. Similar calculation models for the green target size are used by Usenius et al. (1983, p. 75), and Brown (1979, p. 52).

The standard deviation of a saw machine and the selected confidence level determine a target size. The target size is calculated by

$$Target\ size = D_{Min} + Z * s \tag{2.2}$$

where *Target size* is the green saw set-up target size,
D_{Min} is the smallest acceptable green size,
Z is the confidence level value derived from normal distribution statistics, also known as the standardised random variable, and
s is the standard deviation.

Standard deviation is a variable feature of a saw machine and it is generally estimated by experience. The selected confidence level depends on a sawmill's quality criteria for undersized timber. A typical undersize criterion is 2.5%, meaning a 95% confidence level within a control area, as in Figure 6.2. The 2.5% undersize criterion is achieved by using a two-standard deviation and thus value 2 for Z in the calculation.

The work done by Juvonen (1974, p. 112) and comments by Thunell (1966, p. 599) have affected the formation of sawn timber acceptance specifications. Currently the acceptable size variations are determined by applicable rules and standards, which are quality dependent and vary slightly from area to area. Some customers may have their own rules for acceptance. The European Code EN 1313-1 (1997) defines acceptance criteria for dried, finished softwood timber. The thickness and width tolerances at 20% moisture are as follows:

- Mean thickness and width values may not be smaller than the nominal size
- Tolerance for thickness and width ≤ 100mm is +3mm / -1mm
- Tolerance for thickness and width > 100mm is +4mm / -1mm

For construction timber, the final size requirements are somewhat different, according to EN 336 (1996).

Tolerance class 1:
- For thickness and width ≤ 100mm is +3mm / -1mm
- For thickness and width > 100mm is +4mm / -2mm

Tolerance class 2:
- For thickness and width ≤ 100mm is +1mm / -1mm
- For thickness and width > 100mm is +1.5mm / -1.5mm

Professional associations may have their own requirements, as illustrated by the German purchase of Nordic timber (Lohmann, 1998, p. 281-282). The tolerances are:

- ± 1.0mm for thicknesses from 16mm to 32mm
- ± 1.5mm for thicknesses from 38mmto 50mm
- ± 2.0mm for thicknesses from 63mm to 100mm

Width tolerances are ±2.0mm for widths up to 175mm and ±3.0mm for 200mm and wider.

In order to compensate for sawing variation, a sawmill must establish limits within which the process is considered acceptable. While the lower limit is the more significant, the upper limit is more relaxed, and may be twice the size of the allowance for the lower limit. Thus, the total limit range may typically vary from 1.5mm to 4.0mm. When a sawmill uses two-standard deviation as its criterion for accepted timber size, the normal frequency distribution peak, the location of the target size, must be at the mid-point of the range. It is known by those experienced in the field that saw machine behaviour changes all the time, as does the standard deviation. This knowledge generally leads to oversizing, as shown in Figure 6.2. Thus, the saw set-up is not adjusted at 2s distance from the smallest allowed sawn size, but at 2s plus a few additional millimetres.

2.5 Sawn Timber

This study covers all breakdown stages: log, cant and square cant breakdown. These are also known as primary and secondary, or vertical and horizontal breakdown. Secondary breakdown stages are also referred to as resaw, gang or bull saws. Here, the term ‘breakdown’ is used to define both log breakdown, as well as cant and square cant resaw, as depicted in Figure 2.5.

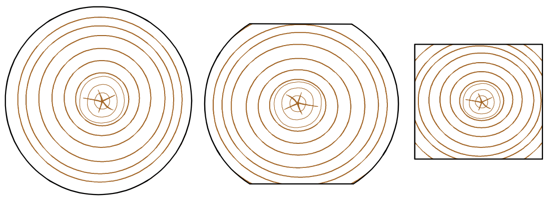


Figure 2.5. *Raw material sawn in breakdown process are logs, cants and square cants of various sizes and lengths.*

The terms ‘timber’, ‘board’ and ‘piece’ are used to define rough lumber, flitches (sideboards with wane), sideboards (profiled sideboards without wane), boards, planks, cants, square cants and dimension, centre or heartwood timber, when discussion concerns size of sawn goods. The term ‘slab’ is used to refer to schaalboards, wood that is cut from the outer part of logs. Slabs are usually converted directly into wood chips. Samples of sawn timber measured in size control are illustrated in Figure 2.6. The size arrow indicates the dimension recorded in the study. The timber may have any practical sizes.

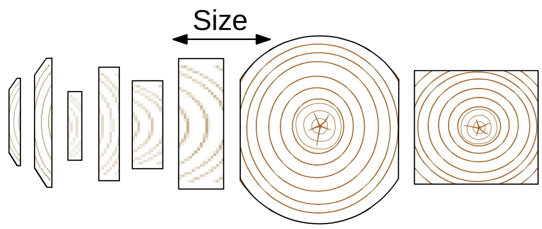


Figure 2.6. *Various shapes of timber produced in breakdown processes. The size arrow illustrates the dimension that is the measured size in this study.*

2.5.1 Seasons

Seasons play a major role in sawing in Nordic countries. The most favourable time for sawing is in early spring, when wood remains clean in transportation after the winter freeze has dried it so that its density is even. Resin does not run and saw machinery stays clean. In summer, the wood becomes dusty and dirty, sawblades wear faster and resin sticks to machinery. The outer wood dries during summer and causes shredding of wood. The shreds remain in the process machinery and block their unhindered operation. Shredding is most virulent in late summer and autumn, when it causes serious problems in feedworks and setworks operation. In fall, wood is tough and requires sharp sawblades. Frozen, winter wood does not cause shredding. However, because the surface of frozen wood is hard and slippery, it reduces feedworks capability. Besides the effects of substandard machine elements, winter emphasises sawblade bend and snaking.

The cutting power of a saw machine, its torque, is directly proportional to the specific weight or hardness of wood. Maximum cutting power is required when moisture in Nordic species is around ten to fifteen percent. The increase in power requirement is approximately twenty percent higher compared with more moist wood (Heikkilä, 1970, p. 92-96).

Frozen wood requires more cutting power than unfrozen wood. Usenius and Viitaniemi (1976, p. 10) found that the power requirement of a canter chipper increases by over forty percent compared with unfrozen wood. In band sawing, the power increase was fifty percent. Power increase is not the only problem. Average sideways movement of a band while cutting unfrozen wood is from 0.2mm to 0.3mm. During the cutting of frozen wood, the movement grew to 0.7mm, and was occasionally over 1.0mm. Cutting of frozen flitches was most difficult, because when a sawblade penetrated into frozen log from the side, the band snaked throughout the entire log. Brown (1982, p. 149) recommends that a bandmill be slowed by 20% in the case of frozen wood. In contrast, Lunstrum (1972) cautions against slowing down, because finer sawdust slips out of the gullet more easily and thus forces the saw off line. Lundberg and Axelsson (1993) noted in their laboratory study that even if the cutting force required by frozen wood increases, the required feed force may decrease. The authors conclude, however, that further work should be done to investigate the phenomenon.

In a study by Usenius and Viitaniemi (1976, p. 15), the degree of freezing increased the standard deviation of heartwood boards by 0.1mm to 0.2mm. In bandsaws, the standard deviation grew increased from 0.7mm to 0.9mm.

2.5.2 Roughness

Such factors as feed speed, saw speed, tooth angle, bite per tooth, gullet capacity and kerf thickness have a direct effect on the strain of a saw, energy consumption and the quality of the sawn surface. Over or under feeding, or too small or full gullets result in rough surface quality. Sawblades with chipped or broken tips, incorrect blade angles or clearances, and unbalanced or improperly tensioned sawblades, are causes of poor surface smoothness. Rough timber surface is usually characterised by striations or saw lines.

The mean deviation of a profile, its surface smoothness and profile depth are used to describe surface roughness. Smoothness values from 0.1mm to a roughness of 0.4mm are reported by Honkanen et al. (1997, p. 42, Table 5), values that are greater than certain reported standard deviations.

Washboarding is a specific form of surface roughness. The term 'washboarding' is used to describe a regular sinusoidal-like pattern that may occur on pieces cut by bandsaws or circular saws. Washboarding is problematic because sawn timber must be made thicker than normal to allow a planer to produce smooth surfaces. Washboarding is frequently encountered when reducing sawblade thickness. The causes of washboarding are not fully understood (Lehmann, 2000b). It can, however, be conjectured that the basic sawblade-wood system frequency coincides with the tooth impact frequency. This vibration makes the entire sawblade plate to vibrate, which leads to washboarding. Changing tooth shape normally prevents washboarding, but occasionally even radical changes have no effect. Other factors that have an effect on washboarding include feed and saw speed and tooth pitch. The problem is further complicated by the changing properties of wood that is sawn.

2.5.3 Kerf Size

Saw kerf refers to the width of the path cut by saw teeth as a sawblade moves through a log. Saw kerf has significant impact on timber recovery. It is natural that the recovery is improved with bandsaws due to their thinner blade thicknesses compared with circular saws. When comparing a typical bandsaw kerf of 2.8mm to a circular saw kerf of 4.8mm, there is significant improvement in recovery due to a reduction of loss of wood. Theoretical comparisons made by Usenius et al. (1983, p. 82) have shown that the difference in recovery can be from 2.4% to 3.7% to bandsaw advantage. Both types of sawing principles have their advantages and drawbacks. Bandsaws are more expensive in terms of unit cost and maintenance, but their recovery is better. Circular saws are more affordable to run, but the recovery loss in sawdust is greater. In both types of machine, thinner sawblades usually result in larger sawing variation arising from sawblade instability.

2.5.4 Gullet Feed Index

Design and geometry of the tooth and degree of gullet filling, i.e. gullet feed index (GFI), are important to cutting performance. There are various conceptions of what is the critical GFI. Birkeland (1967, p. 250) states that the sawing accuracy of bandsaws is practically independent of feed speeds up to a GFI of 0.61. Kirbach (1989, p. T9) notes that for bandsaws the critical value of GFI is 0.7 before saw variation becomes excessive. Further Kirbach notes that in laboratory tests thin circular sawblades rapidly loose sawing accuracy when the GFI exceeds 0.3. Johansson mentions that the critical value for bandsaws is from 0.6 to 0.7 (Johansson, 1986a, p. 23), and from 0.3 to 0.4 for circular saws (Johansson, 1986b, p. 4). The effectivness of the guide system in supporting the saw is a major factor in determining maximum gullet loading. Other important factors are blade thickness, side clearance, gullet size and blade stiffness.

2.5.5 Wane

According to Virtanen et al. (1997, p. 25), the sweep of spruce logs grows almost linearly from 5% to 25% when the top diameter grows from 150mm to 360mm, and the quantity of straight logs drops from 60% to 20%. They found that the sweep of pine was consistently slightly larger than that of spruce. However, in only 10% of the logs, of both species, the sweep was larger than 10mm/metre. The authors conclude that log turning optimisation is more important to the value of recovery than curve sawing. Curve sawing can produce higher recovery compared with turning optimisation only when logs have a heavy sweep, from 6mm to 10mm per metre. The results are, however, according to the authors, not conclusive because of measuring inaccuracies. According to Grondin and Drouin (2000, p. 393), curve sawing generates 2.6% to 3.8% more 50mm boards and 5.3% to 8.4% more 25mm boards because it is difficult to obtain flitches with straight sawing from logs with heavy sweep.

Flitches have wane because they are cut from the outer part of logs or log cants, as can be seen in Figure 2.7. Depending on optimisation and feedworks, wane can also appear in the middle parts when sweep is heavy. According to Virtanen et al. (1997, p. 28), the longest wane can make up 65% of the total piece length. Average wane length in normal flitches is one metre.

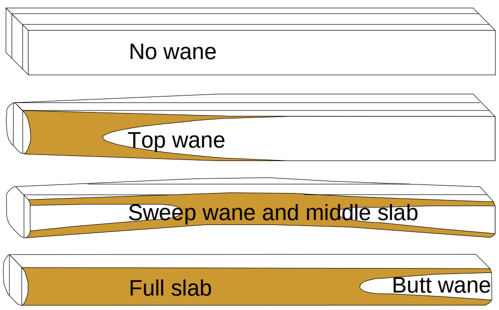


Figure 2.7. *Varying degrees of wane ranging from no-wane at the top to regular wane, sweep wane and slab at the bottom.*

Wane has significance for value recovery and volume of timber that can be produced. Wane is removed to the extent possible in edging and trimming processes in order to optimise yield. The shorter and narrower the wane, the longer and wider the full edge boards, yielding higher value.

2.5.6 Shape Variation

A uniform shape of timber is the aim when sawn pieces leave a saw machine. Depending on the condition of the machinery, cutting parameters, and raw material, different shape forms are possible. The most apparent of these, seen from above, are taper, hook and snaking, as depicted in Figure 2.8. Uniform shape does not necessarily guarantee correct board size but must be verified, and the reasons for other shape defects must be corrected.

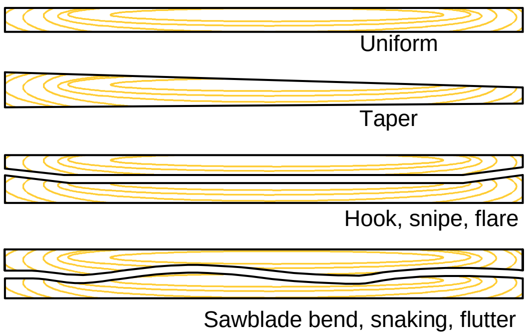


Figure 2.8. *Longitudinal shapes of sawn timber on leaving a saw machine as seen from above.*

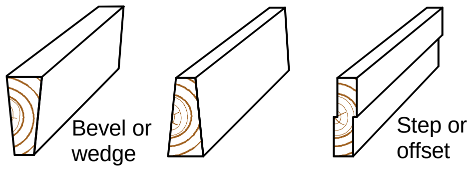


Figure 2.9. *Shape variations in cross-section of timber.*

Wedge refers to the size difference between the upper and lower edges of sawn pieces, as in Figure 2.9. In saws, such as single-arbor circular saws, where the position of sawblades close to the arbor is accurately known, it is sometimes possible to estimate the size of wedge. Bandsaws require a two-sided measuring solution, two systems that are similar to the system presented in Figure 5.15. Detection of step in double-arbor saws requires an entirely different measuring and control approach.

2.5.7 Dynamic Stability

A variety of mechanical and electric disturbances may affect a saw machine in process. The most important of these are self-excited vibrations resulting from dynamic instability of a machine system (Zäh, 2000, p.1). In sawmilling the most typical process, that may push an innately stable saw machine to its stability limit, is increase in feed speed. When feed speed, and thus the saw load and gullet feed index are progressively increased, a machine’s stability threshold is exceeded, and vibrations will disturb production. Apart from increasing sawing variation and sawblade wear, the instability may cause actual tool damage and be heard as noise emissions.

2.6 Discussion

Sawing variation is inevitable. When a process is under control, the variation falls within the inherent capabilities of a saw machine. There are, however, numerous factors that have an effect on saw machine accuracy and precision, as well as on timber quality. Unfortunately, most of these factors have adverse effects. Variation from normal characteristics of a saw machine may signify:

- Change in saw operation
- Change in raw material characteristics

- Incorrect saw speed – feed speed combination
- Incorrect sawblade parameters or dull teeth
- Inaccurate saw guides or setworks
- Inaccurate feedworks or holding
- Worn mechanical elements.

Among these causes certain represent long term phenomena, while others are short-term in real-time, occurring during production sawing. Effective control of sawing variation under all production conditions is one of the fundamental factors in sawmill productivity. Tighter control of standard deviation allows a sawmill to use smaller sawing allowances, to have timely sawblade changes, to maintain high process standards, and to improve recovery of wood.

The importance of effective control of sawing variation is receiving increasing recognition as customers increasingly require customised sizes, tighter size control, and short delivery times whatever the season. At the same time there is an imperative for turnover of material to improve, the number of sawn sizes and machine speeds to increase, new saw machines and technologies to emerge, amid increasing costs of production stoppages. Therefore, it is vital to understand, measure, and control the factors that cause sawing variation.

The method for calculating a target size is generally accepted. The problem in target size determination is that few sawmills understand and are able to control their standard deviations. An understanding of the characteristics of standard deviation and of the behaviour of saw machines is the primary goal of this study.

3 Manual Measurement

Manual measurement is the traditional control method of sawn timber. In manual measurement, quality control personnel pull timber from the production line and set it up on a sawhorse to take measurements. Using a caliper, they take measurements from a number of predetermined points and record them by hand on a sheet of paper mounted on a clipboard, or with a digital caliper in a data logger, as in Figure 3.1. The limitation of a caliper-assisted sampling method is that only a limited number of boards are sampled per shift, and a few measurements per board are taken. Small sample size limits the validity of results and can lead to inaccurate analysis. Causes of errors include:

- Inconsistent number of measurements
- Inaccurate recording of sizes
- Measurement is taken at a 'suitable' spot, leading to biased results
- Measurements are from different set-ups
- Measurements are from different sizes
- Only one board from each cut (between sawblades) is sampled
- Caliper has not been calibrated, or it may be worn or loose
- Personal bias
- Time of measurement may have an affect on results.


Figure 3.1. *Manual measurement of size in sawmills.*

A typical measuring guideline used in Nordic sawmills is illustrated in Figure 3.2. Inspected boards are to be measured at a minimum of five equally spaced places at the top and bottom part of a piece. The first and last places should be about 300mm from the ends to avoid effects of dodge, flare and snipe (Williston, 1988, p. 298, Brown, 1982, p. 121, and Usenius and Viitaniemi, 1976, p. 5). The reason for this measuring principle is difficult to understand because radical sawing variation may take place at the top and butt-end areas. On the other hand, measurement at three places at each edge has also been used (Dramm, 2000, p. 151, Heiskanen and Paajanen, 1997, p. 43, and Virtanen at al., 1997, p. 47, and Eagan, 1982, p. 93). A recommended practise for board sampling is at least five to ten boards for each target size once a shift (Brown, 1982, p. 120). Brown does not mention whether the measuring should be done at each cutting position, between each pair of sawblades, when more than one sawblade is used.

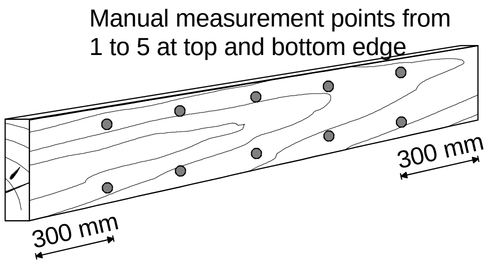


Figure 3.2. *Measurement places in manual thickness inspection of timber.*

Warren (1973, p. 5 and 7)) presents a method to determine sample size for calculation of standard deviation. Board sample sizes proposed by Warren are dependent on the within-board and between-board standard deviations. The larger the deviations, the larger a sample must be. In addition, the number of readings per board has an effect on the board sample size, Figure 3.3. The curves indicate that if the standard deviation of a saw machine is tightly under control, a smaller number of readings is required to verify the situation. However, when standard deviations are larger, the number of required boards increases quickly.

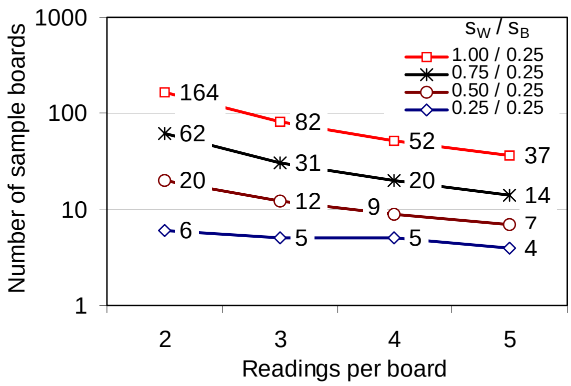


Figure 3.3. *Effect of number of readings per board on the required board sample size. The curves present situations where the between-board standard deviation is 0.25mm and the within-board deviations vary from 0.25mm to 1.00mm.*

Warren (1973, p. 10) concludes that a board sample size of fifty seems a reasonable practical minimum for estimating standard deviation of a sawing process. He further states that an upper limit of 250 boards seems realistic for processes where standard deviation is large, because in such conditions sawing must be regarded as out of control, so that a great degree of precision is probably not required. No sawmill known to the author in Europe or North America samples stacks of fifty boards on a regular basis for their quality and process control purposes.

Current sampling methods whereby three to five manual readings are taken from a sample of four boards are not sufficiently valid to allow one to draw conclusions on individual within-board behaviour. For some reason, the original sampling process proposed by Warren has deteriorated, from a minimum board sample size of 50, when determining within-board and between-board standard deviations, into a practise of measuring a few single boards. In some cases only one reading is taken from one single board. The question of sample size is discussed further in Chapter 6.3.

Because of the small number of readings, the traditional within-board and total standard deviation values, calculated from a small sample, are in practise identical. The deviations are calculated using the same readings in a sample. Information cannot be increased by mathematical manipulation, as is done in the current within-board and total standard deviation calculations.

European standard EN 1309-1 defines the requirements of thickness measurement for rough sawn boards as:

- Reading accuracy of a measuring device must be at least 0.1mm
- Measurement shall take place at least at three clean spots with no defects
- Two of the measurements shall take place close to the ends, but not closer than 150mm
- Additional measurements shall be spaced between the two end-measurements
- Width measurement requirements are the same as for thickness with the exception that the reading accuracy of a measuring device must be at least 1.0mm

Manual readings are recorded with an accuracy of 0.1mm (Asikainen, 1982, p. 216, and Usenius, 1976, p. 5), and in North America with an accuracy of 0.01inch (0.25mm) (Brown, 1982, p. 120). Readings can be reported with a higher number of decimals (Virtanen et al., 1997, p. 23, and Williston, 1985, p. 298), but mills that measure timber in hundredths of mm, or thousandths of inches, should realise that their readings cannot be as accurate. Repeated manual readings by the same person differ more than a tenth of a millimetre, and readings by different persons still more (Brown, 1982, p. 120 and 121). Funck and Leavengood (1995, p. 4) established that the precision of repeated manual measurement is from 0.5mm to 0.8mm depending on the person. No individual was consistently close to the desired ±0.13mm accuracy. In a private consultation, Brown (2000) has indicated that an experienced person can reach an accuracy of 0.13mm, but the typical accuracy is from 0.13mm to 0.25mm. When two persons perform measurement on the same pieces, the readings deviate typically by 0.20mm to 0.50mm, Appendix B.

Manual measurement may be difficult to perform during production. More extensive material for inspection is usually collected by stopping a saw line, and samples are removed from the line. Inspection is done when sawblades are changed, and control measurements for saw machine set-up must be made, or when maintenance activities require test pieces. During regular production continuous, conscientious manual measurement is rare.

Figure 3.4 presents within-board top readings for a board with a 45.8mm target size. Manual measurement was done at fifty equally spaced intervals over the length. The grey columns present the fifty readings and the black ones five equally spaced readings chosen from the fifty measurements. The figure indicates that the more readings are taken, the more information is available. Calculation of mean and within-board standard deviation values for these two data sets will give for the set of fifty readings $\overline{X}_{50}$ = 46.2mm and s_{50} = 0.43mm, and for the set of five readings $\overline{X}_{5}$ = 46.4mm and s_5 = 0.64.

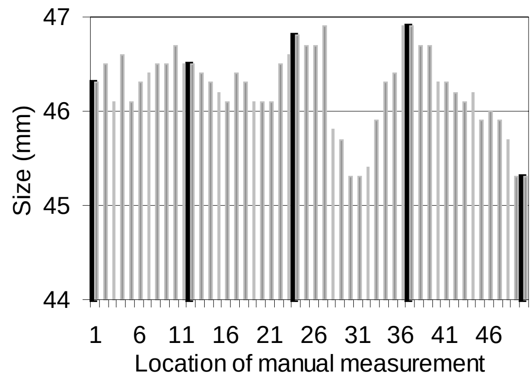


Figure 3.4. *Fifty equally spaced manual readings (light) along a board, and five equally spaced manual readings (bold).*

Brežnjak and Hvamb (1963, p. 62) have examined thickness variations of sawn timber and the effect of number of readings on the accuracy of the measuring results. Their results are similar to Figure 3.4, which demonstrates that manual measurement at five places along a board is, for all practical purposes, not as effective as a more extensive measurement at fifty places on the same board. Brežnjak and Hvamb concluded that fifteen manual measuring points lead to far more accurate estimation of the actual thickness variation than five points. Measurement at fewer places makes an analysis more susceptible to random errors, which may however be eliminated by experienced quality control personnel choosing the right spots for readings. However, when this happens, one can claim that the results are biased. The problem with manual measurement is usually not its quality, but the infrequency of its performance in time, quantity, and physical coverage.

In a comparison test between manual and optical method, fifty manual readings are taken at the top edge of each tested board. This is done by dividing the total length of a board from the first control point at the top-end to the last one at the butt-end, into fifty equally spaced measuring points. Figure 3.5 illustrates an arrangement for manual measurement. The optical readings for the boards that are to be measured manually are recorded when the boards exit from the saw.

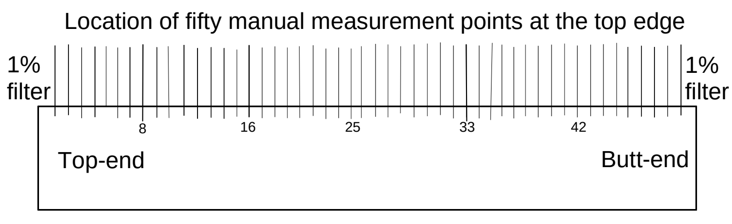


Figure 3.5. *Manual measurement locations.*

In manual measurement a caliper is positioned in such a way that the caliper tips cover an area of 25mm to 50mm in length, and 10mm to 25mm in depth from the top edge of the board under measurement, as in Figure 3.6. The area depends on the size and type of the caliper head. The instruments used in measurement are the regular inspection tools used in each sawmill. Readings for the comparison analysis are taken by the sawmill personnel. Reporting is done either with a data recording digital caliper or in writing when a regular digital caliper is used. The recording resolution is 1/100 of a millimetre.

Figure 3.6. *Caliper position in manual measurement.*

A sample of manual readings in a centrepiece is presented in Figure 3.7. The left-hand figure shows the individual fifty manual readings, and the right-hand figure presents the averaged results in ten segments. Each segment average comprises five individual manual readings.

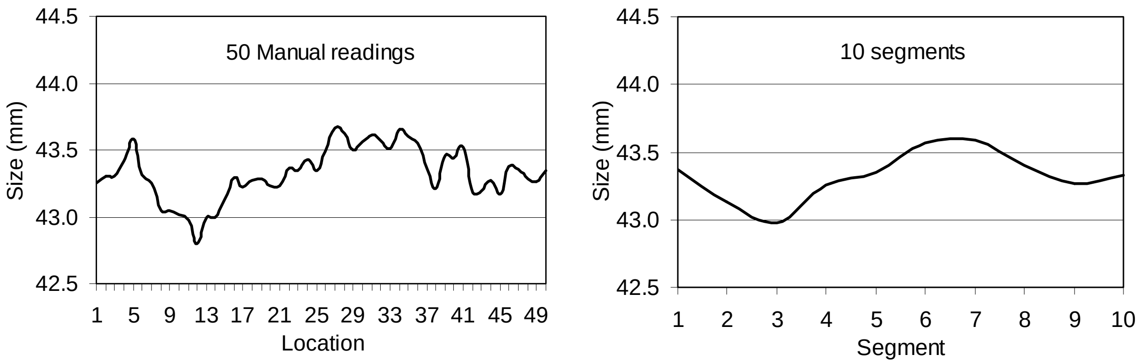


Figure 3.7. *Original fifty manual readings at fifty equally spaced locations, left-hand figure, and 10-segment means based on 5 manual readings in each segment.*

If only three or five readings are taken, the result can vary ± 0.5mm. The averaging of fifty manual readings into ten segment means produces a result that is consistent with the ten segment values of optical measurement, as in Figure 5.23. The correlation of the ten segment means between manual and optical measurement is strong, 0.93.

Judging from the literature in Chapter 2 and the current state-of-the-art of manual measuring, one may claim that much of the measurement of sawn rough timber is ad hoc. However, manual size control is an effective and reliable method when readings are taken in sufficient frequency and quantity. Manual methods are susceptible to errors caused by personal styles of measurement, small sample sizes, and because it is an off-line method. The huge quantities of data required in the proper analysis of a saw machine are impractical in manual measurement. However, manual methods remain an effective means of checking that the more automated systems are functioning properly.

4 Current Size Control Methods

This chapter provides an introduction to the current control methods used in sawmills, and methods that have potential use in breakdown sawing. There are a number of control systems and devices on the market, which perform the tasks or measurements described in this chapter. Manufacturer names are avoided on purpose.

4.1 Servo Control

Servo control can be defined as an internal tactile sensor. Position, force, and torque data are used as feedback devices to control a cutting sawblade inside wood or outside a log under cutting process. The position is defined by a set-up target size. In circular saws the position of the sawblades depends entirely on the precision and accuracy of a servo control system. In bandsaws the position of a sawblade is also influenced by the alignment of the guides and the tensioning of the sawblade. Force is an axial pressure by which the wood under cutting opposes the position control action, causing for example sawblade bending. Torque defines the level of power used to cut logs – and is an indicator, among other factors, of cutting edge wear and tear. Besides the blade dullness, the cutting force of a saw machine is directly proportional to the specific weight or hardness of the wood. Frozen wood is harder than non-frozen wood. Furthermore, the moisture content of wood affects the cutting force – more moist wood is easier to cut. The position, force, and torque data may be reported on saw operator's display. Often, a saw machine manufacturer claims that no other data than the one they supply is needed. A question remains why so much effort is required to have an accurate saw set-up?

Saw machine manufacturers design servo control devices in such a way that positioning accuracy is optimal. However, even the best of ball screw servo positioning systems has an angular resolution and the hydraulic servo systems angular or linear resolution, a window of accepted position. Therefore, servo positioning has an inherent inaccuracy. A servo controlled set-up position is always an approximation, even if it might be an accurate one. The accuracy of linear electro-hydraulic servo systems is ±0.01mm to 0.25mm (Fonselius et al., 1998, p. 108) due to system hysteresis and deadband (Esposito, 1997, p. 559). Typical accuracy of a servo positioning system in a double-arbor circular saw machine is 0.1mm.

In order to cut, a saw machine needs sawblades. The addition of sawblades in a saw machine makes the combined cutting system more susceptible to inaccuracies. A sawblade vibrates, bends, and loses sharpness, while the machine itself might be quite stable. The combined result is that the cutting is not completely dependent on or controlled by the servo positioning. Only approximations of the cutting position can be made. Due to this inherent inaccuracy, sawing variation is inevitable and size control is necessary. Features that may be measured in a breakdown process are:

- Torque energy applied at electric motors to run sawblades
- Position of setworks
- Feed and saw speeds
- Bending, vibration and temperature of sawblades
- Timing of feed and guide rolls
- Surface roughness of sawn pieces

- Surface temperature and moisture of sawn pieces
- Shocks and vibration in saw machine
- Thickness variation of sawn pieces.

This study will cover only the last feature on the list, the size control of sawn pieces. The other aspects are equally important to the sawing process, and may have an effect on the sawn size, but they are outside the scope of this study.

4.2 Size Control Technologies

The purpose of size control systems in sawmills is to 'touch, sense and see' what takes place in a production process and what happens to the produced timber. Tactile sensors touch objects, sensing ones that are close without touching them, and seeing ones at a distance. All such sensors can be used in the breakdown process. Sensing and seeing deal with sizes, shapes, edges, proximity, temperature, moisture, and other detectable features. Saw machine manufacturers do not supply these sensors, and it depends solely on a sawmill itself if any of these are installed or used. Sensors can be classified in four main categories, Table 4.1.

Table 4.1. *Sensors that can be used in breakdown saw applications.*

Tactile	Sensing	Optical	Other
Mechanical	Inductive	Distance	Acoustic
Electrical	Capacitive	Edge	(Ultrasound)
	Magnetic	Shape	Microwave

Tactile, mechanical contact sensors, such as gauges and calipers, were the first ones used in sawmills. The advantage of the non-tactile, sensing and seeing sensors is that they are free from wear. On the other hand, many of them have application limitations in rough conditions. Control opportunities can be divided into two categories: Measurement of the behaviour of a sawblade with indirect conclusions of sawn size and direct measurement of sawn pieces.

4.3 Position of Chipper Canter Knives

Cutting knives of a chipper canter are mounted in an Archimedes spiral or concentrically at intervals around the truncated conical cutter head. The final size of a slabbed log is determined by the inner planer knives. An accurate direct position measurement of planer knives in operation is not possible because of flying chips and wood particles. The only data available is in indirect information on servo positioning.

Width, the distance between the opened flat faces of a slabbed log, can be measured as cants leave a chipper canter. Measurement can be performed using a two sided optical distance gauge or a line-scan camera that looks at both edges simultaneously. Alternatively, measurement can be performed using tactile angle measurement arms, mechanical shoes that ride on cant faces.

A practical problem with the above measurements is that a chipper canter frequently forms a compact integral part of a saw machine and there is no room available between a chipper canter and the adjoining saw machine, in either bandsaw or circular saw systems. Therefore, no control, other than the machine's own servo and torque control, can be used in most chipper canters. Perhaps in the future, when saw machine designers take into consideration the needs of external control technologies, an improvement can be made in feed-back control of canters.

4.4 Sawblade Position and Deflection

The position of cutting sawblades can be measured by recording the sideways movement of sawblades themselves. Besides the indirect servo control of a saw machine itself, the measurement can be accomplished by the use of inductive, capacitive, magnetic, or optical sensors. Inductive sensors will be discussed last because they are the most common.

Magnetically activated sensors, also known as Hall-Effect sensors, detect motion, position, or change in the magnetic field strength of ferromagnetic materials. A magnetic sensor can be built in such a way that a permanent magnet is attached to the magnetic sensor . The magnet creates a magnetic field that envelops both the magnetic sensor and the sawblade. A moving sawblade affects the magnetic field and the changes are detected by the magnetic sensor. A practical problem with a magnetic sensor is that it detects not only the position changes of a sawblade but also any changes in the position of the sensor itself or the magnet. Because saw machines vibrate, this sensitivity to position changes renders the use of magnetic sensors problematic. On the positive side, one can note that magnetic sensors are not affected by impurities such as sawdust and water, and their accuracy can be as high as 0.0005mm at 20mm distance (Gunther and Mehlhorn, 1990).

A plate capacitor changes its capacitance with the distance between the plates. In capacitive measuring, a sensor is one plate and a sawblade forms the other plate. In a measuring system, alternating current with constant high-frequency flows through the sensor, and a field is created around the free capacitor plate. When a sawblade moves in the field, the amplitude of the oscillator output changes. The voltage amplitude at a sensor is proportional to the distance between the sensor electrode and the sawblade. A practical problem with capacitive sensors is that they react not only to the behaviour of a sawblade itself, but also to other components such as water and wood particles on the sawblade, thus changing the signal output and rendering a capacitive sensor impractical in sawmills. The accuracy of capacitive sensors can be in the order of a few micrometers (Turinsky, 1989, and Bonse et al., 1993).

Optical devices, such as laser distance gauges, direct a laser beam on a sawblade. The reflected light spot is projected on a line-scan detector or a linear photo detector element, where it generates a position proportional signal. These systems may be feasible but due to optical interference caused by particles and water from the sawing operation itself, their use is limited. One such application involves casting a laser beam on the tooth end of a bandsaw blade. The beam is recorded with a CCD matrix array camera. The deflection of the sawblade is seen as a moving position of the reflected laser beam on the CCD matrix array. This type of system is sometimes used in headrig carriage bandsaws, where the accessibility to the sawblade is more open.

Currently used sawblade deflection control devices are based on inductance. Inductive sensors give information on sawblade movement - indicating snaking, and on vibration - indicating for example missing or broken teeth. Inductive sensors evaluate damping of a high-frequency electromagnetic field, caused by induced eddy currents in a sawblade. Thus, measurement of proximity is possible using a single-coil construction. Sensitivity of a typical sensor is illustrated in Figure 4.1. An inductive sawblade deflection sensor has a permanent magnet that is close to a wound coil. The coil is part of a resonant circuit where an approaching conductive sawblade alters the inductance of the coil. The demodulated signal is proportional to the distance between sensor and sawblade. When a sawblade is consistently at the same distance, no flux is created and the signal is constant. When a sawblade changes distance in the field of the magnet, the resulting change in the flux lines induces a current change, the amplitude and shape of which are proportional to the rate of change in the flux. The signal varies as a function of the speed at which a sawblade enters and leaves the magnetic field. The signal strength is dependent on the installation distance of the sensor from the sawblade.

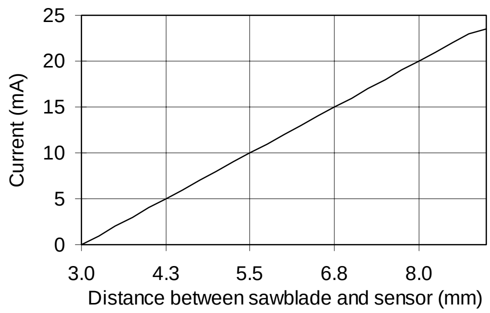


Figure 4.1. *Response curve of an analogue inductive sensor within a typical measuring range. Distance to sawblade is from 3mm to 8mm, and respective linear sensor signal is from 0mA to 20mA.*

Inductive sensors are installed on the upper guide block, below it, as close to the area where the blade enters in a log as possible. The basic presumption is that a sawing process is stable when the signal is constant, and a stable sawblade produces pieces of consistent thickness. When a sawblade deflects, the produced timber sizes vary, and an inductive sensor reports the change. However, because the inductive sensor is not at the exact location of the cut, the estimated thickness is not the exact thickness. One sensor manufacturer indicates repeatability of between 0.015mm and 0.06mm, and another indicates a resolution of 0.1% from a full range of 2mm. Inductive sensors, as do all proximity sensors, provoke a dilemma: closeness to sawblades. The installation distance to a sawblade is typically from five to ten millimetres depending on the sensor. Thus, they are prone to impact and mechanical damage, and sometimes they are torn away. Deflection amplitudes of over 0.6mm have been reported in bandmills in hardwood sawing (Barratt, 1999, p. 13). A practical reporting resolution of a system is typically 0.1mm. Inductive proximity sensors are commonly used in band mills. There are no commercially available sawblade deflection control systems available for circular saws. However, research work has been conducted into their use in circular saws (Danielson and Schajer, 1993).

4.5 Direct Measurement of Timber Size

The environment directly after a breakdown saw machine is not encouraging. Water spray, sawdust, and flying particles cause problems. Process is somewhat gentler further away from operating saw machines, if constructional and production possibilities allow measurement to take place there. Tactile measurement, such as manual measurement or the use of two sided mechanical arms, may be possible. Among the group of sensors, ultrasonic, microwave and optical sensors can be considered as alternatives.

4.5.1 Ultrasound

Ultrasound refers to airborne longitudinal waves with a frequency ≥ 20kHz. The frequency range of ultrasonic vibration used in air borne measurement is from 100kHz to 500kHz. A pulse mode detector evaluates the time elapsing between transmission and reception of an ultrasonic signal and thus is able to determine the distance between the transmitter/receiver and the reflecting object. The speed of sound is approximately 333m/s in normal air pressure. Ultrasonic sensors are relatively slow and their switching rates are from 2Hz to 60Hz. The wavelength of ultrasound depends on the frequency used. The wavelength is 3.4mm at 100kHz and 0.7mm at 500kHz. Thus, the resolutions vary from ±0.5mm to ±3.0mm. The ultrasonic sensors have a sound field area close to the sensor head called Near Field. An unpredictable interference phenomenon takes place in this field and it cannot be used for measurement. Therefore, the usable measuring area starts from a distance of 150mm forward. Besides insufficient resolution, other measurement problems are caused by ultrasound echo pulse spread, both in time and space, as well as the changing speed of sound and attenuation due to temperature changes, moisture and impurities in the air, and roughness of a sawn surface. The effect of temperature is 0.17%/°K, which means that a temperature decrease or rise of 10°K changes the speed of sound by 1.7%. Similarly, the speed of sound is 2% faster in humid air than in dry air. These characteristics lead to measurement errors and to a total resolution from ±1.0mm to ±4.0mm, depending on the frequency used. Ultrasonic sensors are suitable in sawmill applications where high accuracy is not a requisite, but not accurate enough for on-line size control in breakdown processes. The first on-line application of ultrasound in internal cant grading was reported in mid 1999 (Haddox, 2000, pp. 22-26).

4.5.2 Microwave

Microwave sensors are similar to ultrasonic sensors in that they detect distance to an object by its influence on a propagating wave as it travels from a transmitter to a receiver. Where ultrasonic sensors utilise longitudinal sound waves, microwave sensors use electromagnetic waves that propagate at the speed of light ($3*10^8$m/s) in frequencies from 300MHz to 300GHz. Thus, the wavelengths vary from millimetres to metres. The wavelength of a microwave sensor determines the extent to which it is attenuated by impurities and water spray in the environment. If conditions are not extremely severe, a sensor with 10mm (30GHz) wavelength is capable of operating effectively in sawmilling environment.

As with ultrasonic sensors, microwave signals spread out in space and hit an object at an area, and the received signal is a combination of all individual signals. A positive feature of microwaves is that their signals can be polarised, and thus resolution can be improved. Stelzer et al. (1999) report having developed a distance sensor prototype that operates at 35GHz and is capable of measuring distance with an accuracy of 0.1mm. The available commercial devices and resolutions are still neither practical nor accurate enough for breakdown control.

4.5.3 Optical Gauges

Optical distance sensors use a light source to create a spot of light on the surface of an object. Generally, the light sources are diode lasers or infrared diodes. The spot of light is then looked at from an angle with a position sensitive detector. This measurement principle is known as the triangulation method. A laser light source gives a focused spot, resulting in high accuracy. The larger luminescent spot of infrared diodes can be of advantage when a distance to a rough sawn surface is measured. The measurement range is fixed for each measuring head. The angle of incidence of a position sensitive detector determines the resolution and the operative range of a triangulation sensor. The bigger the angle, the better the resolution and the smaller the measuring range. A two-sided optical triangulation distance gauge can measure the size - width of an object between the two units, as illustrated in Figure 4.2. In the case of multiple parallel pieces, this technique does not provide the sizes of the individual pieces – it provides the total width of the stack, or cant. A recent application utilising this technique has been installed to measure width and height of square cants (Buchanan, 2000, pp. 56-57).

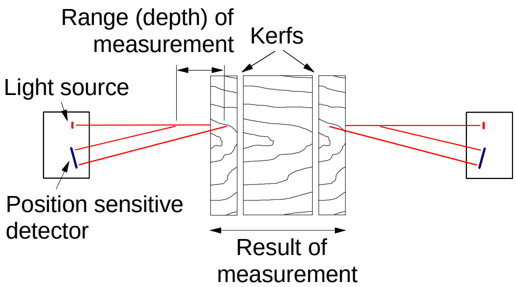


Figure 4.2. *Two sided triangulation system to measure the total thickness of a package of sawn pieces.*

When distance to a measured surface is relatively short, in the order of 50mm, the distance accuracy can be about 0.05mm (Marques et al., 1998). Manufacturers of laser gauges for wood planing applications guarantee resolutions of 0.6mm for a range from 50mm to 150mm, 0.25mm for a range from 50mm to 100mm, and 0.1mm for a range of 40mm to 60mm. On the other hand, a manufacturer of laser gauges for sorting sawn pieces, promises accurate readings within ±0.125mm. Thus for a small range - 10mm - the resolution can be as accurate as 0.05mm. If the range is 100mm, the resolution is 0.5mm. Measurement frequency of a triangulation system varies according to the measurement range because of the needed flight time zone. For a range of 10mm, the frequency can be 1kHz and for 100mm range 200Hz. The minimum measuring range required in breakdown would be from 50mm to 150mm for each optical gauge in a two sided system. Therefore, the resolution of a system would be from ± 0.2mm to ± 0.5mm and the measuring frequency from 0.2kHz to 0.1kHz.

Errors in optical triangulation measurement are generally caused by different intensities of reflection from different places on a surface. In sawmills where objects move at high speeds, and surfaces are uneven, 'hairy', and moist, a reflection can be either extremely strong or almost completely absorbed. Therefore, sensors need to have a high dynamic range. An optical distance gauge may have difficulties in measuring surfaces with wane or curved surface. If waned timber is present in a sawing process, laser gauging technology would need multiple measuring heads. Movement of pieces and changing saw set-ups, however, make triangulation systems difficult to apply when measuring size of timber leaving a saw.

The accuracy and speed of triangulation distance measuring systems is adequate for timber thickness measurement. No, or very few, such systems, however, are utilised in timber breakdown. Optical distance gauges represent a valid thickness measurement technology at later stages of timber control, in sorting and trimming, where the range of measurement is smaller, and accuracy and optical environment are consequently better than in breakdown sawing. For this reason, most triangulation applications occur in timber sorting, where there are numerous system suppliers. However, at that stage the measurement results are not valid real-time data for breakdown control. Some of the concerns related to measurement results in sorting and trimming are expressed by Funck et al. (1992, p. 240). Funck mentions that data cannot be related back to a specific set of saws, snake cannot be detected, and specific measures would be required to separate the boards for transverse measurement in order to control the queuing and location of each board.

4.5.4 Two-dimensional CCD-Gauges

Certain applications for measuring cant sizes have been developed with two-dimensional CCD-matrix array sensors. This technology has its roots in technology that was developed in early 1980's to measure wane in longitudinal transportation of boards in certain types of edger optimisers. A stand-alone measuring device using this technology was used by Viitaniemi (1985, pp. 71-72) in a study of edger yield analysis. Recent applications are 3-D analysis of logs and cants where the surface/face is illuminated with a laser line, and a CCD-matrix array sensor reads the light line at an angle. Similar technology is used in measuring board size. Figure 4.3 presents an arrangement for measuring the size of multiple boards exiting a saw.

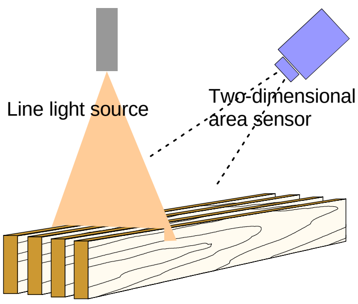


Figure 4.3. *Two dimensional matrix array CCD-camera examining a laser light line on the top edges of multiple boards. Light line lengths and locations are used to calculate board sizes.*

The disadvantage of this technique is that matrix array sensors become expensive when high dynamic range and resolution are required. Furthermore, data processing requirements rise exponentially due to the greater volume of pixel data to be processed. Measuring difficulties may arise from the width of the light line, detection of the diffuse zone at edges, and as a result of the presence of sawdust and slivers.

4.6 Discussion

Measuring devices utilising electrical, magnetic, acoustic, and other measuring principles are widely used in metals, electronic and plastics industries, where the process conditions and product characteristics allow their use. Unfortunately, most of these techniques are unusable in the wood breakdown process. The present control methods provide very few direct methods to control sawn size. Most of the methods are indirect, such as servo positioning of machine elements or sawblade deflection detection.

Some of the used measuring methods are applicable only in bandsaws, such as inductive sawblade deflection control. Only in one reported case has inductive technology been used in a circular saw (Danielson and Schajer, 1993). Currently sawblade deflection control is not used in any commercially available circular saws. Some of the potential control techniques for size control are summarised in Table 4.2.

Table 4.2. *Summary of some mechanical, electrical and optical sensors and techniques.*

Sensor principle	Sensor type	Range Typical values (mm)	Accuracy Typical values (mm)	Remarks
Mechanical	Caliper	300	0.1 – 0.01	Slow. Physical contact required.
Electrical	Inductive	0 to 20	0.01	Economic. Common. Sensitive to vibration.
	Capacitive	0 to 20	0.001	High precision. Sensitive to impurities.
Magnetic	Hall	0 to 20	0.0005	High precision. Sensitive to vibration.
Acoustic	Ultrasound	150 to 1000	0.5 to 3.0	Sensitive to temperature and humidity.
Optical	Triangulation	10 to 1000	± 0.5% to 1% of the range	Depends on surface roughness and reflectivity.
	CCD matrix array sensor	10 to 1000	Depends on the number of pixels in each array dimension and the range. Typically from 0.02 to 2.0	Measurement of two dimensions. Shape measurement. Sensitive to irregularities.
	CCD line-scan sensor	10 to 1000	Depends on the number of pixels and the range. Typically from 0.005 to 0.5	Measurement of one dimension. Measurement of width or height. Sensitive to irregularities.

Because neither servo control nor sawblade deflection is reliable or precise enough for saw machine set-up control, an inspector is needed to verify the sawn sizes and assist in making the adjustments before production sawing can start. This process is slow and leads to varying quantities of reject boards. Wood pieces may become stuck between guides or other factors affecting proper function of machinery may arise during sawing. These problems may not necessarily be revealed by the current methods, which are manual, off-line, or too intimately integrated in machinery. Therefore, there is a need for methods that are independent on a sawing process but that closely monitor the sawn sizes. The developed method discussed in this study is one such approach.

5 Optical Measurement

This chapter discusses the general and specific details of optical measuring technology used in this study. An optical measurement system that can be used in real-time size control in breakdown process of logs is presented and reasons for selecting certain components and methods, and alternative features are covered and comparisons to other technologies are made.

The essential information on the properties of a saw machine, of its breakdown process of logs, cants and square cants, is available in the sawn pieces. Additional secondary information is obtained from individual machinery components in the sawing process, such as data on vibration, amperage, and temperature. Thus, the real-time readings from the sawn pieces must be used as a prime source of data in an analysis. The optically collected readings are the information of the measured boards used in this study. Secondary information, such as saw machine layouts, is used, whenever available, to support the analysis of the optical data.

The major difference between manual inspection and computerised optical control in breakdown process is in sampling frequency and quantity of readings taken. This difference between manual inspection and computerised optical control in wood breakdown can be illustrated by the number of measures taken in a 6-piece saw set-up in a sawmill cutting 500 cants per hour, Table 5.1.

Table 5.1. *The difference in sampling frequency and quantity of readings between manual and optical measurement.*

Method	Sampling frequency	Number of boards measured per hour	Number of measures per stack	Total number of measures per hour
Manual	Once per hour	One cant, one stack of 6 boards	4 measures per board 4 * 6 = 24	24 * 1 cant = 24
Optical	Continuous	All 6 boards in all sawn cants	400 measures per board 400 * 6 = 2400	2400 * 500 cants = 1 200 000

The difference in readings between manual inspection and optical control measuring can thus be in the order of one to hundreds of thousands or even millions depending on process parameters and control practises.

5.1 Formation of Image

The term ‘image’ refers to a two-dimensional light intensity function, where a value of intensity at any point is proportional to the brightness (or grey level) of an image at that point. A digital image is discrete in both spatial co-ordinates and brightness. A digital image can be considered a matrix whose row and column indices relate to a point in the image and the corresponding matrix element value identifies the grey level at that point. The elements of such a digital array are called image elements, picture elements, pixels, or pels; the last two are commonly used abbreviations for ‘picture elements’ (Gonzales and Woods, 1993, p. 7).

Electronic imaging instruments use one or two-dimensional detector arrays of charge-coupled devices (CCDs) for image acquisition. An array has a number of pixels that are sensitive to incoming electromagnetic energy, photons called light. A two-dimensional area sensor can have pixels from 256*256 to 4096*4096 or more, and the array shape does not have to be square. Two-dimensional arrays are typically used in applications where one takes a snapshot of an object – the object is ‘frozen ‘ during the exposure - and then the image of the object is processed. This technology is useful in applications where an object is stationary or speeds are not high, and the resolution requirements are not critical. A one-dimensional line array, a line-scan sensor used in measurement applications, typically has 1*1024 or 1*2048 or more pixels. Line-array technology is used when an object is moving at higher speeds and high resolution is required. In timber size measurement, a two dimensional image of boards is formed when they pass through a line-array sensor’s field of view.

Energy of a photon obeys the equation

$$Q = \frac{hc_0}{\lambda} \tag{5.2}$$

where Q is energy of a photon (J),
h is Planck’s constant ($6.626 * 10^{-34}$ Js),
c_0 is the speed of light ($3 * 10^8$m/s), and
λ is wavelength (nm).

The equation indicates that the energy of a photon is inversely proportional to its wavelength. The shorter the wavelength, the higher its energy content. With shorter wavelengths, one can detect and measure smaller details because resolution of details will be clearer. Ultraviolet (UV) radiation has the shortest wavelength (shorter than 400nm) and infrared (IR) the longest (longer than 750nm for near infrared). Visible light is between UV and IR in wavelengths. The difference in wavelength from UV to IR is approximately 350nm – far less than one thousandth of a millimetre. In the context of sawmill size control, the wavelength of a light source has no practical meaning. Therefore, using an UV light source and an UV sensitive CCD-sensor would bring no particular benefit.

In board size measurement, the light is usually achromatic, void of colour; its only attribute is intensity. When photons strike a CCD-detector array, electronic charges, voltages, are produced that are proportional to the brightness of the viewed object and the wavelength of radiation.

In camera electronics, the created analogue output of each pixel is converted into digital form, usually in multiples of two (2^8, 2^{10}, 2^{11} or 2^{12}). The quality of a CCD-array and the electronics in a camera both have a significant effect on the performance of camera output.

5.1.1 Sensitivity and Dynamic Range

Physical size or length is one feature of a CCD-array. The second feature is its sensitivity to light. The more sensitive each detector element in an array is to variations in light levels without saturation the better. This feature is called dynamics. This feature depends not only on the element itself but also on the camera electronics.

Most CCD-arrays have an 8-bit dynamic range, which means that the digital signal can be divided into 256 (2^8) discreet digital levels. Such cameras are used in applications where sensitivity to small changes is not important, and where environment and conditions of measurement are fair and stable. In applications where more resolution is required, 10-bit (2^{10} or 1024 levels) cameras are used. Quality control systems in graphics and food processing industry are typical users of 10-bit technology, because of the higher speed and strict quality demands. When the measuring environment is very demanding and measurement signals can be disturbed by noise signals, yet more dynamic range is needed. In such applications, a camera should have a 12-bit dynamic range. Such cameras divide the incoming light signal into 4096 (2^{12}) light levels. In such applications, one can lose 90 percent of signal from an object, for example because of bark on a log, or a cloud of water or sawdust spray, and still be as effective as an 8-bit camera in prime conditions. In adverse sawmill conditions an 8- or even a 10-bit camera may be practically 'blind', Figure 5.1.

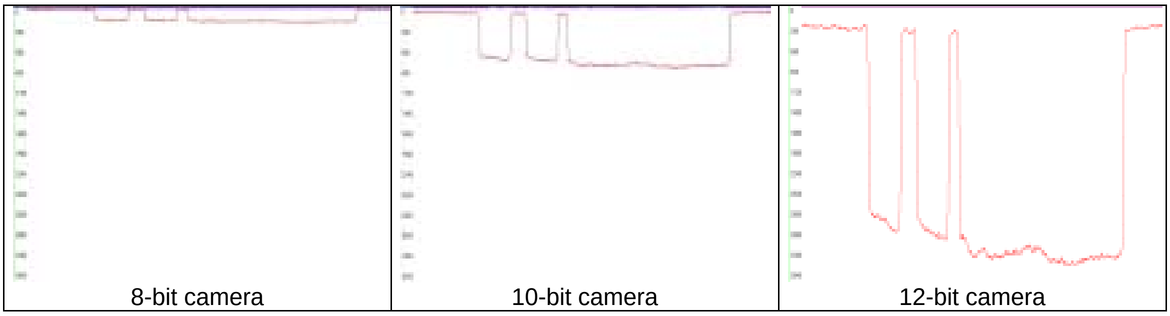


Figure 5.1. *Dynamic range of cameras with different sensitivity. The cameras are viewing the same object. The light level is set so that each camera signal is at its saturation threshold. The scale is identical for all three cameras.*

5.1.2 Resolution and Accuracy

Resolution is the degree of discernible detail. When an exposure is made, an image approximating a continuous object is created by equally spaced digital grey level samples. The sample number is directly related to the number of pixels in a line-scan camera. It is clear that a line-scan camera with 1024 elements has a lower resolution than a camera with 2048 elements, because the latter takes twice the number of samples as the first one. When the range of measurement is 500mm, the optical resolution of a 1024 pixel camera is approximately 0.5mm and that of a 2048 pixel camera 0.25mm. These are the areas an individual pixel 'sees'.

The quantity of grey levels has a direct effect on the detail content. As discussed earlier, an 8-bit element has 256 grey levels and a 12-bit camera 4096 levels. The number of grey levels has significance not only for an individual pixel, but also for its relationship with neighbouring pixels.

Connectivity between pixels is an important concept used in establishing edges of objects in an image. To establish whether two pixels are connected, their grey levels must satisfy a specific criterion that is set in the image processing algorithms. When line-scan technology is used, the object under measurement is moving through the measuring area. The exposures made, also known as sweeps, follow each other with an interval of a few milliseconds. The information in pixels of neighbouring sweeps is also compared with each other. Thus, each pixel has eight neighbours, with which its connections are examined and analysed, as in Figure 5.2.

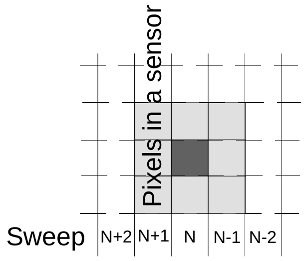


Figure 5.2. *The 8–neighbours of a pixel in the centre.*

5.1.3 Illumination and Reflectance

Optical measurement systems rely on light sent by an object. Light can be created either by the object itself, reflected from the object or, as in many log-scaling applications, as a shadow against an illuminated background. Ambient, natural light is rarely enough in industrial measurement. It varies during the day and seasons, casts shadows and its intensity is far from desirable.

Light sources that are used in machine vision technology have many alternatives. They can be fluorescent, halogen or metal halide lamps, light emitting diode arrays, lasers of various types, or specially built arrangements. Used wavelengths vary from ultraviolet (UV) to visible and to infrared (IR). Because most of the commercial and affordable CCD-elements are sensitive to visible light, typical light sources are different lamps, red light LEDs and visible lasers. In certain cases, IR illumination is used.

Irrespective of the light source used, the sent and reflected light passes some distance, a path length, during which the quality and quantity of light is affected by scatter and absorption. Assuming that all irradiated energy hits a target, the energy used to illuminate an object can be divided by the principle of energy conservation into reflected, scattered, and absorbed components (Lillesand and Kiefer, 1994, p. 12).

The relationship between illumination and the received maximum energy in a camera, the reflected energy from an object, can be expressed as

$$E_R(\lambda) = E_I(\lambda) - E_S(\lambda) - E_A(\lambda) \tag{5.3}$$

where $E_R(\lambda)$ is reflected energy,
$E_I(\lambda)$ is irradiated energy on the object,
$E_S(\lambda)$ is scattered energy, and
$E_A(\lambda)$ is absorbed energy.

The radiance or the total amount of energy of the light that radiates from the source is usually expressed in Watts (W). Energy received from an object, the portion reflected by an object, at the receiver is usually called luminance and is measured in lumens (lm).

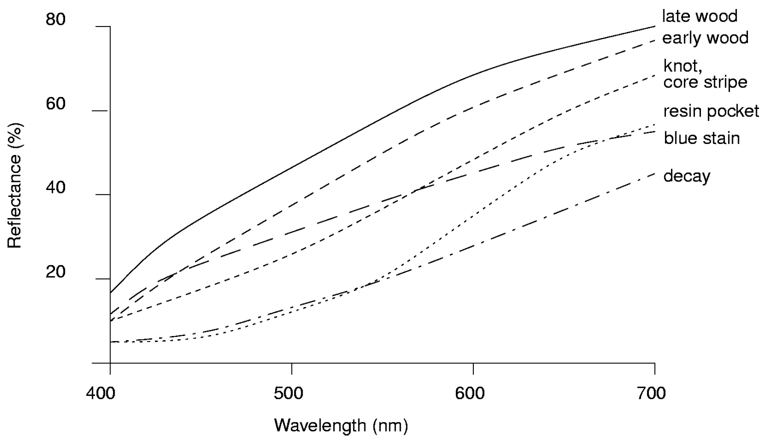


Figure 5.3. *Spectra of late and early wood and wood defects.*

Wood properties have an effect on the reflectance of light, such as in Figure 5.3 (Kauppinen, 1999, p. 41). Besides the mechanical damage at board edges, colour defects, such as knots, resin pockets and blue stain may cause radical changes in reflected light intensity.

5.1.4 Scatter and Absorption

Scatter and absorption diminish reflected energy. Scatter is unpredictable diffusion of radiation by particles in the air at the site of measurement. In sawmills, these are sawdust, flying wood slivers, water vapour, spray and dust in general. Scatter diminishes contrast of an image and causes 'haziness' in the imaging. The dynamic range of the camera is of considerable importance in compensating for this phenomenon. Unless extremely intensive, the scatter does not limit the optical measurement at the breakdown process. In extreme conditions, increasing illumination power does not help because scatter increases proportionally with the used energy and can cause excessive 'white noise' in a camera signal.

Absorption refers to loss of photon energy in the particles along the light path length, and on the dispersive qualities of wood surfaces, as in Figure 5.3. In wavelengths that are used in CCD-camera technology, absorption is even at all wavelengths. Therefore, absorption results in a general loss of light intensity reflected back from an object. Absorption also depends on colour qualities of an object and light source. For example if one illuminates a blue-greenish object with red light, reflectivity is very low and the object looks black (Bonfig & al., 1988, p. 413).

Both scatter and absorption are variables that change constantly in sawmilling conditions. There are variations of surface qualities – water, ice, sawdust, coloration, knots, bark bits. Furthermore, each cut of a sawblade tooth and each log is different from the previous ones. Therefore, the practical way of assuring that a CCD-camera gets enough reflected light energy $E_R(\lambda)$ is by having, within reason, as much light on the object as possible.

5.1.5 Irradiance

The irradiance of light energy from a point source reaching a surface element of an object is inversely proportional to the square of distance. The same law applies to the reflected intensity received by a CCD-element in a camera. This means that if the distance from the light source to an object is doubled, the intensity of light on the object surface drops to one quarter. Therefore, the installation distance and the object size exert a strong influence on the reflected and received energy. It is recommended that one should get the light source as close as possible to a measured object in order to keep the reflected energy as high as possible.

Various systems have been trialled in sawmill conditions. Because the purpose of illumination is to create intensity differences between the surfaces of pieces and the dark kerfs, one idea involves illuminating an object from the sides at an angle. One would need a light source on both sides because an object can have a curved surface. However, in many saw lines there is not sufficient room for a large system with a camera unit in the middle and two light source units extended at distance on both sides of the camera, or there may be mechanical structures that prevent unhindered illumination from sides. One method to increase irradiated energy is to use focussed light sources and concentrating light energy at an area of measurement. A problem with focussing is that the focussed light and the camera view may not necessarily be in the same line of sight, and there might be radical intensity variations.

Light sources may be built in a camera enclosure itself. The benefits of this solution are:

- Light source is close to the camera, and thus the depth of illumination focus is deep within the measuring area, resulting in ‘parallax free’ illumination
- Only one line of sight and illumination is required
- System is compact
- Maintenance, keeping the window clean, is required at one place only.

5.1.6 Exposure Time

Intensive illumination is required chiefly because of short exposure times. Short exposure times are required because an object under measurement moves from 500mm to 2000mm every second. Therefore, exposure time must be in the order of 5ms to 20ms and thus the exposure frequency 50Hz to 200Hz, i.e. 50 to 200 exposures each second. During an exposure, pixels collect incoming photons reflected from an object, and a cumulative energy charge is formed in each pixel. After the exposure, the elements in an array send their voltage data to camera electronics in sequence, and one line of object image is formed. Exposures are taken as long as the object is seen in the field of view of the system. Finally, a complete two-dimensional image of the object is created and computer analysis of the data can begin. There are no set or required levels of intensity of light sources because there is less need for light with lighter coloured surfaces than with darker surfaces. Factors other than reflectivity or exposure times additionally have an effect on illumination.

5.1.7 Edge Detection

An edge is a boundary between two regions with relatively distinct grey-level properties. The idea underlying most edge-detection techniques is the computation of local derivative operators. Figure 5.4 shows an image of a light stripe on a dark background, the grey-level profile along a horizontal scan line of the image, and the first and second derivatives of the profile. The first derivative at the leading edge of a transition is positive, and negative at the trailing edge. The second derivative is positive for that part of the transition associated with the dark side of the edge, negative for that part of the transition associated with the light side of the edge, and zero in areas of constant white or grey levels. Hence, the magnitude of the first derivative can be used to detect the presence of an edge in an image, and the sign of the second derivative can be used to determine whether an edge pixel lies on the dark or light side of an edge. The zero crossing of the second derivative provides a powerful approach for locating edges in an image (Gonzales and Woods, 1993, p. 417-418, and Funck et al., 1992, p. 245).

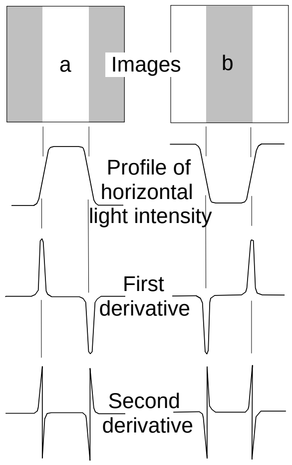


Figure 5.4. *Edge detection by derivative operations: (a) light stripe on a dark background; (b) dark stripe on a light background. The second derivative has a zero crossing at the location of each edge.*

However, not all rising or falling signals are necessarily edges, or at least not significant edges, or the edge data can be diffuse. To enhance the detected images, various processing methods are used. Some of these involve filtering, contrasting, thresholding, and segmentation, methods that in the process of dimension determination should result in improved edge definition.

Because high frequency components characterise edges and other sharp details in an image, and low frequency components mostly cause blurring, high pass filtering that attenuate low frequency components is often used. A method of contrasting is the creation of an image with higher contrast than the original by darkening the pixel levels below a certain value and brightening the levels above this value. This method is called contrast stretching and, when performed to an extreme, will result in two-level binary (black and white) images.

In an image, there are pixels with various grey levels. Selection of a certain grey level above which a pixel data belongs to one mode and below which it belongs to another mode is known as thresholding. Segmentation is then accomplished by scanning the pixels in an image and labelling each pixel as an object or background, depending on weather the grey level of that pixel is above or below the set grey level. These and other image enhancement operations can be performed using a range of algorithms.

Edge detection in timber size control does not rely solely on image processing. Equally important is the continuity of detected potential edges. A kerf has a consistent relative location in an image. Knots, broken edges, and other defects have limited consistency and length. Intelligent realisation of edge detection and image processing operation and the quality of optical arrangement and installation of the physical instrument itself are decisive to the reliability, effectiveness, and accuracy of all optical measurement system.

5.1.8 Optical Considerations

Edge detection can be impeded by the presence of rounded edges, surface roughness, colour variations, and occasional pieces of wood and sawdust. Occluded edges are caused by sawdust or wood pieces covering kerfs on top of the pieces, or creating background reflections. Diffuse edges are caused by slab and broken edges that appear when edge knots break off or wood tears apart during a sawing process. High dynamic range of CCD-elements can solve some of these problems, and mechanical solutions, such as rotating brushes, air blowers and other techniques can solve others.

The effects of variation in surface reflectance due to roughness, insufficient debarking, staining, or rounded corners are visible in Figure 5.5. An optical error caused by such factors is typically one or two pixels – the detected maximum light level jumps from on pixel to the next and back. Fortunately, the pieces under measurement are constantly in motion. Therefore, a reading is an optical averaging over a lengthways area of some ten millimetres, thus evening the pixel errors out. Similarly, the large quantity (several hundred) of readings taken when measuring a board evens out local erroneous measures. Further, the method for calculating a trimmed mean for each segment removes erroneous data from the results. The combined effect of all these procedures results in a measuring method that is robust against local interference.

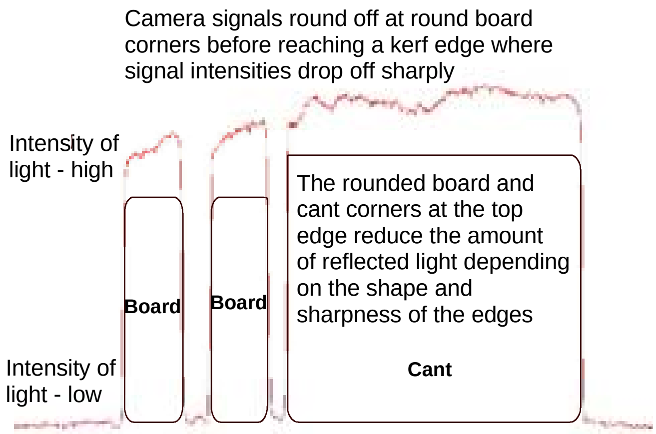


Figure 5.5. *Superimposed images of boards with round and sharp edges on a camera signal.*

An optical device, viewing the top edge of a stack of boards, measures the top edge size data from kerf edge to kerf edge. The device cannot 'see' size or shape features on the board faces down in the kerfs, such as offset in a double arbor circular saw, washboarding, or general surface roughness, unless they are visible at the top edge. Measurement of board features from the sawn faces requires that the boards are singulated and measured separately using other techniques.

Optical measuring starts immediately when a measuring device 'sees' the top-end of a stack of pieces entering its field of view. Because a bucking cut may not be straight, or the top may have suffered mechanical damage, or there may be a projection of wood at the top, it is not advisable to initiate data collection from the very top. Similar reasons apply to the butt-end of logs. The removal of the extremes at the top and butt-end is accomplished by filtering a percentage of the collected data in the image processing software. The percentage used in this study is one, 1.0%, as in Figure 5.19. However, in some cases, larger percentages must be used. One such cases is a situation involving a double-arbor circular saw in log breakdown, where a cant turning mechanism operates while the cant is still being measured. The turning causes erroneous readings and therefore must be removed from the data. The data removal is accomplished by using a twenty percent butt-end filter. An alternative case is one where the flitches are released and dropped while they are being measured. As may be expected, the filtering percentage must be kept to a minimum because with larger percentages valuable data is lost. In this study, the filter percentages, other than one percent, are notified where applicable.

Detection of an edge requires a transition from light to dark and vice versa. There are two separate cases when edge detection is not successful. The first is an occlusion of an edge, which may occur when two boards are pressed so tightly together that no kerf is visible, or when sawdust or wood pieces cover a kerf. In such cases, the resulting board size will be the combined size of the two pieces, and one board will be missing in a stack. Such a reading, which may appear even with full edged boards, will be rejected from the recorded readings. The number of such readings is normally insignificant compared with the total number of readings taken.

In this study, of more interest is the massive loss of readings that occurs in the case of flitches with slab surface. If the face of a board is of slab type, there is no edge to detect, and there will be no size data for that particular location, as in Figure 5.6. Depending on the quantity of the slab surface, there will be a number of board segments without size data.

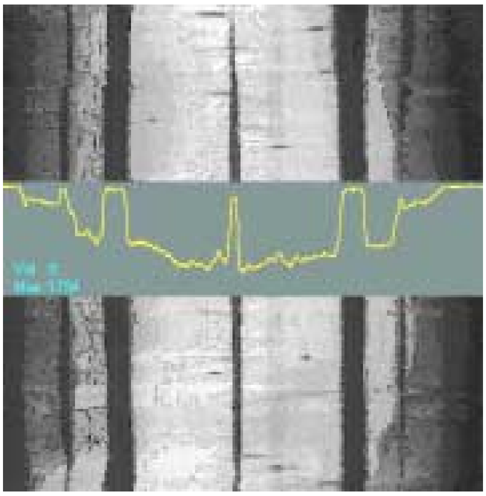


Figure 5.6. *Stack of six boards with a superimposed camera signal at one cross section. Both of the outer flitch faces have numerous slab surfaces, and thus there are not always distinct edges. Consequently, no size reading for outer flitches at certain locations will be available.*

The number of board segments without size data can be used to assess the quality of the sawn outer flitches. If a board has no or very few segments with recorded size, this will indicate that the flitch is mostly slab. Such a flitch is of little value as a board. Normally, such boards will be sent to a chipper by the edger operator. If the phenomenon is consistent, it is an indication of substandard production planning because slabs should not be sawn in the first place. In this study, it is assumed that the slab surface is justified in the first two segments along a board. If the slab surface quantity exceeds twenty percent of the full board length, the board is considered a potential reject board. Thus, the consistent occurrence of segments without size will increase the reject percentage – two segments indicating 0% reject probability and ten segments 100%, such as in Figure 6.24. The outer flitches similarly suffer from larger size variation because sawblades enter the log from the side. This tends to cause blade bend and snaking, which cause variations in the size.

Vibration and shocks caused by feedworks and sawing are another potential source of problems, and should be eliminated as much as possible. However, because of the speed at which the images are taken, optical averaging that takes place during image taking, and the mathematical averaging, shaking is generally not a problem. Some of the installation concerns with optical measuring devices, that should be avoided, include:

- Installation height may be limited because of available space, as in Figure 5.7
- Holding rolls compress kerfs. In some saw machines the kerfs disappear completely and measurement is not possible
- Machine structures, chains or conveyors are seen in the background, Figure 5.8
- First top roll after the saw interferes with the measuring view
- Dirt, sawdust and water spray interfere with the measuring view
- Guide knives interfere with the measuring view, as in Figure 5.9
- Falling flitches or cant turning interfere with the measuring view
- Reflections from behind the measurement area interfere with the measuring view.

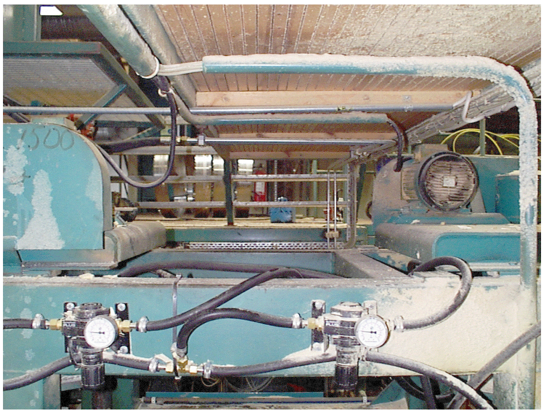


Figure 5.7. *Tight installation location for a measuring device. This area would require a horizontal unit and/or structural changes in the construction above.*

Figure 5.8. *Beam in a potential measuring location collecting wood slivers and obstructing the camera view. Chain may be filtered by software from an image.*

Figure 5.9. *Potential measuring site requiring two modifications. First, an opening must be made at the measurement location to avoid background reflections. The opening will also solve the problem of sawdust accumulation. Secondly, the knives must be modified so that they do not reflect light in the direction of the camera. This may be done by grinding a 45^o notch in the knives.*

The lack of sufficient space close to saw machines has been a limiting factor in utilisation of optical measuring devices since the 1980's (Viitaniemi, 1985, p. 84). The situation seems to persist despite an increasing demand for optical and other control devices that should be installed in the immediate vicinity of saws and saw exits.

5.2 Principle of Parallax

In an optical measuring arrangement with one camera, parallax represents a significant obstacle. In astronomy and remote sensing, the term parallax refers to the apparent change in relative position of stationary objects caused by a change in viewing position (Lillesand and Kiefer, 1994, p. 313). Astronomy and photogrammetry use parallax to their advantage in determining the distance and height of objects by looking at an object from two different locations (two cameras), a principle known as stereoscopic or stereo vision.

The effect of parallax in a measuring system with only one stationary camera is that an object that is closer appears larger than the same object further away, as in Figure 5.10. In many optical measurement applications, this does not represent a problem, for instance, if objects are always against a guide rail or are measured from the same distance, or when objects are moving on a conveyor and their distance (i.e. height) is accurately known. In certain cases, a correction factor must be calculated in order to obtain the correct size.

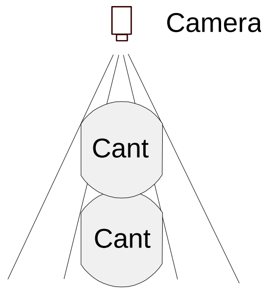


Figure 5.10. *Parallax phenomenon in a one-camera system. The closer to the camera, the bigger the measured object appears.*

Parallax becomes a problem when a device must measure objects that are of unknown height or size, move during the measurement in relation to the camera, or have rounded surfaces. There are two solutions to this problem. The first, stereo vision, is already used in photogrammetry. By placing two cameras directed at the same object from two different locations and angles, one can calculate the distance to and the size of an object, as in Figure 5.11. In industrial applications, this method works when one needs to measure the size of a solid square object with distinct edges. Difficulties may arise with curved surfaces, and detecting such details as kerfs. Stereo vision requires accurate positioning of cameras and calibration of the system, heavier calculation algorithms, and more room for cameras and light sources at the site of installation. The potential of stereo vision is limited in sawmill applications.

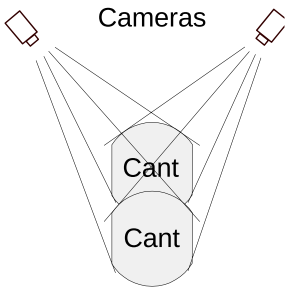


Figure 5.11. *Principle of stereo vision. Accurate information on the position of cameras is required for correct calculation of sizes.*

The second approach to solving the parallax problem involves using parallel lines of light. There are two methods within the approach. The first involves the use of a large convex lens. In industrial applications, a lens with a diameter of 500mm and a thickness of 150mm would not be practical. The problem of large lenses was solved by the French physicist Jean Fresnel (1788-1827), who had the same problem with collimating lenses in lighthouses. He decided to remove the useless internal material of convex lenses, and made lenses flat. Today, these flat lenses are called Fresnel-lenses, as in Figure 5.12. With a Fresnel lens, the distance from the camera to the object to be measured, actually the distance from camera to lens, is constant.

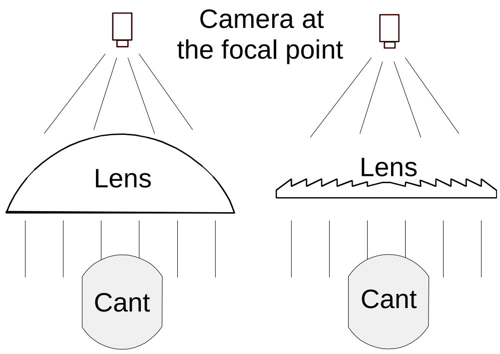


Figure 5.12. *Principle of paralleling the light beams with a conventional lens and a Fresnel lens. The upper surface of the Fresnel lens is formed of small segments of the upper surface of a convex lens. A camera is at the focal point.*

An alternative way of making light beams parallel is by the use of a curved, parabolic mirror, as in Figure 5.13. A property of parabolic mirror is that all light beams that are parallel to the main axis of the mirror pass through the focal point, whatever the aperture of the mirror. A camera is at the focal point to which the light comes parallel from an object. Parabolic mirror systems have been used in log scanning since the mid 1960's (Williston, 1985, p. 125).

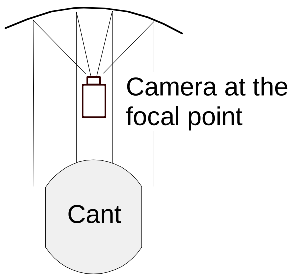


Figure 5.13. *Principle of a parabolic mirror.*

Paralleling the light reflected by logs brings several advantages to optical measuring systems in breakdown sawing:

- Distance from camera to object has no effect on measured size
- Object can move during the measurement vertically and/or horizontally
- Installation distance of a system has no significance to the measurement
- Measuring device can be moved, or even be portable because it is not sensitive to an installation position
- Space requirement for installation is small.

5.3 System Structure

A measuring system consists of a line scan CCD-array with 1024 or 2048 pixels and camera electronics with a dynamic range of 8-, 10- or 12-bits. A CCD array is sensitive to a broad band of visible light. The camera can directed at an object directly through a sequence of mirrors that facilitate seeing into the measuring area, or through a set of paralleling optics, or using a combination of both. Light sources can be separate from the camera unit, or they can be in the same enclosure as the camera and electronics. In both cases, the light is used effectively to illuminate the operational range of the measuring system. Figure 5.14 illustrates the major optical and electronic components in such a system. Some or all of the components can be within a single enclosure to ensure reliability, ease of installation, compactness and maintenance friendliness, or they can be located in separate locations in order to attain the most accurate measurement.

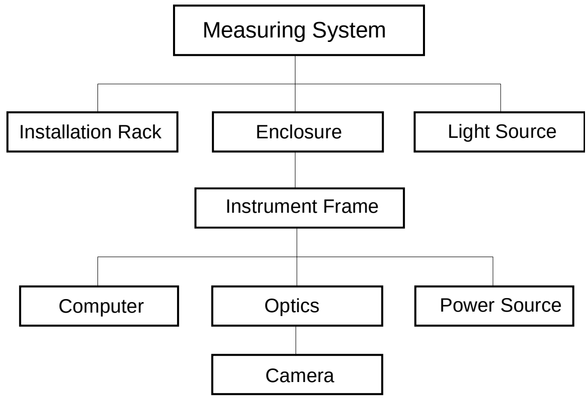


Figure 5.14. *Typical structural elements of an optical measuring system.*

An arrangement of a CCD line-scan system is presented by Funck et al. (1992, p. 239), where a paralleling optics has been used. Figure 5.15 illustrates such an arrangement. A light source illuminates the cants, flitches, centrepieces, and boards to be measured from the direction of the measurement, usually from above or from either side. The reflected light is recorded in a camera, on a one-dimensional line-scan sensor that measures the reflected intensities.

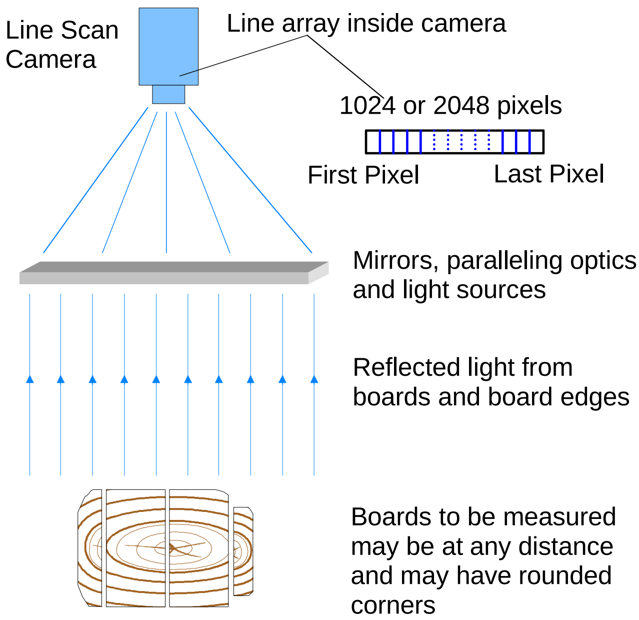


Figure 5.15. *Principle of a CCD line-scan measurement system utilising paralleling optics.*

Kerfs do not reflect, darker wood surfaces reflect some and light coloured wood surfaces reflect a considerable amount of light. Other variations in reflections are caused by surface roughness, knots, sawdust, and slivers. The reflected intensities are registered in a line-scan sensor inside a camera. Figure 5.16 demonstrates the reflected light intensities of samples. The signal shown is known as a video signal or an oscilloscope image. In the image, a signal drop is an accurate measure of the light intensity. The zero level, at the upper edge of the display, indicates total blackness. The deeper a signal drops, the more reflected light is recorded, and the lighter the surface of a reflecting object.

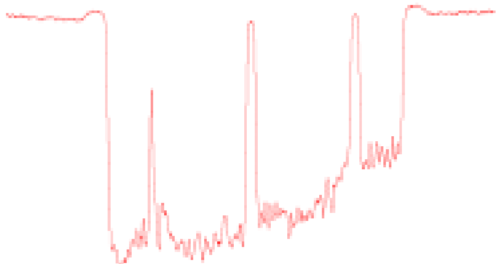
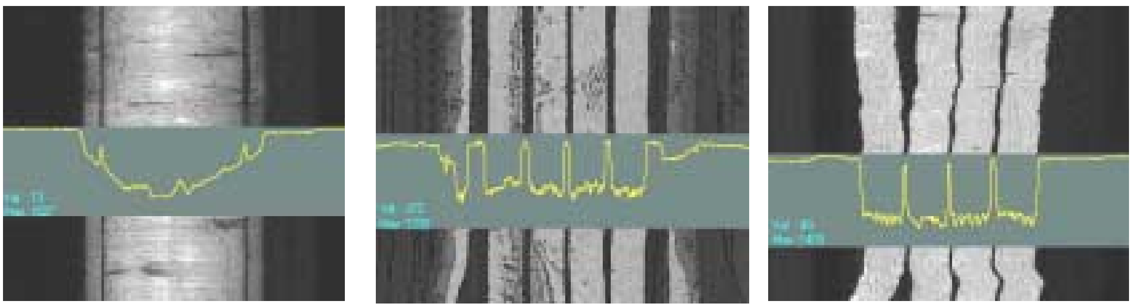


Figure 5.16. *Video signal of a camera view. This is a momentary cross section, one exposure, of recorded board reflections.*

Hundreds of individual exposures, taken while a board package moves through a camera field of view during a measurement, form a two dimensional image of the total length of a board stack. Images formed in this way are shown in Figure 5.17. The kerfs and dark background are quite distinct. All grey-scale CCD line-scan cameras, independent of the optical arrangement, produce similar images in comparable conditions. The images illustrate two-dimensional images in the sawmills examined. The sideways movement seen in certain of the images is natural sideways movement of boards when they leave a saw and open before contact with guide rolls.



Log cant and flitches in log breakdown | Centrepieces and flitches with wane in cant resaw | Centrepieces in square cant resaw

Figure 5.17. *Images of measured pieces and camera signal examples.*

The first step in a process of measuring an unknown size is image acquisition – acquiring a digital image of an object. In log measurement, the image is acquired with a line-scan camera that produces a single image line at a time. Once a digital image is obtained, the next step is pre-processing. The essential function of pre-processing is to improve an image in such way that the chances of successful measurement are increased. Segmentation involves partitioning the features of an input image into its constituent parts for subsequent analysis. Description involves extracting features that have quantitative or qualitative information of interest for resolving the size problem. Interpretation entails assigning meaning to a set of recognised features. The knowledge base that is used in all stages of image processing and data analysis includes knowledge about the sizing problem to be solved. Some of the knowledge is in software databases; some of it is in mathematical relationships known as algorithms, as shown in Figure 5.18 (adapted from Gonzales and Woods, 1993, p. 573).

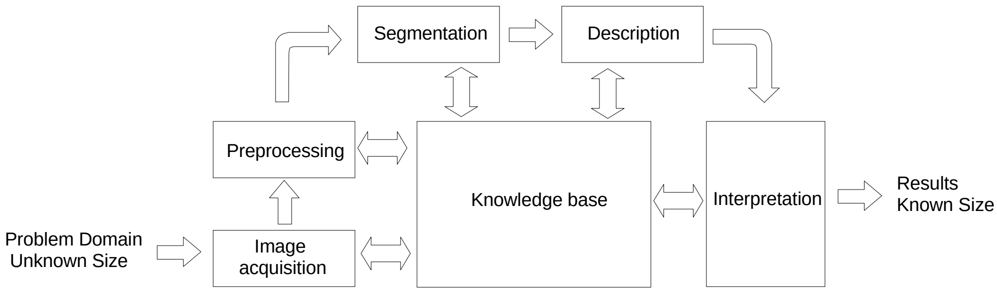


Figure 5.18. *Fundamental steps in digital image processing.*

Real-time measurement and calculation require powerful and fast processors. Because the top to butt distance of successive logs may be as small tens of millimetres, the image processing and data analysis must be almost instantaneous. Modern processors are designed to process signals and data in real-time. The design goal is normally such that all image and analysis processing takes place at the site of measurement, and only finished results are sent to a reporting computer, and into a sawmill's computer network.

5.4 Data Recording

Analysis of data takes place in segments of equal length, along each parallel board in sawn stacks. The physical segment length in each measured board depends naturally on the length of the board. In this study, the number of segments is ten. Numbering of segments starts from the top-end of a log, the part of log that first exits from a saw into the field of view of a measuring device. Logically, the first segment is designated as segment one, and consequently the last segment as segment ten. This principle is illustrated in Figure 5.19. The length of segments depends on the real, physical length of each log.

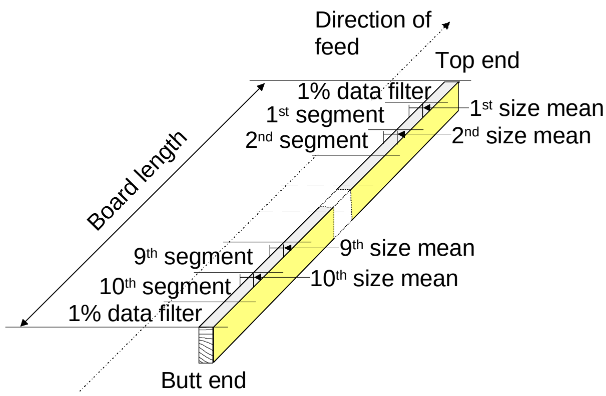


Figure 5.19. *Principle of segment definition. Mean size is calculated for each segment using trimmed data collected in the respective segment range. Top- and butt-end data filter areas are shown.*

An optimal data collection situation exists when all sawn boards have the same length. In such case a saw machine analysis based on the 'segmented' data and graphic presentations would be the best possible. However, in sawmills this is rarely possible. Thus a sample of boards from fifty logs of various lengths will present an average behaviour of these sawn boards. Although the accuracy of the results is somewhat compromised, the large number of measured boards and averaging will give reliable results of the sawing process in each segment. In extreme cases, the person performing an analysis must take this fact into consideration.

Figure 5.20 illustrates the definition of data readings, and how segment values can obtain a large number of readings. Each individual data reading is a result of the cumulative number of photons collected in pixels during an exposure while boards move through the measuring window of a device. Variations in the number of collected photons in pixels create intensity differences that are used to calculate size in individual exposures. The amount of board movement during an exposure is called the optical measuring range. Optical averaging of physical features of a board takes place during an exposure over an optical measuring range, causing variations in photon quantity in pixels. Thus, an individual size data reading is an optically averaged mean over an optical measuring range.

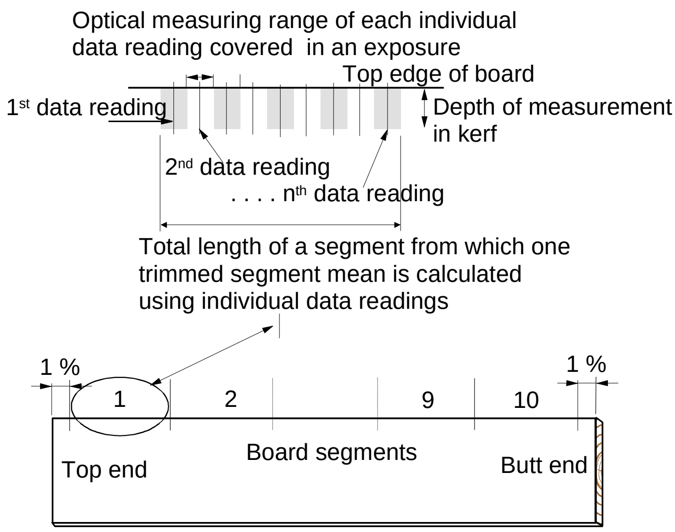


Figure 5.20. *Definition of data readings within segments. Segment means are averages of the individual data readings.*

The number of data readings used to calculate size values for segments depend on the feed speed of a saw and the physical length of segments. Because the exposure time of a CCD line-scan camera is maintained constant, the feed speed defines how many exposures the camera has time to take.

The slower the feed speed, the more data readings will be used to calculate a trimmed mean, Equation 6.7, for each segment, as in Figure 5.21. If feed speed is 30m/min and length of a segment 400mm, eighty data readings will be used to calculate a trimmed mean for the segment. When feed speed is increased to 120m/min, twenty data readings are used to calculate a trimmed mean. However, it must be remembered that 100% optical recording takes place in both cases. The number of data readings additionally depends on the exposure time of the camera, and log length.

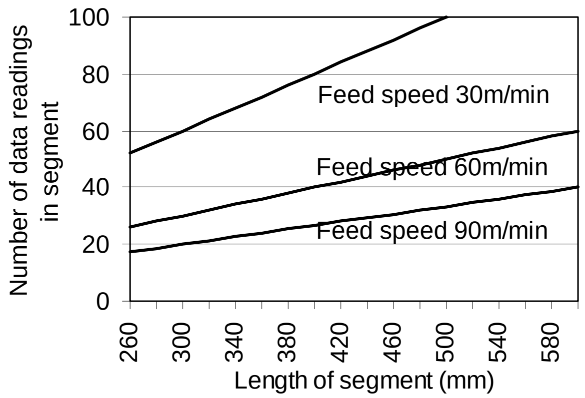


Figure 5.21. *Number of data readings in a segment with different feed speeds and segment lengths when the exposure time is ten milliseconds. When feed speed is 1.0m/s, a segment of 500mm is covered by fifty exposures and thus by fifty individual data readings.*

Irrespective of the purpose of a measurement, all individual data readings are recorded for boards in a sample. The number of recorded readings can range from 200 to 750, depending on board lengths and feed speeds. The ‘raw’, unprocessed data is saved in *.dta format files where the file name is the sample identification code. This data is referred to as the original optical data.

Trimmed means are calculated for each segment, based on the original optical data, using Equation 6.7. The trim percentage for both low and high values is ten. The calculation of trimmed means and a conversion into *.csv format file is performed by using a specific programme, DTA2CSV, that has been developed for this purpose. The format conversion into *.cvs is required because Microsoft Excel is not able to process *.dta type files.

During the conversion from *.dta to *.cvs files, the trimmed segment means are calculated to a designated number of segments. The number of segments used in this study is ten, as determined in Appendix C. The effect of the process from original optical data, as in Figure 5.22, to fifty segment means, and finally into ten segment means, is illustrated in Figure 5.23.

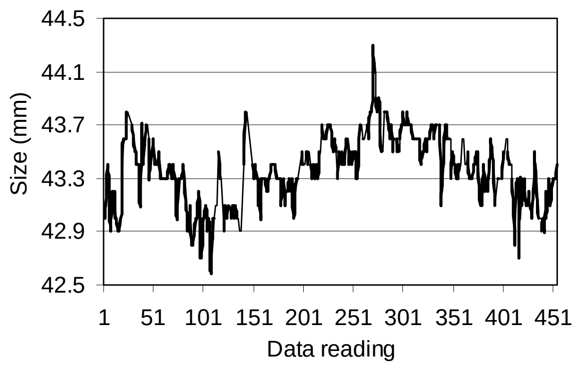


Figure 5.22. *Original 458 optical data readings at equally spaced locations.*

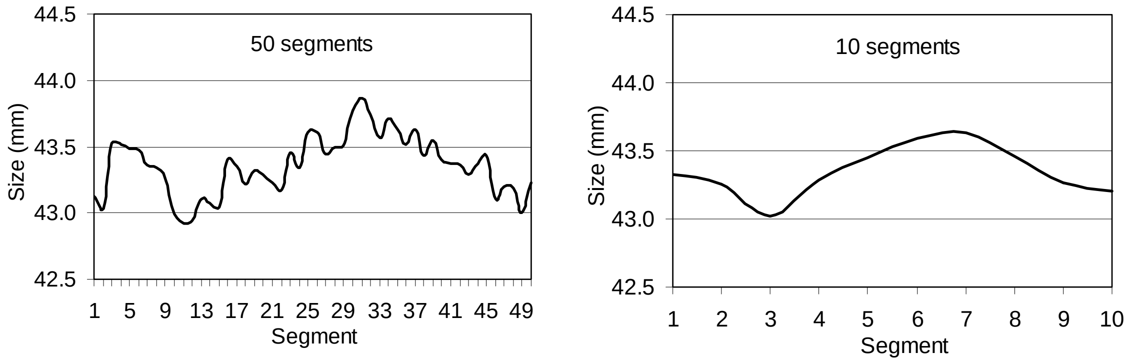


Figure 5.23. *50-segment trimmed means, left-hand figure, and 10-segment means that have been calculated from the original optical data in Figure 5.22.*

The analysis of the behaviour of a saw machine is based on trimmed means and the 10-segment method. Trimmed means are used to calculate various factors and indices used in an analysis. Trimmed means are calculated with an accuracy of 0.01mm. Because an analysis is based on fifty logs, the quantity of logs for each sample must be somewhat larger than the required minimum number, in order to provide back-up in case there are set-up adjustments or process disturbances during a test.

5.5 Verification of Optical Measuring Device

There is no such thing as an absolutely accurate and correct measurement. All measurement systems have their deficiencies. An error in measuring may be an assignable cause of variation, such as an error in operating a measuring device that may cause a sudden shift in general mean. Other sources of errors include drift in a measuring device, or there may appear factors that cause increase in general scatter in a measuring area. Assuming a steady state of conditions, the size of a sawn piece can be expressed as a function of the known accurate size of a test reference, respective readings of a sawn piece and reference, and the systematic error of a measuring device.

$$D_{\mathrm{Sawn}} = \mathrm{f}(D_{\mathrm{Test}}, R_{\mathrm{Sawn}}, R_{\mathrm{Test}}, ER_{\mathrm{Device}}) \tag{5.4}$$

where D_{Sawn} is the true size of a sawn piece,
D_{Test} is the true size of test reference,
R_{Sawn} is a reading of a sawn piece,
R_{Test} is a reading of test reference, and
ER_{Device} is the systematic error in a reading.

For a sawn piece, the systematic errors E_{Device} relevant to readings R_{Sawn} of a sawn piece can be considered further in terms of identifiable elements that have or may have an effect on the reading accuracy and precision (Bonollo, 1983, p. 1269). These elements are defined as

$$ER_{\mathrm{Device}} = \mathrm{f}(ER_{0\mathrm{SP}}, ER_{\mathrm{rSP}}, ER_{\mathrm{lSP}}, ER_{\mathrm{vSP}}, ER_{\mathrm{sSP}}, \ldots, ER_{\mathrm{iSP}}) \tag{5.5}$$

where ER_{Device} is the systematic error of a measured sawn piece,
$ER_{0\mathrm{SP}}$ is the zero or offset error,
ER_{rSP} is the error due to surface roughness and unevenness,

ER_{lSP} is the error due to scatter and absorption of light,
ER_{vSP} is the error due to object and system vibration,
ER_{sSP} is the error in measuring system electronics and software, and
ER_{iSP} is the last systematic error that can be determined.

A similar set of systematic errors can be associated with readings from a manufacturer's calibration reference. However, the errors that take place in calibrating a measuring device using an accurate calibration reference, designed for device adjustment in controlled environment, must be considered small in comparison with an on-line measurement. Thus, the calibration error is considered to be zero.

A measuring device that is used in a sawmill environment is designed to measure moving objects, and thus testing is performed with moving test references. Since the dimension of a test reference D_{Test} is known with an accuracy that is an order of magnitude more precise than the desired measuring accuracy of a sawn piece D_{Sawn}, the test reference reading R_{Test} can be considered accurate in comparison with readings from sawn pieces. Thus, test reference factors can be removed from Equation 5.4. Since D_{Sawn} represents the true size of a sawn piece, its measured value R_{Sawn} can be presented as

$$R_{\text{Sawn}} = D_{\text{Sawn}} + ER_{Device} \qquad (5.6)$$

where R_{Sawn} is the reading of a sawn piece,
D_{Sawn} is the size of a sawn piece, and
ER_{Device} is a measuring error.

Thus, a recorded size R_{Sawn} is an estimate of the true size D_{Sawn}. Determination of measuring error in sawn boards is not possible because sawn boards have no true exact measure (Juvonen, 1974, p. 31, and Brežnjak and Hvamb, 1963, p. 62). This is evident on the sawn board faces, which have dimensional waves caused by knots, Figure 5.24.

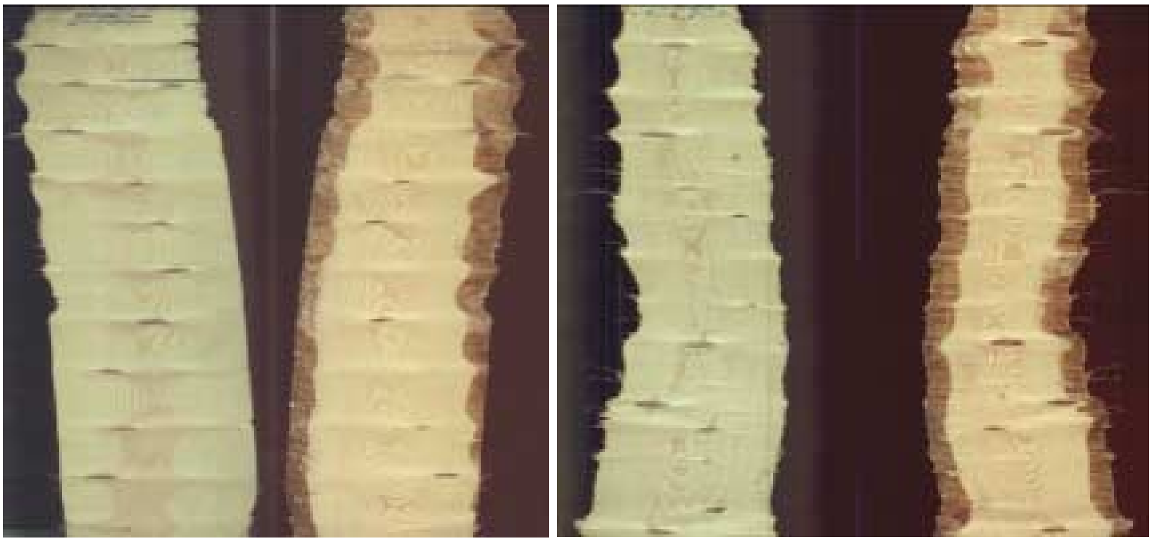


Figure 5.24. *Two faces of two flitches which were sawn in a bandsaw. In the lengthwise compressed images appears a three-dimensional effect, which reveals the waviness of the sawn faces.*

However, an error can be estimated by using test references. Measuring error ER_{Device} can be expressed in terms of two components, accuracy and precision. A measuring device having both high accuracy and precision will have readings that are centred on the sawn target size and will have a small dispersion.

Accuracy of a measuring device refers to the uniformity of readings around a target size, so that, on average, the target size is realised. When individual readings spread on both sides of the target size in almost equal proportion, a measurement is said to be accurate. For a measuring device, the accuracy is dependent on calibration. If a measuring device is properly calibrated, the mean reading, after repeated measurements, will be equal to the target size.

The precision of a measuring device refers to the degree of variation of readings. Readings may be off target but still considered precise if their dispersion is small. A sophisticated measuring device should produce an output with minimal variability. Precision reflects the structural inaccuracy of pixel resolution. Precision is an inherent characteristic of a device and cannot be improved by changing a setting (Mitra, 1998, p. 146).

The top-end size of logs may vary from 100mm to 450mm, and the canted logs entering a saw may have widths of up to 350mm. Therefore, the measuring window of an optical measuring device must be large and reliable within a measuring range of 350*350mm^2. The active width and height ranges are illustrated in Figure 5.25. The measuring device chosen for timber size data collection in this study is a CCD line-scan camera device, such as in Figure 5.15. Determination of the measuring device error is performed in the manufacturer's test bench and in a sawmill.

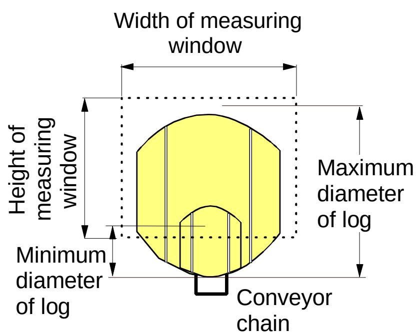


Figure 5.25. *Window of a measuring device must be able to measure accurately from the smallest log to the largest with consistent accuracy and precision.*

A raster, with laser cut square slots of 5±0.02mm width that cover the entire horizontal range of measurement, is used to calibrate a measuring device. Tolerance of the slot positions and the total raster length is ±0.02mm. Calibration raster is used both at the manufacturer's test bench when a device is calibrated, and in a sawmill during device check-ups. A raster is placed to cover the measuring range, the oscilloscope signal is checked, and automatic device calibration is performed. In the calibration process, the response of a measuring device is adjusted accordingly so that eventual optical errors in the internal reflectors are compensated for by using software to make readings linear. Because, reflector surfaces are plane by design and do not have discontinuities, remaining optical errors can be considered insignificant after calibration.

5.6 Verification of Accuracy and Precision

After calibration, the entire measuring range is tested with a set of eight precisely manufactured, parallel reference pieces. Test references simulate eight parallel boards exiting from a saw. Test references are fixed in a frame that can be moved vertically and horizontally over the entire measuring range, as in Figure 5.26. The vertical measuring zone is tested by moving the test piece fixture, in four increments of one hundred millimetres, from the bottom position of -25mm below the minimum log size to the uppermost position of +25mm above the largest log size, so that the entire vertical range is covered. The four vertical test levels are designated as the Top, Top-down, Bottom-up and Bottom quarters. During a test, references are oscillated horizontally at an amplitude of 5mm to 10mm. All test pieces are of identical size, 37.0±0.02mm. Thus, the true test reference size μ_T used in calculations is 37.0mm.

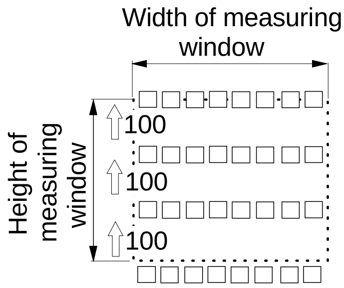


Figure 5.26. *Positions used to test accuracy and precision of a measuring device.*

At each test level, the measuring cycle is repeated 250 times. Each test piece reading is recorded at a resolution of 0.01mm. The accuracy and precision of an optical measuring device are calculated from these readings. Device accuracy is based on the deviation of mean, based on 250 measuring cycles, from the true test reference size. The accuracy of each of the eight test references, at each test level, is calculated as the difference between the recorded mean and the reference piece size. Accuracy at each level is based on the mean of averages at the level, and the total accuracy of an optical device is based on the mean of level averages.

The precision of measurement is calculated using same original data that is used in the calculation of accuracy. Precision is calculated as standard deviation. Thus, the precision of one test reference is calculated as the regular standard deviation, as in Equation 6.13. The precision at each level is calculated as the standard deviation of all readings at a level, and the total precision is the standard deviation based on all readings on all levels.

The smaller the values of accuracy and the total precision, the better the behaviour of a measuring device. While the theoretical opto-electronic resolution, based on the pixel size of the selected device, is 0.35mm, the expected accuracy and precision values will be smaller than pixel resolution because the performance characteristics are calculated using a large number of readings that concentrate around the true test reference size.

5.6.1 Device Accuracy and Precision

The testing of accuracy and precision was performed using devices that are installed at single-arbor circular saws in log breakdown and cant resaw. The results of accuracy and precision of the device used in log breakdown control is presented in Tables 5.2 and 5.3.

Table 5.2. *Accuracy of measuring device based on 250 readings per test piece at each level. Values are in mm.*

Test piece / Location	Top	Top-down	Bottom-up	Bottom	Accuracy at the location
	Measuring level				
	Individual test piece reading accuracy				
Left 1	0.01	-0.01	0.02	-0.01	0.00
2	0.07	0.03	0.09	0.07	0.07
3	0.06	0.04	0.00	0.02	0.03
4	0.04	0.14	-0.08	0.04	0.04
5	-0.07	0.02	-0.04	0.04	-0.01
6	0.04	0.08	0.10	0.08	0.08
7	0.02	0.07	0.04	0.06	0.05
Right 8	0.03	0.06	0.04	-0.04	0.02
Accuracy on the level	0.03	0.05	0.02	0.03	
Total accuracy	0.03				

Table 5.3. *Precision of measuring device based on 250 readings per test piece at each level. Values are in mm.*

Test piece / Location	Top	Top-down	Bottom-up	Bottom	Precision at the location
	Measuring level				
	Individual test piece reading precision				
Left 1	0.10	0.13	0.13	0.09	0.11
2	0.12	0.13	0.08	0.12	0.12
3	0.09	0.11	0.17	0.14	0.14
4	0.16	0.14	0.15	0.13	0.16
5	0.15	0.13	0.17	0.13	0.15
6	0.11	0.13	0.14	0.09	0.12
7	0.10	0.16	0.09	0.11	0.12
Right 8	0.13	0.11	0.17	0.13	0.14
Precision on the level	0.13	0.14	0.15	0.12	
Total precision	0.13				

A small variation in accuracy exists between the individual measuring devices because electronic and optical components are not identical. Overall precision of the measuring devices is the same. Results indicate that the average measuring error of a device, its accuracy, is ±0.05mm, and the one-standard deviation, its precision, is 0.15mm. These values are inherent to this type of optical measuring device. More precise calibration or change of settings cannot improve them.

Trimmed means are used in sawmill descriptor calculations and relate solely to the capability of a measuring device to produce readings uniformly around the process mean, to the accuracy of the device. Thus, it can be claimed that the inherent measuring accuracy and precision in the descriptor determination is 0.05mm.

5.6.2 Long Term Drift of Mean

Test pieces used in the determination of accuracy and precision are similarly used to test the long-term drift of a measuring device. Because a device measures constantly when it ‘sees’ an object in its field of measurement, the drift test was performed merely by keeping test pieces in the measuring zone as long as necessary. In order to get discrete readings for individual test pieces, a device is programmed to take hundred exposures –

a measurement of one ‘set of pieces’ - after which it begins to take the next set of exposures. The programme treats each set of hundred exposures as if taken from separate pieces exiting a saw, and records the data in normal manner. Any inherent device drift will be seen as a trend, a change in the reported readings.

Drift test was performed by positioning test pieces at the vertical medial position in the measuring zone, and allowing the device to continue measuring for one hundred hours, during which period the device recorded approximately 350 000 measured sets. The readings of the first ten and last ten sets of pieces were recorded. The means for both sets of ten test pieces were calculated, and are shown in Table 5.4.

Table 5.4. *Stability of a measuring device based on an one-hundred-hour test. Values are in mm.*

Reference piece	Mean of the first 10 pieces	Mean of the last 10 pieces	Drift at the location
Left	37.04	37.04	0.00
2	36.91	36.93	-0.02
3	36.95	37.00	-0.04
4	37.15	37.17	-0.01
5	36.99	36.97	0.02
6	36.94	36.92	0.03
7	37.21	37.14	0.07
Right	37.02	37.04	-0.02
Average of means	37.027	37.025	
Average drift	0.002		

The results in Table 5.4 indicate that the optical measuring device is stable and produces similar readings over long periods.

5.7 Verification of Accuracy and Precision in Sawmills

Verification of a measuring device in a sawmill involves a comparison of manually measured top edge size with optically recorded data. This comparison is of interest both to the manufacturer of an optical device and to a sawmill, because it provides information on the capability of a device to operate correctly in a sawmill environment.

The sample size required to compare manual caliper measurement with optical measurement may be estimated using Equation 6.3. In order to be confident with the results, a 3s level of confidence (99.73%), and thus $Z_{\alpha/2}=3$, is selected. One must also estimate the standard deviation of manual measurement. Although resolution of a modern digital caliper can be in the order of 1/100mm, the precision of manual measurement is not in the same order of accuracy. Wood is an elastic material and roughness of sawn faces can be in the order of 0.4mm. If a regular caliper is used, accuracy of reading may be at best 0.1mm, and precision about 0.5mm (Funck and Leavengood, 1995, p. 4). Tests on the precision and accuracy of manual measurement performed during this study are discussed in Appendix B. Manual measurement tests were conducted in two sawmills using their regular digital measuring tools. An estimated one-standard-deviation of 0.3mm for manual measurement is used in this study. Furthermore, it should be noted that the results of optical and manual measurement may not differ more than 0.2mm, thus d is 0.2mm. Within these parameters, the minimum sample size is 21.

The number of boards in sawmill verification is selected to be ten pieces, and the number of readings in each board fifty. Thus, the total number of readings is 500. In order to increase the robustness of the comparison, means are calculated for ten segments. The comparison is accomplished by using the resulting hundred segment means (10 pieces times 10 means). The boards used in this test have full edge in order to avoid measuring complications caused by wane. Therefore, test boards are centrepieces from ten successive cants. The centrepieces were measured optically when they exited the saw, after which they were selected from the line for manual measurement. In optical measurement, each size reading is an average of eight to ten individual data readings. Therefore, optical size data is not from the same physical spot as manual data. Where an optical reading is an average size of a lengthways segment, manual measuring produces size data at one physical spot within the particular length segment.

Sawn boards have no true exact measure. Therefore, manual or optical readings cannot be compared with any true reference. A comparison must be made between the measuring results of the two methods. Means for ten along the length segments are used, thus each manual segment value is an average of five readings and each optical segment value an average of 36 readings.

Board means and standard deviations for the two methods are calculated with within-board and total standard deviation, using Equations 6.11, 6.13 and 6.20. The results for measurements are presented in Table 5.5. Correlation between board means and within-board standard deviations are strong, respectively 0.98 and 0.92.

Table 5.5. *Comparison of manual and optical measurement in a single-arbor sawmill.*

	Manual measurement		Optical measurement		Difference	
Test piece	Mean	Within-board std. dev.	Mean	Within-board std. dev.	Mean	Within-board std. dev.
Board 1	42.83	0.12	42.73	0.11	0.09	0.01
2	43.51	0.17	43.44	0.21	0.07	-0.04
3	42.39	0.37	42.14	0.35	0.25	0.02
4	42.61	0.28	42.48	0.27	0.13	0.01
5	42.77	0.27	42.73	0.32	0.04	-0.05
6	43.00	0.14	42.99	0.11	0.01	0.03
7	42.82	0.50	42.55	0.37	0.27	0.12
8	42.88	0.22	42.79	0.22	0.08	-0.01
9	42.58	0.25	42.47	0.25	0.11	0.00
Board 10	43.02	0.18	42.95	0.18	0.08	0.00
Mean of means	42.84		42.73		0.11	
Total standard deviation		0.39		0.42		-0.03

The correlation between manual and optical measurements is strong, 0.99.

Comparison of measuring results is also performed individually on all ten boards with an analysis of mean and standard deviation. Board size is a variable that has normal distribution, thus both manual and optical size reading distributions are normally distributed. Because readings are from identical boards, the sample variances should similarly be identical. $\overline{X}_1$ represents the mean for manual measurement with standard deviation s_1, and $\overline{X}_2$ and s_2 respectively for optical measurement.

The confidence interval requirement that the population means μ_1 and μ_2 do not differ significantly is set at 95%, and thus $Z_{\alpha/2}$ is 2. A 100(1-α)% two-sided confidence interval for a difference between two means (Devore, 2000, p. 362) is given by

$$\left(\overline{X}_1 - \overline{X}_2\right) - Z_{\alpha/2}\sqrt{\frac{s_1^2}{n} + \frac{s_2^2}{n}} \le \mu_1 - \mu_2 \le \left(\overline{X}_1 - \overline{X}_2\right) + Z_{\alpha/2}\sqrt{\frac{s_1^2}{n} + \frac{s_2^2}{n}} \qquad (5.7)$$

Using this equation, the bounds for confidence interval can be expressed as

$$\mu_1 - \mu_2 = \left(\overline{X}_1 - \overline{X}_2\right) \pm Z_{\alpha/2}\sqrt{\frac{s_1^2}{n} + \frac{s_2^2}{n}} \qquad (5.8)$$

where μ_1 is the population mean of manual measurement,
μ_2 is the population mean of optical measurement,
$\overline{X}_1$ is the mean of manual measurement,
$\overline{X}_2$ is the mean of optical measurement,
$Z_{\alpha/2}$ is half of the two-sided confidence interval,
s_1 is the standard deviation of manual measurement,
s_2 is the standard deviation of optical measurement, and
n is the number of means per board, in this case 10.

If the two measuring methods, manual versus optical, produce equal population means, the difference of population means, μ_1 - μ_2, should be zero. Thus, the result of the right side of Equation 5.8 should produce a value that includes zero, in which case one can say that both methods produce similar results with a 95% confidence interval.

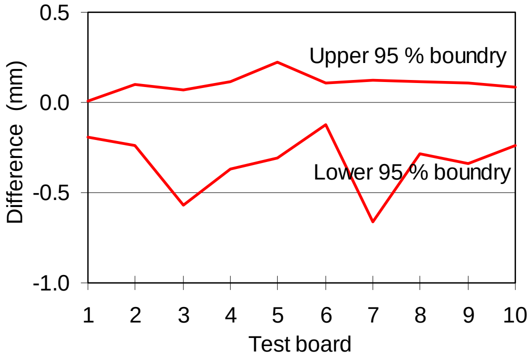


Figure 5.27. *The 95% confidence interval for manual and optical measurement population means in a case study of ten different boards.*

The confidence interval bounds for the ten measured boards have positive and negative values, and the zero value is included, in all cases, in the interval, as in Figure 5.27. Thus, it can be concluded that the two measuring techniques, manual and optical, produce similar results within a 95% confidence level.

5.8 Effect of Measuring Error on Process Capability Index

Measured size R_{Sawn} is the sum of the true size D_{Sawn} plus the measuring error ER_{Device}, Equation 5.6. Because the true size is independent of the measuring error, the variance of measured readings can be expressed as

$$s^2_{\text{R}_{\text{Sawn}}} = s^2_{\text{D}_{\text{Sawn}}} + s^2_{\text{ER}_{\text{Device}}} \tag{5.9}$$

where $s^2_{\text{R}_{\text{Sawn}}}$ is the variance of measured readings,

$s^2_{\text{D}_{\text{Sawn}}}$ is the true process variance (the true variance of a sawn piece), and

$s^2_{\text{ER}_{\text{Device}}}$ is the variance of measuring errors.

Measuring error is normally distributed, and thus in sawmill applications, the lower half of a two-sided confidence interval $2s_{\text{ERDevice}}$ is a valid representation of the range of measuring error. An estimate of the effect of measuring error on device capability is obtained by using the precision-to-tolerance ratio (Mitra, 1998, p. 390), which is calculated using the measured total standard deviation of a saw machine. Thus, the ratio can be expressed as

$$C_{\text{r}} = \frac{s_{\text{ER}_{\text{Device}}}}{s_{\text{Measured}}} \tag{5.10}$$

where C_{r} is the precision-to-tolerance ratio,

$s_{\text{ER}_{\text{Device}}}$ is the standard deviation of measurement errors, and

s_{Measured} is the measured standard deviation of a saw machine.

The precision-to-tolerance ratio represents the percentage of standard deviation used by the measuring error. The tested measuring devices' capability in hitting a target size is better than 0.05mm. Typical standard deviation of a saw machine is 0.5mm. Thus, the ratio is 0.10 and consequently the measuring device error uses ten percent of the size control process capability, its tolerance limits. It is generally preferable that the percentage be less than or equal to ten percent (Mitra, 1998, p. 392). In saw machines with larger standard deviation, the precision-to-tolerance ratio is better, and in saw machines with smaller sawing variation, the precision-to-tolerance ratio is larger. However, in better saw machines, the greater precision-to-tolerance ratio has less significance because the machine operation in general is under better control.

5.9 Discussion

Sawmill personnel have an intuitive tendency to consider manual measurement an absolutely accurate and precise control method, independent of the frequency and manner of measurement. Similarly, they consider optical measuring imprecise because size estimation by eye is inaccurate. None of these conceptions is entirely correct or incorrect. The main feature of manual measurement is that it is a straightforward and commonly used control method. However, when it is properly used, it is a time consuming off-line inspection method.

Optical measuring techniques that did not exist ten years ago are available today. Both hardware and software have developed to such an extent that real-time measuring systems are feasible. Previously machine vision applications were developed principally for timber grading in trimming and sorting. New approaches are also tested in the size control of boards exiting saw machines. The use of CCD line-scan cameras is a technology that is tried in size control at breakdown saw machines. The advantages of this technology are its cost effectiveness and compactness. The complications of the technique stem from the pieces that are to be measured. Besides the difficult measuring environment, the pieces manifest all the variations that nature and the sawing process can provide. However, with efficient algorithms, powerful computing, and use of the Central Limit Theorem, discussed in Chapter 6.1, most of the measuring tasks can be performed. Only in cases where the camera view is physically obstructed or rendered useless by sawdust lumps, boards pressed tightly together, or collapsing, can measuring not be performed. There are a number of optical measuring devices that may be used in size control in log breakdown, cant, and square cant resaw.

The accuracy of the optical measuring devices examined is acceptable. Generally, the accuracy of the recorded sizes is within 0.05mm or better. Precision is reasonable. The average variation of readings around a target size is 0.15mm. The variation of 0.15mm means that the 2s standard deviation is 0.3mm, which is the pixel resolution of the optical device. However, because only trimmed segment means that satisfy the Central Limit Theorem requirement are used in sawmill analysis, the accuracy of the measuring device is at the same time the precision of the data used in analysis. Thus, the precision of used data is 0.05mm.

The correlation between the means in manual and optical techniques in sawmill tests is strong, 0.98, as is the correlation of the within-board standard deviations, 0.92. Furthermore, the 95% confidence intervals of the pieces tested include zero values. Thus, manual and optical techniques produce equal board size results.

The accuracy and reliability of the optical measuring device is adequate for calculating saw machine descriptors and for drawing conclusions on saw machine behaviour.

6 Statistics and Descriptors

On-line process control involves the collection of information from the process while it is functional. When the output differs from a determined norm, corrective action is taken in that operational phase. It is preferable to take corrective action on a real-time basis in the case of quality control problems. This approach attempts to bring the system to an acceptable state as quickly as possible, thus minimising the number of unacceptable items produced. In sawing processes, an off-line control by inspection is inadequate because sawing variation of timber is inevitable.

Statistical process control uses statistics, the science of collecting, analysing, and interpreting data, to achieve and maintain control of processes and production variation within the manufacturing process (Young and Winistorfer, 1999, p. 11). Before analysis of a process, one must verify that a saw machine is stable. This step concerns establishing control of a process. The verification is accomplished by a preliminary control measurement of a saw machine. If the measurement shows erratic behaviour, for example excessive standard deviation, sudden changes in mean or heavy taper, the cause must be identified and corrected. When the mean size of sawn pieces is consistent, and the total standard deviation reasonable, the saw machine is under control and collection of process data can begin. After process data collection, the data is used to produce sample descriptors. The descriptors are used to draw conclusions on the sawn samples and the saw machine. In this study, the process control is established during normal production tests, and the saw machines are examined both in normal production and in benchmarking tests, as presented in Chapter 1.3.

An example of near-on-line statistical process control is when readings of timber size are taken in production process and these data are charted to determine if the sizes fall within control limits. If the data indicate problems, the process can be adjusted to eliminate the unacceptable variation. A size control statistics programme allows one not only to evaluate how well the machines operate on a particular day, but also provides data to allow comparisons with past performance figures and with industry standards. However, perhaps the most important benefit derived from the size control programme is the ability to decrease target sizes once sawing variation is stabilised (Eagan, 1982, p. 104). Sawmill variables can be divided into the following categories, as in Figure 6.1 (Körner and Wahlgren, 1998, p.15).

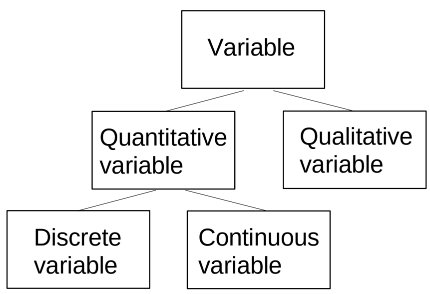


Figure 6.1. *Definition of variables.*

Non-numerical, qualitative variables refer to quality grading, i.e. boards belonging to discreet quality grade classes. These qualitative variables have one or more subjective values, typically assessed by humans, such as the number, type, and location of knots, pitch pockets, stain, wane and other visual marks, and sales value that lead to a quality grade. The numerical, quantitative variables include discrete physical variables that can be counted, such as a non-arguable number of knots in a board, and continuous variables that one measures, such as timber size.

Application of off-line statistical process control was introduced into sawmill timber inspection over thirty years ago. The understanding of statistics, and in the processing power of computers have increased significantly during the last twenty years, bringing various new inspection and analysis products to the market. Only the method of obtaining data from a breakdown process has remained the same – it is still manual. According to Young and Winistorfer (1999, p. 16), the most advanced method of taking thickness readings is a digital caliper.

Optical control devices produce size data of practically every board exiting from a saw. Thus, a sample population approaches infinity, and frequency distribution approaches true normal distribution. Knowledge of correct distribution function describers will make analysis of saw machines easier. Size variations seen on boards leaving a saw machine are the result of variations in raw material, sawblade, saw setworks, and feedworks features and behaviour. True within-board, within-segment, between-board, between-segment and grand total values, and other board data can be used to isolate causes of variation so that saw machines can be controlled more effectively. Continuous on-line measurement offers improved opportunities to achieve the correct green size, to adjust saw servo controls, feed and saw speeds, and to perform timely sawblade changes.

6.1 Normal Distribution

When one takes a large number of readings of board thickness, these readings will tend to group around a central value with a certain amount of variation or ‘scatter’ on either side. The pattern or shape formed by the grouped readings is called a ‘population’ or ‘frequency distribution’. If the causes that produce the measurement data remain essentially unchanged, the distribution tends to have certain distinguishable and stable characteristics. The measured distribution tends to approach, as a statistical limit, a distribution that is normal to all natural processes. Normal distribution is a basic distribution of statistics. It was first described in 1733 by De Moivre as being the limiting form of the binomial density as the number of trials becomes infinite. The theorem was further elaborated by Laplace and Gauss in the early nineteenth century into a theorem, known as the Central Limit Theorem. The theorem can be used to normalise distributions of random variables that may not be normally distributed. The theorem indicates that a mean of values of n observations approaches normal distribution, irrespective of the form of the original distribution under quite general conditions when n approaches infinity (Mitra, 1998, p. 173, and Grant and Leavenworth, 1996, p. 201). Devore (2000, p. 236) proposes as a rule of thumb that if n is larger than 30, the Central Limit Theorem can be used. Koskela (1999, p. 16), on the other hand, suggests that in sawmilling, each mean can be calculated using a minimum of four readings. In practice, this means that even if the individual values are not normally distributed, the distribution of means will tend to have a normal distribution, and the larger the sample size, the greater will this tendency be. The Central Limit Theorem principle is used in this study to calculate statistical describers for saw machine analysis. In this study, the analysis is based on 200 to 750 readings which are used to calculate the ten segment means for each board. Thus, the requirement for the Central Limit Theorem is satisfied and the means can be considered normally distributed.

Milton and Arnold (1995, p. 100) define a continuous random variable as: "continuous if it can assume any value in some interval or intervals of real numbers and the possibility that it assumes any specific number is zero". Sizes produced in sawing along a board satisfy this essential condition. Therefore, the basic assumption is that the variable, size of a sawn board, has a Gaussian standard normal distribution with a probability function (density) of

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad -\infty < x < \infty \tag{6.1}$$

where $f(x)$ is a probability function,
$1/\sqrt{2\pi}$ is a scale factor required to make the total area 1,
μ is an arithmetic mean of a population,
σ is the standard deviation of a population, and
e is the base number of natural logarithm.

The factor in brackets of the power of e in Equation 6.1 is the standardised normal random variable, defined as

$$Z = \frac{\overline{X} - \mu}{\sigma} \tag{6.2}$$

where Z is the standardised normal random variable,
$\overline{X}$ is the sample mean,
μ is the population mean, and
σ is the standard deviation.

The graphic representation of a probability function is a symmetric, bell-shaped curve with a total area of 1, centred around μ. In a normal distribution, the standard deviation indicates the probability in percentage of the quantity of timber sizes that fall within the limits of deviation. Table 6.1 presents some of the percentages of a population within an interval of $\mu \pm$ a number of standard deviations in a normal population.

Table 6.1. *Percentages of a population inside an interval.*

Interval	% inside the interval
$\mu \pm \sigma$	68.26
$\mu \pm 1.65\sigma$	90.30
$\mu \pm 2\sigma$	95.44
$\mu \pm 3\sigma$	99.74
$\mu \pm 6\sigma$	99.99

With a normally distributed estimate, the entire shape of a frequency distribution is known, provided that the mean and the standard deviations are known. In statistics, $\overline{X}$ denotes a mean of a measured sample and μ denotes a mean of the entire population.

While s denotes the standard deviation of a sample and σ the standard deviation for the entire population. Values $\overline{X}$ and s are estimates of μ and σ. Because this study deals chiefly with values from one or more samples rather than from the entire population, definitions of $\overline{X}$ and s are used to describe the distribution parameters. The standard deviation ±2s value is important to sawmills, because 95% of the produced timber sizes reside within the ±2s limits, as in Figure 6.2.

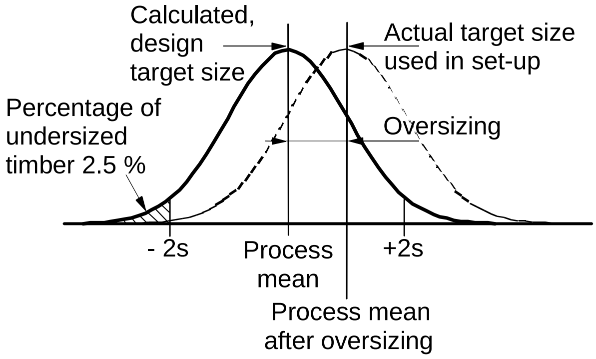


Figure 6.2. *Calculated, planned target size and an oversized, produced target size.*

6.2 Normalcy and Independence

Formal statistical methods require certain assumptions, the most common of which are:

- Normalcy of a distribution
- Equivalence of variances
- Constancy of system causes.

A saw machine leaves its marks on produced boards as discreet dimensional changes along the pieces. The size variations are recorded and used in solving causes of undesired saw machine behaviour. An analysis requires that two successively sawn logs are independent in statistical meaning. In a log population, all variables are random, and logs are independent by nature. In a sawmill, they are sawn with the same machinery that repeats a sawing process as closely as possible from log to log. Because the population of readings from log A and log B are independent in an intuitive sense, then A and B can be considered independent events. For reasonably large amounts of data, the size means can be treated as having come from a normal population. Because variance in a saw machine is caused consistently by the same elements of machinery, one can consider the variances equivalent. For constancy, there is no convenient way of assessment. In classical analysis, one assumes that the cause systems do not change provided that conditions are maintained constant while collecting data. Thus, board sizes fulfil the requirements of normalcy, equivalence, and constancy set for a statistical analysis.

6.3 Sample size

The size of a sample has a direct impact on the reliability of the information provided by the data. The larger the sample size, the more valuable the data (Mitra, 1998, p. 191). The assumption of independence is important when measuring samples. The manual readings are taken by one individual at a time using his/her personal method of measuring, as in Appendix B. Thus, the data may be biased, particularly if the number of readings is small. Because wood is an elastic material with some harder spots, and a sawing process produces uneven, rough surfaces, the number of boards and the readings per board should be higher than is the current practice.

The minimum sample size, according to Milton and Arnold (1995, p. 295), to be used when estimating process mean, when conditions are kept constant, is defined as

$$n_{\min} = \frac{Z_{\alpha/2}^{2}\, s^{2}}{d^{2}} \qquad s \text{ known or estimated} \qquad (6.3)$$

where $n_{\min}$ is the minimum sample size,
$Z_{\alpha/2}$ is half of the area that remains outside a probability area,
s is the standard deviation, and
d is the targeted accuracy of a sawing process.

This equation is adequate unless $n_{\min}/n$ is appreciable (Cochran, 1962, p. 76). Because the sawn populations size n is usually calculated in hundreds or even thousands, $n_{\min}/n$ approaches zero, and the sample size estimates from Equation 6.3 are valid.

Unfortunately, the choice of sample size is not straightforward, because it depends both on the desired accuracy and precision of the process and its total standard deviation. Therefore, an estimate must be made concerning these values. Figure 6.3 illustrates this case. If a sawing process must be 0.1mm accurate within a 95% confidence interval and its estimated standard deviation is 0.4mm, the sample size must be 64. The board sample size proposed by Warren (1973) is also dependent on the within-board and between-board standard deviations, as in Figure 3.3. The sample size is not merely five, as proposed by Williston (1985, p. 298). When s and d are equal, the Equation 6.3 always gives a result that is the second power of Z. Thus, the resulting number of samples is four or nine, depending on the Z criteria used for the lower limit. In practice, this means that if the accuracy requirement for a saw with 0.5mm standard deviation is 0.5mm, then the sample size of four within a 95% confidence interval is sufficient. This kind of thinking is the probable cause of current practice as regards sample size.

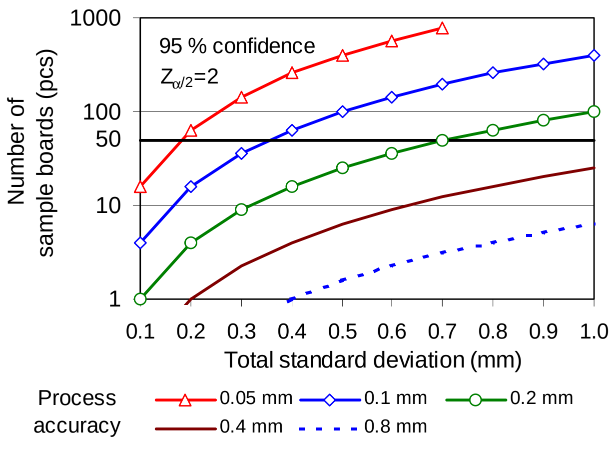


Figure 6.3. *Number of samples required to determine process accuracy when process precision varies.*

When the requirement for process accuracy is low, a limited number of boards in a sample are required. The minimum sample size, with a confidence interval of 2s for a sawmill using a bandsaw with a one-standard-deviation of 0.76mm (Steele et al., 1996, p. 57), and a sawing accuracy requirement of 0.5mm, is 9. However, if an accuracy of 0.2mm is required, the sample size is 58 boards. Furthermore, even with the lower accuracy requirement, one must remember that when a changing saw set-up is used, the minimum sample size remains 9 for each new saw set-up, assuming that the standard deviation remains constant. In practice, this would mean that every board should be controlled.

The correctness of the one-standard-deviation is significant for a sample size because it affects the sample size in the second power. According to Oakland (1999, p. 123), a sample size should be at least two to give an estimate of residual variance, but a minimum sample size of four is preferred. Sample sizes of four or five are quite common in industry (Mitra, 1998, p. 264). However, due to the large unisotrophy of wood, the above assumptions are not relevant in sawmill industry. Due to the inherent variation of raw material, the sample sizes should be large. Koskela (1999, p. 120) demonstrates, in his study of sampling technology in the mechanical wood industry, that the accuracy of testing improves up to a sample size of 200 when analysing logs. Koskela states that an optimal sample size is in the order of 30 to 50. The size is independent of the factors tested. Warren (1973, p. 10) concludes that a sample size of fifty boards seems to be a reasonable practical minimum for estimating standard deviation of a sawing process.

In optical measuring, a large number, several hundred, of readings are taken, which are used to calculate the means for ten equally divided lengthways segments along each board. Thus, there are ten trimmed means for each board in a sample, and the total number of means used in the standard deviation calculation for a sample is 500. The conclusions of both Koskela and Warren indicate that a board sample size of fifty is adequate for determining standard deviation in sawmilling. This is the board sample size, which is selected for this study.

There are no general rules for the frequency of taking samples. Generally samples are taken relatively often at the beginning of a process capability assessment and process inspection. When process control has been confirmed, the frequency of sampling may be reduced. In sawmilling, this has meant that sampling is being carried out after each change of a saw set-up or sawblades, and at somewhat irregular intervals during sawing. However, the properties of a saw machine change and deteriorate during sawing because of log size variation, sawblade wear, changes in feed speed, and other sawing parameters. Thus, control of a process, its accuracy and precision, is required not only at start-up, but constantly during production.

When a fixed saw set-up is used, it can be claimed that the population size is the number of logs sawn in the set-up. When saw set-up is changed for almost every log, the population size is of the same order as the minimum sample size because, in a changing set-up, sawing conditions are not maintained constant, and the regular calculation of minimum sample size is not valid. In such cases, boards from all logs should be measured in order to maintain both process accuracy and precision.

6.4 Cutting Path Length

The cutting path length and the number of teeth processing wood have an effect on saw load and thus on sawing variation. The number of teeth, their material, shape, and filing characteristics are variables that can be used to alter the sawing parameters. Therefore, it is important to know the true cutting path length.

The height of a piece is equal with the cutting path length in a bandsaw because the cutting line is straight and perpendicular to a log. The case is more complicated with circular saws because the sawing path inside wood is a curved line, a line that is longer than the sawn height. In single-arbor circular saws, the curvature depends on sawn cant size, sawblade diameter and chain level distance from the sawblade centre, as in Figure 6.4. The smaller the sawblade diameter, the more curved the sawing path.

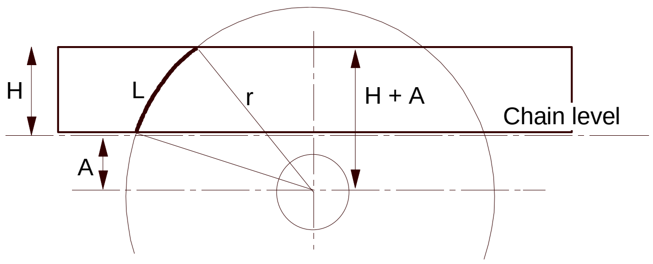


Figure 6.4. *Determination of cutting path length L in a single-arbor circular saw.*

$$L = r*\left(\arcsin\left(\frac{H+A}{r}\right) - \arcsin\left(\frac{A}{r}\right)\right) \qquad (6.4)$$

where L is the cutting path length,
r is the sawblade radius,
A is the chain level distance from saw axis, and
H is the log or cant height.

In a double-arbor circular saw, the cutting path length determination differs from a single-arbor saw because the sawblade top cuts inside wood, as in Figure 6.5.

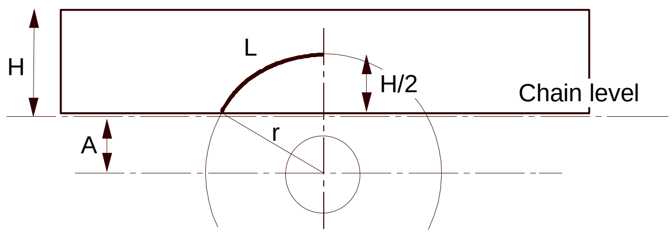


Figure 6.5. *Determination of cutting path length L in a double-arbor circular saw.*

$$L = r * \arccos\left(\frac{A}{r}\right) \qquad (6.5)$$

where L is the cutting path length,
r is the sawblade radius, and
A is the chain level distance from saw axis.

The benefit of using the cutting path length in descriptor equations, as in Equations 6.21 to 6.24, is that the path length is also an indicator of wood removal and the number of teeth that are cutting at a particular time, and reference can be made to various teeth characteristics, when required.

Sawn logs and cants are not uniform, and thus cutting path lengths differ slightly from log to log. Saw mechanism will also cause sawing variations, both short and long term. Therefore, cutting path calculation is an approximation. However, the large log quantities in samples will average differences out, and the error in path length will have no particular significance.

6.5 Segment Symbols

In order to make the presentation of segment data clearer, the sawn pieces are portrayed as thick lines, on which the individual segment size values are illustrated as circles. Presentation of one set of measured boards is seen in Figure 6.6, where the boards are successive boards from the same sawing position, from between the same two sawblades. For the purpose of visual presentation, these boards are placed parallel to each other. The first sawn board, selected for analysis, is referred to as number 1, the second as number 2 and the 50th board as number 50. The within-board and between-board standard deviations for the boards are calculated in the sawing direction.

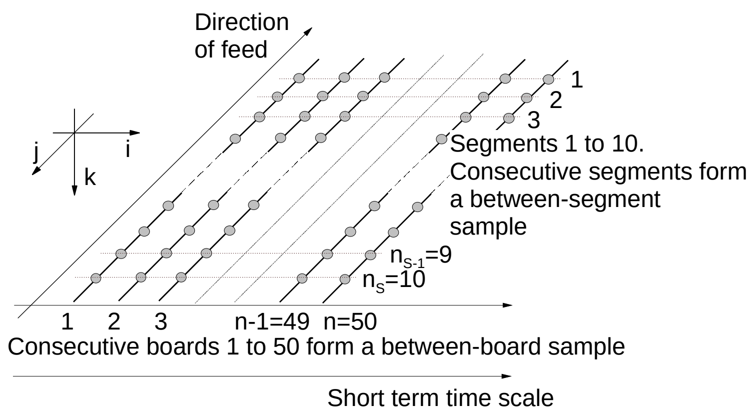


Figure 6.6. *Example of sawn and measured consecutive fifty boards divided into ten segments.*

Segments are numbered from their top-end, segment 1, to the butt-end, segment 10. Individual board segments that belong to the j^{th} segment will be treated as if they form a true board, as in Figure 6.6. The within-segment and between-segment standard deviations are calculated perpendicular to the sawing direction. For example, a between-segment standard deviation is equivalent to a between-board standard deviation.

Short and long term changes inevitably take place in sawing processes. Therefore, one must be able to analyse these variations. For this purpose, sets of samples may be taken under detailed scrutiny from time to time. The period can be minutes, hours, days, months, or seasons, however long is deemed necessary. These periodic tests are illustrated in Figure 6.7. The sets are successive sets using identical log size, cutting pattern and feed speeds. For example, day 1 is the first sample, k=1, and day 2 the second sample, k=2, up to any number of sets and periods to be analysed.

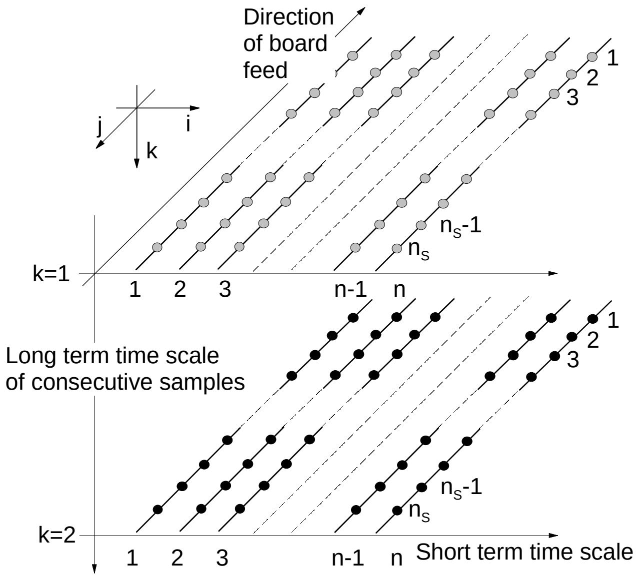


Figure 6.7. *Presentation of consecutive periodic sets of measurement.*

6.6 Definition of Describers

Main features of data collection in this study are:

- Sample size is fifty pieces
- Number of segments along each piece is ten
- Trimming percentage of ten is used in calculating of the segment means
- Top- and butt-end data filter percentage is one.

Trimmed means of individual segments are used in all descriptor calculations as if the trimmed means were the only recorded optical readings. Thus, the segment means have an inherent normal distribution based on the Central Limit Theorem. A trimmed mean in each segment is calculated using Equation 6.7. The trimmed means are then used to calculate all other descriptors presented in this study.

6.6.1 Mean

In the sawmill industry, the essential parameter of statistical size control is the mean. A mean value $\overline{X}$ indicates where a process is centred. If value $\overline{X}$ is natural, the centre of a process should not shift. If $\overline{X}$ shows a trend, the centre of a process moves gradually up or down. If $\overline{X}$ moves erratically and out of control, something is changing the centre of a process rapidly and inconsistently.

The process mean of sawing is affected by:

- characteristics of logs being sawn
- cutting parameters
- saw setworks operation
- feedworks operation
- some other process adjustment (maintenance, change of components etc.)
- change of technique used.

Within each segment a number of readings are taken and a mean is calculated. A mean of readings for a group of individual readings in a segment is

$$\overline{X} = \frac{1}{n}\sum x_i \tag{6.6}$$

where $\overline{X}$ is the mean of one individual segment,
x_i is the ith individual data reading in a segment, and
n is the number of data readings in a segment.

Because the measuring environment in sawmills is not perfect, the mean must be as robust an estimator as possible. This is done by trimming the means by calculating a mean of the readings that remain after a proportion of the high and low values have been deleted (Mitra, 1993, p. 149). A trimmed mean T(α) is the mean of the readings that remain after trimming, or deleting, α% of the high readings and α% of the low readings. According to Mitra, this is a suitable measure when the existing outliers do not represent unusual process characteristics. In adverse process conditions, trimming of extreme readings caused by faults in a measuring process will provide a more accurate estimate of a population's central tendency. Such readings can be caused for example by hard knots, sawdust, or slivers covering a kerf, air borne particles in the line of sight of an optical system, or extreme shaking. In this study, the trim percentage used is 10%, as discussed in Appendix C. Trimming of data is performed intuitively similarly in manual measurement, when measurement locations are chosen, and the caliper is manipulated into a better position during measurement. The wild values, or 'circus giants' as they are sometimes called, are discarded as a means of avoiding problems in manually recorded values (Williston, 1985, p. 305).

A 10% trim is accomplished by calculating the total number of data points in a segment. Then a numerical value for the 10% is calculated and rounded down to next integer. An equal number of maximum and minimum readings are deleted from the data point values. After trimming, a mean $T(0.1)$ is calculated using equation

$$T(0.1) = \frac{1}{n}\sum x_i \tag{6.7}$$

where $T(0.1)$ is the trimmed mean for a segment,
x_i is the ith individual data reading after trimming, and
n is the number of readings after trimming in a segment.

This study refers to the $T(0.1)$ values simply as trimmed means T. A trimmed mean for each segment is the basic data value for calculations, analyses, and deductions in this study.

The within-board and within-segment means are calculated with trimmed segment means as

$$\overline{X}_W = \frac{1}{n_S} \sum T_j \qquad (6.8)$$

$$\overline{X}_m = \frac{1}{n} \sum T_i \qquad (6.9)$$

where $\overline{X}_{\mathrm{W}}$ is the within-board mean,
$\overline{X}_{\mathrm{m}}$ is the within-segment mean,
T_j is the jth segment mean on a board,
T_i is the ith board mean in subsequent segments,
n_{S} is the number of segments on a board, and
n is the number of boards in a sample.

The use of an equal number of individual readings, relative to the board length, in each segment, and an equal number of segments on each board, prevents the necessity to use the number of individual readings at each segment or board in the calculations. This reduces the calculation of between-board and between-segment mean into a calculation of mean of means. Because a trimmed mean at each segment is identical for the both data sets, the means are also identical.

$$\overline{X}_B = \frac{1}{n} \sum \overline{X}_{Wi} = \frac{1}{n_S} \sum \overline{X}_{mj} = \overline{X}_M \qquad (6.10)$$

where $\overline{X}_{\mathrm{B}}$ is the between-board mean,
$\overline{X}_{\mathrm{M}}$ is the between-segment mean,
$\overline{X}_{\mathrm{W}i}$ is a within-board mean of board i,
$\overline{X}_{\mathrm{m}j}$ is a within-segment mean of segment j,
n is the number of boards, and
n_{S} is the number of segments.

The mean of a sample population, which is also $\overline{X}_{\mathrm{B}}$ and $\overline{X}_{\mathrm{M}}$, is calculated using all trimmed mean values in the sample

$$\overline{X} = \frac{1}{n} \sum T_i \qquad (6.11)$$

where $\overline{X}$ is the sample mean,
T_i is the ith trimmed mean in a sample, and
n is the number of trimmed means in a sample.

6.6.2 Range

Range is the difference between the largest and smallest reading in a sample of n readings. Range is a good first approximation of a system ‘scatter’, standard deviation, and it is simple to calculate. Range shows process uniformity and consistency. Range is not used in this study because it does not convey new information compared with the extensive standard deviation data processing in a saw machine analysis.

6.6.3 Within-board and Within-segment Standard Deviation

Although means are probably the most important single statistic used in statistical process control, it is additionally important to know how spread out or varied the readings are.

In readings, there are always positive and negative values that deviate from a mean. Thus, a mean deviation would almost always be zero. One may avoid this by using absolute values, but this is not very common. Another method is to square each deviation in order to get a mean square deviation. Mean square deviation is a good measure of spread, if a sawmill only needs to describe one batch of timber. However, sawmills normally want to go further, and make a statistical inference about an underlying timber population. For this purpose, sample variance is preferable.

If only one reading (n = 1) were available, the single measurement would be the sample mean and would give some idea of the thickness of a produced batch. Since there is no spread in the sample, there would be no indication of the underlying timber population standard deviation. Only when n exceeds size 1 does one get information about standard deviation. Thus, there are essentially only (n – 1) pieces of information available for standard deviation. Therefore, the divisor for variance is (n – 1).

Variance for a single board or segment is

$$s^2 = \frac{1}{n-1} \Sigma \left(T_i - \overline{X}\right)^2 \tag{6.12}$$

where s^2 is the variance of a single board or segment,
T_i is the ith trimmed segment mean,
$\overline{X}$ is the within-board or within-segment mean, and
n is the number of segments in a board or boards in a segment.

When calculating a standard deviation, one must take the square root of the variation in order to compensate for having squared the deviations. This will give a standard method for measuring a deviation from a mean – thus it is called the standard deviation. Standard deviation is a typical deviation lying somewhere between the smallest and largest deviation.

The within-board standard deviation for one single board is

$$s_W = \sqrt{\frac{1}{n_s - 1} \sum \left(T_j - \overline{X}_W\right)^2} \tag{6.13}$$

where s_W is the within-board standard deviation,
$\overline{X}_W$ is the single board mean,
T_j is the jth segment mean, and
n_s is the number of segments.

In this study the within-board standard deviation is a calculated separately for each individual board. The within-board standard deviation for a sample of boards is calculated as an average value of the individual values.

The equation that is used for s_W, Equation 6.13, can be used to calculate a standard deviation for a single segment. In this case, the segment rows replace the boards, and calculation for within-segment values can be presented as

$$s_m = \sqrt{\frac{1}{n-1}\sum\left(T_i - \overline{X}_m\right)^2} \qquad (6.14)$$

where s_m is the within-segment standard deviation,
$\overline{X}_m$ is the within-segment mean,
T_i is the ith segment mean, and
n is the number of boards.

The standard deviation of a single segment s_m is a descriptor of sawing process consistency in different, lengthways areas of a log. If s_m is 'tight', the sawing follows the same pattern of cutting at the same place on each log from log to log. If s_m is 'wide', cutting is irregular and varies from log to log.

6.6.4 Between-board and Between-segment Standard Deviation

Between-board standard deviation is defined as the deviation of the mean thickness of each board from the between-board mean. Standard deviation for a group of boards (between-board) is

$$s_B = \sqrt{\frac{1}{n-1}\sum\left(\overline{X}_{Wi} - \overline{X}_B\right)^2} \qquad (6.15)$$

where s_B is the between-board standard deviation,
$\overline{X}_{Wi}$ is the ith within-board mean,
$\overline{X}_B$ is the between-board mean, and
n is the number of within-board means.

The standard deviation for a group of segments (between-segment) is expressed in a similar manner as

$$s_M = \sqrt{\frac{1}{n-1}\sum\left(\overline{X}_{mj} - \overline{X}_M\right)^2} \qquad (6.16)$$

where s_M is the between-segment standard deviation,
$\overline{X}_{mj}$ is the jth within-segment mean,
$\overline{X}_M$ is the between-segment mean, and
n is the number of within-segment means.

Standard deviations of s_B and s_M are used to evaluate sets of samples and compare them with other samples taken at different times.

6.6.5 Total Standard Deviation

The standard deviation of a sum of any number of independent variables is the square root of the sum of the squares of the standard deviations of the independent variables (Grant and Leavenworth, 1996, p. 342)

$$s_{sum} = \sqrt{s_1{}^2 + s_2{}^2 + s_3{}^2 + ... + s_i{}^2} \tag{6.17}$$

where s_{sum} is the standard deviation of the sum of any number of independent variables,
s_i is a standard deviation of *i*th independent variable.

This theorem further states that if the total standard deviation s_{sum} is known, and all but one of the independent standard deviations s_i are known, the unknown standard deviation can be calculated as

$$s_x = \sqrt{s_{sum}^2 \text{-} \ s_1{}^2 + s_2{}^2 + s_3{}^2 + ... + s_i{}^2} \tag{6.18}$$

where s_{x} is an unknown standard deviation,
s_{sum} is the standard deviation of the sum of any number of independent variables,
s_i is the standard deviation of *i*th independent known variable.

Equation 6.19 is frequently used to describe the total standard deviation of a saw machine when using the traditional within-board values. It is defined as

$$s_{TWW} = \sqrt{s_{WW}{}^2 + s_B{}^2} \tag{6.19}$$

where s_{TWW} is the total standard-deviation of a saw centre,
s_{WW} is the within-board standard deviation (Brown, 1982, p. 132), and
s_{B} is the between-board standard deviation.

Computing power has simplified the determination of the total standard deviation of a saw machine into a calculation using all data in a sample

$$s_T = \sqrt{\frac{n_{ij} \sum T_{ij}^2 - \left(\sum T_{ij}\right)^2}{n_{ij}(n_{ij} - 1)}} \tag{6.20}$$

where s_{T} is the total standard deviation of a saw machine,
T_{ij} is the *ij*th individual trimmed segment mean, and
n_{ij} is the number of all trimmed means in a sample.

Total standard deviation s_{T} is a good measure of the behaviour of a saw machine at one point of time. However, it will change even during one shift when sawblades get dull or set-up is changed.

6.6.6 Time*Saw Load Factor

The stresses that cause sawing variation in a saw machine depend on multiple factors, the most significant of which is the volume of removed wood in a cut (Kivimaa et al., 1964). The volume of removed wood by a tooth depends on kerf width, saw speed, feed speed, and on the cutting path length, the path that a tooth cuts inside wood. When the saw speed is kept constant, the power requirement of a sawblade can be expressed as

$$P = n * k * F * L * Ps \qquad (6.21)$$

where P is the required cutting power (W),
n is the number of teeth cutting at the same time,
k is the kerf width (m),
F is the feed speed (m/s),
L is the cutting path length (m), and
Ps is the specific cutting work (J/m^3) that depends on the sawn species and kerf size.

The geometry and number of the sawblade teeth, side clearance, blade stiffness, and the gullet feed index, have also an effect on the power requirement in a saw, and the sawing variation. In order to reduce the number of variables in determining the saw load, the participating sawmills used sawblades with similar parameters throughout the study. If sawblade parameters, saw speed or species are changed, the test conditions will be new. Dynamic instability of a saw machine system does not necessarily increase power consumption, but will cause uncontrolled vibrations and increase in sawing variation.

The total power requirement for a set of sawblades in a set-up is

$$P_{Total} = n * P \qquad (6.22)$$

where P_{Total} is the total cutting power (W),
n is the number of sawblades in a set-up, and
P is the cutting power requirement of one sawblade (W).

The total stress under which a saw machine operates thus depends on the characteristics and number of the cutting sawblades on an arbor or in a saw, and on saw and feed speeds. In this study the species and sawblade characteristics, such as the tip width, the shape and number of teeth and filing details, and saw speed are maintained constant in each saw machine. Thus, the stress in a saw machine depends on feed speed, cutting path length, and sawblade wear variables. The sawblade wear is expressed as the usage time of a blade. These three factors are studied in benchmarking tests. In normal production, sawblade wear is not a reliable variable, and only feed speed and cutting path length are used. When tests are made using different sawblade characteristics, such as kerfs, saw speeds or species, the results can be compared, for example, by graph charts.

The effects of various saw load factors on sawing variation have been examined by Juvonen (1974), Birkeland (1967) and Thunell (1966). Among other effects, their results show a clear tendency of growing sawing variation when the feed speed and log size increase, such as in Figures 6.12 and 6.13 of this study.

The increase in sawing variation is time dependent as in many other physical phenomena, such as cooling and decay. In sawmills the deterioration of performance is characterised by sawing variation that increases as operation hours are accumulated. Juvonen (1974, p. 63) has noted that in frame saws the sawing time has the largest effect on sawing variation. The situation is comparable with Weibull's time dependent exponential distribution for a failure due to wear and tear. As time goes by a failure is more likely to occur because of wear and tear. The Weibull failure density $f_f(t)$ is defined as (Milton and Arnold, 1995, p. 130)

$$f_f(t) = \rho_f(t)R_f(t) = abt^{b-1}e^{-at^b} \tag{6.23}$$

where f_f is the failure density,
ρ_f is the hazard rate function,
R_f is the reliability function,
t is time, and
a and b are Weibull random variable parameters.

The Weibull parameters *a* and *b* are determined by experience. *a* is a time scale parameter (*a* > 0), and *b* is a shape parameter (*b* > 0). Figure 6.8 illustrates some failure probability situations (Mitra, 1998, p. 518).

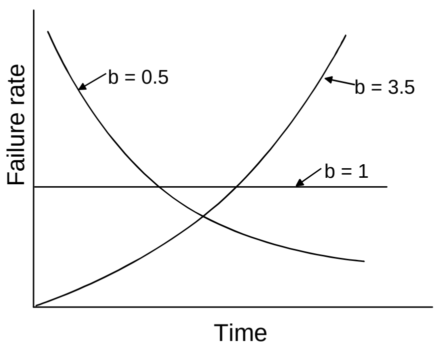


Figure 6.8. *Failure probability based on different Weibull shape parameters b.*

As there are multiple factors affecting the standard deviation of a saw machine, its evolution will most likely resemble Weibull distributions when the shape parameter *b* is equal or larger than 1. Because the standard deviation of a saw machine is not zero even at the start of sawing, an equation, either linear, exponential or some other type must be used to describe the start-up standard deviation and other descriptors, and their further evolution.

The observational data in Chapters 7 and 8 indicate that a linear regression line and an exponential curve have in most cases equal fit with the data. The coefficient of determination r^2 (Devore, 2000, p. 506), which indicates how much the use of a regression line improves the predictability of a descriptor compared to a simple linear regression model, vary for both models from 0 to 0.63. For single-arbor circular saws the r^2 values vary between 0.24 and 0.40, for double-arbor circular saws the values are almost zero, because the regression curves are nearly horizontal lines, and for bandsaws the r^2 values vary between zero and 0.63. The theory assumes that one can control independent variables, however, in sawmilling the variables are often correlated, and the affecting variables are subject to a certain amount of experimental variation, too.

Therefore the regression curves' coefficient of determination is not necessarily a reliable indicator of good or poor fit, as is discussed in Chapters 7.5 and 8.6. In this study the reproducibility value R, Chapter 6.6.7, is used to express the fit of the observed data with the chosen equation, Equation 6.24. The reproducibility represents the dispersion of the observed data around the equation directly in millimetres.

The current, conservative sawmill production and sawblade change practises, seem to lead to a situation where the time dependent sawblade wear usually does not have much time to have an effect on the sawing variation. In spite of this, an exponential function is selected to present the behaviour of a saw machine under the influence of various sawing times, feed speeds, and log sizes, because it works with the observational data. Another reason to use an exponential presentation for the descriptors is that a linear regression line may intercept the descriptor value axis at unrealistically low values. The linear model would also have a mathematical formula containing the intercept value as a plain number, which may easily be confused, with the reproducibility value. Finally the purpose of this study is to develop a method which can be used to test new sawblade shapes, thinner kerfs, variable saw speeds and other variables of interest. In these experimental conditions the time dependent wear and instability factors may be more pronounced. The descriptor function is written as

$$y = \alpha e^{\beta tnkFL} \pm R \tag{6.24}$$

where y is a saw machine descriptor, such as standard deviation or sawblade bend (mm),
- α is the inherent descriptor constant when both sawing time and load are zero,
- β is the saw time-wear effect constant,
- e is the base number of natural logarithm,
- t is the sawing time (h),
- n is the number of cutting sawblades in a set-up,
- k is the kerf size (m),
- F is the feed speed (m/min),
- L is the cutting path length (m), and
- R is the reproducibility, Equation 6.26, the standard deviation of the descriptor (mm).

The determination of constants *α* and *β* in Equation 6.24 requires accurate knowledge of sawing time and behaviour of the examined saw machine descriptor under controlled production situation. A benchmarking test provides such conditions. When the constants *α* and *β* are known, it is possible to describe the general characteristics and behaviour of a saw machine. The constant α shows the minimum level of a saw descriptor possible, and the constant *β* descriptor dependence on sawblade wear and load.

Equation 6.24 can also be used to determine sawblade change time

$$t = \frac{1}{\beta nkFL} \ln\left(\frac{y}{\alpha}\right) \tag{6.25}$$

where t is the sawing time (h),

y is a saw machine descriptor (mm),
α is the inherent descriptor constant when both sawing time and load are zero,
β is the time-wear effect constant,
n is the number of cutting sawblades in a set-up,
k is the kerf width (m),
F is the feed speed (m/min), and
L is the cutting path length (m).

Equation 6.25 is helpful in determining the available sawblade usage time up to a pre-set sawing variation, such as the total standard deviation of 0.5mm.

The product of $n*k*F*L$ (m^3/min) represents the volume of wood that is removed in a sawing process. When this figure is multiplied with the species' specific cutting work unit (J/m^3), the product is the power (W) required to perform the cutting. Thus, the product of $n*k*F*L$ is called *Saw load*. Sawing time is not a factor in saw load and therefore it can be used to describe sawing processes where the sawblade wear factor is unknown. Because of an unknown usage time of a sawblade, the *Saw load* is predominantly used in normal production analysis.

The product of the *Sawing time* times *Saw load*, $t*n*k*F*L$ (h*m^3/min), is called *Time*Saw load*. In the graph equations it is represented by the symbol *x*. The sawing time represents the sawblade wear at a particular point of time, expressed in usage hours. The *Time*Saw load* is used extensively in figures in Chapters 7 and 8. The *Time*Saw load* and *Saw load* standardises a sawing event in such a manner that various production stages, change over time in a saw machine, and even various saw machines can be compared with each other.

6.6.7 Reproducibility

Reproducibility is defined as the spread of sample standard deviations around a *Time*Saw load* descriptor curve. The reproducibility is calculated as

$$R = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(\alpha e^{\beta x_j} - y_j\right)^2} \tag{6.26}$$

where *R* is the process reproducibility (mm),
α is the inherent descriptor constant when both sawing time and load are zero,
β is the time effect constant,
x_j is the *Time*Saw load* (h*m^3/min),
y_j is the observed standard deviation (mm) at x_j, and
n is the number of observed standard deviations.

Reproducibility is an estimate of a saw machine's capability to produce repeatedly consistent sawing variation. Reproducibility can be estimated only in the context of a benchmarking, because it is, de facto, the standard deviation of a descriptor, such as the total standard deviation. Reproducibility is also an indicator of the 'goodness', or 'error' of a descriptor function.

6.6.8 Taper and Snaking

Within-board taper and snaking are calculated for each individual board in a sample. Of interest are the absolute values of taper and snaking, both of which take place along a board, and data for their assessment is available in segment means. Thus, in a graphic representation, the x-axis is always the length position on a board. The taper and snaking descriptors for the entire sample are calculated as mean values of the within-board values.

The slope of the linear regression line can be used to assess the longitudinal shape of a sawn board. The slope is an indicator of potential board taper, as presented in Figure 6.9. The slope is calculated using a least-squares estimator (Milton and Arnold, 1995, p. 388). In the equation, the distance along a board x is replaced with segment designations (from 1 to n_s), because segments are spaced equally, and thus represent length. The slope is written as

$$b = \frac{n_s \sum_{i=1}^{n} x_i \overline{X}_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} \overline{X}_i\right)}{n_s \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \qquad (6.27)$$

where b is the regression slope,
x_i is a segment number,
$\overline{X}_i$ is the size of a segment,
n_s is the number of segments, and
i is designation of a segment.

Because the regression line slope coefficient is dimensionless, and normally relatively small, its usefulness as a descriptor for absolute size of taper is limited. Since the purpose is to obtain an estimate to describe the change of thickness from the top-end of a board to its butt-end, an estimator is calculated by using the end points of the regression line, the line that describes the average difference of size between points 'segment 1' and 'segment 10', points that correspond with the top- and butt-ends of a board, as in Figure 6.9. The size difference is a direct estimator of board taper in millimetres. Thus, the within-board taper is calculated as

$$Taper = 10 * b \qquad (6.28)$$

where *Taper* is the taper in an individual piece (mm), and
b is the regression line slope.

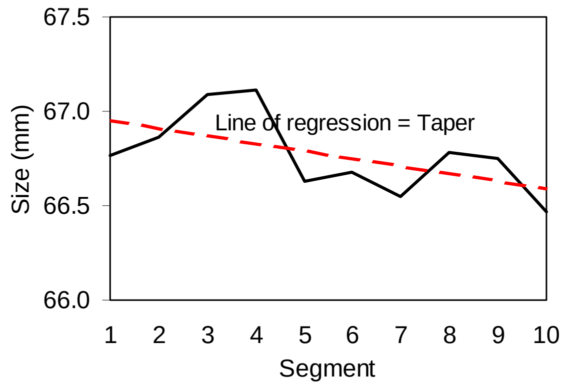


Figure 6.9. *Board taper is seen in the shape of a size curve, and in the slope of its regression line.*

Acceptable taper is a matter of local sawmill practice. Generally tapers less than 0.5mm are considered insignificant and a consistent taper over 1.0mm a cause for concern.

Quantification of sawblade snaking (flutter, wander, wobble) is more difficult. A regression slope cannot be used to indicate sawblade snaking. If snaking is symmetric, the regression line is completely horizontal, and thus the slope coefficient very small or zero. On the other hand, local size variation among segments is a good indicator of extreme values and potential snaking. If absolute change from one segment to the next is small, the probability of snaking is small. If the variation among the segments is large, snaking is probable. In this study, snaking is a feature in an individual board. The sawblade bend is used as a 'snake' descriptor for a whole sample.

Variation of segment means around a regression line is used as an estimator of tendency to snake. The distance of a segment mean from the respective regression line point is the deflection at that point. Snaking, the value of deflection, is independent of board taper. Snaking is calculated for each consecutive segment. The maximum deflection amplitude is the estimate for snaking.

$$\textit{Snaking} = \textit{Maximum Deflection Amplitude Around Regression Line} \qquad (6.29)$$

Acceptable snaking is a matter of local sawmill practice and varies according to the saw machines used. Snaking less than 0.5mm is considered insignificant, while consistent snaking over 1.0mm is a cause for concern. Figure 6.10 illustrates snaking in the sample shown in Figure 6.9.

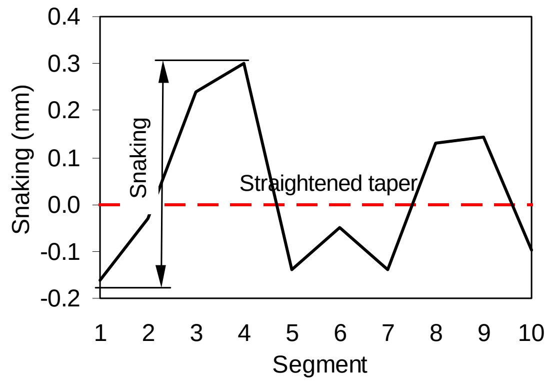


Figure 6.10. *Snaking is the maximum amplitude around taper. The value of snaking is 0.4mm.*

6.6.9 Within-segment Bend and Bend Amplitude

Within-segment bend, also called as sawblade bend, and bend amplitude, uses data successively from one segment in all boards in one sample at a time. Thus, they describe behaviour of the entire sample in particular segments. The bend and amplitude descriptors for the entire sample are calculated as mean values of the within-segment values.

Sawblade bend is calculated as the difference between a within-segment mean and the total sample mean. The sawblade bend is calculated as

$$Bend_j = \overline{X}_{mj} - \overline{X} \qquad (6.30)$$

where $Bend$ is the j[th] segment bend,
$\overline{X}_{mi}$ is the j[th] segment mean, and
$\overline{X}$ is the sample mean.

Bend may be expressed as bend with a sign, indicating size and direction, or as sawblade bend amplitude, describing the largeness of bend in general. The former is used in the graphs and the latter in the numerical saw machine descriptors. A succession of bends in ten segments is illustrated in Figure 6.11. The figure shows a bend towards thicker top-end sizes and thinner sizes at the butt area, indicating either sawblade bend during sawing.

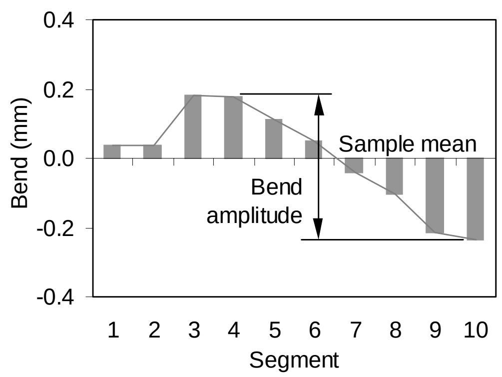


Figure 6.11. *Sawblade bend observed in a single-arbor circular saw.*

Bend amplitude is calculated as the difference between the maximum and minimum bend values, as in Figure 6.11. Bend amplitude is an indicator of sawblade instability during sawing. The smaller the value, the more stable the sawing process. Large bend amplitude values indicate insufficient sawblade control.

6.7 Short- and Long-Term Graphs

Graphs illustrating the short-term and long-term behaviour of saw machine descriptors can be drawn using data either from normal production or benchmarking tests. There are various ways of drawing the graphs. Chronological graphs, such as Figures 8.1 and 8.4, reveal trends and events in an illuminating manner, although they do not disclose detailed facts.

Feed speeds are of great interest to sawmills. However, as shown in Equation 6.24, the feed speed is but one of the factors that have an effect on saw descriptors. Figure 6.12 illustrates standard deviation growth as the feed speed increases, but it also indicates dispersion growth as the sawing time increases. The effect of cant size is more difficult to discern.

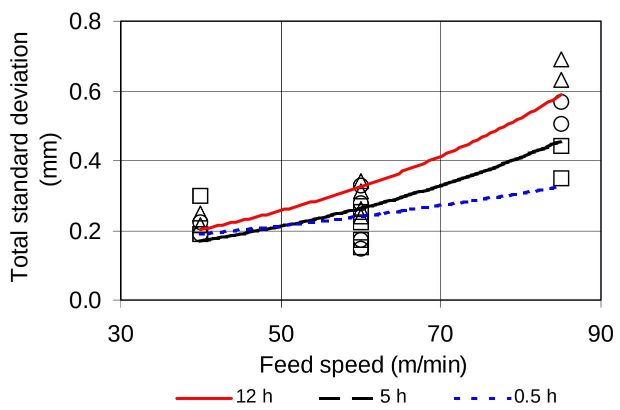


Figure 6.12. *Effect of feed speed on the total standard deviation in a 4-piece set-up in a single-arbor circular saw, type A. The effects of sawblade wear and varying cants sizes are seen in the data dispersion.*

The effect of log or cant size is illustrated in Figure 6.13. Increase in cant size has an effect on the sawing variation, but it is difficult to discern the effects of sawing time and feed speed variations.

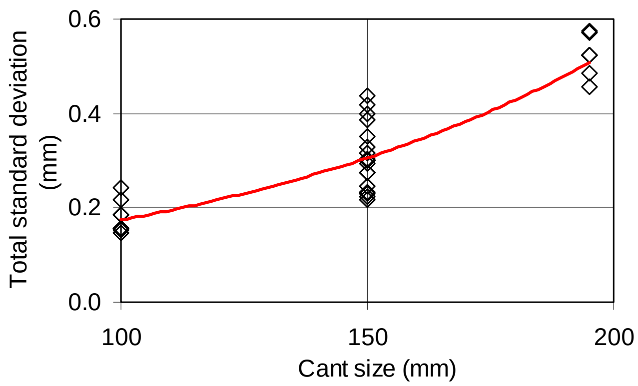


Figure 6.13. *Effect of cant size on the total standard deviation in a 4-piece set-up in a single-arbor circular saw, type B. The effects of sawblade wear and feed speed are seen in the data dispersion.*

The effect of sawing time on the total standard deviation in a 4-piece set-up in a single-arbor circular saw, type A, is seen in Figure 8.15. Presentation that is based on *Saw load* is practical when the sawing time is unknown, Figures 8.3 and 8.5. When sawing time is accurately known, as in benchmarking, *Time*Saw load* presentation will reveal the detailed behaviour of a saw machine, as in Figure 8.6.

6.8 Detailed Graphic Descriptors

Equations and simple numbers are an averaged, general way of presenting behaviour of a saw machine. In an analysis of problem causes, concrete visual tools are of considerable help. The graphs will disclose more information when graphs from neighbouring parallel boards are examined simultaneously. Simultaneous examination will indicate behaviour of individual sawblades and reveal potential causes of process problems. The usefulness of a specific graph depends on the problem at hand. For example, certain graphs may be used to disclose taper and others to detect hook. The following samples are from a single-arbor circular saw. The sawn cant size is 125mm and feed speed 60m/min. The samples describe boards that have been sawn between two sawblades. The entire set-up consists of five parallel pieces.

6.8.1 Mean

Mean, together with the total standard deviation, represents the most useful descriptor for a sawmill. The location of the distribution mean and the standard deviation of sawing variation assist a sawmill in adjusting the target size, and in alerting an operator to potential problems, as in Figure 6.14. The goal of a saw operator is to set the -2s limit on top of the smallest allowed sawn size. When this is accomplished, the wood use from the sawmill point of view is optimal. The customers will not get too much or too little of wood.

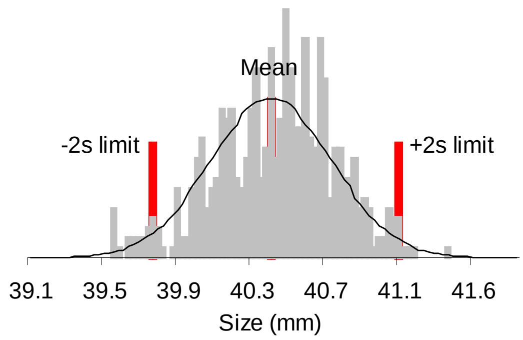


Figure 6.14. *Frequency distribution of a fifty board sample.*

A frequency distribution will help a sawmill to check if the target size hits the process mean for boards produced between two sawblades and if the lower half of the process standard deviation is equal to or smaller than the sawing allowance. The ±2s range will determine the risk of producing excessively oversized timber. The 2s value will also provide the process capability index. The process mean and the location of the -2s limit can be expressed as simple numbers.

A graph illustrating the along-the-length size profiles of individual boards with their mean and ±2s limits can render an overall picture of a sawing process, as in Figure 6.15, which shows the cutting start size variation and process standard deviation at various locations along the length. The figure also reveals potential shape defects, such as taper.

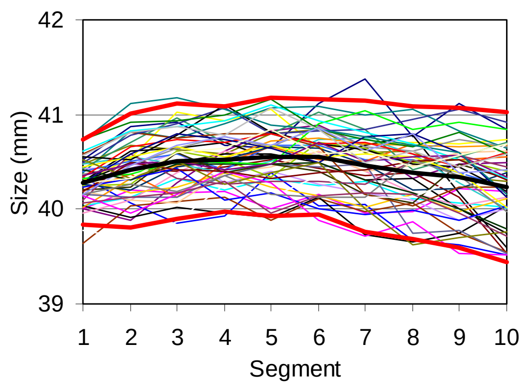


Figure 6.15. *Along-the-length size profiles of individual boards, and curves illustrating their mean and ±2s limits.*

A view of the individual board size variations from top-end to butt-end, with their curves showing the mean and ±2s limits for each board, gives an overall picture of the sawing process variation from board to board, as in Figure 6.16. This presentation will show set-up adjustments, involuntary changes in average size, drift of mean, as well as the standard deviation of individual boards.

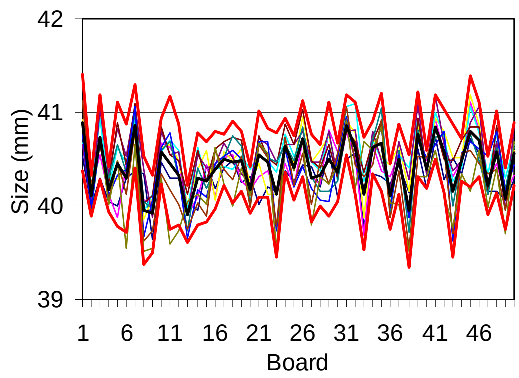


Figure 6.16. *From-top-to-butt-end size profiles of individual boards, and curves illustrating their mean and ±2s limits.*

6.8.2 Total and Within-board Standard Deviation

The total standard deviation is the most important descriptor of a saw machine. The problem remains, however, that there is no total standard deviation for any saw machine. There are different total standard deviations for each:

- Log size
- Feed speed
- Sawing time, sawblade wear
- Cutting position
- Sawing pattern
- Sawblade characteristics
- Season.

Therefore, the matter of correct target size is extremely difficult. Nowadays, it is solved by using excessive oversizing. Notwithstanding the true total standard deviations, it may be impossible to use the information adaptively enough, because the saw machine set-up systems are not designed or built to make the required adjustments.

The total standard deviation is a result of the within-board standard deviations in all the individual boards, as in Figure 6.17. A within-board standard deviation for each board in a sample shows the sawing variations in the sample. The presentation shows the best and the worst boards, and systematic behaviour. The clearest way to present the individual within-board standard deviations is in the form of a graph.

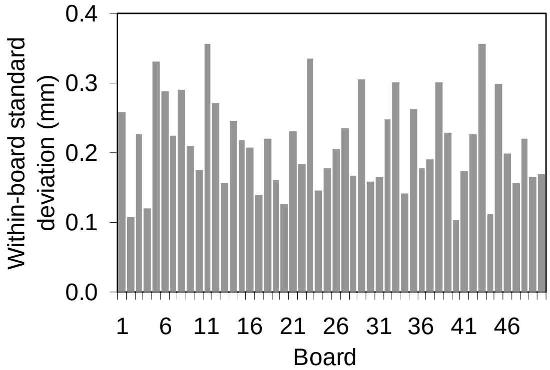


Figure 6.17. *Within-board standard deviations of individual boards in a sample. Total standard deviation of the sample is 0.34mm.*

The total standard deviation for each cutting position can be expressed as a simple number with respect to the existing sawing conditions.

6.8.3 Between-board Standard Deviation

The between-board standard deviation is calculated as the variation of individual board means from the sample mean, as in Figure 6.18.

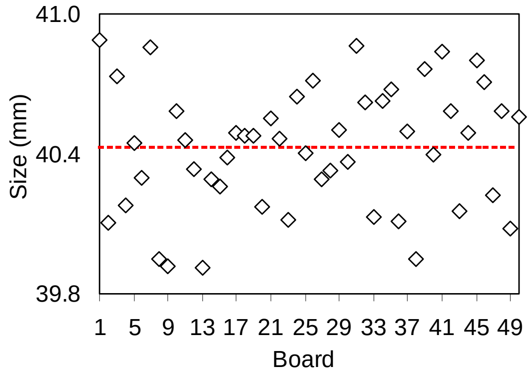


Figure 6.18. *Variation of individual board means around the line showing the total mean of 40.43mm. The between-board standard deviation is 0.26mm.*

The between-board standard deviation is an indicator of the capability of the setworks and feedworks to produce consistently same size of timber. The between-board standard deviation for each cutting position can be expressed as a simple number with respect to the existing sawing conditions.

6.8.4 Between and Within-segment standard deviation

Although the length variations between individual boards in a sample have an effect on the segment-based analysis, the large number of samples and averaging compensates this inherent error source, Chapter 5.4. The consistency of results can be seen when comparing graphs in Figure 6.15, showing the lengthwise size data in a sample, and Figures 6.19 and 6.20.

The between-segment standard deviation is calculated as the variation of individual segment means from the sample mean, as in Figure 6.19.

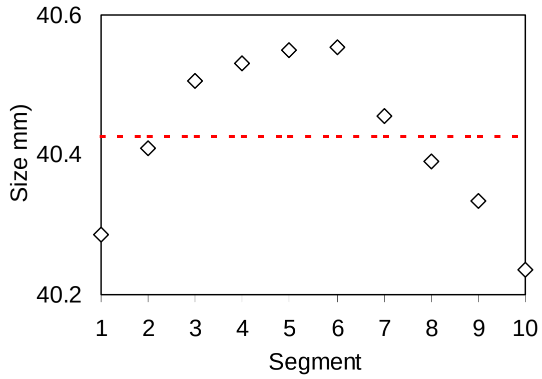


Figure 6.19. *Variation of individual segment means around the line showing the total mean of 40.43mm. The between-segment standard deviation is 0.11mm.*

The within-segment standard deviation for each segment represents the sawing variation of individual boards in that segment in a sample, as in Figure 6.20. This standard deviation shows if the process displays systematic, different behaviour at different locations along the length, for example, increase in the standard deviation towards the butt. The easiest way to present the individual within-segment standard deviations is in the form of a graph.

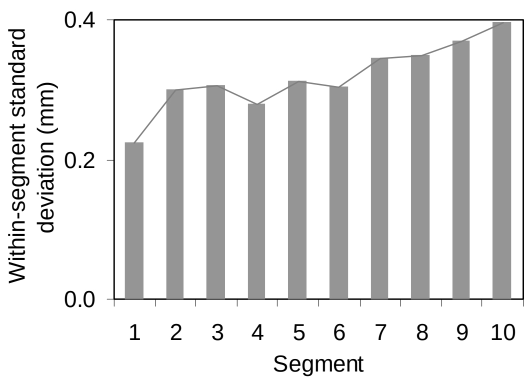


Figure 6.20. *Within-segment standard deviations of individual segments in a sample.*

The between-segment standard deviation is an indicator of the consistency of the cutting process of a sawblade. The standard deviation may be smaller or greater, but if it remains stable throughout the entire length of a board, it is consistent, and the between-segment standard deviation remains small. The between-board standard deviation for each cutting position can be expressed as a simple number with respect to the existing sawing conditions.

6.8.5 Taper

Taper may be evident in a graph displaying the board means, as in Figure 6.15. However, because of the large number of curves, it is difficult to verify whether the potential taper is systematic or not. A graph showing the taper in individual boards renders a clearer image of the general situation. Occasionally, all boards show taper in a similar manner, or the taper is random, as in Figure 6.21. The within-board taper values indicate the size difference between the top- and the butt-ends. Systematic taper is an indicator of systematic sawblade bend or feedworks malfunction. Irregular taper is normally caused by random sawblade bend.

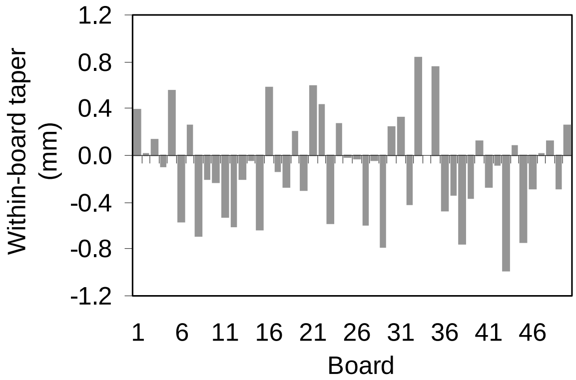


Figure 6.21. *Within-board taper in individual boards.*

The easiest way to present the individual within-board tapers is in the form of a graph. The sample taper for each cutting position can be expressed as a simple number with respect to the existing sawing conditions. It is calculated as an average value of the within-board tapers.

6.8.6 Bend and Bend Amplitude

Within-segment bend shows the average mean behaviour of the entire sample from segment to segment, as in Figure 6.22. Bend in an individual segment describes its mean difference compared to the sample mean. The causes for bend are various. Fluctuation may depend on sawblade behaviour, malfunctioning in feedworks, or alignment errors. The best way to present the individual within-board tapers is in the form of a graph. Bend amplitude is the range from the smallest bend value to the largest. Bend amplitude for each cutting position can be expressed as a simple number with respect to the existing sawing conditions.

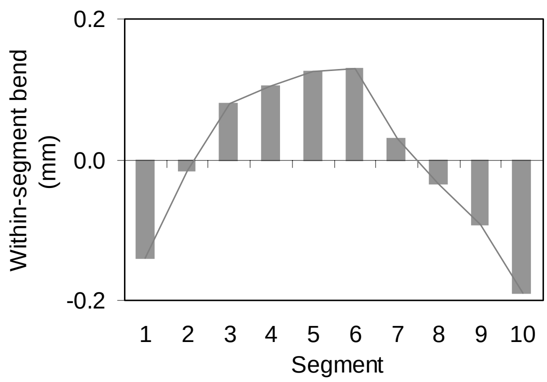


Figure 6.22. *Within-segment bend in segments. The bend amplitude is 0.32mm.*

Examination of bend in parallel boards gives information on individual sawblade behaviour, as in Figure 6.23. The sawblades may have mirror, similar or individual bend images that indicate the action of a sawblade between the boards or when cutting the other faces of boards.

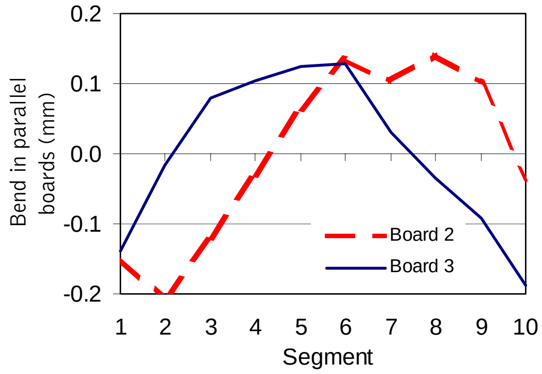


Figure 6.23. *Mirror image bend in two parallel boards. The sawblade cutting between the boards is the main cause of the mirror image bend.*

6.9 Reject Board Probability

When outer flitch faces are slab, a measuring device cannot record size data, because it does not exist, and thus fewer segment size readings are recorded. This fact can be used to assess the quality of a flitch for an edging process. Because slab quantity is mostly dependent on the match between the top-end diameter of a log and the selected sawing pattern, an analysis of slab content must involve a large sample of logs. In this study, the reject board probability is estimated by using a sample size of fifty logs. Reject board analysis is used in flitch analysis in Appendix A, Chapter A.3.

Slab surface in flitches is generally acceptable in the first two segments along a flitch, typically the first metre from the top-end. If slab surface quantity exceeds 20% of a board length, the board may be considered a potential reject board. Thus, consistent appearance of segments without size data will increase the reject probability percentage; two segments indicate 0% reject probability and ten segments 100%, as in Figure 6.24.

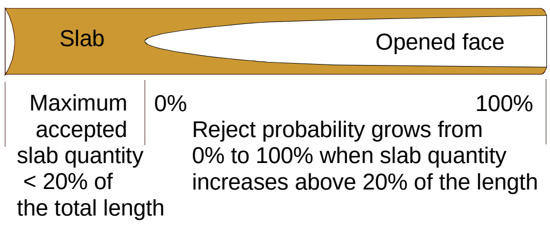


Figure 6.24. *Flitch face with partial slab surface. The edging value of a flitch depends on the quantity of opened face. When slab surface quantity increases above 20% of the total length, the reject probability increases in relation to the slab quantity.*

Calculation of reject board probability percentage is as follows:

$$P_R = \frac{n_X - n_2}{n - n_2} * 100 \qquad \text{when } n_x > n_2 \tag{6.31}$$

where P_R is the reject board probability percentage,
n_X is the number of segments without a reading,

n_2 is the number of accepted segments without a reading (in this study 2 segments times 50 flitches = 100), and
n is the total number of segments (in this study 10 segments times 50 flitches = 500).

Usability and significance of the reject board probability percentage varies among mills because sawmill criteria vary. Some mills edge boards with only 2.1 metres of opened face, while others require at least 2.7 metres. Outer flitches suffer also of larger deviations from the target sizes because the sawblade enters the wood from the side, which tends to cause blade bend and snaking, which in turn lead to size variations.

6.10 Process Capability

Process capability represents the performance of a sawing process under control. It is determined by the total inherent variability that exists in a saw machine. Because of the complicated nature of a saw machine it is evident that certain specific causes will remain and new ones will appear in a system, and the capability of a process will always accommodate improvement.

The common measure for process capability is given by 6s, which is also known as the process spread (Mitra, 1998, p. 374). It is assumed that 6s encompasses almost all values that a process produces. A spread of 6s is, however, not practical in the case of a saw machine. The process is designed so that, depending on the sawmill and its customer, 10%, 5% or 2.5% of the sawn boards may have a final size below the size specification. Thus, if a 5 percent rule is used, the capability index is calculated using 3.3s value (Z=3.3), or in the case of 2.5 percent, a value of 4s (Z=4) is used. The value 4s is used in the capability calculation in this study. Therefore, the process analysis will include a safety margin for sawmills using 5 percent acceptance rules.

Sawn board data is used to calculate a process capability. The capability indices used are dimensionless. One way of describing the potential of a sawing process is the process capability index that utilises both tolerance limits

$$C_p = \frac{\text{Upper Tolerance} - \text{Lower Tolerance}}{4\,s} \qquad (6.32)$$

where C_p is a double sided process capability index, and
s is the standard deviation of a sawing process.

Because sawmills do not generally use tolerances in their breakdown sawing, Equation 6.30 is not practical. The capability index must be calculated using only the lower part of the process, from the saw set-up target size to the smallest acceptable green size, Equation 2.2. This range is known as the sawing allowance and is used to compensate for sawing variation, as in Figure 2.4. The capability index of a saw machine is expressed as

$$C = \frac{Target\ Size - Smallest\ Allowed\ Sawn\ Size}{2\ s} \qquad (6.33)$$

$$C = \frac{Sawing\ Allowance}{2s}$$

where C is the process capability index of a saw machine, and
s is the standard deviation of the sawing process.

A sawing process is capable if the process capability index $C > 1$. In the case of $C > 1$, the lower limit of the process is well within the allowed lower sawing limit, and all sawn pieces will meet the specification. If the capability index $C = 1$, the process is barely capable and any shift in the process mean towards a thinner size than the target size will produce non-conforming boards. If the capability index $C < 1$, the process is not capable. Its standard deviation is wider than the allowed range and the saw machine will produce non-conforming boards independent of an otherwise accurate target size. In the case of $C < 1$, a sawmill must change its target size to correspond to the true, required sawing allowance in order to avoid massive production of non-conforming boards.

A commonly used sawing allowance in resaw is 0.5mm for circular saws and 0.7mm for bandsaws. Based on these values and the observed total standard deviation data in Table 8.8, the process capability of the single-arbor circular saws is approximately 0.8, the double-arbor circular saw's 0.9 and the triple bandsaw's 0.6. Considering these process capabilities it is natural that oversizing must be used in the set-ups to avoid substandard rough boards.

6.11 Discussion

The values that are used as the basis of the descriptor calculations and analysis in this thesis are means of tens of individual readings. The Central Limit Theorem states that such a sample is normally distributed. Principles of data collection and classification, the currently used statistical descriptors, and a number of new descriptors developed for this thesis are presented in this chapter.

The conventional within-board standard deviation differs from that used in this thesis. Here, the within-board standard deviation is calculated for each board separately, and the total standard deviation is calculated using all segment mean values in a sample. The traditional method calculates the within-board standard deviation as a square root of the mean of variances using all 16 or 20 readings in a sample, and the total standard deviation as a square root of the sum of the squares of the within-board and between-board standard deviations (Brown, 1982, p. 132-133).

The new descriptors require of the taking of many readings, otherwise, for example, the use of the within-segment and between-segment descriptors would not be possible. At the same time, a greater number of readings improves the information content of the traditional descriptors.

Equations are a practical, compact way of describing the characteristics of a saw machine. The total standard deviation and other saw machine descriptors can be expressed using the equation $y=\alpha e^{\beta x} \pm R$, where α and β are constants typical for each saw machine, and x is a product of sawing time and saw load. The spread of total standard deviation values around the total standard deviation descriptor equation is a measure of saw machine reproducibility R, its capability to saw with consistent sawing variation. Reproducibility is defined in benchmarking, but process consistency can be checked against the equation in normal production, too.

Simple numbers are in many cases not very descriptive when a cause analysis must be made. Examination of descriptor graphs, presenting the various standard deviations, sawblade bend, and other features, provides a useful source of information when analysing reasons for particular behaviour. Of particular value is the comparison of graphs representing neighbouring boards. This type of analysis will reveal information on individual sawblades and process tools.

The sample size used in sawmills today is clearly too small, chiefly because sawmills regard their saw machines as a unit having one, ‘fixed’ standard deviation. Therefore, it is thought sufficient to collect data from one sawing position alone, or one board from each sawing position, satisfying the conventional conception of four boards and four measures. However, the guidelines proposed by Warren (1973) indicate sampling quantities that depend on the size of sawing variation. Warren’s conclusion is that a board sample size of fifty is a reasonable minimum for estimating standard deviation and it is the sample size used in this study.

7 Case Studies in Log Breakdown

The details of normal production are presented in Tables 1.2 and 1.3, and benchmarking details in Tables 1.4 and 1.5. Each mark in the data presentation figures represents an average value of fifty sawn pieces. The trends in the normal production figures are shown to assist the reader to discern the general behaviour of presented descriptors. The trends in the benchmarking figures are supplied with descriptor equations that represent the behaviour of a saw machine in the benchmarking conditions.

7.1 Single-arbor Circular Saw

The saw machine used in this case study is presented in Appendix A, Chapter A.2.1. In normal production, the saw machine has an average total standard deviation 0.71mm in cants, and 0.93mm in flitches. Trends in the total standard deviations have not been consistent over the period of three months. There was a shift in the level in early June, after which the level started to rise again, as in Figure 7.1. In May, the mill was sawing in two shifts using higher feed speeds. In early June, the mill started to operate in one shift. Drier wood, as summer proceeded, may have been an additional factor in the level of standard deviation. The same effect of increasing deviations is seen in cant resaw, Figure 8.10. Thus, it is clear that changes in sawing operations are the major cause of increase in standard deviation levels.

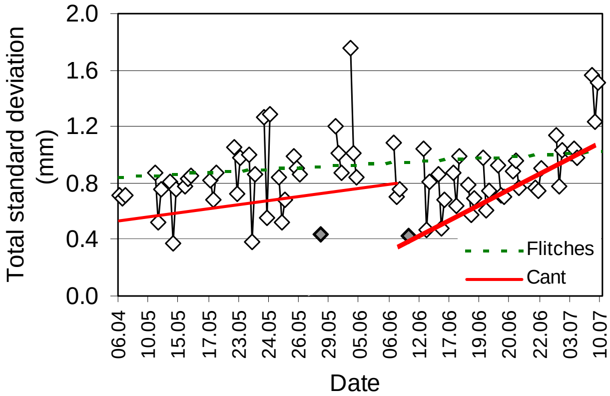


Figure 7.1. *Total standard deviation of cants and flitches in a single-arbor circular saw in normal log breakdown. The data includes all log sizes and feed speeds. Set-ups are connected with a line.*

In Figure 7.1 the two single values in 'bold type', the first one on 29 May and the other on 12 June, are from cants without flitches, with chipped outer faces, representing the standard deviation of the chipper canter, 0.4mm.

When the results are presented as a function of the *Saw load*, the total standard deviation of log cants approaches a level of 0.8mm to 0.9mm in large *Saw loads*, as in Figure 7.2. The trend indicates that the sawing variation of the process is smaller with small and medium size logs.

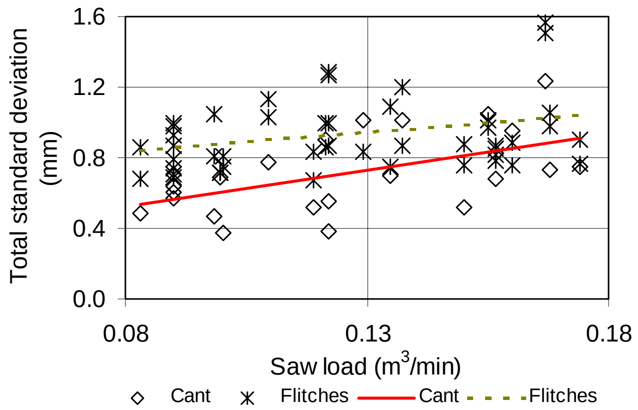


Figure 7.2. *Total standard deviation of cant and flitches in a single-arbor saw circular in normal log breakdown as a function of the Saw load.*

The between-board standard deviation increases with growing *Saw load* more markedly than does the between-segment standard deviation. This and the increasing sawblade bend amplitude indicate that the sawblade deflection is the probable cause of increase in the total and in the between-board standard deviations in normal production.

7.1.1 Benchmarking of Single-arbor Circular Saw

The total standard deviation has an upward trend over the benchmarking period of eight hours, indicating wear of the sawblades, as in Figure 7.3. The total average standard deviation of cants is 0.68mm, and of flitches 0.92mm, which are consistent with the normal production values. Thus, the test conditions are similar to normal production conditions.

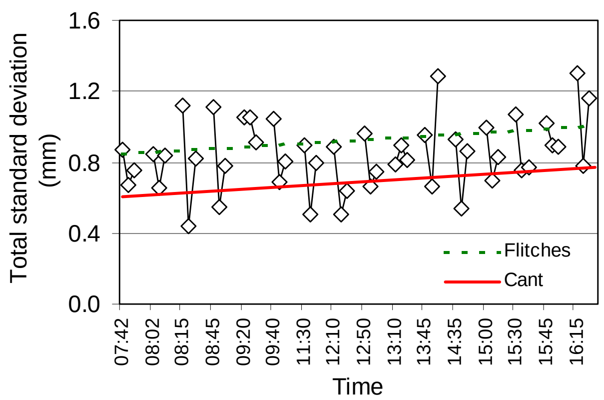


Figure 7.3. *Total standard deviation of cants and flitches in a single-arbor circular saw in benchmarking log breakdown. The data includes all feed speeds, log sizes and sawing times. Set-ups are connected with a line.*

More detailed data is revealed when the results are presented as a function of the *Time*Saw load*, as in Figure 7.4.

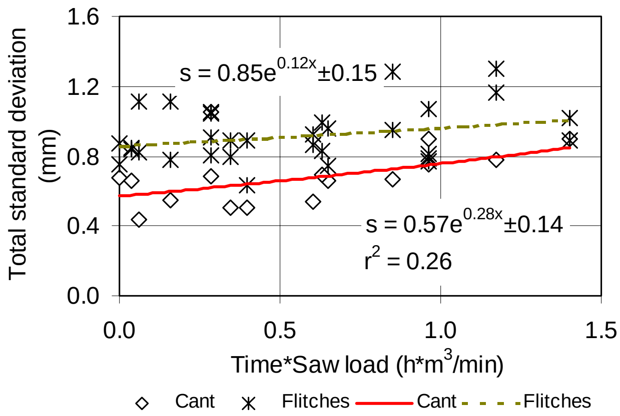


Figure 7.4. *Total standard deviation of cant and flitches in a single-arbor circular saw in benchmarking log breakdown as a function of the Time*Saw load.*

The total standard deviation function is $s_T=0.57e^{0.28}\pm0.14$, where the cant production reproducibility is 0.14mm, as in Figure 7.4. The descriptor equation for the between-board standard deviation of the cant is $s_B=0.53e^{0.32}\pm0.18$, and for the between-segment variation $s_M=0.12e^{0.72}\pm0.08$. The sawblade bend amplitude function $B=0.40e^{0.69}\pm0.24$ indicates strong sawblade deflections because the minimum is 0.40mm. Furthermore, the reproducibility of bend is poor, 0.24mm, indicating unstable sawblade behaviour, as in Figure 7.5. Small between-segment variation, 0.12mm, indicates consistent, unstable behaviour over the entire length of cants. Therefore, sawblade behaviour is the cause of the large total and between-board standard deviations. In the flitches, bend is a sum of canted faces, side penetration, and sawblade bend. Therefore, flitch data alone cannot be used to evaluate sawblade bend in log breakdown. The average taper of cant in benchmarking is 0.64mm.

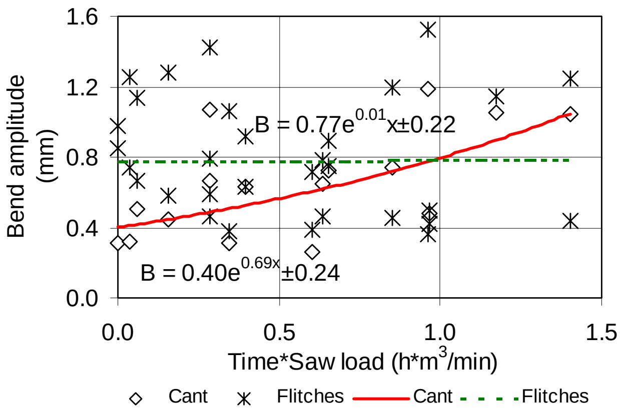


Figure 7.5. *Sawblade bend amplitude in cant and flitches in a single-arbor circular saw in benchmarking log breakdown as a function of the Time*Saw load.*

7.1.2 Conclusions on Single-Arbor Circular Saw

The log breakdown process of cant is stable, but not necessarily under control. An average total standard deviation of 0.7mm may be considered normal in log breakdown in the examined single-arbor saw. However, a normal level of 0.5mm sawing variation may be attainable, as is indicated by a number of samples in Figures 7.1 and 7.3. The average descriptor values in normal production correspond closely to the benchmarking values, as in Table 7.1.

Table 7.1. *Benchmarking descriptors in a single-arbor circular saw in log breakdown.*

	Benchmark value		Equation constants		Reproducibility
	Cant (mm)	Flitches (mm)	Cant α	Cant β	Cant (mm)
Total standard deviation	0.68	0.92	0.57	0.28	0.14
Between-board standard deviation	0.66	0.71	0.53	0.32	0.18
Between-segment standard deviation	0.20	0.30	0.12	0.72	0.08
Taper	0.64	-0.28			
Bend amplitude	0.65	0.89	0.40	0.69	0.24

This analysis does not include the final twenty percent of log or flitch length due to existing measuring limitations.

7.2 Double-arbor Circular Saw

The saw machine used in this case study is presented in Appendix A, Chapter A.4.1. The total standard deviation of the square cant in the examined double-arbor circular saw approaches a level of 0.2mm, as in Figure 7.6. The average total standard deviation during normal production is 0.18mm. The deviation is even, but the saw machine has deteriorated slightly during the recording period. The process parameters are under control.

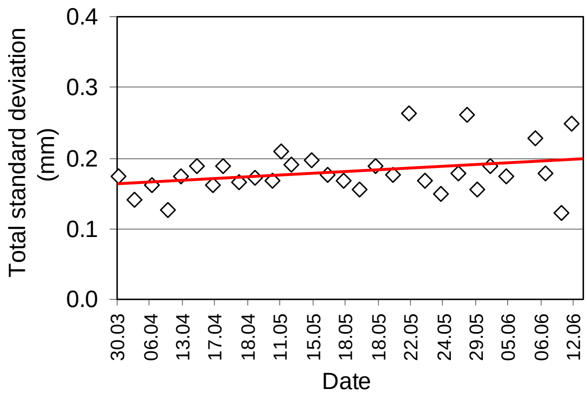


Figure 7.6. *Total standard deviation of cants in a double-arbor circular saw in normal production. The data includes all log sizes and feed speeds for the recorded samples.*

The between-board standard deviation does not depend on the *Saw load*, whereas the total standard deviation does. An observed small increase in the between-segment standard deviation indicates an increase in sawing variation as the *Saw load* grows. The growing sawblade bend amplitude and the increasing spread of values, as in Figure 7.7, demonstrate increasing sawblade deflection. This phenomenon is consistent with the increase in the total standard deviation. Thus, the cause of sawing variation is sawblade bend.

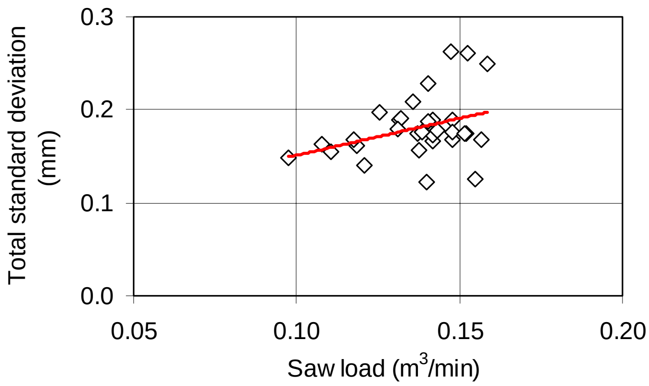


Figure 7.7. *Sawblade bend amplitude in cants increases and disperses noticeably as the Saw load grows in a double-arbor circular saw in log breakdown.*

7.2.1 Benchmarking of Double-arbor Circular Saw

The low, 40m/min, and high, 85 and 100m/min, feed speeds used in the benchmarking test are not used in regular sawing for some of the tested log sizes. Thus, some of the data is from the limits of double-arbor log breakdown process. However, this data also emphasises saw system behaviour at the limits.

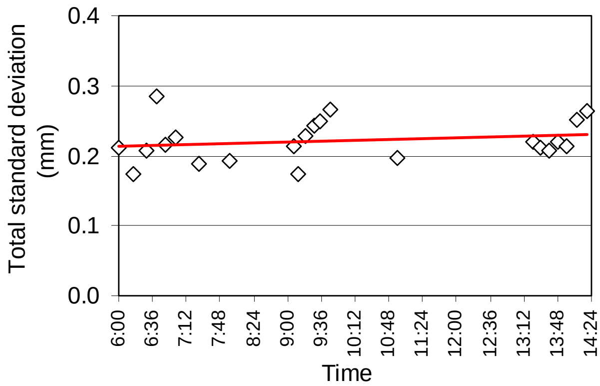


Figure 7.8. *Chronological development of the total standard deviation of cants in a double-arbor circular saw in benchmarking. The data includes all feed speeds, log sizes and sawing times.*

The chronological growth and spread of the total standard deviation reveals an evenly behaving double-arbor saw machine, as in Figure 7.8. Larger log sizes and faster feed speeds have little effect on sawing variation.

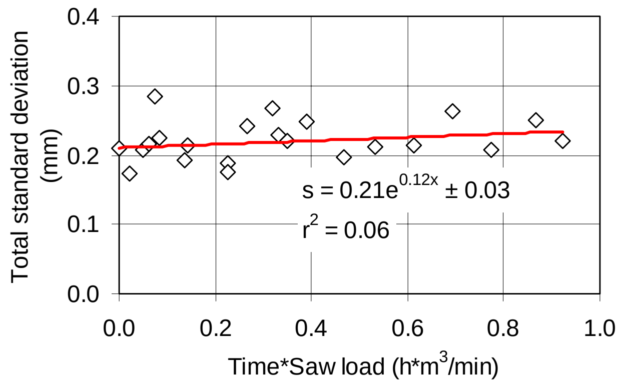


Figure 7.9. *Total standard deviation of cants in a double-arbor circular saw in benchmarking log breakdown as a function of the Time*Saw load.*

The total standard deviation is almost independent of the *Time*Saw load*, displaying minimal increase in deviation as the sawing time and load increase, as in Figure 7.9. The average total standard deviation during the test was 0.22mm. The average deviation in normal production was 0.18mm. Three causes may be identified for the larger benchmarking deviation:

- Benchmarking was partly performed with sawing parameters that were outside the normal production parameters
- Because of deterioration of the saw machine, the system's deviation was already approaching a level of 0.2mm
- Sawblades were from a different manufacturer to those normally used.

Similar changes in the value levels are observed in other descriptors. Benchmarking values are slightly larger than those recorded in normal production.

The descriptor equation for the total standard deviation is $s_T=0.21e^{0.12x}\pm0.03$, where 0.03mm is the reproducibility of cant production. The between-board standard deviation, $s_B=0.13e^{0}\pm0.03$, is level at 0.13mm. The between-segment standard deviation, $s_M=0.06e^{0.24x}\pm0.04$ indicates a gradual increase in deviation as the *Time*Saw load* increases. The increase of saw load and sawing time have a clear effect on bend. The sawblade bend indicates wide variation between sawn batches, $B=0.18e^{0.30x}\pm0.09$. Log holding may be the cause of instability identified in the bend.

7.2.2 Conclusions on Double-arbor Circular Saw

The log breakdown process is under control. The total standard deviation of 0.2mm, under normal production parameters, is typical in the log breakdown in the case of the examined double-arbor saw. However, the sawing process is less stable during the first third of log length, perhaps a result of holding problems and canter effects. The numerical benchmarking descriptors are presented in Table 7.2.

Table 7.2. *Benchmarking characteristics of a double-arbor circular saw in log breakdown.*

	Benchmark value (mm)	Equation constants α	β	Reproducibility (mm)
Total standard deviation	0.23	0.21	0.12	0.03
Between-board standard deviation	0.13	0.13	0	0.03
Between-segment standard deviation	0.08	0.06	0.24	0.04
Taper	0.10			
Bend amplitude	0.28	0.18	0.30	0.09

The slightly larger standard deviations in benchmarking may be attributed to the tested Böhler-Miller sawblades. However, the difference compared to the total standard deviation of 0.18mm in the case of Kanefusa sawblades is so insignificant that it has no practical meaning in regular production.

The analysis does not include the final twenty percent of square cant length due to existing measuring limitations.

7.3 Twin Bandsaw

The saw machine used in this case study is presented in Appendix A, Chapter A.5.1. The average total standard deviation of the examined twin bandsaw in normal production is 0.54mm, as in Figure 7.10. The deviation displays a diminishing trend, indicating improved process control, while some large variation values appear from time to time.

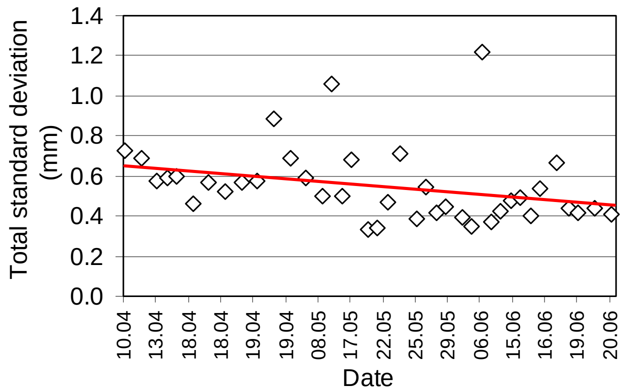


Figure 7.10. *Total standard deviation of cants in a twin bandsaw in normal log breakdown. The data includes all log sizes and feed speeds for the recorded samples.*

Although the changes in feed speed and log size influence the total standard deviation, the data indicates that, in general, the sawing process parameters are under control. The 'random' large values indicate sawblade or other process problems.

When the results are presented as a function of the *Saw load*, the data indicates that the maximum total standard deviation approaches a level of 0.6mm in large *Saw load*s, as in Figure 7.11.

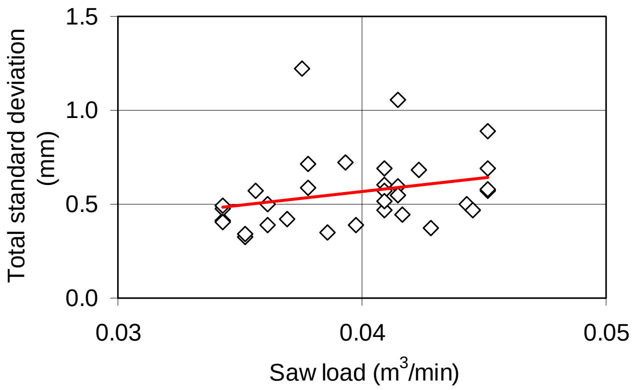


Figure 7.11. *Total standard deviation of cants in a twin bandsaw in normal log breakdown as a function of the Saw load.*

The between-board standard deviation displays similar growth, depending on the increase of *Saw load*, as does the total standard deviation. The between-segment standard deviation is independent of the *Saw load*, which indicates that the behaviour in longitudinal segments along the sawn cants changes similarly in all segments, as the *Saw load* increases. For the same reason, sawblade bend amplitude similarly remains consistent.

7.3.1 Benchmarking of Twin Bandsaw

Additional logs of size 225mm and 234mm were sawn between the benchmarking test lots with feed speeds of 65m/min and 60m/min, respectively. These were included in the benchmarking analysis.

During the set-up change between samples two and three, the sawblade in saw two wandered out and hit a wheel cover with the result of broken bits. After sawblade change, the sawing was recommenced. Data from the broken sawblade is marked in the charts in bold type as ‘broken’.

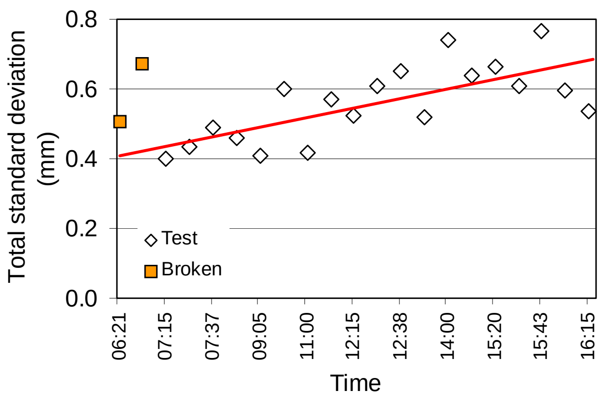


Figure 7.12. *Chronological total standard deviation of cants in a twin bandsaw in benchmarking log breakdown. The data includes all feed speeds, log sizes and sawing times.*

The process shows growing dependence on sawing time, and thus on sawblade wear, as in Figure 7.12. The broken sawblade consistently displayed behaviour that is typical of sawblades that have been used for six hours or more.

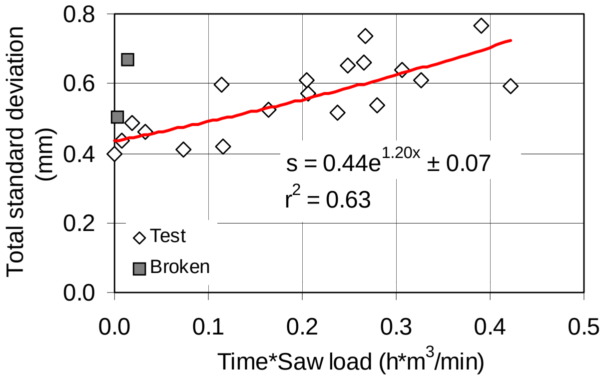


Figure 7.13. *Total standard deviation of cants in a twin bandsaw in benchmark log breakdown as a function of the Time*Saw load.*

The total standard deviation depends on the *Time*Saw load*, showing clear increase in deviation as the sawing load increases, $s_T=0.44e^{1.20x}\pm0.07$, as in Figure 7.13. The average total standard deviation during the benchmarking test is 0.56mm. This is slightly larger than the average variation in normal production. A similar change is observed in other saw descriptors, too. All benchmarking values are larger than the values recorded in normal production. The reproducibility of cant production is 0.07mm.

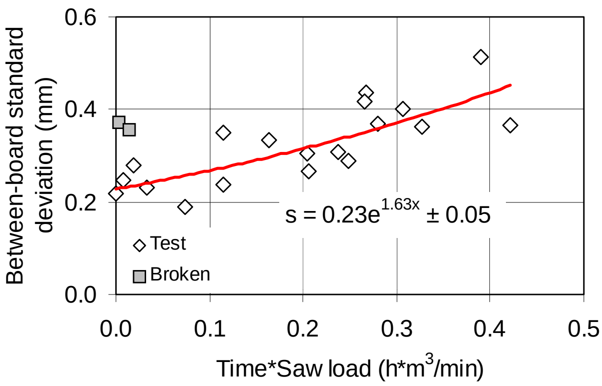


Figure 7.14. *Between-board standard deviation of cants in a twin bandsaw in benchmarking log breakdown as function of the Time*Saw load.*

The between-board standard deviation increases more markedly than the total deviation as sawing time and load increase, $s_B=0.23e^{1.63x}\pm0.05$, as in Figure 7.14. Similar behaviour is observed in the between-segment standard deviation, $s_M=0.17e^{1.08x}\pm0.06$. The consequence of increasing saw load and time is seen in the bend amplitude, $B=0.50e^{0.92x}\pm0.16$. The bend indicates that the sawing variation in the log breakdown process is chiefly caused by snaking sawblades.

7.3.2 Conclusions on Twin Bandsaw

The log breakdown process of the cant is under control. Total standard deviation of 0.6mm is normal in log breakdown in the twin bandsaw centre. The total standard deviation with a newly installed sawblade may be less than 0.5mm. After 8 hours of use, the deviation is approximately 0.6mm. The numerical benchmarking descriptors are presented in Table 7.3

Table 7.3. *Benchmarking characteristics of a twin bandsaw in log breakdown.*

	Benchmark value (mm)	Equation constants α	β	Reproducibility (mm)
Total standard deviation	0.56	0.44	1.20	0.07
Between-board standard deviation	0.32	0.23	1.63	0.05
Between-segment standard deviation	0.22	0.17	1.08	0.06
Taper	0.68			
Bend amplitude	0.62	0.50	0.93	0.16

The analysis and conclusions include the entire length of log cants.

7.4 Descriptor Correlations

The number of potential descriptors is too large for practical use in an analysis, as in Table 7.4. Therefore, certain the descriptors yielding identical information must be discarded from the reported descriptors. For this purpose, a descriptor correlation analysis is performed. The descriptor values are calculated based on readings recorded during normal production.

The total standard deviation is the main descriptor used for all saw machine types. The between-board standard deviation and the between-segment standard deviation are similarly used for all saw machines, even if they may show a strong correlation to the total standard deviation. Other descriptors are selected according to their importance and correlation to the total standard deviation. For example, if the smallest within-segment standard deviation has a strong correlation of 0.95, as in Table 7.4, to the total standard deviation, it does not convey additional information and can be deleted, in most normal cases, from the used descriptors.

The single-arbor circular saw descriptor correlation analysis was performed using the cant data. The correlation results are presented in Table 7.4.

Table 7.4. *Correlation of saw descriptors in a single-arbor circular saw in log breakdown.*

	Total standard deviation	Smallest within-board std. dev.	Largest within-board std. dev.	Between-board standard deviation	Taper	Snaking	Between-segment standard deviation	Smallest within-segment std. dev.	Largest within-segment std. dev.	Bend amplitude
Total standard deviation		-0.01	0.70	**0.96**	0.18	0.61	0.79	**0.95**	**0.91**	0.77
Smallest within-board std. dev	-0.01		0.23	-0.13	0.11	0.60	-0.10	0.02	0.07	-0.11
Largest within-board std. dev	0.70	0.23		0.56	0.04	0.63	0.51	0.66	**0.80**	0.49
Between-board std. dev.	**0.96**	-0.13	0.56		0.23	0.46	0.73	**0.94**	**0.82**	0.72
Taper	0.18	0.11	0.04	0.23		0.06	0.45	0.16	0.03	0.50
Snaking	0.61	0.60	0.63	0.46	0.06		0.39	0.56	0.64	0.37
Between-segment std. dev.	0.79	-0.10	0.51	0.73	0.45	0.39		0.63	0.71	**0.98**
Smallest within-segment std. dev.	**0.95**	0.02	0.66	**0.94**	0.16	0.56	0.63		**0.81**	0.61
Largest within-segment std. dev	**0.91**	0.07	**0.80**	**0.82**	0.03	0.64	0.71	**0.81**		0.66
Bend amplitude	0.77	-0.11	0.49	0.72	0.50	0.37	**0.98**	0.61	0.66	

There exists a strong correlation between the total standard deviation and the between-board standard deviation and the smallest and largest within-segment standard deviations. Thus, the total standard deviation can be used to represent these descriptors. The between-segment standard deviation and sawblade bend exhibit moderate correlation with the total standard deviation. Taper exhibits no correlation with the total standard deviation. Thus, they contribute information to an analysis. Although the bend amplitude has a strong correlation to the between-segment standard deviation, it will be used because it indicates process instability more clearly than the between-segment deviation.

Corresponding correlations are obtained for the double-arbor and the twin bandsaw. In log breakdown, both single-arbor and double-arbor saw machines have a strong correlation only between the between-board standard deviation and the total standard deviation. In the twin bandsaw, all main descriptors exhibit a strong correlation to the total standard deviation. This represents a fundamental difference between the twin band and the circular saws in log breakdown. For the purpose of saw machine analysis, in log breakdown, identical descriptors can be used for all saw machine types. These descriptors are:

- Total standard deviation
- Between-board standard deviation
- Between-segment standard deviation
- Taper
- Bend amplitude.

7.5 Discussion

In normal log breakdown production, all three saw machine types exhibit both consistent and inconsistent behaviour. Inconsistency in the total standard deviation in the single-arbor circular saw, as well as in the twin bandsaw, can be in the order of 0.4mm, and in the double-arbor circular saw 0.2mm. The cause of inconsistencies can be examined with the use of graphic descriptors, as discussed in Chapters 6.7 and 6.8. The main causes of problems are typically unstable sawblade behaviour and insufficient holding capability. The long-term average descriptors of the three saw machines, when only cant variations are analysed, are presented in Table 7.5.

Table 7.5. *Average saw descriptor values in log breakdown in normal production. Values are in mm.*

Saw machine type	Total standard deviation	Between-board std. dev.	Between-segment std. dev.	Taper	Bend
Single-arbor circular saw	0.69	0.22	0.11	0.41	0.79
Double-arbor circular saw	0.18	0.10	0.05	0.29	0.28
Twin bandsaw	0.55	0.34	0.23	0.66	0.59

Inconsistencies are of the same order in benchmarking as in normal production. The average benchmarking descriptors for the three examined saw machines, when only cant variations are analysed, are presented in Table 7.6.

Table 7.6. *Average saw descriptor values in log breakdown in benchmarking. Values are in mm.*

Saw machine type	Total standard deviation	Reprodu cibility	Between-board std. dev.	Between-segment std. dev.	Taper	Bend
Single-arbor circular saw	0.68	0.14	0.20	0.10	0.64	0.49
Double-arbor circular saw	0.23	0.03	0.13	0.08	0.10	0.28
Twin bandsaw	0.56	0.07	0.32	0.22	0.68	0.62

Benchmarking provides data for the determination of the constants in Equation 6.24. A descriptor equation presents the general characteristics of a saw machine in a compact manner, including the total standard deviations for the examined log breakdown saw machines, Equations 7.1 to 7.3.

$$s_T = 0.57e^{0.28tnkFL} \pm 0.14 \quad \text{Single - arbor circular saw, n = 2, k = 0.0046m} \qquad (7.1)$$

$$s_T = 0.21e^{0.12tnkFL} \pm 0.03 \quad \text{Double - arbor circular saw, n = 1, k = 0.0050m} \qquad (7.2)$$

$$s_T = 0.44e^{1.20tnkFL} \pm 0.07 \quad \text{Twin bandsaw, n = 1, k = 0.0028m} \qquad (7.3)$$

where s_T is the total standard deviation (mm),
t is the sawing time (h),
n is the number of sawblades in a set-up,
k is the kerf size (m),
F is the feed speed (m/min), and
L is the cutting path length (m).

The total standard deviation, as well as the between-board standard deviation and the sawblade bend of the single-arbor saw and the twin bandsaw display sawing time dependence, Figures 7.3 and 7.12. Only minimal sawing time dependence is observed in the double-arbor circular saw, which uses 535mm diameter sawblades and kerf sizes of 5.0mm, Figure 7.8. This observation supports the conclusion that sawblade instability is a significant factor in sawing variation. The negative effect of thick, stable sawblades is naturally greater loss of wood in sawdust.

The descriptor functions confirm the observations above. The standard deviation of the single-arbor circular saw, Figure 7.4, and the twin bandsaw, Figure 7.13, show dependence on the *Time*Saw load* factor. The effects of sawblade wear start to cause increasing snaking in the twin bandsaw, as indicated by β = 1.20, sooner than in the single-arbor circular saw, which has β = 0.28. The standard deviation of the double-arbor circular saw is almost level over the whole test period, β = 0.12, Figure 7.9. The behaviour of the double-arbor circular saw indicates that the used sawblade change interval of eight hours may be unnecessarily short, and the blades could be used for significantly longer periods.

The coefficient of determination r^2 indicates improvement in predictability in using an exponential regression curve for the total standard deviation of the twin bandsaw, r^2 = 0.63, Figure 7.13. The value of r^2 = 0.06 for the double-arbor circular saw indicates no improvement, and the value r^2 = 0.26 some improvement for the single-arbor circular saw, Figures 7.9 and 7. 4. Critical approach is necessary when assessing the usefulness of the r^2 values, because the observed standard deviations have relatively small dispersion around descriptor functions, Equations 7.1 to 7.3. One may claim that the observed dispersion of data around a descriptor function, the reproducibility R, is a better indicator of the predictability of an equation than the r^2 value.

A graphic presentation reveals the individual differences between the saw machines, as in Figure 7.15. The evolution of total standard deviation in the double-arbor saw is level, indicating little dependence on sawblade wear and saw load. The single-arbor circular saw and the twin bandsaw have increasing dependence on sawing time and saw load. The difference between the saw machine types is in their inherent, characteristic levels of sawing variation in various production situations. The curves for the twin bandsaw and the double-arbor circular saw in Figure 7.15 stop at the *Time*Saw load* limit of their benchmarking tests.

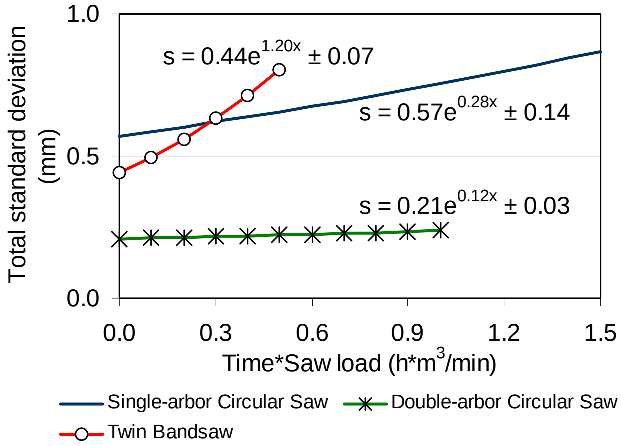


Figure 7.15. *Total standard deviation of three examined saw machines in log breakdown as a function of the Time*Saw load.*

When analysing a sawing situation in the context of sawblade wear, one can use average feed speed and cant height, which are used in normal log breakdown, in Equation 6.25 to calculate the function between sawing time and average increase in the total standard deviation, as in Figure 7.16, which indicates that, after eight hours of sawing, the sawing variation in the double-arbor circular saw increases by 0.1mm, whereas the variation in other saws increases by 0.2mm.

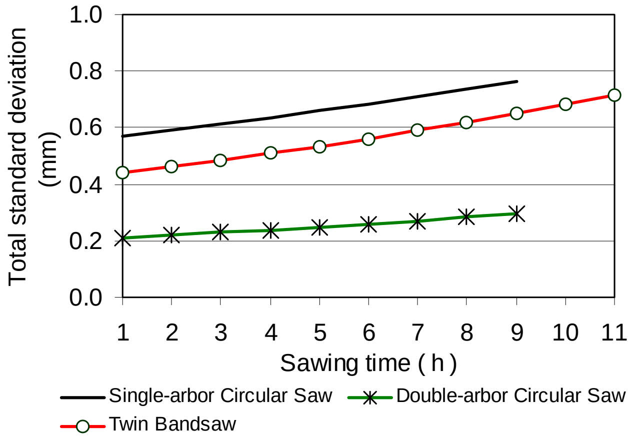


Figure 7.16. *Evolution of the total standard deviation over sawing time in log breakdown in three saw machines.*

Figure 7.17 demonstrates that sawblade bend is the major cause of sawing variation in all three saw machine types. The different bend behaviour of saw machines indicates different cause-effect processes. Besides sawblade wear and saw load, such factors as the mechanical details, particularly the maintenance of the saw machinery, have an effect on sawblade stresses.

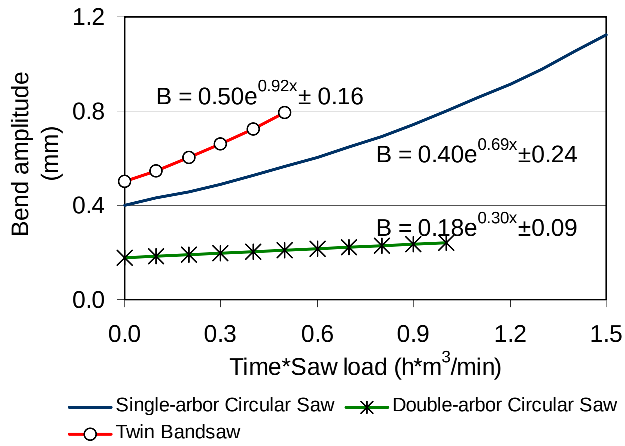


Figure 7.17. *Sawblade bend amplitude in the three examined saw machine types in log breakdown as a function of the Time*Saw load.*

Figures 7.15 and 7.17 illustrate the capabilities of the different saw machines. However, the main use of the method is aimed at analysing each individual saw machine in a sawmill under various process conditions over long periods.

Figures presenting the various standard deviations and sawblade bend provide a useful source of information when analysing a log breakdown saw machine. The graphic presentation of size curves and shapes, such as means and bend, is a further source of useful information. The examples presented in Appendix A, Chapters A.2.1, A.4.1 and A5.1, illustrate some such cases.

8 Case Studies in Cant Resaw

The details of normal production are presented in Tables 1.2 and 1.3. Benchmarking details are presented in Tables 1.4 and 1.5. Each mark in the data presentation figures represents an average value of fifty sawn pieces. The purpose of presenting trends in the normal production figures is to assist the reader to discern the general behaviour of presented descriptors. The trends in the benchmarking figures are supplied with descriptor equations that represent the behaviour of a saw machine in the benchmarking conditions.

8.1 Single-arbor Circular Saw, Type A

The saw machine used in this case study is presented in Appendix A, Chapter A.1. At early stages of tests, it became evident that the sawmill uses very tight patterns on their cants. This causes situations where outer flitches have a considerable amount of slab surface, particularly in set-ups with six or more boards. In certain cases, the chipper canter comes in contact with a cant only at butt end segments. This observation led to development and utilisation of a Reject Board Probability describer, as discussed in Chapter 6.9, and reported in Appendix A, Chapter A.3.

The total standard deviation of a single-arbor circular saw in normal production cannot be estimated from data containing too many variables, as in Figure 8.1. Sawing variation in set-ups is variously depending on:

- Size and shape of cants
- Number of pieces in a set-up
- Board's location in a set-up
- Precision of feedworks
- Use of fixed or changing set-up
- Sawblade condition in each kerf.

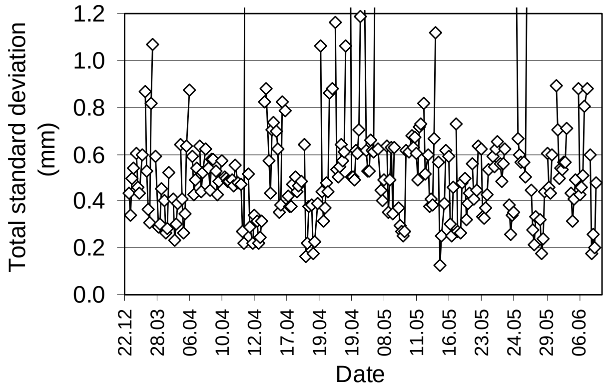


Figure 8.1. *Variation of total standard deviation in a single-arbor circular saw in normal production. The average of all grand total standard deviations is 0.54mm. Set-ups are connected with a line.*

Flitches are affected chiefly by variation arising from unfit cant size for a pattern, inaccuracy of centring, and side penetration of sawblades. The centrepieces are least effected by such factors. However, the centrepieces 'feel' the general effects of sawing stresses, and show variation in saw machine behaviour under varying load situations.

Therefore, it is possible to estimate the saw machine behaviour by observing the sawing effects on centre heartwood pieces. The following discussion exclusively relates to centrepieces, because the differences in flitch behaviour require an alternative analytical approach. Flitches are discussed separately in Appendix A, Chapter A.3.

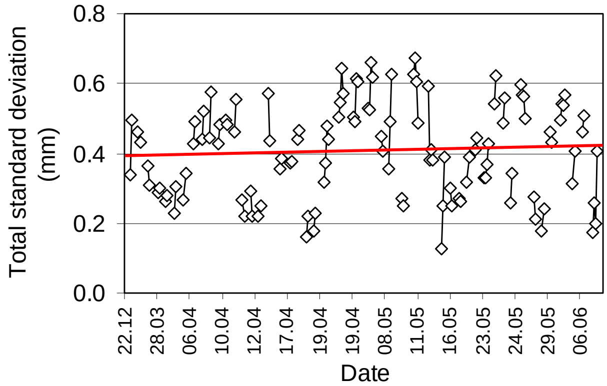


Figure 8.2. *Total standard deviation of the centrepieces in cant resaw in a single-arbor circular saw. The total standard deviation of the centrepieces is 0.41mm.*

Although the average total standard deviation of the centrepieces in normal production is quite stable, the total standard deviation shows considerable dispersion of values, indicating that the process parameters are not under control over a longer periods, as in Figure 8.2. The cause of such a degree of variation may be:

- Change in saw operation
- Use of a changing set-up
- Number of pieces in a set-up (saw load)
- Raw material properties, frozen wood
- Unstable sawblade behaviour.

When results of sawing variation in normal production are presented as a function of the *Saw load*, based on the number of pieces in a saw set-up, the average standard deviations vary from each other, as in Figure 8.3. The more pieces there are in a set-up, the larger the deviation. The average total standard deviation in a 4-piece set-up is approximately 0.32mm, in a 6-piece set-up 0.38mm, and in 8-piece 0.55mm.

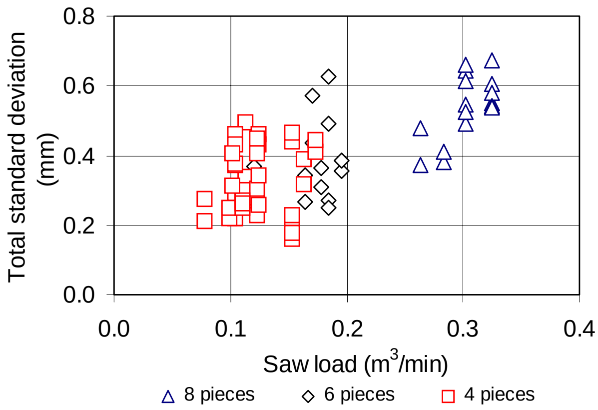


Figure 8.3. *Total standard deviation of centrepieces in cant resaw in a single-arbor circular saw based on the Saw load. The data includes all feed speeds, cant sizes and sawing times.*

The between-board standard deviation shows similar behaviour to the total deviation but on a lower level. The average between-board standard deviation in a 4-piece set-up is approximately 0.22mm, in a 6-piece set-up 0.27mm, and in 8-piece 0.35mm. The between-segment standard deviation is independent of the *Saw load*, but the values indicate relatively similar behaviour in all set-ups. The average between-segment standard deviations are between 0.10mm and 0.16mm. The average sawblade bend amplitudes vary as strongly as the total standard deviation in the different set-ups. The amplitude in a 4-piece set-up is 0.31mm, in a 6-piece set-up 0.39mm and in 8-piece set-up 0.51mm. Sawblade bend amplitudes of up to 1.0mm are observed.

8.1.1 Benchmarking of Single-arbor Circular Saw, Type A

The tested saw set-up was a 4-piece set-up, with the exception of cant size 175mm that was sawn in a 6-piece set-up.

The chronological presentation of the total standard deviations in benchmarking discloses similar behaviour to that seen in normal production, as in Figure 8.4.

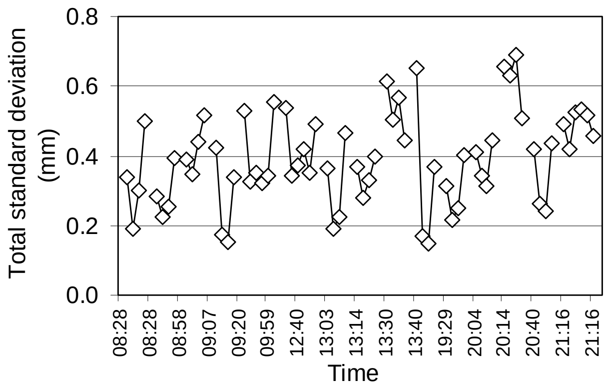


Figure 8.4. *Total standard deviation in a single-arbor circular saw in chronological order during the benchmarking test. The average standard deviation is 0.4mm.*

When the centrepieces are displayed as a function of the *Saw load*, the total standard deviation indicates layered, increasing dependence on the *Saw load*, as in Figure 8.5. Variations in the test groups are more compact at the lower *Saw load*s of 0.1m^3/min, and disperse more strongly at higher *Saw loads*. Evaluation of the 4-piece set-up indicates that sawblade wear increases the total standard deviation at all *Saw load* levels. The increase is more prominent at higher *Saw load* levels. In a 4-piece set-up, a *Saw load* $0.12m^3$/min or less produces an average total standard deviation of 0.4mm or less, independent of sawing time. A level of 0.3mm deviation is reached at a *Saw load* $0.1m^3$/min. This data is consistent with the values recorded in normal production, as in Figure 8.3.

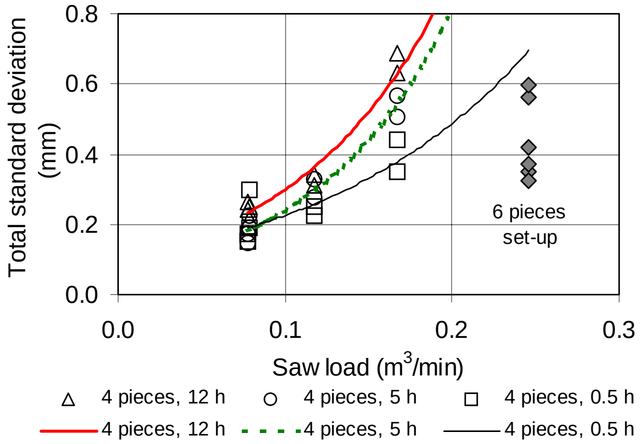


Figure 8.5. *Total standard deviation of the centrepieces as a function of the Saw load in cant resaw in a single-arbor circular saw. The 6-piece set-up is marked in bold type.*

Because the sawing time is known accurately in benchmarking, the descriptors can be presented as a function of the *Time*Saw load*. The equation presented for the total standard deviation in Figure 8.6 shows that the characteristic minimum standard deviation of the examined single-arbor circular saw in heartwood sawing in a 4-piece set-up is 0.21mm.

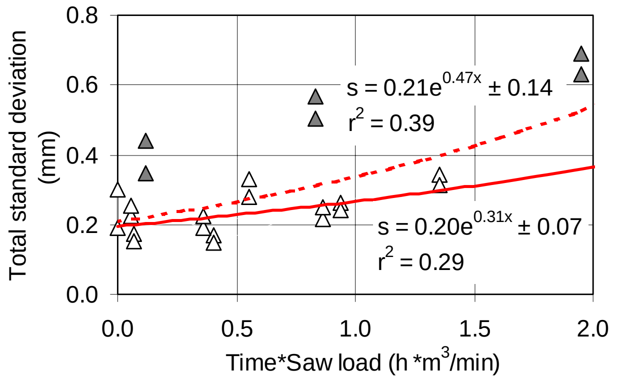


Figure 8.6. *Total standard deviation as a function of the Time*Saw load in cant resaw in a single-arbor circular saw. The feed speed in bold type marks is high 85m/min.*

The descriptor equation for the total standard deviation for all benchmarking deviations is $s_T=0.21e^{0.47x}\pm0.14$. The reproducibility of the centrepiece production is 0.14mm. The effect of high feed speed is a cause of poor reproducibility. When the samples sawn at 85m/min feed speed are discarded, the equation will be $s_T=0.20e^{0.31x}\pm0.07$, and the reproducibility is 0.07mm. Similar behaviour is seen in the between-board standard deviation. The phenomenon is not as clear in the between-segment or bend data. The increase of total standard deviation in large *Time*Saw loads* is chiefly due to the increase in the between-board standard deviation, $s_B=0.12e^{0.51x}\pm0.10$, as in Figure 8.7, and sawblade instability, as in Figure 8.9. This indicates increasing instability of the saw machine as the load on the machinery increases. At lower *Time*Saw load*s, the between-board standard deviation level of 0.2mm is consistent with the values recorded during normal production. The characteristic minimum between-board standard deviation of the examined single-arbor circular saw in heartwood sawing of a 4-piece set-up is 0.12mm.

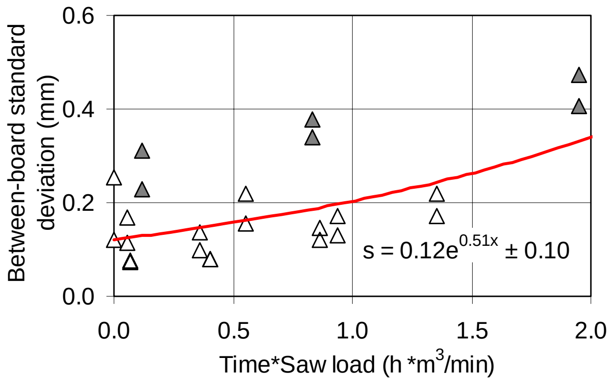


Figure 8.7. *Between-board standard deviation in a single-arbor cant resaw as a function of the Time*Saw load. The feed speed in bold type marks is high 85m/min.*

The between-segment standard deviation is an indicator of the consistency of a sawblade's cutting process. Size may vary, but if it remains relatively stable over the entire length of a board, the cutting is consistent, and the between-segment standard deviation remains negligible. The between-segment standard deviation is nearly independent of load and time, $s_M=0.08e^{0.35x}\pm0.03$, as in Figure 8.8. The independence indicates that the increasing sawing load does not cause local disturbances in the process. It may be assumed that, when the between-segment standard deviation is less than 0.1mm, a single-arbor circular saw does not have significant process instabilities. The characteristic minimum between-segment standard deviation in heartwood sawing of a 4-piece set-up is 0.08mm. Constant β of 0.35 in the equation indicates that the deviation is less affected by the increase in saw load and time than the total and between-board deviations.

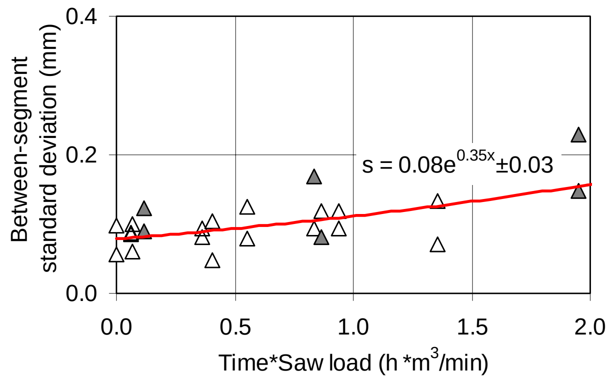


Figure 8.8. *Between-segment standard deviation as a function of Time*Saw load in a single-arbor cant resaw. The feed speed in bold type marks is high 85m/min.*

Sawblade bend increases with increasing *Time*Saw load*, $B=0.22e^{0.35x}\pm0.18$. The sawblade bend increase contributes most to the growth of the total standard deviation, as in Figure 8.9. The remaining effect is caused by the saw machine itself. The characteristic minimum sawblade bend amplitude in heartwood sawing of a 4-piece set-up is 0.22mm. The power of 0.35 in the equation indicates that the deviation is less affected by the increase of saw load and time than the total and between-board deviations.

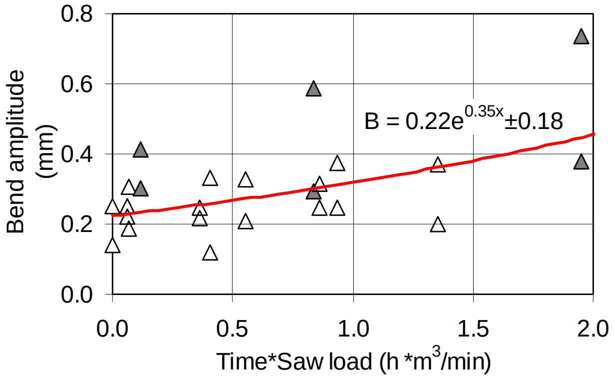


Figure 8.9. *Sawblade bend in cant breakdown in a single-arbor circular saw as a function of the Time*Saw load. The feed speed in bold type marks is high 85m/min.*

8.1.2 Conclusions on Single-Arbor Circular Saw, Type A

The sawing process of centrepieces in the examined single-arbor circular saw is under control. The normal, average level of total standard deviation is from 0.3mm to 0.4mm. Data indicates that the saw machine operation is consistent. Thus, it is reasonable to assume that the standard deviation level of 0.3mm to 0.4mm is characteristic of the saw machine, and that the average level cannot be further reduced with improved maintenance activities. However, use of reduced *Saw load*s, in the area of 0.1m^3/min, may result in a standard deviation level of 0.2mm. How practical this may be, in the context of production and surface quality, is an other question.

The average total standard deviation depends on the number of pieces in a saw set-up. Thus, the descriptors must be presented in the context of each set-up, Table 8.1.

Table 8.1. *Benchmarking descriptors for centrepieces in a single-arbor circular saw.*

	Benchmark value		Equation constants in 4-piece set-up		Reproducibility
	4-piece (mm)	6-piece (mm)	α	β	(mm)
Total standard deviation	0.31	0.44	0.20	0.31	0.07
Between-board standard deviation	0.19	0.30	0.12	0.51	0.10
Between-segment standard deviation	0.10	0.11	0.08	0.35	0.03
Taper	0.47	0.49			
Bend amplitude	0.74	0.47	0.22	0.35	0.18

The behaviour of the total standard deviation in high feed speeds indicates that there is a limit to the feed speed that can be used if one wants to keep the deviation within acceptable limits. In the benchmarking, a feed speed of 60m/min did not cause excessive total standard deviation, whereas a feed speed of 85m/min produced deviations that were twice as large. Evidently, the limit lies between these values.

8.2 Single-arbor Circular Saw, Type B

The saw machine used in this case study is presented in Appendix A, Chapter A.2.3. Analysis of the saw machine is performed by observing variation of the centrepieces. Flitches are analysed separately in Appendix A, Chapter A.3.

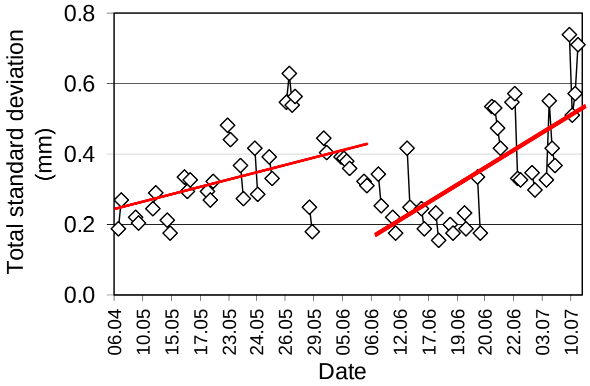


Figure 8.10. *Total standard deviation of centrepieces in a single-arbor circular saw in normal cant resaw. The grand total standard deviation of the centrepieces is 0.35mm. Set-ups are connected with a line.*

The standard deviation of the centrepieces in normal production is not even, as in Figure 8.10. A shift in the standard deviation level has taken place in early June in the same manner as observed in log breakdown, as in Figure 7.1. The sawing parameters are not under control throughout the period of production data collection. The range of total standard deviation of the centrepieces exceeds 0.4mm. Wide variation in the total standard deviation is due partly to changes in saw operation arising from production pressures in May, as well as to the change from two-shift to a one-shift sawing in June.

When results are presented as a function of the *Saw load*, based on the number of pieces in a saw set-up, the standard deviation groups of the three set-ups vary from each other, as in Figure 8.11. The average total standard deviation level for a 4-piece set-up is 0.28mm, for 6-pieces 0.42mm, and for 8-pieces 0.53mm.

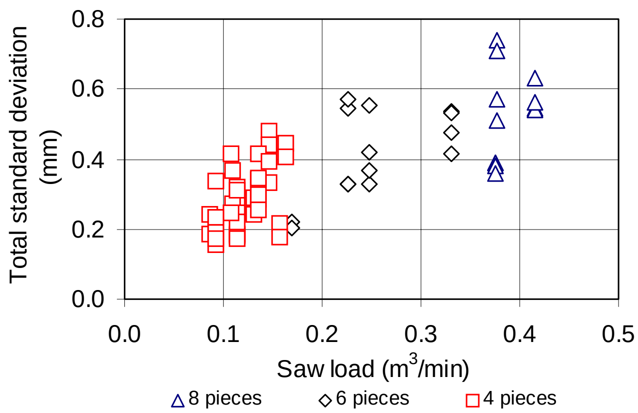


Figure 8.11. *Total standard deviation of centrepieces in cant resaw in normal production in a single-arbor circular saw based on the Saw load. The data includes all feed speeds, cant sizes and sawing times.*

The average bend amplitude of 0.2mm and its independence of the *Saw load* indicate a relatively stable sawing process, as is similarly indicated by the small between-segment deviation, less than 0.1mm. On the other hand, the between-board standard deviation is almost equal to the total standard deviation. Therefore, one can assume that the main cause of sawing variation is inaccurate curve sawing mechanism.

8.2.1 Benchmarking of Single-arbor Circular Saw, Type B

The standard deviation of flitches differs from that of centrepieces, Figure 8.12, in the manner already noted in Chapter 8.1. Therefore, the benchmarking analysis of the single-arbor saw machine, type B, is based on data from the centrepieces.

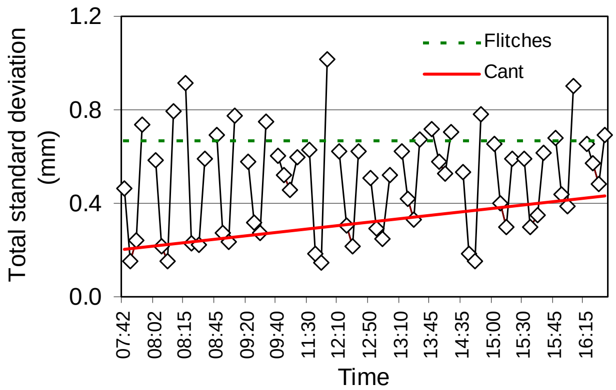


Figure 8.12. *Total standard deviation of cants and flitches in a single-arbor circular saw in benchmarking in chronological order. The average standard deviation of cants is 0.32mm, and for flitches 0.67mm.*

Presentation of data as a function of the *Time*Saw load* shows considerable dependence on saw load and time, as in Figure 8.13.

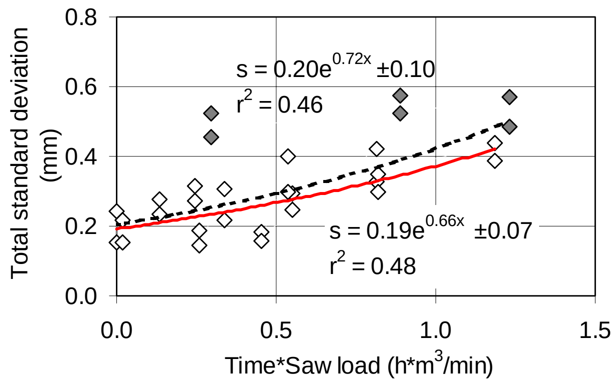


Figure 8.13. *Total standard deviation as a function of the Time*Saw load in cant resaw in a single-arbor circular saw in a fixed 4-piece set-up. The feed speed in bold type marks is high 70m/min.*

The descriptor equation for the total standard deviation with all benchmarking deviations is $s_T=0.20e^{0.72x}\pm0.10$, where the reproducibility of centrepiece production is 0.10mm. The effect of high feed speed 70m/min, is the cause of poor reproducibility. When the samples sawn at 70m/min feed speed are discarded, the equation will be $s_T=0.19e^{0.66x}\pm0.07$, and the reproducibility 0.07mm. Similar behaviour is seen in the sawblade bend. The phenomenon is not as clear in the between-board standard or between-segment deviation. Three quarters of the increase in the total standard deviation is due to increase in the between-board standard deviation, $s_B=0.15e^{0.78x}\pm0.09$. The increase in the between-board standard deviation, on the other hand, is a result of increasing sawblade bend $B=0.11e^{0.81x}\pm0.11$, as in Figure 8.14. Process instability along the board lengths has less effect in the total standard deviation because the consistency of process is stable, $s_M=0.04e^{0.79x}\pm0.04$.

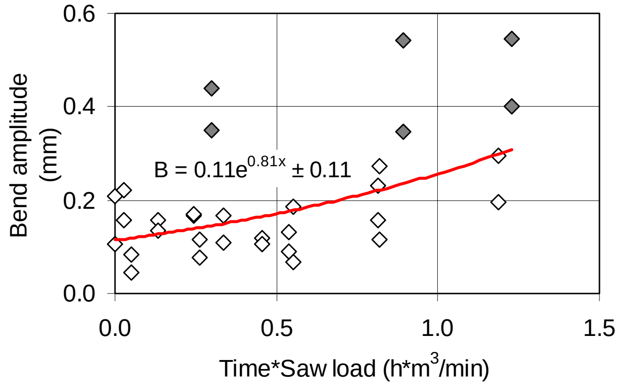


Figure 8.14. *Sawblade bend in cant resaw in a single-arbor circular saw based on the Time*Saw load. The feed speed in bold type marks is high 70m/min.*

There is no correlation between the total standard deviation and feed speed, the correlation is 0.07. Therefore, tests studying effects of feed speed alone would not give relevant results. The correlation between the total standard deviation and cant size is 0.87 and with sawing time 0.47. Thus, the cant size is the strongest factor affecting sawing variation. Sawing time exerts a marked effect on the total standard deviation, as in Figure 8.15. The range of marks at one, four and seven hours, representing the various feed speeds and cant sizes, are more distinct than the sawblade wear itself. This indicates that sawblade wear, although important, is not the most important factor influencing sawing quality. The standard deviation of a worn sawblade is, on average, 0.2mm greater than in the case of a newly installed blade.

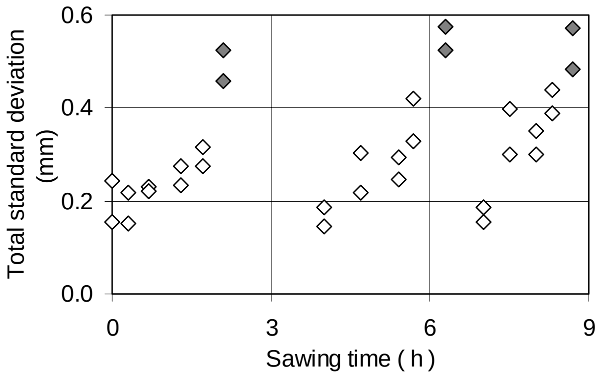


Figure 8.15. *Effect of sawblade wear (sawing time) on the total standard deviation is seen in the test groups during benchmarking in a single-arbor circular saw. The feed speed in bold type marks is high 70m/min.*

8.2.2 Conclusions on Single-Arbor Circular Saw Type B

In benchmarking, the sawing process of centrepieces in the examined single-arbor circular saw is under control. However, in normal production, this is not the case, as in Figure 8.10. The normal average level of total standard deviation for all cant sizes is close to 0.4mm. Data indicates that the saw machine operates consistently, as in Table 8.2. Thus, it is reasonable to assume that a standard deviation level of 0.4mm is characteristic of the saw machine, although the benchmarking indicates that a level below 0.3mm is attainable. For example, use of proper saw loads, in the range of 0.1 m^3/min, may lead to a consistent standard deviation level close to 0.3mm. For a cant size of 150mm, this results in a feed speed of 50m/min.

Table 8.2. *Benchmarking descriptors for centrepieces and flitches in a single-arbor circular saw type B.*

	Benchmark value 4-piece (mm)	Equation constants α	β	Reproducibility (mm)
Total standard deviation	0.32	0.19	0.66	0.07
Between-board standard deviation	0.24	0.15	0.78	0.09
Between-segment standard deviation	0.07	0.04	0.79	0.04
Taper	0.09			
Bend amplitude	0.51	0.11	0.81	0.11

The behaviour of the total standard deviation in high feed speeds indicates that there is a limit to the feed speed that can be used if one wants to maintain the deviation within acceptable limits. In the benchmarking, the feed speed 50m/min did not cause excessive total standard deviation, whereas the feed speed 70m/min produced a twofold increase in deviations. Therefore, the limit lies between these values.

This analysis does not include the final 15 percent of log length due to existing measuring limitations.

8.3 Double-arbor Circular Saw

The saw machine used in this case study is presented in Appendix A, Chapter A.4.3. The average total standard deviation of the double-arbor circular saw is at 0.25mm, as in Figure 8.16. The average deviation remains relatively even. However, large deviations exist, particularly in the outer centrepieces and in splitting only two pieces, indicating that the process parameters are not quite under control.

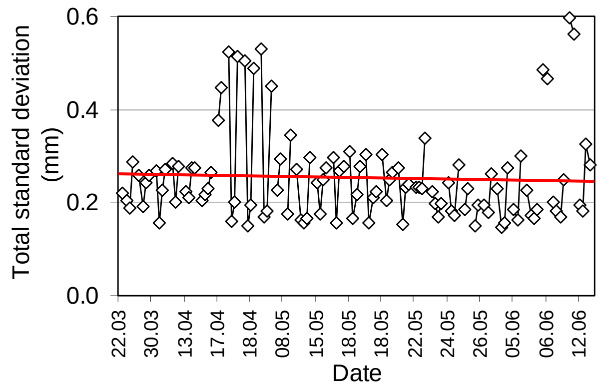


Figure 8.16. *Total standard deviation in a double-arbor circular saw in normal production. The data includes all cant sizes, feed speeds and sawing patterns for the recorded samples. Set-ups are connected with a line.*

When results are presented as a function of the *Saw load* and the number of pieces in saw set-ups, the standard deviation reveals that some of the 2-piece set-ups differ from others significantly, as in Figure 8.17. Set-ups with 3, 4 and 5 pieces concentrate around the standard deviation level of 0.2mm. On the other hand, half of the 2-piece set-ups, and the 4-piece set-ups that have standard deviation problems in outer boards, have a standard deviation of over 0.4mm, as in Figure 8.16.

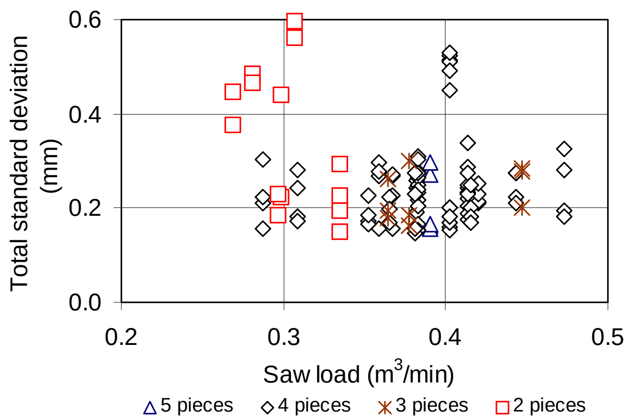


Figure 8.17. *Total standard deviation in cant resaw in a double-arbor circular saw in normal production.*

The between-board and the between-segment standard deviations, as well as the bend amplitude, indicate a decreasing trend as the saw load increases, as in Figure 8.18. This phenomenon indicates that the process problems are more significant with smaller cant sizes, sawn at higher speeds.

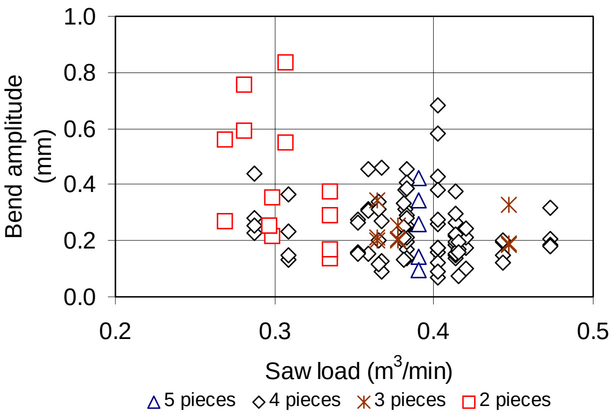


Figure 8.18. *Increase of sawblade bend trend is significant as the Saw load grows in normal production.*

8.3.1 Benchmarking of Double-arbor Circular Saw

Owing to the abundance of certain cant sizes, additional feed speeds of 70m/min and 100m/min are used with certain cant sizes of 110mm and 150mm. The low (40m/min) and high (85m/min and 100m/min) feed speeds are not used in regular sawing for some of the tested cant sizes. Thus, some of the measured data is taken from the extreme limits of the double-arbor cant resaw process. However, this data also emphasises system behaviour at these limits.

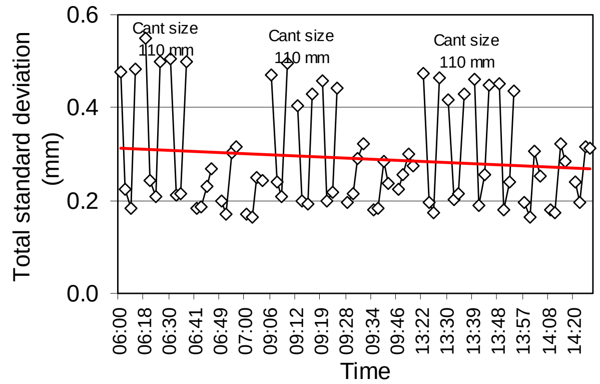


Figure 8.19. *Total standard deviation in a double-arbor circular saw in benchmarking. The data includes all test cant sizes and feed speeds. The cant size of 110mm shows large outer board variations during all test periods and feed speeds.*

The total standard deviation results are presented chronologically in Figure 8.19. The standard deviation of the outer boards of 110mm cants differ significantly from the outer boards in other cant sizes. Therefore, the outer boards sawn from the 110mm cants are presented separately in the graphs, as in Figure 8.20, and are examined in more detail. All between-board and between-segment standard deviations are almost independent of the *Time*Saw load*. The average total standard deviation of all pieces during the test is 0.29mm. If the outer boards at a cant size of 110mm are excluded from the calculation, the total standard deviation is 0.23mm, which is a ‘normal’ level for the examined double-arbor resaw machine, $s_T=0.22e^{0.04x}\pm0.05$. The reproducibility of centrepiece production is 0.05mm, without the outer boards from 110mm cants.

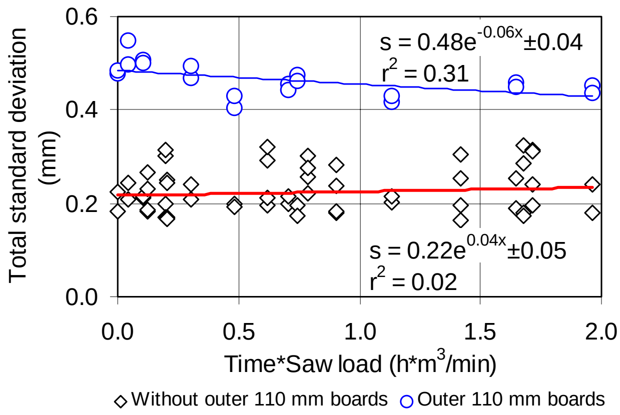


Figure 8.20. *Total standard deviation versus the Time*Saw load in cant resaw in a double-arbor circular saw.*

The between-board standard deviation, $s_B=0.14e^{-0.02x}\pm0.04$, which represents the size variation between boards without the outer 110mm boards, is relatively small. Similar standard deviation is seen in between-segment standard deviation, $s_M=0.07e^{0.06x}\pm0.02$. The small between-segment deviation indicates that the sawing process is even throughout the board lengths, with the exception of the outer boards sawn from 110mm cants, which display large deviations, as in Figures 8.20 and 8.21.

Sawblade bend, without the outer 110mm boards, shows similar independence, $B=0.21e^{0.08x}\pm0.07$, as seen in the between-segment standard deviation, of the saw load, as in Figure 8.21. The bend amplitude of the outer boards of small cants is three to four times larger compared with the more stable sawing process of larger cant sizes.

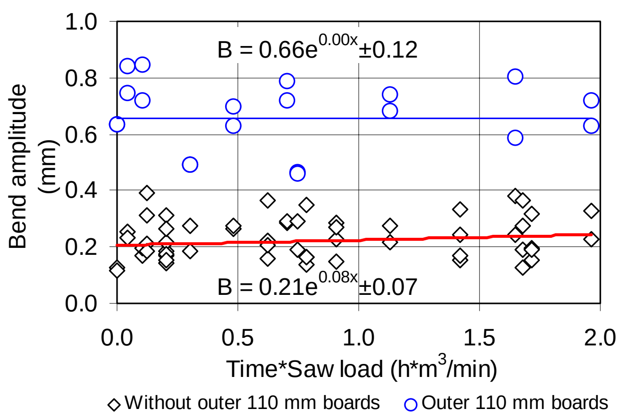


Figure 8.21. *Sawblade bend in a double-arbor circular saw in log breakdown as a function of the Time*Saw load.*

The total standard deviation as a function of feed speed, log size or sawing time alone do not have a marked effect on the deviation. The various feed speeds and cant sizes have an effect on the data groups, but the general trend is level.

8.3.2 Conclusions on Double-arbor Circular Saw in Cant Resaw

The cant resaw process is under control, with the exception of the small cant sizes, which experience serious instability problems. The average total standard deviation of 0.23mm, under normal production parameters, may be considered normal for the double-arbor cant resaw examined. The numerical benchmarking results are presented in Table 8.3.

Table 8.3. *Benchmarking characteristics of the double-arbor cant resaw without the 110mm cants.*

	Benchmark value (mm)	Equation constants α	β	Reproducibility (mm)
Total standard deviation	0.23	0.22	0.04	0.05
Between-board standard deviation	0.14	0.14	-0.02	0.04
Between-segment standard deviation	0.07	0.07	0.06	0.02
Taper	0.34			
Bend amplitude	0.23	0.21	0.08	0.07

8.4 Triple Bandsaw

The saw machine used in this case study is presented in Appendix A, Chapter A.5.3. The average total standard deviation of the triple band saw is 0.48mm, as in Figure 8.22. The average total standard deviation is relatively steady, showing improvement over time. However, large deviations exist in the centrepieces, where standard deviation may be about 0.2mm larger or smaller than in the outer boards. Considering the structure of the triple bandsaw centre, it is evident that the length of the free span before cutting the centrepieces, compared with the outer boards, may be a cause of the variation.

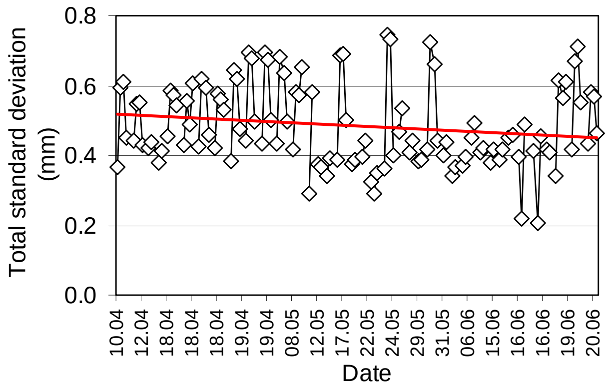


Figure 8.22. *Total standard deviation in a triple bandsaw in normal cant resaw. The data includes all cant sizes, feed speeds and sawing patterns for the samples. Each set-up is connected with a line.*

In general, the sawing process is under control. However, the variation of boards sawn in saw 3 is significantly different from those sawn in saws 1 and 2 alone.

When results are presented as a function of the *Saw load* and the number of pieces in a saw set-up, the standard deviation indicates that the 2-piece set-ups differ from the 4-piece set-up. The general level of total standard deviation in 4-piece set-ups is approximately 0.5mm, and in 2-piece set-ups 0.4mm. The standard deviation in 2-piece set-ups is relatively consistent, whereas the 4-piece standard deviation has wider range, from 0.4mm to 0.7mm.

A detailed examination of bandsaws requires an analysis of each board in the triple bandsaw. When the boards in a 4-piece set-up are presented individually, as in Figure 8.23, the differences in the boards become obvious. The total standard deviation in both centrepieces is 0.6mm (boards 2 and 3), and from 0.4mm to 0.5mm in the outer boards (boards 1 and 4).

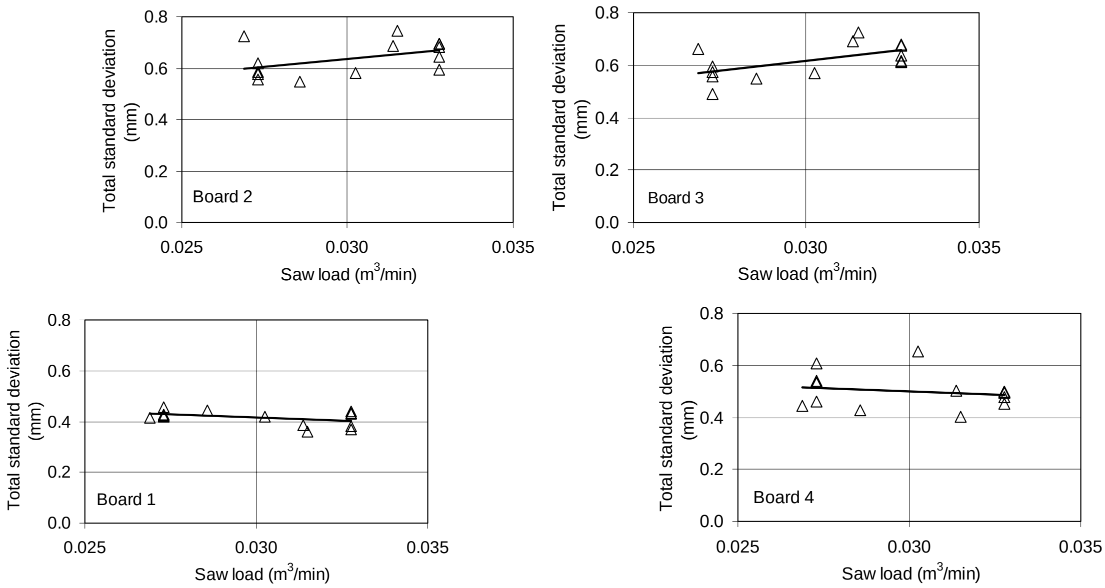


Figure 8.23. *The total standard deviation of boards sawn in a triple bandsaw in normal cant resaw. The data includes all cant sizes and feed speeds in a 4-piece set-up. The outer boards are at the bottom and centre ones at the top.*

Assuming that the total standard deviation of 0.4mm in the left outer board is normal, the standard deviation in the right outer board is 0.1mm inferior. Because the standard deviation in the left centrepiece is 0.6mm, as is the standard deviation in the right centrepiece, one may assume that the sawing quality of saw 2 is equal to that of saw 1 in the triple bandsaw centre. The cause of the 0.1mm greater standard deviation in the right outer board thus lies in the previous saw machine producing the outermost right face.

The between-board standard deviations are smallest, near 0.2mm, for the centrepieces, indicating good accuracy from board to board. Even the better outer board on the left displays a larger between-board standard deviation than the centrepieces, albeit only slightly. The right outer board differs from the others. The range of values is wider and the average differs 0.2mm from the centrepiece values. A cause of the larger standard deviations in the outer boards may lie in square cant size variation due to the previous saw centre, or in feedworks operation.

The between-segment standard deviation in the outer boards is less than 0.2mm, and in the centrepieces from 0.2mm to 0.3mm. This indicates larger local size variations in the centrepieces compared with the outer boards. The probable cause for these local variations is the shaking of the final part of the square cant to be sawn. The outermost faces of the outer boards, on the other hand, are from a previous cutting process using a larger cant, and the inner faces of the outer boards are sawn in a more stable process situation, and thus the local size variations along the faces are less prominent.

The level of bend amplitude in the centrepieces is approximately 0.8mm, and in the outer boards 0.5mm. The bend amplitude is the value of sawblade deflection about the board mean. The amplitude is a result of two sawblades, one of which may act in a stable manner, and the other erratically. The data indicates that the sawblade behaviour in saw 2 is the major cause for the bend, since the outer boards show smaller bend values.

8.4.1 Benchmarking of Triple Bandsaw

The normal 4-piece lots sawn between the benchmarking test samples are also used in benchmarking. These lots had cant sizes of 150mm and 175mm, and were sawn at 65m/min and 60m/min feed speeds, respectively.

The average total standard deviation of the triple band saw is at 0.6mm, as in Figure 8.24. The average total standard deviation is steady, but the standard deviation in the centrepieces is approximately 0.4mm larger than that in outer boards.

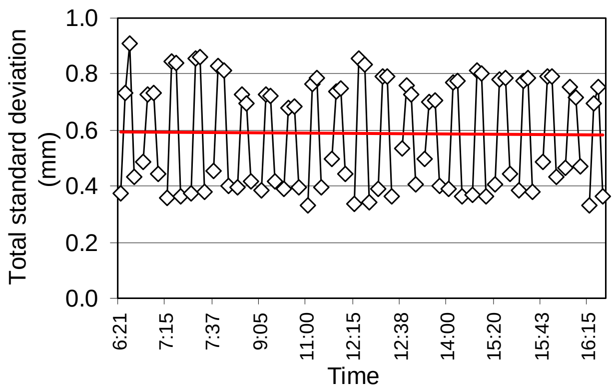


Figure 8.24. *Total standard deviation in a triple bandsaw in benchmarking. The data includes all cant sizes and feed speeds for the samples. Set-ups are connected with a line.*

The sawing process parameters are steady, but not under control. The total standard deviation is presented as a function of the *Time*Saw load* in Figure 8.25. The total standard deviation in bandsaws in a 4-piece set-up is relatively independent of the *Time*Saw load*. There are, however, two standard deviation levels, one for the centrepieces (boards 2 and 3), $s_{TCentre}=0.78e^{-0.09x}\pm0.05$, and one for the outer boards (boards 1 and 4), $s_{TOuter}=0.39e^{0.26x}\pm0.05$. The reproducibility of production at both standard deviation levels is 0.05mm.

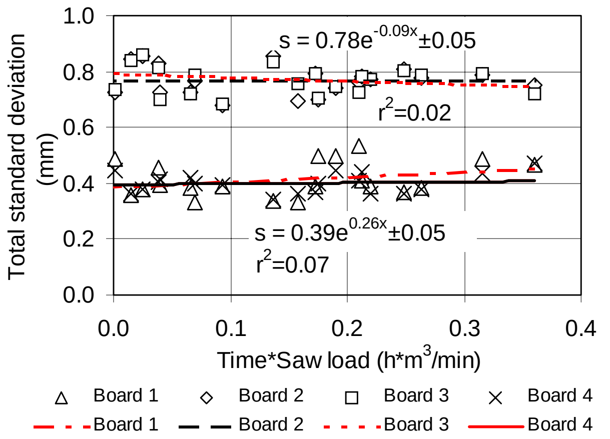


Figure 8.25. *Total standard deviation in a triple bandsaw as a function of the Time*Saw load.*

The average between-board standard deviation of 0.23mm is relatively independent of the *Time*Saw load* and the cutting location. However, the outer and inner deviations show clear differences, $s_{Bcentre}=0.25e^{-0.17x}\pm0.04$, and outer boards, $s_{BOuter}=0.18e^{0.54x}\pm0.05$. Thus, the process is consistent for the inner pieces, but increases with time for the outer pieces. The dispersion of values is larger than in the total standard deviations because the reproducibility values are higher, respectively 0.17mm and 0.13mm.

There are two levels of between-segment standard deviations depending on the cutting location, $s_{MCentre}=0.49e^{-0.32}\pm0.06$ and $s_{MOuter}=0.20e^{-0.37x}\pm0.03$. There are similarly two levels of sawblade bend depending on the cutting location, as in Figure 8.26. The average level of bend in the centrepieces is 1.4 mm and in the outer boards 0.6mm.

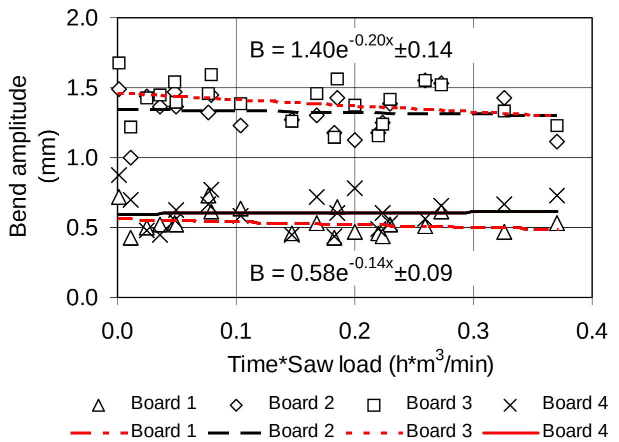


Figure 8.26. *Sawblade bend as a function of the Time*Saw load in a triple bandsaw.*

The two bend levels, $B_{Centre}=1.40e^{-0.20x}\pm0.14$ and $B_{Outer}=0.58e^{-0.14x}\pm0.09$, indicate that sawblade behaviour is the principal cause of large standard deviation in general and of the variation difference between the cutting positions in particular.

8.4.2 Conclusions on Triple Bandsaw in Cant Resaw

Based on the data collected during benchmarking and normal production, one may assume, that the total standard deviation of 0.4mm in the outer boards is characteristic to the triple bandsaw group. The inner boards displayed an inferior sawing capability on 9

August compared with the normal production from 10 April to 20 June. During normal production, the total standard deviation was 0.6mm and during benchmarking 0.8mm. The between-board standard deviations are all in average 0.2mm, indicating consistent accuracy from board to board.

The between-segment standard deviation in the outer boards is 0.2mm, and in the centrepieces from 0.4mm to 0.6mm. This indicates large local size variations in the centrepieces compared with the outer boards. A probable cause of such local variations is sawblade deflection, or shaking of the final part of the cant being sawn. The outermost faces of the outer boards, on the other hand, are from a previous cutting process being used to centre the cant, and the inner faces of the outer boards are sawn in a more stable process situation in saws 1 and 2, and thus the local size variations along the faces are less prominent. The level of sawblade bend amplitude in the centrepieces is approximately 1.5mm, and in the outer boards 0.6mm.

The cant resaw process is not under control. The centring roll mechanism, and the cant release from it, causes extensive sawblade bend, that increases standard deviation in saw 3 by 0.2mm to 0.4mm, and approximately 0.1mm in saws 1 and 2, Tables 8.4 and 8.5. After centring mechanism maintenance, a total standard deviation of 0.4mm or better can be reached. Currently, the average total standard deviation is 0.59mm.

Table 8.4. *Benchmarking characteristics of saws number 1 and 2 in triple bandsaw.*

	Benchmark value (mm)	Equation constants		Reproducibility (mm)
		α	β	
Total standard deviation	0.41	0.39	0.26	0.05
Between-board standard deviation	0.20	0.18	0.54	0.05
Between-segment standard deviation	0.19	0.20	-0.37	0.03
Taper	-0.12			
Bend amplitude	0.58	0.58	-0.14	0.09

Table 8.5. *Benchmarking characteristics of saw number 3 in triple bandsaw.*

	Benchmark value (mm)	Equation constants		Reproducibility (mm)
		α	β	
Total standard deviation	0.77	0.78	-0.09	0.05
Between-board standard deviation	0.25	0.25	-0.17	0.04
Between-segment standard deviation	0.47	0.49	-0.32	0.06
Taper	0.06			
Bend amplitude	1.36	1.40	-0.20	0.14

This analysis and conclusions include the entire length of centrepieces.

8.5 Descriptor Correlations

A study on saw descriptor correlations was performed using the data collected from normal production. The number of descriptors used in this thesis is large and therefore not practical for sawmill applications. Thus, the purpose of the correlation study was to identify those descriptors providing the most value to sawmill management and as potential alert factors in future automated applications. A sample of a correlation study for the single-arbor circular saw, type A, using data from the inner centrepieces, is presented in Table 8.6.

Table 8.6. *Correlation of saw descriptors in a single-arbor circular saw, type A, in cant resaw.*

	Total standard deviation	Smallest within-board std. dev.	Largest within-board std. dev.	Between-board standard deviation	Taper	Snaking	Between-segment standard deviation	Smallest within-segment std. dev.	Largest within-segment std. dev.	Bend amplitude
Total standard deviation		0.76	**0.88**	**0.95**	-0.35	**0.90**	0.62	**0.89**	**0.98**	0.41
Smallest within-board std. dev.	0.76		0.71	0.62	-0.27	**0.83**	0.64	0.64	0.75	0.40
Largest within-board std. dev.	**0.88**	0.71		0.74	-0.36	**0.89**	0.60	**0.80**	**0.88**	0.39
Between-board std. deviation	**0.95**	0.62	0.74		-0.26	0.75	0.46	**0.86**	**0.92**	0.32
Taper	-0.35	-0.27	-0.36	-0.26		-0.30	-0.49	-0.32	-0.31	-0.06
Snaking	**0.90**	**0.83**	**0.89**	0.75	-0.30		0.65	0.78	**0.89**	0.39
Between-segment std. deviation	0.62	0.64	0.60	0.46	-0.49	0.65		0.48	0.52	0.55
Smallest within-segment std. dev.	**0.89**	0.64	**0.80**	**0.86**	-0.32	0.78	0.48		**0.86**	0.40
Largest within-segment. std. dev.	**0.98**	0.75	**0.88**	**0.92**	-0.31	**0.89**	0.52	**0.86**		0.35
Bend amplitude	0.41	0.40	0.39	0.32	-0.06	0.39	0.55	0.40	0.35	

The correlation shows that there exists a strong correlation between the total standard deviation and between-board standard deviation, largest within-board standard deviation, snaking, and the smallest and largest within-segment standard deviations. Therefore, the total standard deviation can be used to represent these descriptors. Table 8.6 shows that the between-segment has no strong correlation with any of the other descriptors. Taper is an independent descriptor, having no correlation with other characteristics. The bend amplitude has a moderate correlation with the between-segment standard deviation. Thus, they provide information to an analysis. The bend amplitude has also additional value in its graphic form.

The correlation analysis was performed in all four saw machines. The results show that, in cant resaw, the descriptors of the two single-arbor circular saws, from two different manufacturers, behave almost identically. The double-arbor circular saw similarly manifests similar descriptors to those of the single-arbor saws. The triple bandsaw differs from the circular saws only in that there is no strong correlation between the total standard deviation and the between-board standard deviation. Otherwise, the bandsaw behaviour is relatively similar from the correlation point of view.

For the purpose of saw machine analysis, same descriptors can be used for all saw machine types. The descriptors are:

- Total standard deviation
- Between-board standard deviation
- Between-segment standard deviation
- Taper
- Bend amplitude.

8.6 Discussion

Some of the detected, erratic behaviour of the examined saw machines – such as the adverse effect of higher feed speeds in the single-arbor circular saw, type B, Figure 8.13, and the holding problems of smaller cants in the double-arbor circular saw, Figure 8.20, and the effects of heartwood beam vibration on the inner board size variation in the triple bandsaw, Figure 8.25 – show both the potential of the analysis method, and its vulnerability in determining reliable descriptor equations when saw machines have erratic behaviour. Inconsistency of the total standard deviation of centrepieces in the single-arbor circular saws, and the triple bandsaw, can be in the order of 0.4mm to 0.5mm. In the double-arbor circular saw, it is from 0.2mm to 0.4mm. The causes of such inconsistencies can be examined with the use of detailed graphs of the method. The major causes of problems, shown by the examples, include unstable sawblade behaviour, insufficient holding capability, and erratic feedworks operation. The behaviour of the single-arbor circular saw, type B, is either due to too large gullet feed index or saw machine instability, Appendix A, Figures A.11 and A.12. In the double-arbor circular saw the holding of small cants is clearly the problem, as seen in Appendix A, Figures A.30 and A.31. The large standard deviation in the triple bandsaw, and in the quad bandsaw before it, are also caused by holding problems, Appendix A, Chapters A.5.4 and A.5.5. There is no major difference between the inconsistencies in benchmarking and those in normal production.

The long-term average descriptors of the saw machines, when only 4-piece set-up variations are analysed, are presented in Table 8.7.

Table 8.7. *Average saw descriptor values in normal cant resaw. Values are in mm.*

Saw machine type	Total standard deviation	Between board standard deviation	Between segment standard deviation	Taper	Bend
Single-arbor circular saw A	0.41	0.27	0.14	-0.11	0.40
Single-arbor circular saw B	0.35	0.28	0.06	0.08	0.20
Double-arbor circular saw	0.26	0.15	0.09	-0.15	0.26
Triple bandsaw	0.48	0.24	0.19	0.22	0.59

The average 4-piece set-up benchmarking descriptors for the four saw machines are presented in Table 8.8.

Table 8.8. *Average saw descriptor values in cant resaw in a 4-piece set-up in benchmarking. Values are in mm.*

Saw machine type	Total standard deviation	Between board standard deviation	Between segment standard deviation	Taper	Bend
Single-arbor circular saw, A	0.31	0.19	0.10	0.47	0.74
Single-arbor circular saw, B	0.32	0.24	0.07	0.09	0.51
Double-arbor circular saw	0.28	0.16	0.10	0.13	0.35
Triple bandsaw	0.59	0.23	0.33	0.67	0.97

The values in Table 8.8 are average values for the entire benchmarking test. However, the sawing inconsistencies that occurred in the double-arbor saw and the triple bandsaw centres, caused standard deviation on two levels, as in Figure 8.27. Similar two-layered standard deviation structure did not occur in the single-arbor saws. Their production capability remained consistently at their inherent levels.

Benchmarking provides data to determine the constants in Equation 6.24. A descriptor equation presents the general characteristics of a saw machine in a compact manner, such as the total standard deviations for the examined resaw centres, Equations 8.1 to

8.4. The equations for the double-arbor saw and the triple bandsaw are presented for their efficient performances.

$$s_T = 0.20e^{0.31tnkFL} \pm 0.07 \quad \text{Single - arbor circular saw, Type A, } n = 3,\ k = 0.0040\text{m} \tag{8.1}$$

$$s_T = 0.19e^{0.66tnkFL} \pm 0.07 \quad \text{Single - arbor circular saw, Type B, } n = 3,\ k = 0.0044\text{m} \tag{8.2}$$

$$s_T = 0.22e^{0.04tnkFL} \pm 0.05 \quad \text{Double - arbor circular saw w/o cant size 110mm, } n = 2 \text{ or } 3, \text{ in average } 2.5,\ k = 0.0048\text{m} \tag{8.3}$$

$$s_T = 0.39e^{0.26tnkFL} \pm 0.05 \quad \text{Saws 1 and 2 in Triple bandsaw, } n = 1,\ k = 0.0028\text{m} \tag{8.4}$$

where s_T is the total standard deviation (mm),
t is the sawing time (h),
n is the number of sawblades in the set-up,
k is the kerf size (m),
F is the feed speed (m/min), and
L is the cutting path length (m).

Differences between saw machines and saw machine types can be seen in the descriptor functions. The inherent saw descriptor constant α indicates that circular saws exhibit similar inherent sawing precision, 0.20mm to 0.19mm, whereas bandsaw precision is 0.39mm. The differences in the time dependent β constant values between the two single-arbor circular saws may derive from the fact that the saw Type B is a curve-sawing saw. In the saw Type B, the sawblades wear faster, $\beta = 0.66$, compared with $\beta = 0.31$ in the saw Type A.

The descriptor functions support the observation that the descriptors of the single-arbor circular saws display sawing time dependence, such as in Figures 8.5 to 8.12. Whereas the double-arbor and triple bandsaws are almost immune to sawing time, Figures 8.19 and 8.24.

The coefficient of determination r^2 indicates some improvement in predictability in using an exponential regression curve for the single-arbor circular saws, $r^2 = 0.29$, and $r^2 = 0.48$, Figures 8.6 and 8.13. Whereas the r^2 values indicate no improvement in predictability in using an exponential regression curve for the total standard deviations of the double-arbor circular saw, $r^2 = 0.02$ and the triple bandsaw, $r^2 = 0.07$, Figures 8.20, and 8.25. Critical approach is necessary when assessing the importance of the r^2 values, because the observed standard deviations have relatively small dispersion around descriptor functions, Equations 8.1 to 8.4. One may claim that the dispersion of the observed data around the descriptor functions, the reproducibility R, is a better indicator of the predictability of an equation than the r^2 values.

The graphic presentation reveals the individual differences between the saw machines, as in Figure 8.27. The evolution of standard deviation for the double-arbor saw and triple bandsaw is level, indicating minimal dependence on sawblade wear and saw load. When comparing the two single-arbor circular saws, it is evident which one uses a curve sawing technique that wears the sawblades faster. The curves for the various saws end at the *Time*Saw load* limit of their benchmarking tests.

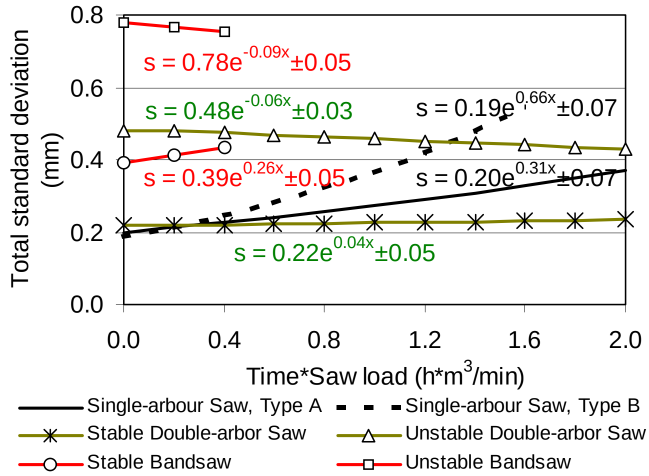


Figure 8.27. *Total standard deviations of the examined four saw machines in cant resaw as a function of the Time*Saw load.*

When analysing a situation from the sawblade change point of view, one can use the average feed speeds and cant heights, used in normal resawing, in Equation 6.25 to calculate a relationship between sawing time and increase in the total standard deviation, as in Figure 8.28, which indicates that, after nine hours of sawing, the sawing variation in the single-arbor circular saw, Type B, will soon be out of bounds, whereas the other saws are still in good or fair condition.

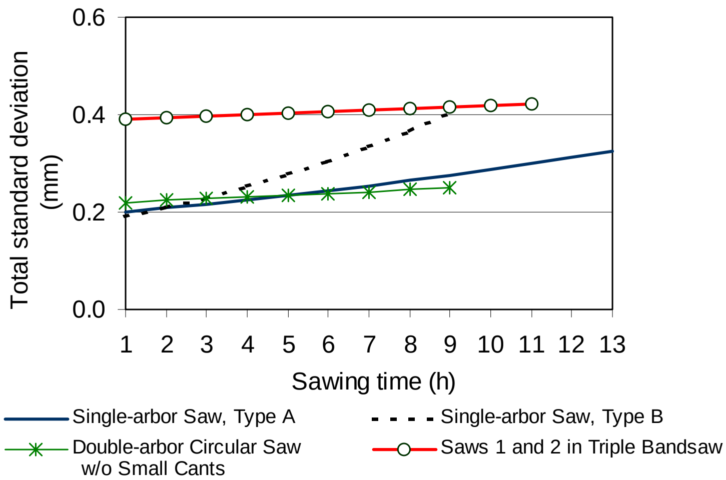


Figure 8.28. *Evolution of the total standard deviation over sawing time in 4-piece set-ups in the examined four saw machine types.*

Figure 8.29 shows that sawblade bend is the major cause of sawing variation. The single-arbor circular saw, type B, which uses curve sawing, initially displayed small sawblade bend as a result of the feedworks forces that keep the sawblades under sideways stress during sawing. When the sawblades become dull, the bend increases at a faster rate than in the case of the other single-arbor saw that does not use curve-sawing technique.

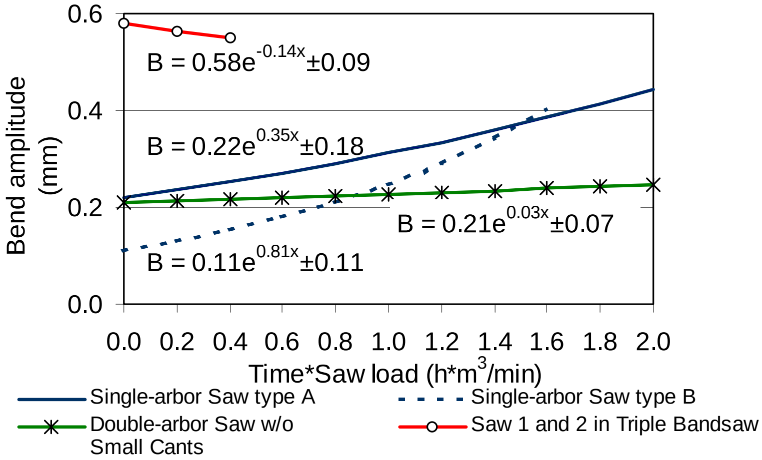


Figure 8.29. *Sawblade bend amplitude in the examined saw machines in 4-piece set-ups.*

Figures 8.27 and 8.29 illustrate the capabilities of different saw machines. The main use of the method is, however, in analysing the same saw machine under various process conditions over longer periods.

Comparison of graphs, presenting the various standard deviations and sawblade bend, provide a useful source of information when analysing the causes of certain behaviour. The graphic presentation of size curves and shapes, such as the means and bend, provides a further source of useful information. Simple numbers are not sufficiently descriptive in many cases when the causes of behaviour are to be analysed. The examples presented in Appendix A, Chapters A.1, A.2.3, A.4.3 and A.5.3, illustrate some such cases.

The method discloses characteristics of cant resaw machines equally in normal production and in benchmarking. The major difference in the results is that benchmarking yields accurate information on existing conditions and systematic behaviour of the saw machines. Benchmarking discloses a centre's behaviour depending on feed speed and cant, and correct information on sawblade wear. Periodic tests during normal production render basic knowledge of a saw machine's behaviour but they do not reveal its accurate, systematic characteristics. Benchmarking may be used for such purpose, alone, to chart the basics of a saw machine, or as a control test to certify normal production parameters.

9 Economics

The main purpose of a sawmill is to produce sawn goods that meet the qualitative requirements of the end-users (SIND, 1980, p. 109). This requires correct target sizes, knowledge and control of sawing variation, and proper drying and handling processes in a sawmill. To achieve this goal, modern information technology is becoming increasingly important both for operational and strategic reasons. The key to improving utilisation of the raw material is information (Åstrand, 1996, p. 4). Eventually, a sawmill-wide network, both for control and information needs, will become the norm. With appropriate applications, all production data collected on the sawmill floor will be instantly available to production planning, maintenance, scheduling, financial and other company-wide applications. Improved knowledge of saw machine behaviour will lead to more efficient operation, filing and maintenance, and will train personnel in best practices. Readily available information will also support the increasing demand for customised products, as well as the desire of customers to check the status of made-to-order goods. More effective sawmill practises will lead to:

- Improved production control
- Improved profitability
- Improved competition position on the market.

The overall outlook for the sawn goods market for the new millennium is promising (UN/ECE Timber Committee, 1999) with high and rising demand for sawn wood. However, prices are not growing accordingly. Pressure on sawmills is intense to increase their efficiency and add value to their product range in order to survive against market pressures arising, for instance, from the increasing globalisation of the sawn wood market. In the final analysis, an important survival strategy for a sawmill is successful production of wood of superior quality.

From the management and economic perspective, many of the benefits of improved size control in breakdown and resaw processes are difficult to express in numbers – How does one assess the value of increasing awareness of a saw operator? How does one assess the value of gained cubic centimetres of wood, which nobody knows has been lost? How does one assess the value of preventing the incidence of stoppages? Or that of preventing boards being sawn in the wrong size? Saw operators are the people who make sawing happen. It is vital that they are motivated and have the tools to make the difference between profit and loss. With modern continuous size control, a saw operator has continuous visual and technological information of the sawing process and he/she can intervene immediately when required, or let an automatic adjustment take place. With traditional manual measurement, it is difficult to analyse in real time how much a process truly varies, and what to do.

9.1 Increase in Production Time

Some of the benefits of optical size control that directly influence a sawmill's yield and value recovery include maximum uptime and minimum downtime of production, faster start-ups and increased production time, increased quantity of boards, increased and correct sizes and lengths, new improved sawing patterns and new improved overall production planning. The uptime can be maximised with on-line process control. An example calculation of the economic benefits to a sawmill in maximising up-time is presented in Tables 9.1 and 9.2.

This example assumes that the gained economic benefits are materialised only through the increase in production time when the time consuming manual measurement and adjustments are replaced by real time optical size control. Excluded from this calculation are those advantages and savings that follow from improved production control in the form of correct sawing allowance and accurate rough sizes, fewer reject pieces, timely sawblade changes and better motivation of personnel. The example is calculated using production values identified as typical in a typical Nordic softwood sawmill, as in Table 9.1.

Table 9.1. *Typical operation values of a Nordic softwood sawmill.*

Annual production capacity (1000m^3*230 days)	230 000m^3
Production per day	1 000m^3
Production time per day	20 hours
Production per minute	0.84m^3/min
Average sales price of sawn timber	165€/m^3
Average purchase price of logs	60€/m^3
Average number of set-up or sawblade changes per day	8
Average start-up time after set-up or sawblade change using manual measurement	12min
Average start-up time after set-up or sawblade change using optical size control	4min
Time used in start-ups per day using manual measuring (8*12min)	96min
Time used in start-ups per day using optical control (8*4min)	32min

Based on these operative values, the increase in productivity and profits can be calculated as presented in Table 9.2. Because the sawmill industry is process industry, slight improvements can lead to significant gains. In this example, the increase in profit will be half a million Euros.

Table 9.2. *Increase in productivity with optical size control.*

Increase in sawing time per day (96min - 32min)	64min
Increase in production per day (64min*0.84m^3/min)	54m^3
Increase in production per year (230 days*54m^3)	12 420m^3
Increase in sales per year (12 420m^3*165€/m^3)	€2.0 million
Increase in log usage (12 420m^3*2 (recovery factor))	24 840m^3
Increase in cost of logs (24 840m^3*60€/m^3)	€1.5 million
Increase in earnings per year (€2.0 - €1.5 million)	€0.5 million

A production line is in full production speed faster after a change of sawblades or set-up when feedback is available from an on-line size control system, and adjustments can be made without stopping the line. If an adjustment is based on manual measurement, amid running and shouting of corrections, then boards with incorrect sizes are produced. With an on-line measuring device, every piece is measured, and adjustments can be made instantly with minimum loss of wood due to incorrect size. Smaller production tolerances may even mean that an extra board can be added to a sawing pattern. At least more valuable, fresh chips will be available for sale.

9.2 Reduction in Downtime

The downtime due to sawblade changes and other maintenance activities can be pre-planned and optimised with on-line process control. With the help of consistent data collection and analysis, the characteristics of a saw machine are revealed and can be used to predict required maintenance activities. In a Scandinavian softwood mill producing 160 000 cubic metres of timber per year, each hour of downtime costs an average €5000.

9.3 Reduction in Target Size

In the final analysis, the most important action a sawmill can take is reduction of target sizes and cutting closer to them. A small but consistent reduction on all pieces will result in significant gains. Usenius (1984) studied the significance of increase in target and kerf size to sawmill profits, and he concluded that an increase of one millimetre in either of these means a gain or loss of 1.8% in revenue in resaw, and 0.7% in log breakdown. Based on Usenius' research a rule of thumb has emerged, stating that 'one millimetre of wood means a gain or loss of 0.2 million Euros in sawmill profits'.

This rule has proved to be rather correct in many sawmills using the optical measuring technology and method described in this study. Such as in a sawmill utilising double-arbor circular saw machines and thinner sawblades than previously because the developed analysis method proved that they could still maintain their small sawing variation even with the thinner blades. The savings that originate from the use of 0.6mm thinner kerfs are approximately €0.1 per sawblade. Thus, the savings per log in a set-up is from €0.4 to €0.8, and the total savings in a two-shift production per day from €2500 to €5000, depending on the set-ups. The cumulative earnings over a year amount to almost one million Euros. Another sawmill using single-arbor circular saw machines has been able to reduce its target sizes on average with 0.6mm for each sawn piece. In each continuously size controlled saw machine, the savings per month are €15 000, amounting to €180 000 per year per saw machine. The cumulative savings, e.g. extra profits in a bandsaw mill controlling continuously two saw groups is nearly one million Euros per year. The above-mentioned calculations and statements have been made by the respective mill managers. These savings are possible without extra raw material purchase or investment in new production machinery.

Smaller production tolerances additionally produce an increase in the full edge length of sideboards in a pattern. Where logs have significant cone (taper), width or thickness of sideboards in a pattern will increase. Because target sizes change, sawing patterns must be re-optimised for maximum value recovery. Major changes to the sawing patterns will force a mill to re-optimise its log sorting strategies for maximum efficiency. The entire mill process must be studied from log sorting to kiln drying because improved sawing control may lead to, or require, changes in other processes, too. Careful analysis and improvements in sawmilling will result in greater productivity and profitability.

Although flitches are often considered to be of less importance than centrepieces, there is no reason not to produce flitches to specification. Controlled flitch and sideboard production is essential when the goal is to attain higher performance standards and best practices. Careless flitch production affects not only the sawn pieces themselves but the attitudes of personnel on quality control in general.

9.4 Other Considerations

Utilisation of new technology is always difficult. Apparently simple applications are difficult and difficult applications may prove impossible. From process control viewpoint, the difficulties are currently, in most cases, the fault of sawmill machine manufacturers and production line designers. Integration of reliable, large-scale control systems immediately after or even inside a saw machine is possible only when manufacturers of sawmill machinery collaborate with suppliers of control technology.

Progressive sawmills have already discovered that new process control systems incorporate many of the following features:

- Better size control of rough timber will result in increased grade recovery.
- As machines are brought to and kept at higher performance standards, they will not only produce better quality timber, they will produce more of it
- Saw machine maintenance and control becomes easier
- Predictable sawing process makes adaptive Just-On-Time production to meet customer requirements possible
- Non-tactile measuring technology leads to long operational lifetime and low lifecycle maintenance costs of control devices
- Investment in modular plug-and-play components of hardware and software make investments in new technologies attractive
- Open system platforms, computer networks and standard interfaces, make integration of commercial and user proprietary technologies easier.

An important consideration is attention to the promises made by suppliers of sawmill machinery. As sawmilling equipment becomes more sophisticated and more expensive, it becomes imperative that the accuracy of suppliers' claims are verified by the purchasing sawmill. A verification size control programme may be used to set and evaluate the specifications of the new machinery besides verifying its capacity performance. These acceptance specifications give mill management the baseline performance descriptors for the sawmill personnel to maintain.

Best sawing practice in the sawmill industry in major industrial areas have an enormous potential in wood savings. Total global sawmill production in 1998 was 430 million cubic metres (UN/ECE Trade Division, 2000). When sawmills are aware of, and can control, standard deviations in their sawing processes, they can cut with better precision. Theoretically, each tenth of a millimetre saved in target size, or in kerf thickness, will earn an extra 50mm*100mm board length of 0.6 metres in each cubic metre of timber produced. A tenth of a millimetre is a modest goal, because target size improvements of 0.6mm have been made in several sawmills. However, one tenth of a millimetre would lead to the recovery of an extra 0.7 million cubic metres of timber, worth 100 million Euros, with no new raw material purchase or environmental effects. Since lumber recovery factor in an efficient softwood mill is around 2.2, each tenth of a millimetre of wood saved by professional sawing variation control will reduce global usage of trees by 1.5 million cubic metres.

10 Discussion and Conclusions

As far as analysis of breakdown process in sawmills is concerned, there are two alternatives, periodic manual measurement and automated continuous on-line size control. Manual measurement is straightforward and commonly used method. However, it is time consuming and susceptible to errors arising from personal styles of measurement and small sample sizes, and it is by nature an off-line method. The huge quantity of data required in quantitative analyses of saw machines is impractical in manual measurement. On the other hand, optical measuring techniques that did not exist ten years ago are available today. The positive features of optical technology include uninterrupted operation and high repeatability, accuracy and precision.

The relationship between sawing variation and sawmill profitability is direct, as described in Chapter 9. Efficient control of target sizes and sawing variation is important to the profitability of a sawmill. The most important action a sawmill can take, is reduction of target sizes. It has been shown that additional revenue up to €200 000 per year and saw machine can be gained when the target size reduction is 0.6mm per piece. Faster start-ups and longer up-times increase the profitability of a sawmill further. The cumulative increase in sawmill profits, when saw house activities from production planning and sawing to maintenance, using the technique described in this study, are optimised, may be over one million Euros per year.

10.1 Developed Method

The developed method, which is not in any way fully developed, represents a flexible multipurpose tool that produces useful information for performance analyses of breakdown saw machines, and for reduction of sawing variation. The traditional and new numerical and graphic descriptors of saw machine behaviour have shown their usefulness in tests with seven saw machines, as described in Chapters 7 and 8, and in Appendix A. The improved control of target sizes and sawing variations is possible not only in real time during sawing, but offers also new tools for production and maintenance planning in long term. In particular, the developed method can be used to determine:

- Present process capability
- Long-term process capability
- Process capability descriptor functions.

A thorough understanding of sawing processes is a critical asset in sawmilling. When a sawing process is under control, the descriptors will indicate variations that are within the inherent capabilities of a saw machine. The inherent capabilities vary according to process conditions, and countless adverse factors reduce a saw machine’s accuracy and precision from the optimum. Thus sawing variation is inevitable even in the best of conditions. Furthermore, all production lines and saw machines are different and determination or use of universal standard deviations is not possible. The production conditions and factors affecting the sawing results include:

- Raw material
- Cutting parameters
- Setworks operation

- Feedworks operation.

The method was developed to be a general-purpose tool for examination of various variables that effect the sawing results. Although the method was tested only by using three variables, feed speed, log size and sawing time, there should be no reason why it could not be used also to examine other variables, such as sawblade shapes, gullet feed indices, sawing practises, cutting patterns, saw speeds, changing set-ups, seasons, frozen wood, extreme process conditions approaching limits of system's dynamic stability. Other factors to examine can be the effects of maintenance, alignments, change of machine or structural components, change of distance between process units, and adaptive servo control systems, or other factors of interest to a sawmill.

The tested saw machines represented horizontal single- and double-arbor saws and vertical bandsaws. Other types of saws, such as sash gangs, bull edgers, vertical arbor circular saws, horizontal bandsaws, carriage headrigs and cross saws, have different characteristics. The usability of the method with these saw machines depends not on the method's capability to analyse data, but on the data collecting possibilities of the used measuring device.

10.2 Statistical Descriptors

Although the method of calculating a target size is generally accepted, its determination presents a problem because sawmills do not know their standard deviations. The sample size used in manual measurement in sawmills today is clearly too small chiefly because within sawmills, saw machines are thought of as one single unit having one, 'fixed' standard deviation. Therefore, it is considered sufficient to measure a few boards satisfying sawmills' conception of effective quality control. However, the guidelines set by Warren indicate sampling quantities that depend on the size of sawing variation. The conclusion is that a board sample size of fifty is a reasonable minimum in estimating standard deviation.

The main difference between manual inspection and computerised optical control in breakdown process is the sampling frequency and number of readings taken. Because measuring frequency of optical devices is hundreds of readings per each sawn piece, the difference between manual inspection and optical control may be in the order of one to several millions. Hundreds of optical readings are used to calculate ten segment means for each measured board. The segment means fulfil the Central Limit Theorem requirement for statistical normalcy. The segment means are used to calculate one or more of the following statistical process descriptors:

- Process mean
- Total standard deviation
- Between-board standard deviation
- Between-segment standard deviation
- Sawblade bend and amplitude in a sample
- Within-board standard deviation
- Within-segment standard deviation
- Average taper in a sample
- Within-board taper
- Average snaking in a sample

- Within-board snaking.

The numeric descriptors of the method together with their graphic presentations provide opportunities for detailed analyses on what is happening in breakdown saw machines, and why. However, too much data is not practical in everyday sawmilling. Therefore, the number of descriptors must be kept small enough to be handled and understood easily. The most useful descriptors are:

- Total standard deviation
- Between-board standard deviation
- Between-segment standard deviation
- Taper
- Bend amplitude.

With a small number of descriptors, it is possible to work out equations, tables and other tools for the main classes of logs, feed speeds and sawing patterns. Tools that can be used to maintain practical, optimum target sizes and small sawing variation in most conditions.

10.3 Descriptor Function

The difference between normal production analysis and system benchmarking is that normal production analysis can be performed at any time using current process parameters, while benchmarking requires designed test parameters and pre-sorted samples that represent the factors that are to be analysed. Normal data describe a saw machine at the time of the test with the type of raw material and settings used. Benchmarking is the method used to establish saw descriptors and descriptor constants.

The benchmark determination of descriptors in different production conditions facilitates the creation of mathematical functions that describe the performance of a saw machine in the designed production conditions. Equations are a practical, compact way of describing the characteristics of a saw machine. The total standard deviation, and other saw machine descriptors, can be expressed with an equation, type $y=\alpha e^{\beta x}\pm R$, where α and β are constants typical for each saw machine, and x is a product of sawing time and saw load. The dispersion of total standard deviation values around the total standard deviation descriptor function is a measure of saw machine reproducibility R, of its capability to saw with consistent sawing variation. For example, the total standard deviation of $s=0.21e^{0.47x}\pm0.11$ tells that the inherent total standard deviation is 0.21mm, the sensitivity to sawblade wear is 0.47, and the process reproducibility is 0.11mm. An exponential function is suitable in describing the behaviour of single-arbor circular saws, and less so in describing the behaviour of double-arbor circular and band saws. Because the latter ones tend to have more level descriptors, such as in Figures 8.20 and 8.25. However, the exponential function works with these types of saws, too. An example of a group of descriptor functions for three different saw set-ups is presented in Figure 10.1. The knowledge of such functions makes possible various types of problem analysis, alerts, and even automated process control with an adaptive adjustment. The constants and reproducibility are defined in benchmarking, but process consistency can be checked against the equations also in normal production.

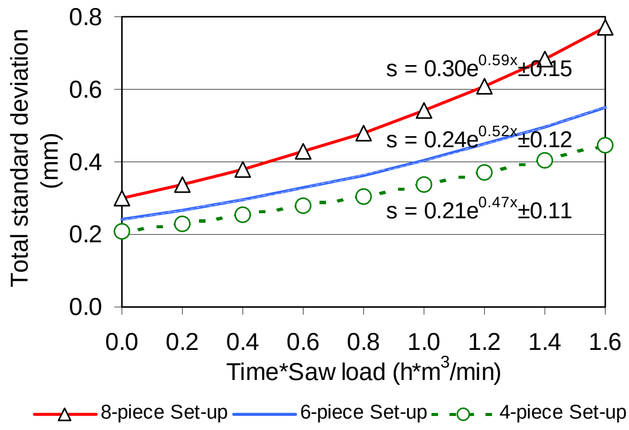


Figure 10.1. *Effect of sawing Time*Saw load on the total standard deviation in a single-arbor circular saw in three set-ups.*

The various descriptors can be used to establish current, short-term or long-term capabilities and characteristics. The presented saw machine case studies represent samples of current capabilities in normal production, short-term capabilities in benchmarking tests, and long-term behaviour in normal production.

In this study, the normal production of saw machines display both consistent and inconsistent behaviour. Inconsistencies are of the same order in benchmarking as in normal production. The main causes of problems, which affect the sawing variation and the reliability of the descriptors include unstable sawblade behaviour, insufficient holding capability, and erratic feedworks operation. The causes of inconsistencies can be examined with the use of detailed graphs of the developed method as illustrated in Appendix A. The observations with the single-arbor saws indicated additionally that there is a limiting maximum feed speed that can be used if one wants to keep the total standard deviation of a saw within reasonable values, such as in Figures 8.6 and 8.13.

10.4 Graphic Descriptors

The descriptors may be used both in numerical and graphic form. Simple numbers are in many cases not sufficiently descriptive for carrying out a cause analysis. Graphic presentation of a descriptor function reveals the character of a saw machine in a tangible form. Descriptor functions can also be used to illustrate the individual differences between saw machines.

The saw machine cases have shown that usefulness of each descriptor depends on the problem at hand. In general, the figures presenting the various standard deviations and sawblade bend, provide a useful source of information when analysing a breakdown saw machine. The graphic presentation of size curves and shapes, such as means, taper and bend, represents a further source of useful information. The graphic descriptors are especially useful in the effect analyses because of their more detailed process information content. Of special value may be comparison of graphs representing neighbouring boards. This type of analysis will reveal information on individual sawblades and process tools, Figure 10.2. In all sawmills that participated in this study, the developed method uncovered phenomena, which were previously unknown, such as described in Appendix A.

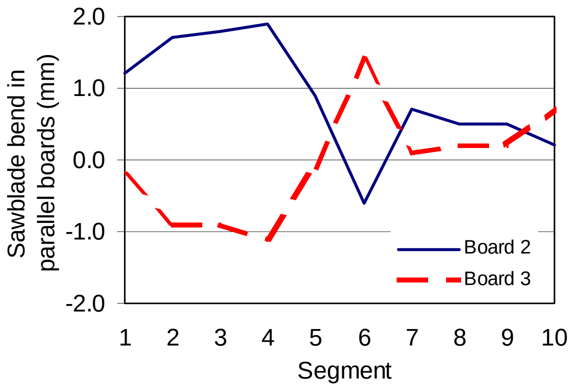


Figure 10.2. *Mirror image bend in two parallel boards that indicate sawblade behaviour in the kerf between boards. It is obvious that the sawblade between the two pieces is the cause of size variation.*

10.5 Limitations and Error Sources

The descriptor equations are based on experimental observations made in this study. Because the number of tested saw machines and benchmarking tests has been limited, the selected exponential function may have limitations in illustrating some of the saw machine behaviour. However, the equation in its present form fits the data, it is compact, and it describes the essential factors in an effective manner. Furthermore, because the number of tested saw machine types in each application was one, no universal conclusions can be draw from the presented analyses. Neither can one draw conclusions on the superiority of any of the saw machines. The results are valid exclusively for the 4-piece set-ups in the examined individual saw machines at the time of benchmarking. Better understanding of the saw machines examined in this study would also require repeated benchmarking tests with different saw set-ups in different seasons. Future studies with larger numbers of 'similar' types of saw machines in various applications may potentially reveal more general patterns of behaviour of various saw machine types.

Wood is natural material and logs come in various sizes and lengths. Thus the developed method has some limitations. Because the analysis uses data, which is divided in ten segments along the length of each board, the physical board length affects the location of the data from board to board. In addition, the cutting path length and thus the saw load varies somewhat in each cut. Inconsistencies in sawing time are another source of dispersion in data. Although these factors play a role in measurement, the saw machine case studies show that these variations do not have too adverse effects. The effects of length, size and material properties are seen in the reproducibility values, which describe the 'error' of the descriptor functions.

A weakness, which is also the strength of the method, is its sensitivity to malfunctioning machinery. The saw machine case studies show that holding problems, overfeeding and sawblade instability cause readings that deviate significantly from 'normal' values. The 'deviate values' lead to uncharacteristic descriptor values. These must be analysed with care in order to avoid misleading conclusions.

A future improvement of the method will be calculation and use of exact sawing time and accurate feed speeds. This will be accomplished when a digital encoder is connected with the feeder conveyor to provide actual board lengths and feed speed data. Accuracy and precision of the method will improve further when new line-scan sensors with larger number of pixels will emerge. However, the practical limit in resolution in sawmill applications will be around 0.1 to 0.05mm.

10.6 Application Potential

The quality yield capability function may be used to calculate the appropriate sawblade change intervals for a log size or different log sizes depending on what or which feed speeds are planned to be used during the shift. Equally can be assessed the suitability of specific feed speeds to various log or cant sizes, and sawblade wear in different seasons. When the constants α and β in the quality yield equation are known for set-ups, sawblade types, seasons and timber species, the equation provides a simple method to calculate the most productive feed speed and sawblade change interval for each log size. The knowledge of this will improve collaboration between production planning, filer room and sawing, because everyone will know how the process will evolve during a shift. Calculation of the time for sawblade change or correct feed speed for a certain log size can be calculated with a calculator or a simple computer program.

The quality yield equation can be utilized in adaptive servo control of saws to adjust the feed speed so that the sawing variation stays within the allowed limits independent on the log size and sawing time. In practice this may mean that in the beginning of a shift the sawing may take place with higher feed speeds and in the end with lower ones. When the sawblade change, based on the removed wood volume, approaches, the control system informs about this in good time to the filer room and the sawyer. Thus the ’untimely’ clock-based sawblade changes are avoided, and the blades are changed only when required.

The determination of the quality yield capability equation and its constants, requires disciplined measurements in production conditions, that cover a period between sawblade change, in order to specify the saw machine behavior in various, time dependent conditions. With proper production planning, the quality yield equation can be determined for the current parameters without noticeable effect on the production. When the basic definitions have been made, the ’condition’ of the sawing process can be followed by collecting samples of fifty logs and comparing them with the results of the quality yield equation. When the values are within the reproducibility no significant change has taken place. When the data indicates that changes may have happened, it is reasonable to repeat the determination of the constants of the equation with some of the most common set-ups in normal production.

When connected with saw machine set-up data and data from filing and maintenance activities, the method will provide new information on behaviour of sawblades, effects of alignments and service activities, and general behaviour of sawing lines during various production conditions. Other data to be integrated in a control system of saw machines will be log and cant temperature and moisture, and power consumption, vibration and temperature changes in saw machinery. The marking of individual boards after measurement with data containing information on their features will help sorting, drying and trimming processes. The development will eventually lead to expert systems based on neural networks or self-organising maps, which are used to supervise and optimise sawing processes and perform fault diagnostics. The saw machines will be integrated into such systems and will perform adaptive process adjustments automatically. Thus, the integration of information technology will radically change the tasks and improve the working conditions in future sawmills.

The use of on-line size control and analysis methods offers to sawmill management improved opportunities that have beneficial effects on sawmill productivity and wood recovery. In the beginning, the use of new methods may appear to cause an increasing need for adjustments, alignments, sawblade changes, component replacements, and other maintenance activities. However, it is preferable to bring a saw machine up to specification performance than to continue to produce substandard timber. The presented analysis method is one of the sawmill tools that can be used to produce better quality timber, in greater quantities.

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Appendix A: Production Lines and Saw Machines

This appendix introduces the examined sawmills and production lines, and the details of saw machines. Use of graphic descriptors is illustrated by examining various effects and observations made in normal production and in benchmarking tests. The graphic descriptors used in this appendix are described in detail in Chapter 6.8 of this study.

The sequence of various operations in a saw machine may have an effect on the sawing results. These effects are seen in the longitudinal profile of sawn pieces, such as in the general shape indicated by segment means, within-segment standard deviation, taper, and sawblade bend. Therefore, it is important to know the layout of sawing machinery. Because segment lengths may vary from 350mm to 600mm, an analysis of actuator effects cannot be accurate as far as location is concerned. Thus, the actuator-effect data must be considered only as an additional piece of information in problem solving. A short description of possible actuator effects on each saw machine is presented.

A.1 Single-arbor Circular Saw, Type A

The sawmill using a type A single-arbor circular saw has two chipper canter-circular saw centres with a maximum design capacity of 150 000 m^3 in two shifts, as in Figure A.1. The breakdown process is controlled by one person from log infeed to edging.

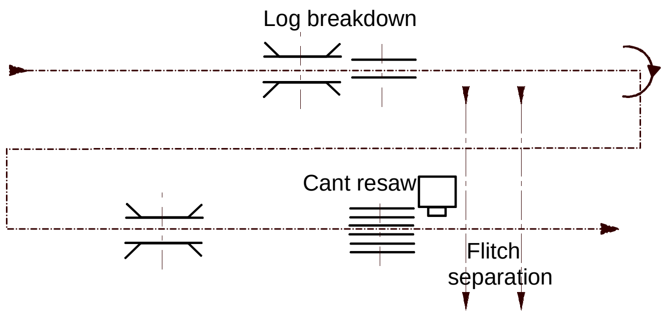


Figure A.1. *Layout of the single-arbor circular sawmill, Type A. Measuring of centrepieces and flitches takes place immediately following cant resaw.*

The saw machine is an ARI single-arbor circular saw DS 74 + 1V. Servo control of sawblades is performed with sawblade guides. The saw has a constant rotation speed of 1500rpm, the sawblade diameter is 700mm, and thus the cutting speed is fixed at 55m/s. The kerf size is 4.0mm. The sawing allowance used by the sawmill, established during the saw start-up 1996, is 0.5mm. Log cants are first chipped in a separate canter, and then sawn in the circular saw to produce centrepieces and flitches. Twenty different green sizes are produced in cant resaw, ranging from 23.4mm to 78.2mm. The number of pieces in a set-up varies from 4 to 8 pieces. In a saw set-up of 8 pieces, the outer flitches are ‘slave boards’ with no individual servo position control.

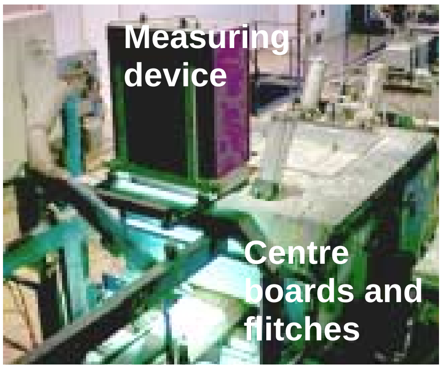


Figure A.2. *Single-arbor circular saw machine with an optical measuring device at the saw exit. A stack of boards is exiting from the saw.*

An optical measuring unit is located immediately after the saw machine, as in Figures A.2 and A.3. Kerfs are easily visible, and the entire length of boards can be measured. Flitch separation takes place following the measuring. When flitches are short, have a large amount of slab, or when a log has entered the process butt-end first, the flitches may start to fall when still in measurement. This is not the case with the centrepieces or inner flitches. Occasional measuring problems with individual segments may be caused by lumps of sawdust dropping on kerfs, and cannot be removed by an air-blower.

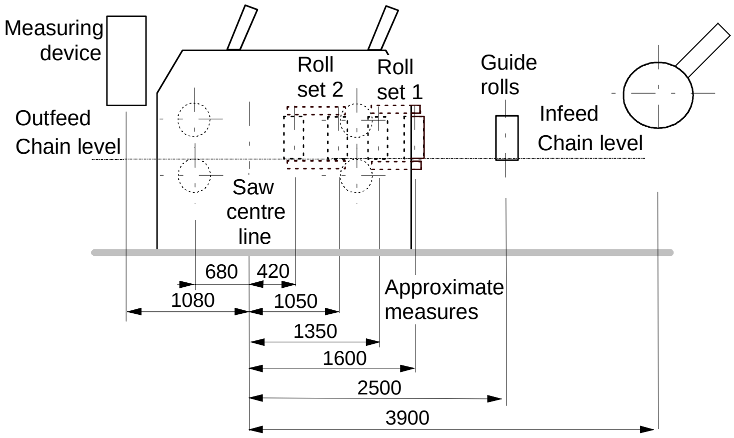


Figure A.3. *General layout of the single-arbor circular saw type A used in this study.*

The effects of machinery on the sawing process are:

- Horizontal outfeed rolls stabilise the process from segments 2 to 3 onwards
- Release from guide rolls is seen in segments 4 to 5
- Release from roll set 1 is seen in segments 6 to 7
- Release from roll set 2 is seen in segments 9 to 10.

An example of the use of the layout effects is shown in Figure A.4, which shows the effects of frozen wood on saw machine behaviour in a set-up of six pieces. The normal total standard deviation of unfrozen wood in the right outer centrepiece is approximately 0.3mm, which freezing increases to 0.81mm. The stabilising effect of outfeed rolls is seen in segments two and three, following which the sawing variation is even until butt. One or both sawblades deflect, causing a strong hook in segment two.

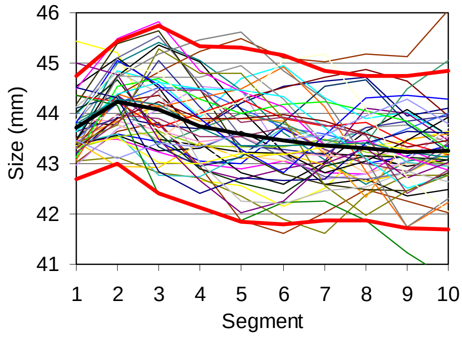


Figure A.4. *Sawing variation has increased due to frozen wood. The figure shows individual board sizes, the sample mean and ±2s limits. The total standard deviation of 0.81mm is over double compared with unfrozen wood.*

A.1.1 Sawblade Bend in Benchmarking

In single-arbor circular saws, the sawblade bend is a major cause of large standard deviation. Sawblade wear tends to intensify this behaviour, as in Figure A.5.

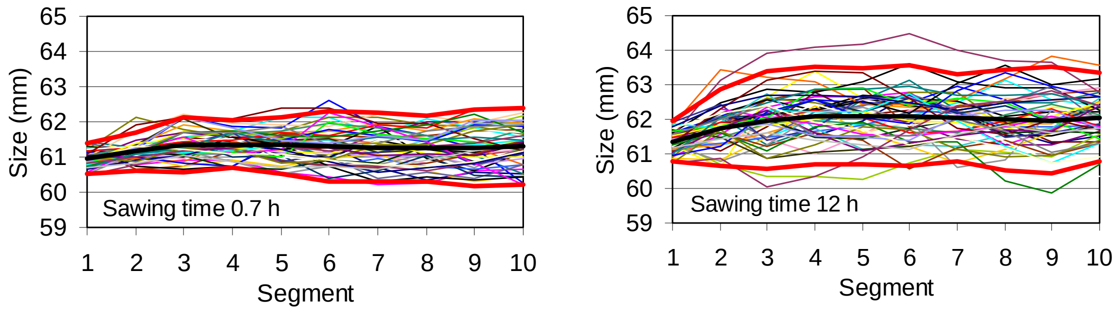


Figure A.5. *Effect of sawblade wear on the dispersion of sawn size in centrepieces. Cant size is 145mm and feed speed 85m/min.*

Sawblade bend is measured as the difference of a segment mean from the sample mean. Thus, the bend represents the curvature of the sawn surface around the average size. Bend is a result of the working of two sawblades cutting each individual piece. Figure A.6 illustrates the bend of samples shown in Figure 8.9, Chapter 8.1.1. The shape of bend remains consistent over a period of 12 hours, while the amplitude of bend increases from 0.4mm to almost 0.8mm.

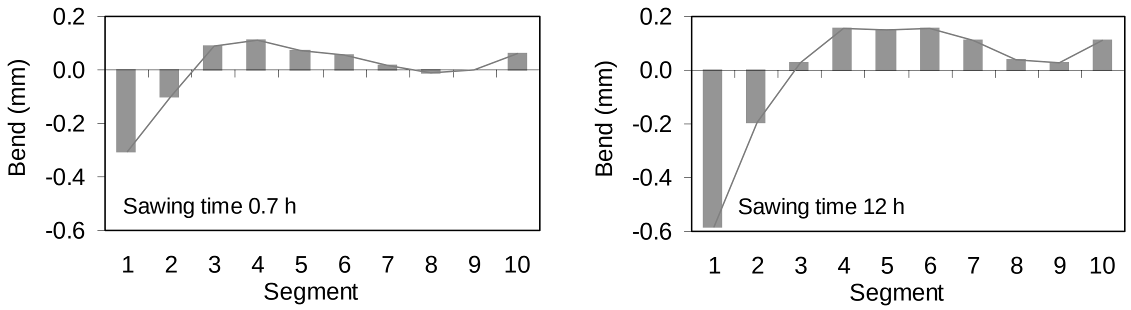


Figure A.6. *Effect of sawblade wear on the sawblade bend in centrepieces. Cant size is 145mm and feed speed 85m/min.*

Occasionally, it is possible to identify pairs of parallel boards that show extraordinary bend with a particular sawblade, as in Figure A.7. Clearly, the large bend is caused by a single sawblade splitting the centre part into centrepieces. Because the standard deviation of means is otherwise uniform, a possible cause of the behaviour of a single piece may be the quality of wood in the sawn cant.

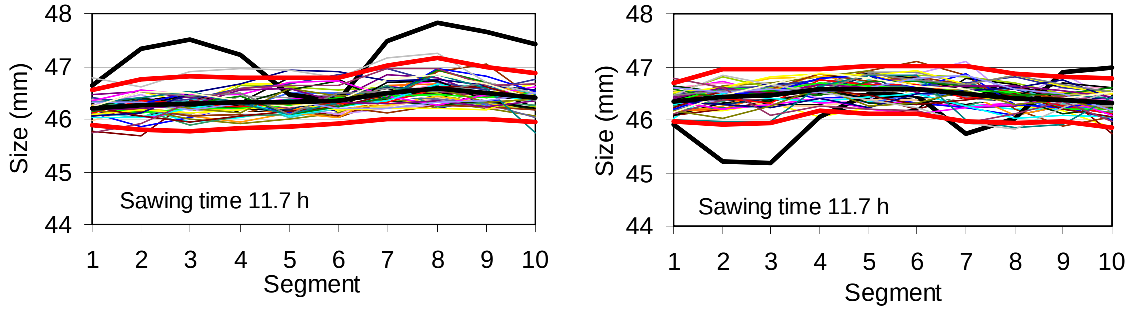


Figure A.7. *Large deflection of a sawblade in two parallel, neighbouring boards. Cant size is 100mm and feed speed 60m/min.*

A.2 Single-arbor Circular Saws, Type B

The sawmill using type B single-arbor circular saws has two chipper canters and circular saws with a maximum design capacity of 60 000m^3 in two shifts. Logs are consecutively canted and sawn in the first saw centre. Following flitch separation, cants are turned and canted in another chipper canter. Square cants are then circulated into the second saw machine for final resaw, as in Figure A.8. The breakdown process is controlled by one person from log infeed to edging.

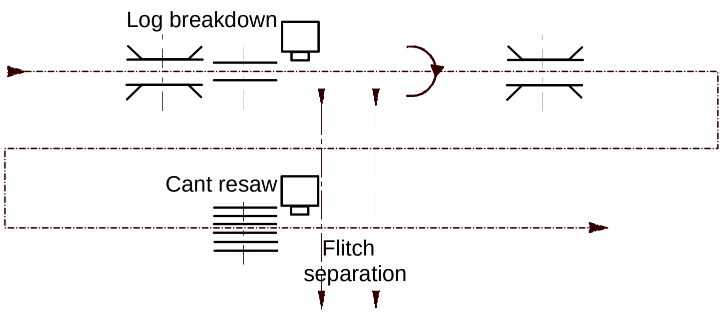


Figure A.8. *Layout of the single-arbor circular sawmill, Type B. Measuring of log cants and flitches takes place directly following log breakdown, and centrepieces and flitches immediately following cant resaw.*

A.2.1 Log Breakdown

The canter - single-arbor circular saw centre produces log cants with or without flitches. There are 21 different cant and 3 flitch sizes produced in log breakdown. The Vislanda RKS 600-4 saw has a constant rotation speed of 1000rpmrpm. The sawblade diameter is 1100mm, and thus the cutting speed is fixed at 58m/s. The kerf size is 4.6mm. Sawblades float on an arbor and the servo control is performed with sawblade guides. A measuring device is located at a distance of approximately one metre from the saw exit, before flitch separation, as in Figures A.9 and A.10. Because flitch separation starts while cant and flitches are still being measured, data from the last twenty percent of the length is discarded. When the drop-off starts, the measures are not correct, and therefore not useful. Thus, the analysis relates only to the first eighty percent of piece length. The total standard deviation guaranteed by the saw manufacturer at saw start-up 1994, was 0.6mm.

Figure A.9. *Exit area of the single-arbor circular saw used in log breakdown. The measuring device is at the top, above the structural beams. Cant and flitches move from right to left. The side rolls seen in the figure are not in use.*

The canter and the saw machine form an integrated unit. Besides the cant guide plates between the machines, there are no actuators for cant positioning inside the centre. The process inside the saw centre is a 'free flow' system.

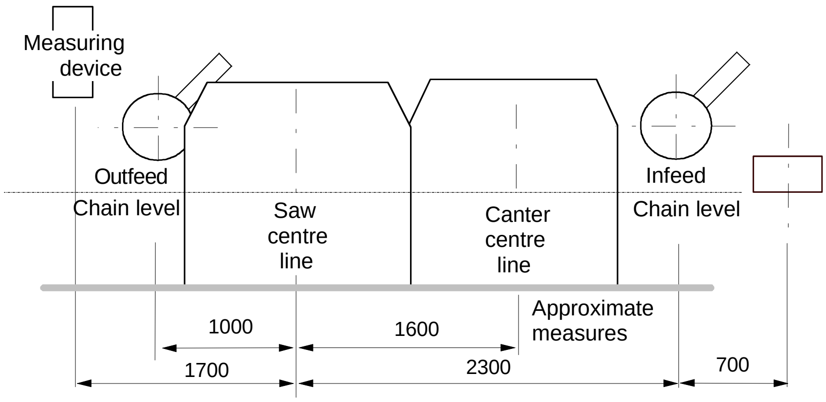


Figure A.10. *General layout of a canter–single-arbor circular saw centre used in log breakdown.*

The feed tyres and wheel before the canter maintain the process stability until log butt leaves them. At this stage, heavier vibration may occur at the saw end of the chipped log. This effect is seen in segments six to seven. The out-feed wheel has no particular effect on the sawing process. The chipper canter is the dominant cause of vibration during sawing, and thus, when canter operation is impaired, a source of increase in size variation.

A.2.2 Effect of Feed Speed on Sawblade Bend in Log Breakdown

An increase of feed speed from 35m/min to 70m/min increases the standard deviation of cants from 0.50mm to 0.90mm in 265mm logs. With increasing feed speed, the sawblades bend more strongly. This is seen in the level of means as the sawblades bend out, as in Figure A.11. The increase in mean is over 1.5mm. The bend also increases wedge, which was measured manually and found to be in the order of 3.7mm at the butt-end of individual cants when feed speed was 70m/min. The increase in sawblade bend increases also the between-board variation, which is 0.44mm at speeds of 35m/min, and 0.77mm at 70m/min.

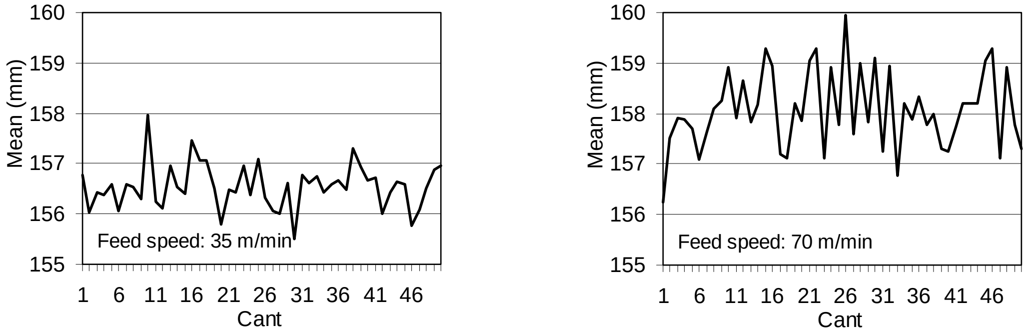


Figure A.11. *Variation of cant means with two different feed speeds in a single-arbor circular saw in log breakdown. Increase in feed speed causes a shift in mean.*

The increase in feed speed doubles the sawblade bend from 0.63mm to 1.19mm, as in Figure A.12. At the same time, the right-hand flitch manifests a mirror image of the bend behaviour, indicating that the sawblade between the cant and the right flitch tends to bend strongly at higher speeds. At lower speeds, the correlation with the right flitch is not as evident as at higher speeds.

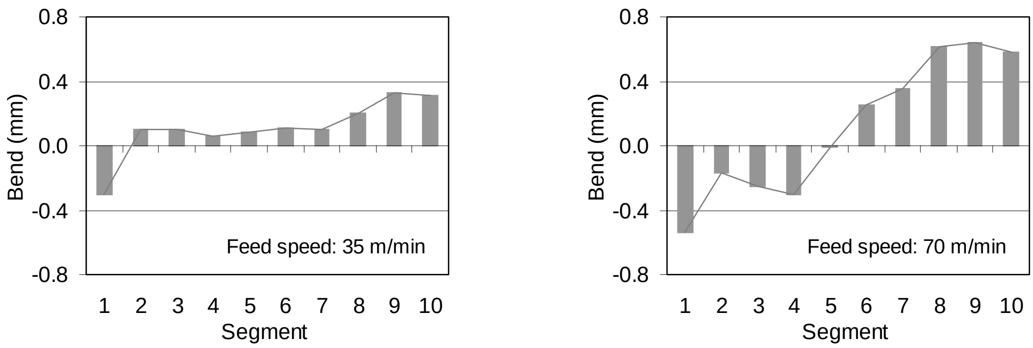


Figure A.12. *Sawblade bend in cants in two consecutive samples with two feed speeds. Increase in sawblade bend is evident.*

The observed within-segment sawblade bends are typical for the produced cants. The behaviour indicates that the sawing process produces cants that are always butt-end thick and that the sawblades bend out increasingly as log cutting proceeds.

A.2.3 Cant Resaw

The examined cant resaw is a Vislanda 509-7F single-arbor circular saw with curve sawing device 500-A. The square cants are resawn in 24 different green sizes, ranging from 20.1mm to 80.6mm. The number of pieces in a set-up may vary from four to eight. A set-up is determined by collars between the saw guides. Position of the entire sawblade package can be adjusted manually in relation to the feedworks centre line, but individual sawblade control is not possible. The saw machine has a constant rotation speed of 1500rpm. The sawblade diameter is 700mm, and thus the cutting speed is fixed at 55m/s. The kerf size is 4.4mm. The standard deviation guaranteed by the saw manufacturer in start-up in 1994 was 0.5mm.

Figure A.13. *Single-arbor circular saw machine, type B, with an optical measuring device at the saw exit.*

An optical measuring unit is located immediately after the saw machine, as in Figures A.13 and A.14. The kerfs are easily visible. Flitch separation starts when the butt of boards leaves roll set two in the saw. Therefore, the data from the last 15% of board length is discarded from analysis.

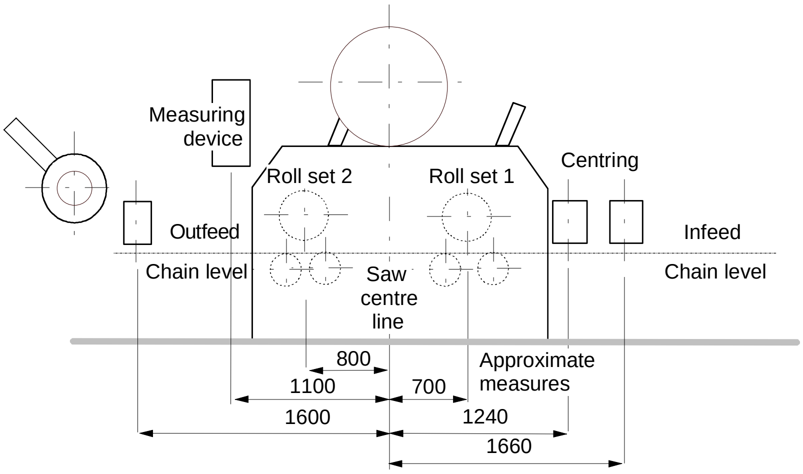


Figure A.14. *General layout of a single-arbor circular saw, type B, used in this study.*

The effects of machinery on the sawing process are:

- Entering into roll set 2 stabilises the process in segment 3
- Entering in out-feed roll stabilises the process in segment 6
- Release from centring rolls is seen in segments 9 to 10
- Release form roll set 1 is not seen due to the 15% data loss at the butt-end.

A.2.4 Sawblade Bend in Cant Resaw Benchmarking

Bend is a result of two sawblades cutting a single piece. Cant size, feed speed and sawblade wear have an effect on sawblade bend. In Figure A.15, the effects of sawblade bend in one particular cutting position is monitored through a set of set-ups sawn at various intervals in benchmarking. Feed speed is 50m/min.

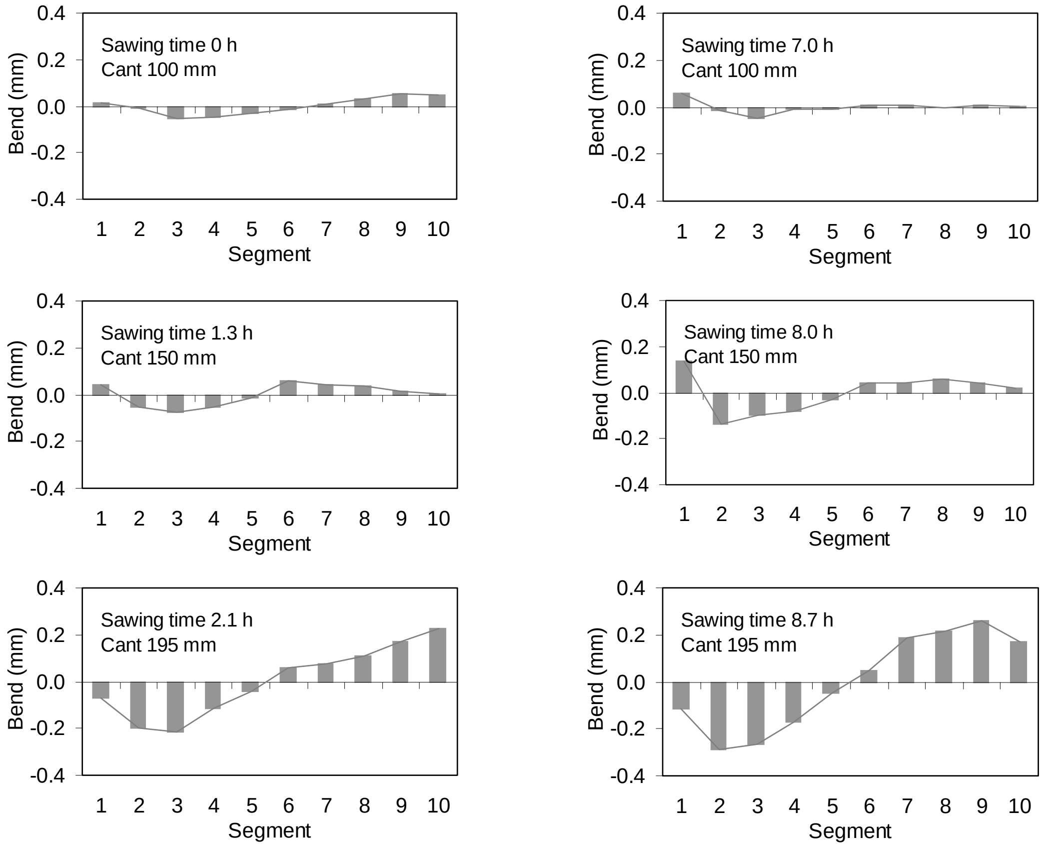


Figure A.15. *Effect of cant size and sawing time (sawblade wear) on sawblade bend in a single-arbor circular saw. Cant size runs from top to bottom, and time from left to right.*

The shape of bend is identical in all cases and lasts throughout the period of eight hours, as in Figure A.15. Cant size is the most significant factor affecting the sawblade bend. The bend amplitude in cants of 100mm remains at 0.1mm throughout the period of eight hours. Bend amplitude in cants of 150mm grows from 0.14mm to 0.27mm, and in cants of 195mm from 0.44mm to 0.55mm.

In order to find out which of the sawblades is performing poorly, one must analyse parallel pieces in a set-up. The set-up sawn during the benchmarking at 6.3 hours shows that the board means in the left flitch and the left centrepiece are mirror images, as in Figure A.16. The means in the right centrepiece, on the other hand, does not correlate with the means in the left centrepiece. This indicates that sawblade bend in Figure A.15 is principally caused by the sawblade between left flitch and left centrepiece.

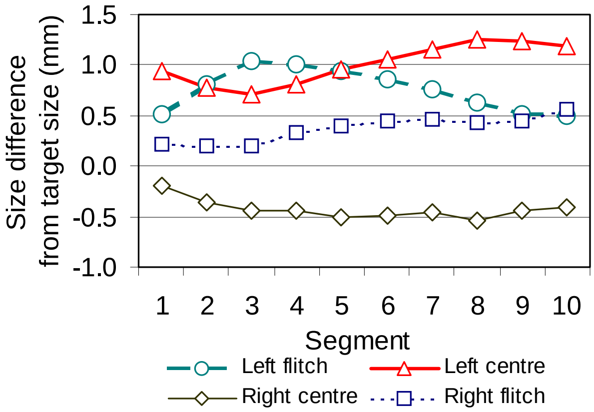


Figure A.16. *Size variation in parallel boards. Cant size is 195mm and sawing time 6.3 hours.*

A.3 Flitch Analysis in Single-arbor Circular Saws

Flitches are the outermost boards sawn from a log or cant. Slab surface and wane are typical of flitches. Figure A.17 illustrates a typical flitch situation. The number of flitches on both sides may be either one or two, depending on the set-up. Nominal thickness of flitches is usually less than 25mm. The outer borads have a lot of wane and slab, leading to fewer readings. The inner boards may have some wane, but readings can usually be taken for the entire board length.

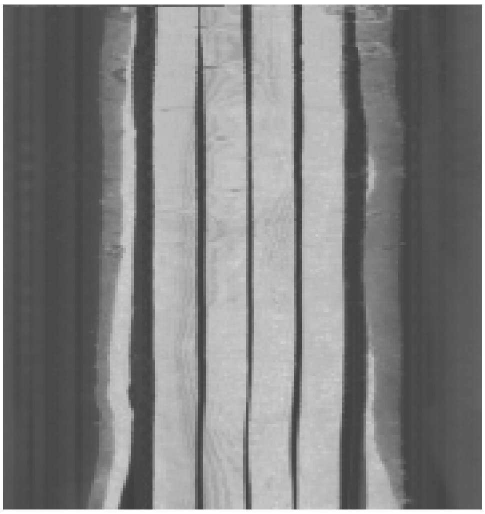


Figure A.17. *Image of one stack of boards with wane and slab on flitches sawn in normal production.*

In single-arbor circular saws, the outermost faces are usually chipped in a canter. If the top end size of a cant entering in a canter is too small, no chipping takes place. This will have two results. First, there is no edge to measure the size from, resulting in segments without readings. Secondly, the cant centring in a saw will be less precise, resulting in considerable sawing variation. In sawmills using ‘tight’ set-ups, this will lead to a situation whereby an edger operator must judge and drop a lot of ‘slab’ flitches, or reject boards, in the chipper chute.

In one of the examined single-arbor circular saws, the total standard deviation of flitches, during normal production, indicates a layered structure of deviations, as in

Figure A.18. The average standard deviations vary from 0.48mm in a 4-piece set-up to 0.89mm in an 8-piece set-up. Because the trends are reasonably level, the size variations do not depend on the saw load, but on other factors, such as cant fit in a set-up and variation in centring. The fewer pieces there are in a set-up pattern, the smaller the standard deviation.

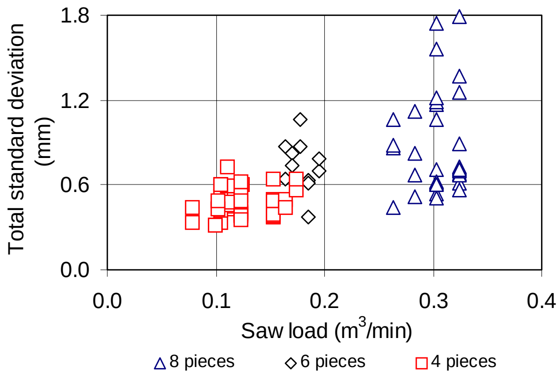


Figure A.18. *Total standard deviation of flitches in cant resaw in a fixed single-arbor circular saw set-up as a function of Saw load.*

The descriptors of a sample are presented in Table A.1. All descriptors of the outer right flitches have large values, indicating poor performance. Significant for the entire set-up is that over 50% of the three flitches (left inner, right inner and right outer) are scrap. It is evident that the flitches are undersized or they are slab.

Table A.1. *Main descriptors of a 6-piece set-up on 6 April. Two flitches are sawn from both sides of cants. Values are in mm.*

	Left outer flitch	Left inner flitch	Left centrepiece	Right centrepiece	Right inner flitch	Right outer flitch
Total standard deviation	0.64	0.41	0.27	0.34	0.62	0.87
Between-board standard deviation	0.39	0.25	0.17	0.23	0.72	0.77
Between-segment standard deviation	0.22	0.15	0.09	0.05	0.13	0.26
Bend amplitude	0.80	0.59	0.23	0.15	0.40	0.95
Undersized timber	5%	58%	0%	0%	78%	5%
Slab probability	0%	0%	0%	0%	0%	50%
Reject board probability	5%	58%	0%	0%	78%	55%

Existence of slab surface does not necessarily result in flitches that have no value. In the examined sample of fifty left outer flitches, 64 segments from the total of 500 were without a segment mean, thus missing readings in a segment. On the other hand, there were 300 segments without a mean in the right outer flitches, and thus the slab quantity in these flitches is far more significant.

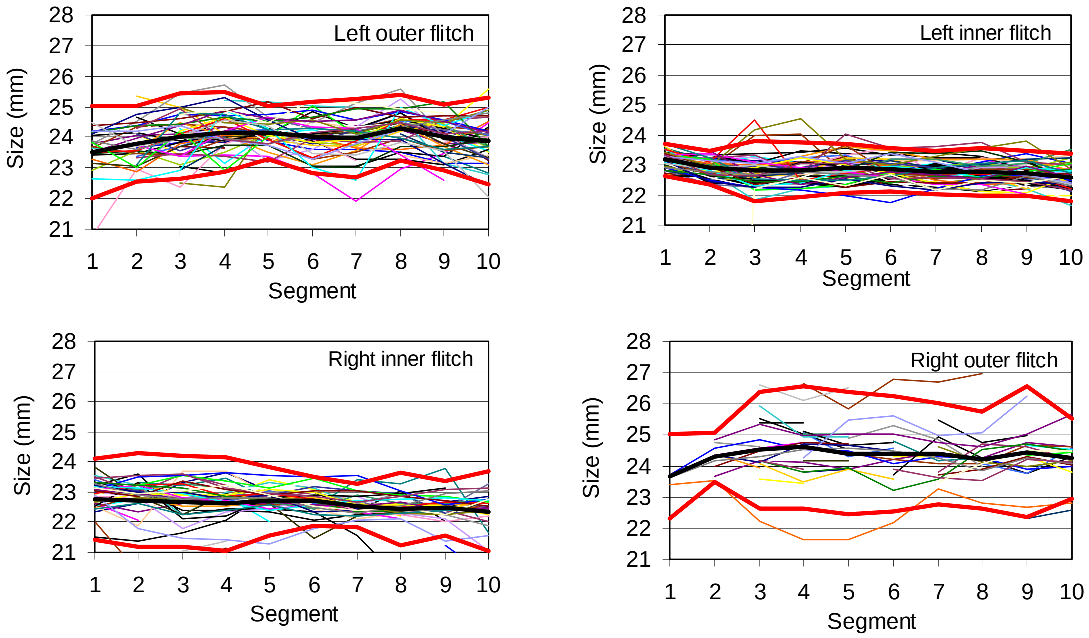


Figure A.19. *Board means in flitches sawn on 6 April. The outer flitches have larger standard deviation compared with the inner flitches. The missing data is obvious in the right outer flitch figure at the lower right-hand corner.*

The average size of the left outer flitches is thicker than the left inner flitches, as in Figure A.19. 58% of the segment means in the left inner flitches are smaller than the -2s limit, indicating undersize rejects, as can be seen in Table A.1. The right inner flitches have 78% reject probability due to undersize. However, the right outer flitches are of appropriate size, as are the left outer flitches, but they are mostly slab. Slab of 50% indicates that more than 50% of flitch length is slab, and it will probably be dropped into a chipper chute.

Most flitches have a significant percentage of undersize. When the undersize and slab reject probabilities are combined, independent of the set-up type, the trend indicates that the incidence of rejects is smallest at cant sizes of 125 to 150mm, as in Figure A.20. Data indicates that larger sawing allowances should be used for flitches in all cant sizes, but particularly in the case of large cant sizes.

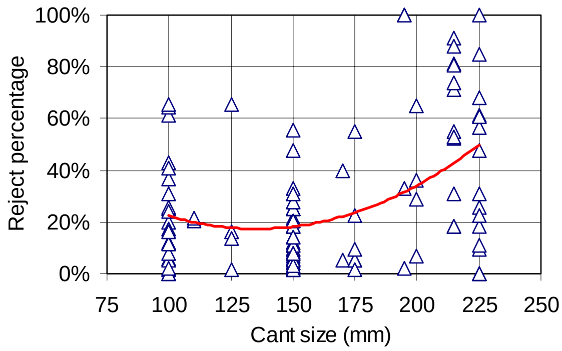


Figure A.20. *Total reject percentage of all flitches, independent of set-up, in normal production. The percentage includes both undersize and slab rejects.*

The reject percentage is independent of the *Saw load*, and depends only moderately on the number of pieces in a set-up. The correlations are -0.02 and 0.50. Reject percentage displays weak correlation with feed speed, -0.38, and cant size, 0.36. Thus, it is evident that the major cause of the incidence of rejects lies not in the process or machinery, but in production planning and log sorting.

Flitch analysis based on benchmarking or normal production data analysis yields different results, because the number of sample patterns in benchmarking is limited. Therefore, flitch analysis in benchmarking is less useful than analysis based on normal production data.

A.4 Double-arbor Circular Saws

The sawmill using double-arbor saw machines has a combination of canters and double-arbor circular saws with a maximum design capacity of 300 000m^3 in two shifts. First, logs are canted, then turned and canted again, profiled, and full edge sideboards and square cant are sawn. The cant width is measured optically, and then turned again, as in Figure A.21. Finally, the square cant enters the second saw centre, where it is profiled, a second set of sideboards is sawn, and the heartwood is split into two to five centrepieces. The centrepieces are measured in a second optical measuring device. In the saw house, the breakdown process is controlled by one person from log infeed into green sorting.

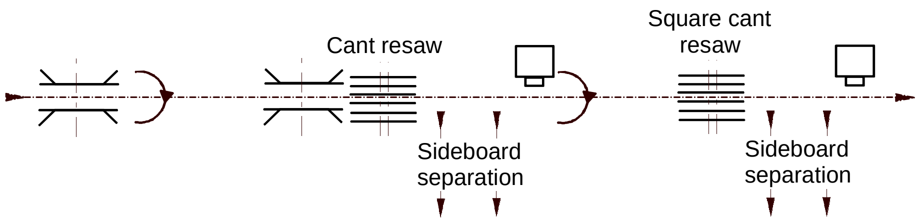


Figure A.21. *Layout of double-arbor circular sawmill. Measuring of square cant, and centrepieces takes place following sideboard separation.*

A.4.1 Log Breakdown

The examined 90kW Linck CSMK log breakdown double-arbor circular saw produces square cants. The saw has a constant rotation speed of 2800rpm. The sawblade diameter is 535mm, and thus the cutting speed is fixed at 78m/s. The kerf size is 5.0mm. Because of mechanical obstructions the measuring device is located at a distance of approximately ten metres from the saw exit, following sideboard separation, directly before the cant turning mechanism, as in Figure A.22. Thus, information is not available from the profiled sideboards. Because cant turning begins while a cant is still being measured, data from the last twenty percent of the cant length must be discarded. When the turning begins, the measures are not cant width data, but readings from the diagonal size that grow as the turning process proceeds. Thus, the analysis relates exclusively to the first eighty percent of cant length.

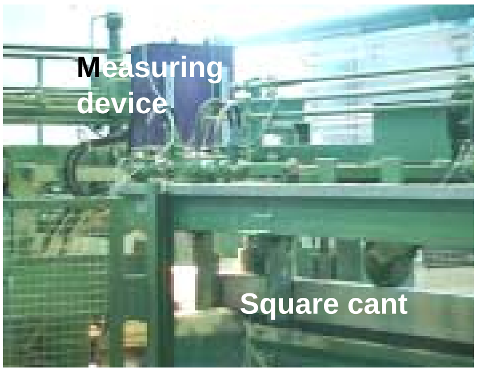


Figure A.22. *Measuring location of square cants after the first double-arbor circular saw centre. A cant is entering in the measuring zone from the right.*

Twelve different cant sizes are produced in log breakdown, ranging from 110mm to 250mm. The sawing allowance used by the sawmill, established during the saw start-up 1998, is 0.5mm. The double-arbor circular saw has the general structure presented in Figure A.23.

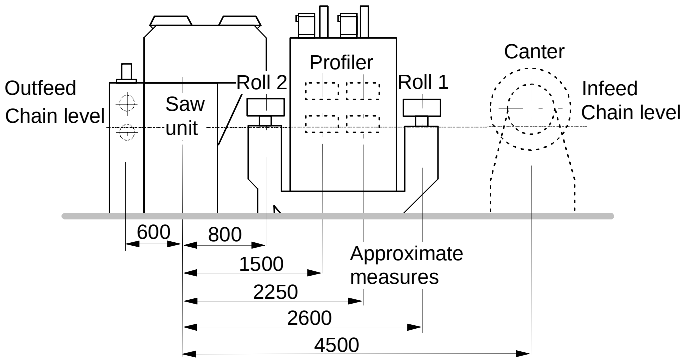


Figure A.23. *General layout of a double-arbor circular saw in log breakdown.*

The effects of machinery on the sawing process are:

- Profiling effects sawing up to segment 10
- Out-feed rolls' stabilising effect is seen on segment 3
- Release from feed roll 1 is seen in segments 5 and 6
- Release from profiler 1 is seen in segments 7 and 8
- Release from profiler 2 is seen in segment 9 to 10
- Canter effects are seen in long logs in segments 1 to 3
- Release from feed roll 2 is not seen due to the 20 percent data loss at the butt-end.

The within-segment bend illustrates log cant movement, as in Figure A.24. Loss of holding control following release from feed roll one may be the cause of bend in segments five to seven. The size of resulting taper is 0.64mm. Because sideboards are sawn, the only remaining cause of taper is sawblade bend.

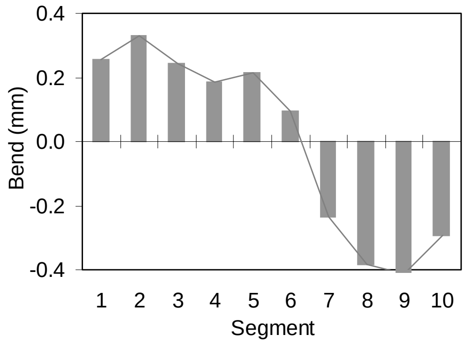


Figure A.24. *Within-segment bend shows butt-end thin taper of 0.8mm. The total standard deviation of the sample is 0.36mm.*

A.4.2 Large Top-end Size Variation in Log Breakdown Benchmarking

Large sawing variation in the top-end segments (segments 1 to 4) is visible in all log sizes during the benchmarking period, as in Figures A.25 and A.26. The data indicates that the process is less stable during the first thirty percent of the log length because of holding problems in profiling and log butt release from the canter. The more stable sawing after segment four may be due to improved holding by the outfeed rolls. This process phenomenon is also a likely cause of the deteriorating stability of normal production observed during the recording period, as in Figure 7.6, Chapter 7.2.

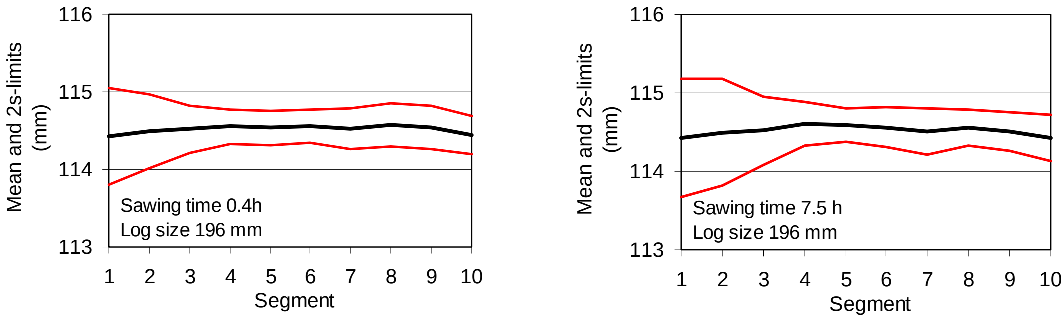


Figure A.25. *Change in cant size variation over seven hours. The total standard deviations are respectively 0.17mm and 0.21mm. Feed speed is 60m/min.*

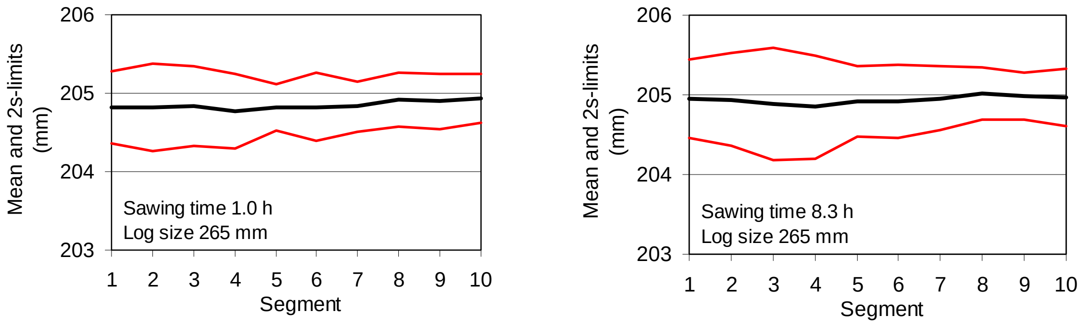


Figure A.26. *Change in cant size variation over seven hours. The total standard deviations are respectively 0.23mm and 0.26mm. Feed speed is 60m/min.*

The transition area in segments three to six can be quite prominent, as in Figure A.27. The level of standard deviation may be reduced by 0.2mm from the top-end maximum in minimum segments. Similar trend is apparent in all log sizes and feed speeds.

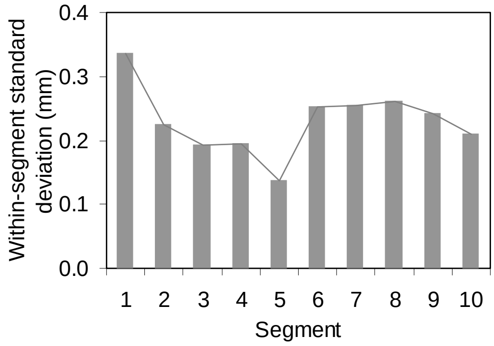


Figure A.27. *Average within-segment standard deviation of fifty logs. Sawing time is 0.7h, log size 225mm and feed speed 85m/min.*

A.4.3 Cant Resaw

The examined 160 kW Linck CSMK double-arbor circular saws produces centrepieces and sideboards. Thirteen green sizes are produced in cant resaw, ranging from 25mm to 100mm. The saw has operates at a constant rotation speed of 2800rpm and the sawblade diameter is 535mm. Thus the saw speed is 78m/s. The kerf size is 4.8mm. Because of mechanical obstructions, the measuring device is located at a distance of approximately ten metres from the saw exit, following the sideboard separation, at the transition area from the saw conveyor to the exit conveyor, as in Figure A.28. Thus, information is not available from the profiled sideboards. The entire length of the heartwood boards is measured.

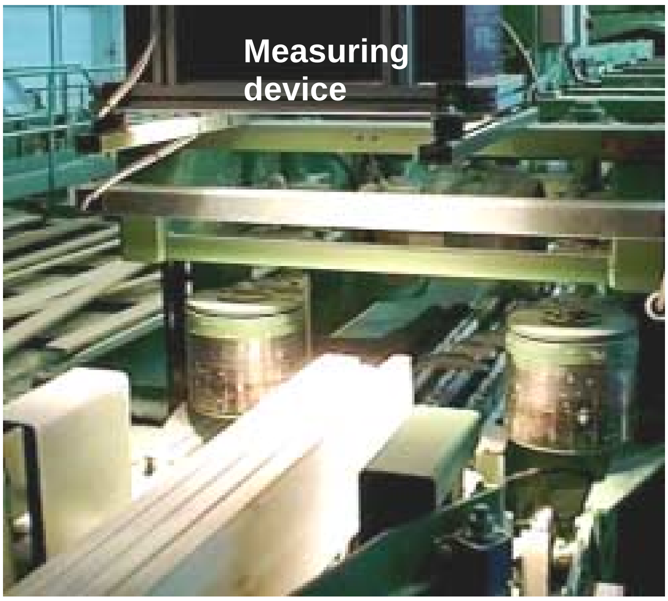


Figure A.28. *Centrepieces exiting from a double-arbor circular saw.*

The general structure of the double-arbor circular saw machine used in square cant resaw is shown in Figure A.29.

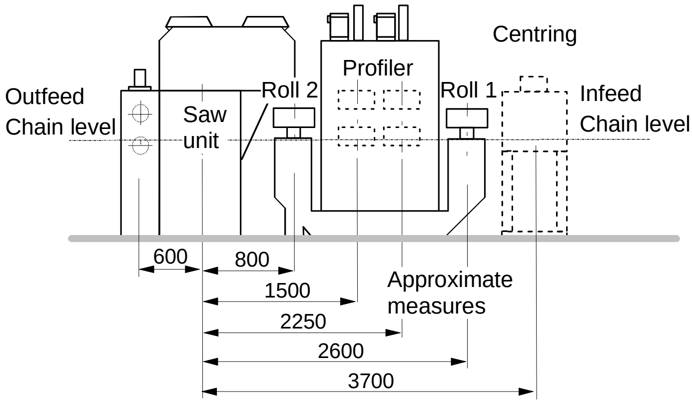


Figure A.29. *General layout of a double-arbor circular saw used in this study.*

The effects of machinery on the sawing process are:

- Profiling effects sawing up to segment 8
- Out-feed rolls' effects are seen in segments 2
- Release from centring guide is seen in segments 3 and 4
- Release from feed roll 1 is seen in segments 5 and 6
- Release from profiler 1 is seen in segments 6 and 7
- Release from profiler 2 is seen in segments 7 and 8
- Release from feed roll 2 is seen in segments 8 and 9.

A.4.4 Large Sawing Variation of Outer Boards in Cant Resaw

The general trend of large standard deviations in the outer boards sawn from the 110mm cants is visible in all 110mm cants throughout the test period of eight hours. Figure A.30 presents the difference between the inner and outer boards in the 110mm cant resaw. The feed speed has no effect on the standard deviation of the pieces in the set-up. The outer boards, Left and Right, have large standard deviation, and the centrepieces small standard deviation at all feed speeds. Sawing time during the test was 7.5 hours. This phenomenon is absent in the larger cants sizes, indicating cant feed and holding problems with the smaller cant sizes.

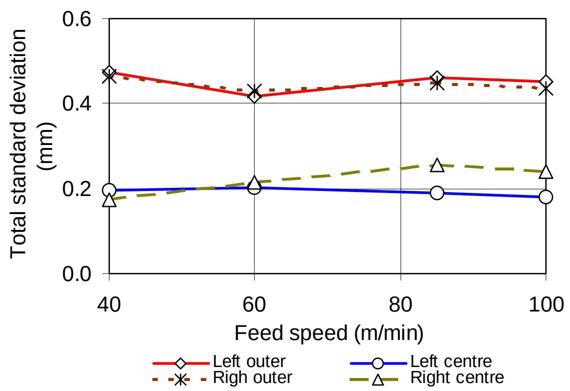


Figure A.30. *Effect of feed speed on the standard deviation of the centrepieces sawn from the 110mm cants.*

The instability of the sawing process in outer boards is demonstrated in Figure A.31 in the left figure. The 'normal' sawing process of inner boards have a characteristic tight standard deviation, shown in the right side figure.

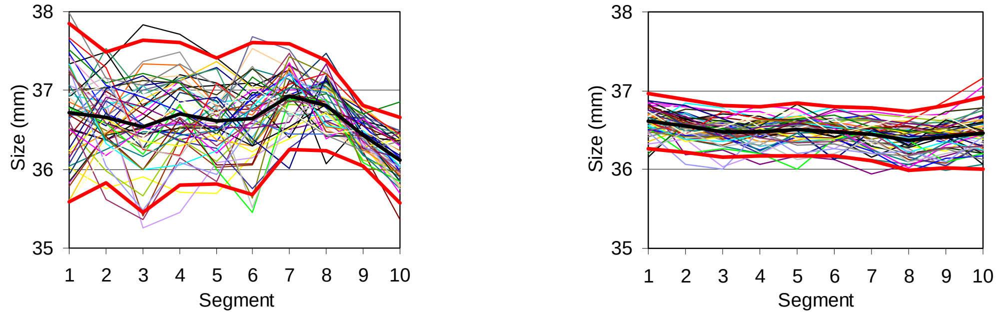


Figure A.31. *The outer left boards (in the left) indicate unstable sawing process compared with the left centrepieces (in the right). The outer boards shake when they are sawn. The saw machinery does not hold pieces firmly enough. The cant size is 110mm and feed speed 85m/min. The total standard deviations are respectively 0.46mm and 0.19mm.*

From segment 6 onward, the outer board's standard deviation starts to diminish. This is due to the cant butt exiting the profiler unit. At the same time, the released cant moves sideways, and the saw cuts a 0.5mm thinner butt on the left side and a 0.5mm thicker butt on the right side outer boards. After cant release from the profiler, the standard deviation level drops to the same level as that of the left centrepiece.

A.5 Twin Bandsaw and Triple Bandsaw

The sawmill using bandsaws has, in their main line, four bandsaw centres with a total capacity of 500 000m^3 in three shifts. They comprise a quad bandsaw for log breakdown, a twin for cant resaw, a quad for cant resaw, and finally a group of three bandsaws for square cant resaw, as in Figure A.32. The investigated processes include the log breakdown in the first machine, and the square cant resaw in the fourth and final machine.

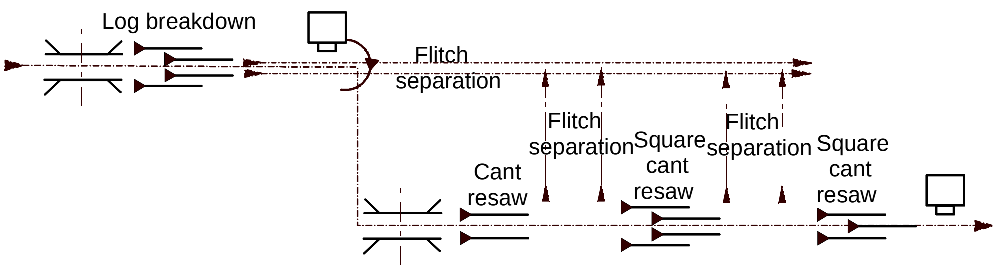


Figure A.32. *Bandmill layout. Measuring of log cant takes place following flitch separation, and heartwood pieces immediately following final square cant resaw.*

A.5.1 Log Breakdown

The examined canter-twin bandsaw centre produces log cants and flitches. The centre is in effect a quad bandsaw, but only the first pair of saws is normally used, and thus the examination treats the saw centre as a twin bandsaw, as in Figures A.33 and A.34. Thirty-four different cant and five flitch sizes are produced in log breakdown. The Kockum bandsaws operate at a variable rotation speed of 500mm to 850rpm. The wheel diameter is 1500mm, and thus cutting speed varies from 40m/s to 67m/s. The cutting speed is usually kept at 46m/s to 47m/s. The kerf size is 2.8mm. Log is first chipped in a canter. Then flitches are sawn in the twin bandsaw to produce a log cant. The used sawing allowance depends on cant size and varies from 0.7mm to 1.0mm. A measuring device is located at a distance of approximately fifteen metres from the saw exit, following flitch separation. Thus, flitch information is not available. The entire cant length is measured.

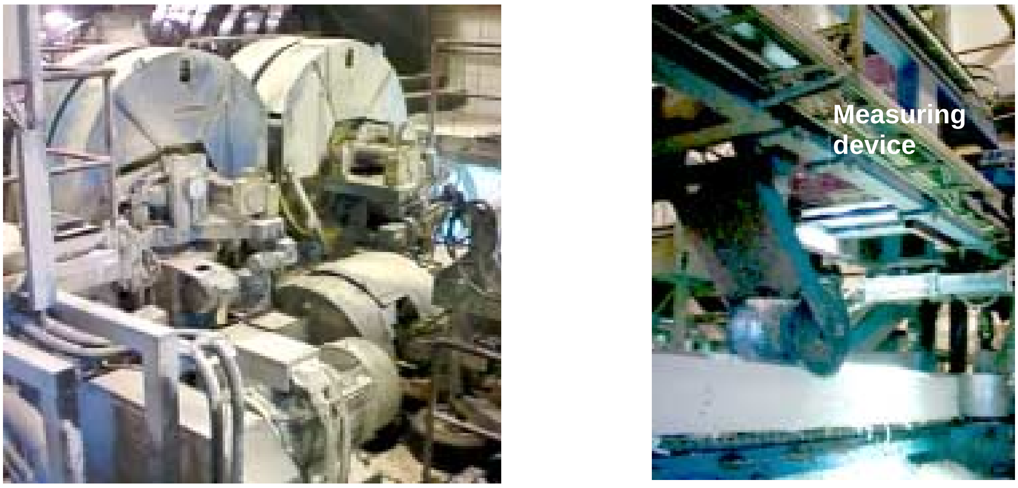


Figure A.33. *View of the twin (quad) bandsaw and canter. On the right, an optical measuring device, between the structural beams at the top, measures the size of log cants after the twin bandsaw. Flitch separation takes place before the measurement.*

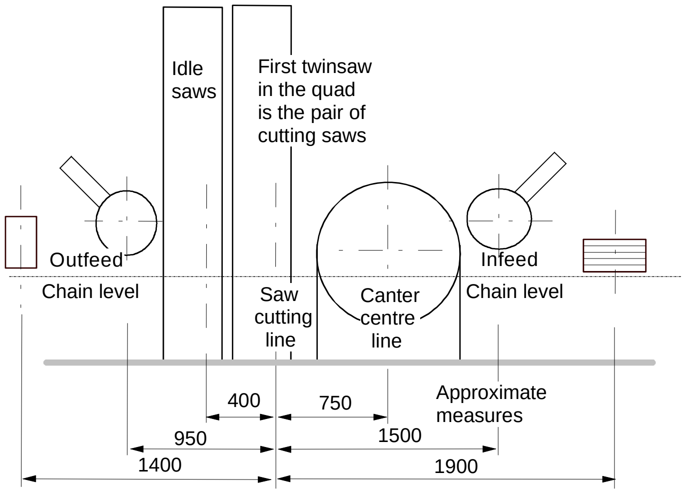


Figure A.34. *General layout of the twin bandsaw centre used in log breakdown.*

The effects of machinery on the sawing process are:

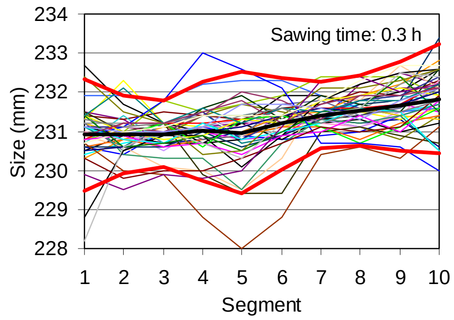
- Release from the feed tyres is seen in segments 5 to 6
- Release from the canter is seen in segments 7 to 8
- Action of the out-feed holding roll is seen in segments 5 to 10.

The feed tyres and wheel before the canter maintain process stability until log butt leaves them. At this stage, heavier vibration may occur at the saw end of a log. The chipper canter is the dominant cause of vibration during sawing, and thus a cause of size variation.

A.5.2 Broken Sawblade in Twin Bandsaw

After the sawing of the second sample set, during the change of set-up, the sawblade in saw two hit the wheel cover for no apparent reason. The sawblade was changed and the benchmarking test was continued.

The standard deviation and bend values of the samples sawn with the broken sawblade are large compared to the standard deviation with the replacement sawblade, as in Figures 7.12 to 7.14, considering that the sawing time had only been minutes. The main descriptors of the almost unused broken sawblade resemble the values of a 'normal' sawblade that has been used for many hours. Figures A.35 and A.36 illustrates different aspects of the broken sawblade compared with the new sawblade that has been used for 4.2 hours. The log size is 285mm, target 225mm, and feed speed 60m/min.



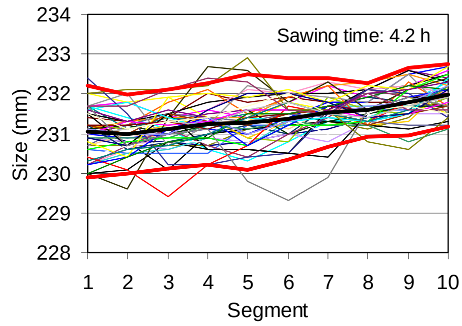
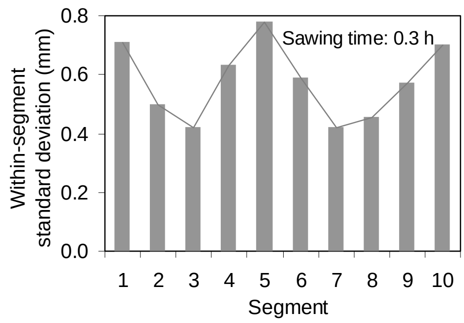


Figure A.35. *Large sawing variation of the 'broken' sawblade in a twin bandsaw at 0.3 hours, on the left, and normal sawing variation at 4.2 hours.*

The entry and exit standard deviations, as well as the standard deviation bulge at segment 5, of the 'broken' sawblade are exceptional, and they differ from a normal sawblade, as in Figure A.35. The sawing process with the broken sawblade displays large standard deviation peaks with alarming frequency compared with the normal sawblade.



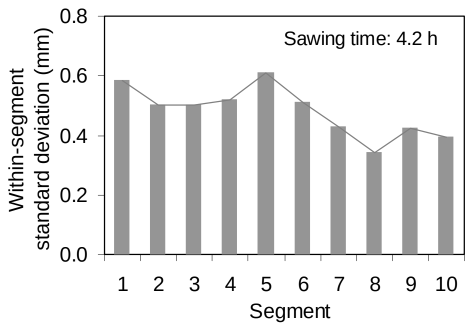


Figure A.36. *Large within-segment variation of the 'broken' sawblade in a twin bandsaw at 0.3 hours, on the left, and normal within-segment variation at 4.2 hours.*

The within-segment standard deviation in the 'broken' sawblade, which can be seen in Figure A.36, shows enhanced variations at the top-end, middle, and butt-end of sawn cants. This may indicate sawblade wander back-and-forth on band wheels.

The clearest indicator of potential sawblade problems is an exceptionally high total standard deviation compared with its peer sawblades at similar sawing times and parameters. Alternative indicators include non-uniform sawing variation along cants and across segments, and multi-peaked within-segment standard deviation.

A.5.3 Cant Resaw

The examined triple band resaw produces centrepieces out of square cants. The Kockums saws have a constant rotation speed of 580rpm. The wheel diameter is 1500mm, and thus the cutting speed is fixed at 46m/s. The kerf size is 2.8mm. There are 31 different nominal sizes ranging from 16mm to 150mm. The number of pieces in resaw varies from two to four pieces. The sawing allowance depends on centrepiece size and varies from 0.5mm to 0.7mm. A measuring device is located at a distance of one metre from the saw centre exit, at the transition area from the saw to the exit conveyor, as in Figures A.37 and A.39. The entire length of centrepieces is measured.

Figure A.37. *Triple bandsaw centre on the left. On the right, an optical measuring unit at the exit of the saw centre, seen from below. A stack of boards is exiting from the saws. Boards move from right to left.*

Depending on the square cant size, all three bandsaws, or two or only one, are processing wood. The outmost faces are produced in the previous bandsaw centre. The benchmarking analysis is performed with a set-up of 4-pieces, as in Figure A.38. The 3-piece set-up analysis presented in Chapter A.5.4 is sawn with saws 1 and 2.

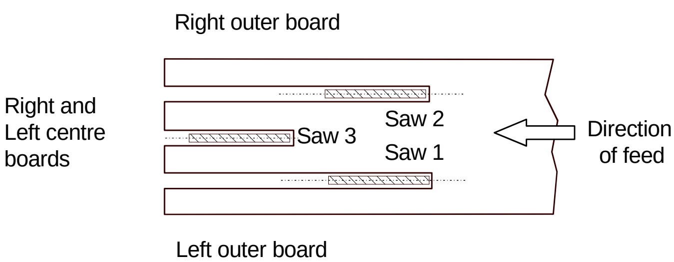


Figure A.38. *Designations of saws and boards in the triple bandsaw centre (seen from above) in a 4-piece saw set-up.*

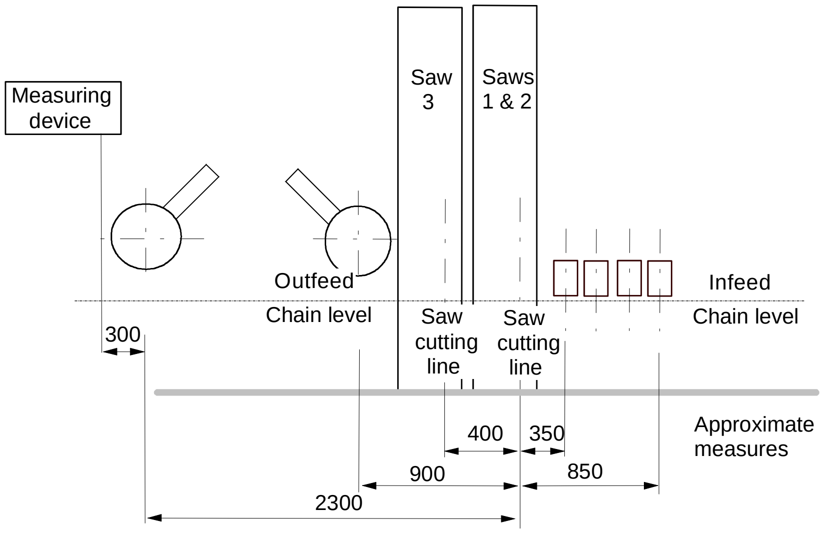


Figure A.39. *General layout of the triple bandsaw centre used in this study.*

The effects of machinery on the sawing process are:

- Entering into saw 3 is seen in segment 2 on the outer boards
- Top roll action is seen in segment 3 on the outer boards and segment 2 on inner boards
- Release from centring rolls is seen in segments 8 to 10 on the outer boards and segment 7 to 9 on the inner boards
- Release from saws 1 and 2 are seen in segment 10 on the inner boards.

A sample with large size variation in a board sawn between saws 1 and 3 is seen in Figure A.40. The total standard deviation is 0.73mm. The standard deviation is greatest at the top end, and smallest at the butt, following release from the centring rolls. Data indicates serious disturbances.

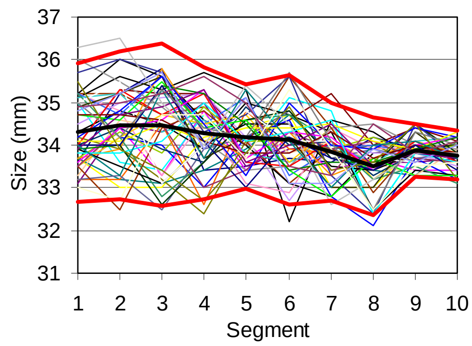


Figure A.40. *Large sawing variation in a triple bandsaw. The standard deviation at the top end is 0.8mm and in the butt 0.3mm.*

Progress of pieces through machinery can be analysed with sawblade bend data, as in Figure A.41. Comparison of the sawblade bend with the right centrepiece indicates that the sawblade in saw 3 bends towards the left centrepiece in segments one to six. At segment seven, the release from the centring rolls becomes apparent. In segment eight, the final release causes a large sideways shift, following which the process stabilises.

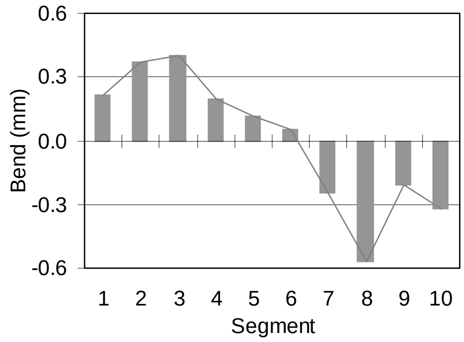


Figure A.41. *Sawblade bend discloses changes in sawing process as pieces progress through saw machinery. The average taper is 0.9mm.*

A.5.4 Observations on 3-piece Set-up during Normal Cant Resaw

Because the centrepieces in 4-piece set-ups have exceptionally large standard deviation of 0.7mm to 0.8mm, it is of interest to examine why the centrepieces in a 3-piece set-up display an ‘abnormally’ small variation of 0.2mm, as in Figure A.42. The outer boards in a 4-piece set-up display small sawing variation, while in a 3-piece set-up the variation is large.

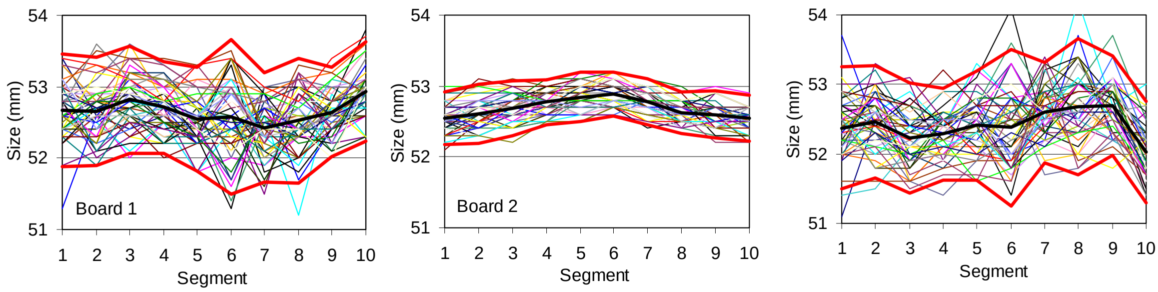


Figure A.42. *Sawing variations in a 3-piece set-up in a triple bandsaw centre. The thick lines represent the mean and ±2s limits. Boards run from left to right.*

From Figure A.42, it is evident that the centrepieces, sawn with saws 1 and 2, display small standard deviation, indicating that the saw operation is stable. On the other hand, the outer pieces have twice the variation and evident sawblade bend problems.

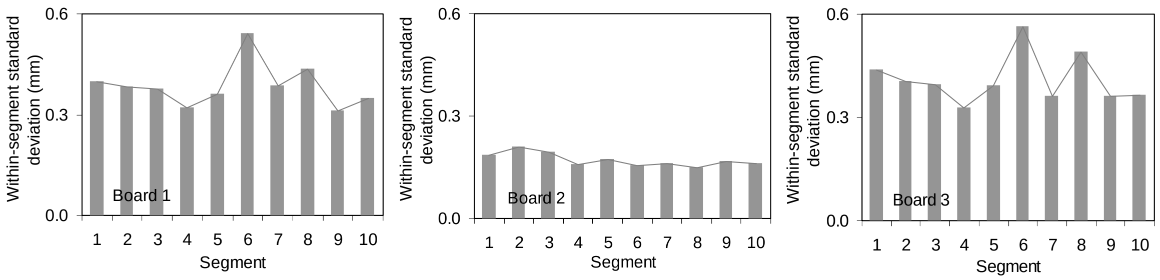


Figure A.43. *Within-segment sawing variations in a 3-piece set-up in a triple bandsaw centre.*

The within-segment graphs in Figure A.43 show that an increase in standard deviation takes place at segments 6 an 8 in the outer boards, while the centrepiece remains stable.

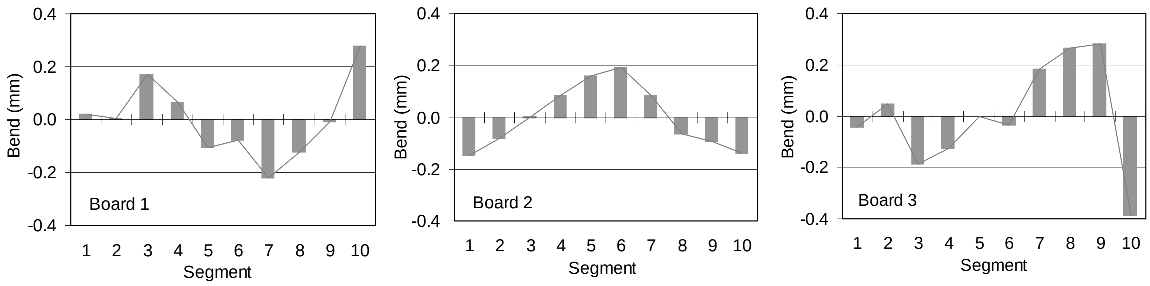


Figure A.44. *Sawblade bend in a 3-piece set-up in a triple bandsaw centre.*

The sawblade bend in both outer boards results in taper; the left board is butt thick and the right one butt thin, as in Figure A.44. The centrepiece has no taper. The strong bend deflection at the butt end of the right outer board indicates process problems. This effect in the left outer board is not as prominent. However, when the outer boards are compared side to side, the mirror image of behaviour is evident, as in Figure A.45.

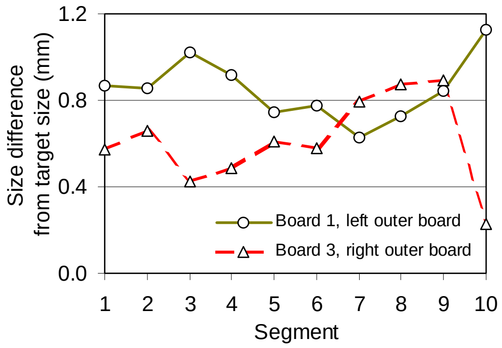


Figure A.45. *Size variations in the outer boards in a 3-piece set-up in a triple bandsaw centre.*

Although no direct data from the preceding bandsaw centre producing the outermost faces of the outer boards is available, it is evident that the large variation in size is caused by the previous centre. If the problem were in the triple bandsaw with two cutting sawblades, the standard deviation of the centrepiece would be identical to that of the outer boards. Because this is not the case, the standard deviation of the outer boards is seen as inherited from the previous bandsaw centre.

The previous bandsaw centre is a quad. Thus, the square cant, proceeding to the triple bandsaw, is sawn with saws that have the least holding support during cutting. In particular, the final release from the centring rolls results in heavy bend at segments 9 to 10. Other variations may be caused by 'normal' sawblade instability.

A.5.5 Sawblade Bend in Cant Resaw Benchmarking

Sawblade snaking is a common phenomenon in bandsaws. Snaking is a consequence of sawblade characteristics, sawn wood, and cutting parameters, such as saw and feed speed. Snaking is an individual occurrence in each saw cut, and it varies from log to log. A snaking value can be calculated for each individual board, and an average snaking value for an entire sample can be obtained. These values do not, however, tell us a great deal about potential systematic behaviour of the sawblades. The within-segment sawblade bend, on the other hand, illustrates clearly how individual parallel sawblades behave during the sawing process, as in Figure A.46.

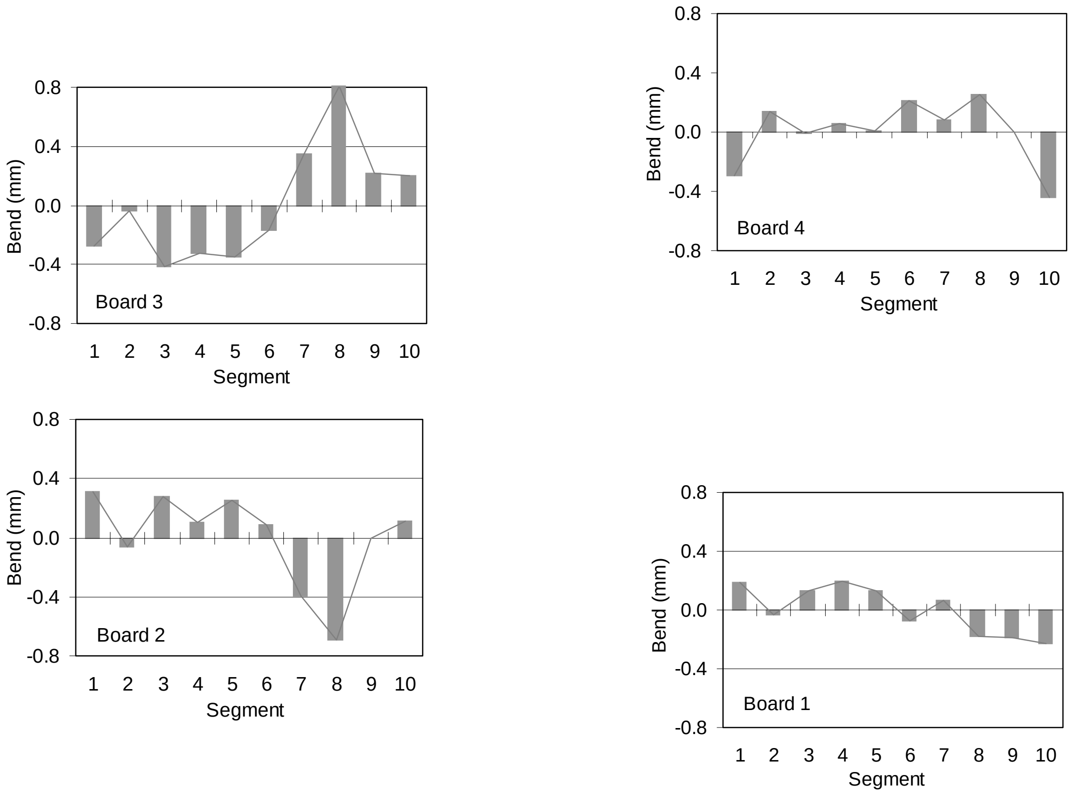


Figure A.46. *Sawblade bend in a 4-piece set-up in a triple band saw. Although sawing time is only 0.3 hours, the sawblade in saw 3, splitting the centre part, bends strongly towards board 2, the left centrepiece, starting to cut it thin at segment 7. The mirror image of the bend shape in the centrepieces is an indication that sawblades in saws 1 and 2 have very little connection with this phenomenon.*

The strong bend effect in segments seven to eight in centrepieces is the cause of the large difference in total and between-segment standard deviations and bend amplitude between outer and inner boards. The bend behaviour of the same set-up 9.5 hours later is identical to that in Figure A.46. Consistent sawing process in the top end segments one to six indicates the 'normal' level of sawblade bend. The physical distance from the last centring roll to sawblades in saws 1 and 2 is approximately the length of one segment, and the distance to the sawblade in saw 3 two segments, as in Figure A.39. The cause of the strong bend in segments lies in the feedworks. While a cant is held between all rolls, the sawing is steady. When partial and final release from the centring rolls occurs, the transversal position of the cant changes, which results in bend. The smaller the cant, the more prominent the phenomenon is, because cants with smaller resistance to bending spring more.

Appendix B: Precision and Accuracy of Manual Measurement

This appendix presents results of two tests made on precision and accuracy of manual measurement. The first test was done by using a data collector device, which automatically records the measures by a push of a button, and the other one by using conventional manual recording.

B.1 Recording Digital Caliper

Accuracy and precision of manual measurement with a recording digital caliper was tested with four inspectors, who measured a board twice successively, at fifty equally spaced, marked points on a board, as in Figure B.1. The board was four metres long, having freshly emerged from a single-arbor circular saw with a target size of 42.6mm.

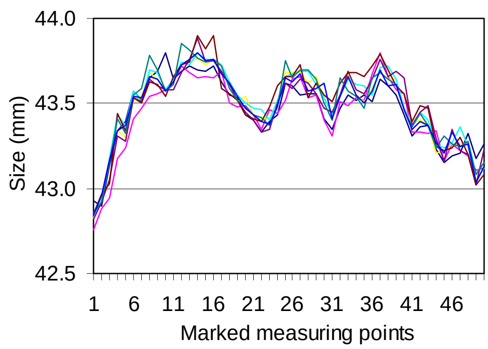


Figure B.1. *Manual readings by four inspectors. Each inspector measured a board two times at marked points.*

A comparison of results between the individual readings at each measuring point yielded 400 individual data samples. Figure B.2 presents the variation between individual readings. The average standard deviation of readings is 0.05mm, and the maximum deviation 0.09mm.

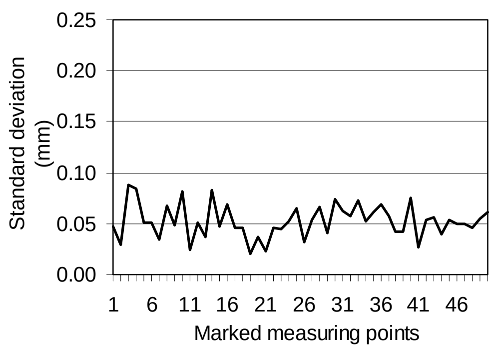


Figure B.2. *Standard deviation of two sets of readings by four different inspectors using a recording digital caliper.*

The benefit of a digital recording caliper is that reading errors are eliminated. Errors occur only due to variation in caliper manipulation. The results indicate that the average precision of manual measurement with a digital recording caliper at marked spots is 0.05mm.

B.2 Regular Digital Caliper

Precision of manual measurement with a digital caliper with manual recording was tested by having four inspectors measure a board at 30 non-marked locations along a board, as in Figure B.3. The board was 6.1 metres long and having freshly emerged from a double-arbor circular saw with a target size of 48.6mm. Because the measuring locations were not marked on the board, each inspector chose measuring locations by approximation.

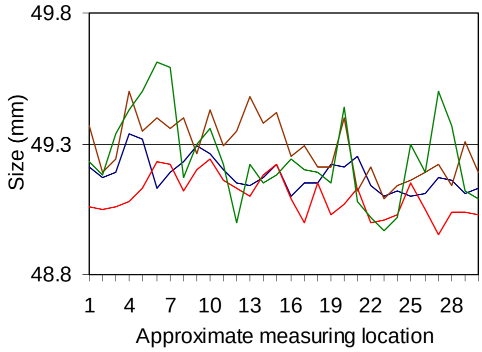


Figure B.3. *Manual readings by four inspectors. Measuring locations were not marked.*

A comparison of the results between the individual readings at each measuring point yielded 120 individual data samples. Figure B.4 presents the variation between individual readings. The average standard deviation of readings is 0.13mm, and the maximum 0.23mm.

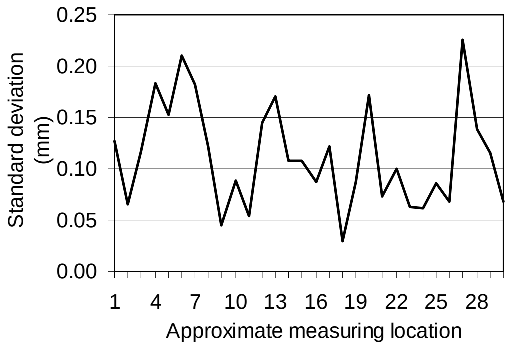


Figure B.4. *Standard deviation of readings by four different inspectors using a digital caliper with manual recording. Measuring locations were not marked.*

A major benefit of using a digital caliper is that reading errors are smaller than with a dial caliper or a regular caliper. Errors may occur as a result of variation in caliper manipulation, reading a value on caliper display, and in communicating a reading to a person making the entry on a report sheet.

Manual measurement is a reliable method when the measuring is performed in a controlled manner. When measuring points are known and marked, repeated measurements of different inspectors yield similar results, and the total variation is small, less than 0.1mm, as in Figures B.1 and B.2. When measuring is performed at non-marked locations, the results vary more and the total variation is bigger, approximately 0.15mm, as in Figures B.3 and B.4. The respective maximum variations are 0.1mm and 0.25mm. In this test, the inspectors knew that the measuring results were to be compared and analysed. Therefore, one may assume that the inspectors were more careful than usual, and the results are the best possible in manual measurement.

A realistic value for the precision of manual measurement is 0.3mm.

Appendix C: Effect of Trim Percentage and Segment Quantity

This appendix presents the effect of trim percentage and segment quantity on segment means. This appendix is support material to Chapter 5.4 where the discussed segment quantity is ten, and to Chapter 6.6.1 where the discussed trim percentage is ten.

C.1 Effect of Trim Percentage

The effect of trim percentage on the sample mean and standard deviations were tested using a sample of ten right centrepieces sawn in a single-arbor circular saw. The target size was 42.6mm and board length 5.3m. The number of readings from each centrepiece was 676. Thus, the entire sample yielded 6760 readings. From this original data, trimmed segment means were calculated for ten segments using trim percentages of 0, 10, 20 and 30. Thus twice the number of readings is filtered from a sample, because the trimming is done both at the low and high end of values. Therefore trimming by 30% means that 60% of the readings are filtered from a calculation of a trimmed segment value. Trim percentage effects are presented in Figures C.1 and C.2.

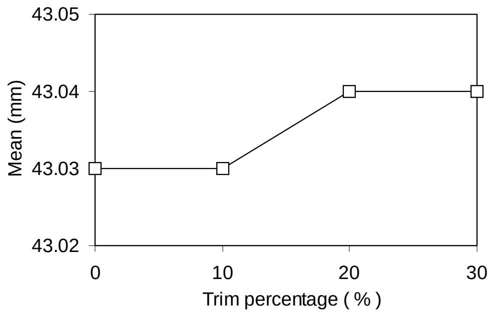


Figure C.1. *Effect of trim percentage on sample mean.*

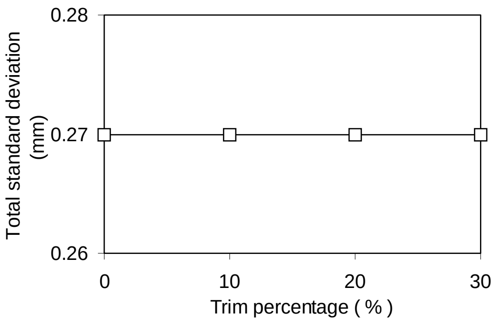


Figure C.2. *Effect of trim percentage on sample standard deviation.*

The effect of a trim percentage on mean and standard deviation is in the order of one hundredth of a millimetre when the trim percentage is between 0 and 30. Only minor differences can be observed in the board segment mean curves, as in Figures C.3 and C.4.

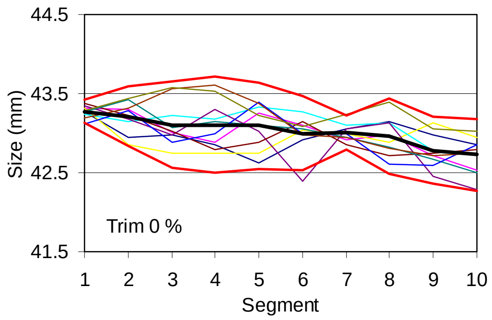


Figure C.3. *Effect of 0% trim on sample and segment means.*

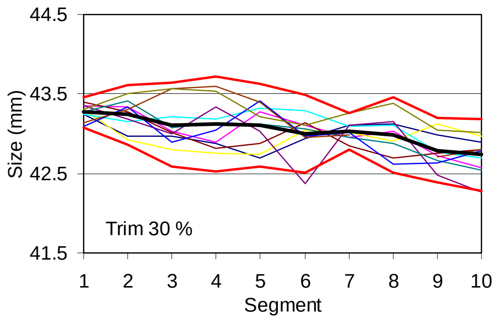


Figure C.4. *Effect of 30% trim on sample and segment means.*

The robustness of 10-segment calculations is evident because each segment mean is calculated using 67 original readings (before trimming). The original data can tolerate a 30 percent trim without corrupting sample descriptors.

C.2 Segment Quantity

The quantity of required segments in tests was analysed with two alternative combinations of:
fifty boards and ten segments (B50/S10), and fifty boards and fifty segments (B50/S50). The purpose of the evaluation is to determine if more detailed data, such as fifty segments versus ten segments, will give improved results.

Readings from fifty cants sawn in a single-arbor circular saw were used in the evaluation. The set-up produced two flitches and two centrepieces. The data used is from the left side centrepieces because these pieces are sawn with sawblades on the same arbor, and thus the effect of external factors, such as setworks and feedworks, is smallest. A comparison of the two calculation methods is presented in Table C.1.

Table C.1. *Comparison of main descriptors in left centrepiece. Values are in mm.*

Number of boards and segments	B50/S10	B50/S50
Mean	66.77	66.76
Total standard deviation	0.31	0.33
Between-board standard deviation	0.20	0.20
Between-segment standard deviation	0.16	0.15
Taper	-0.35	-0.37
Bend amplitude	0.43	0.50

The main descriptors, Table C.1, and frequency distributions, Figure C.5, indicate that the two methods are for all practical purposes equal.

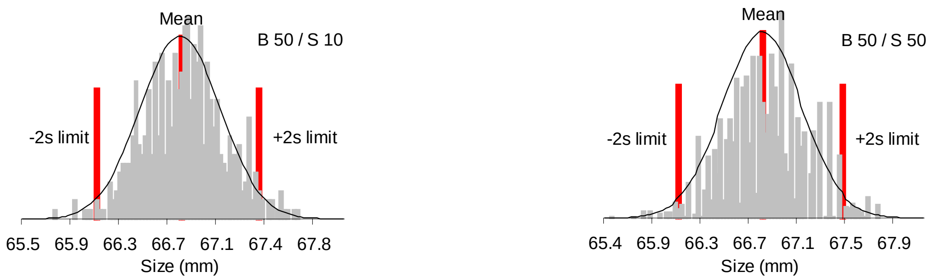


Figure C.5. *Frequency distribution of readings from fifty boards calculated with 10-segment method (B50/S10), on the left side, and with 50-segment method (B50/S50).*

Similarities are further confirmed by the within-board standard deviations, as in Figure C.6, and the within-segment standard deviations, as in Figure C.7.

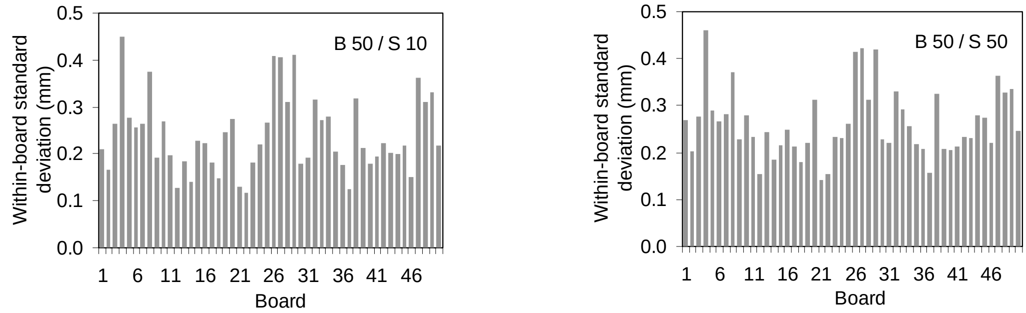


Figure C.6. *Within-board standard deviations of fifty boards calculated with 10-segment method (B50/S10), on the left side, and with 50-segment method (B50/S50).*

The within-segment standard deviations calculated with 50-segments naturally expose more detail of board profiles. However, the 10-segment results are relatively similar to the 50-segment results; the results vary only some hundredths of a millimetre from each other. In sawmill analysis, the difference has no practical significance, and thus the within-segment standard deviations can be calculated with either of the two methods.

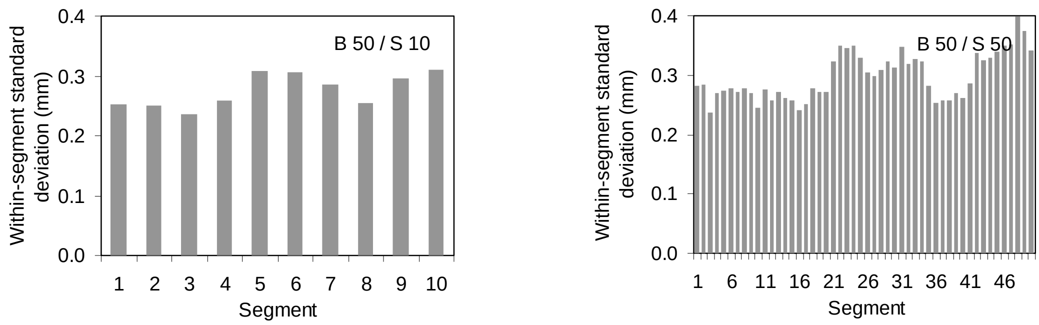


Figure C.7. *Within-segment standard deviations of fifty boards calculated with 10-segment method (B50/S10), on the left side, and with 50-segment method (B50/S50).*

Graphic presentations of size of individual boards are presented in Figure C.8. The curves for mean and ±2s limits are included in figures. Figure shows board sizes along board length from segment to segment. The average curves show taper, thinner butt, and similar spread of readings.

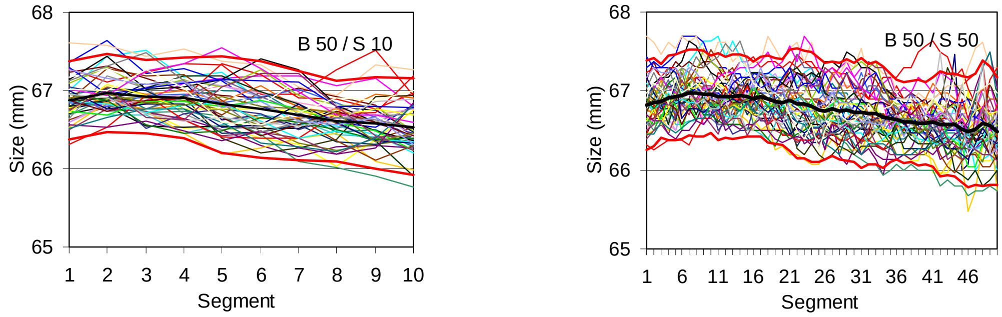


Figure C.8. *Board size from top to butt, and the 2s variation of fifty boards are calculated for 10-segment method (B50/S10), on the left side, and with 50-segment method (B50/S50).*

Sawblade bend shows the differences in process performance throughout the entire sample population from segment to segment. In Figure C.9, the dominant feature is sawblade bend leading to taper and wedge. Both methods display identical bend.

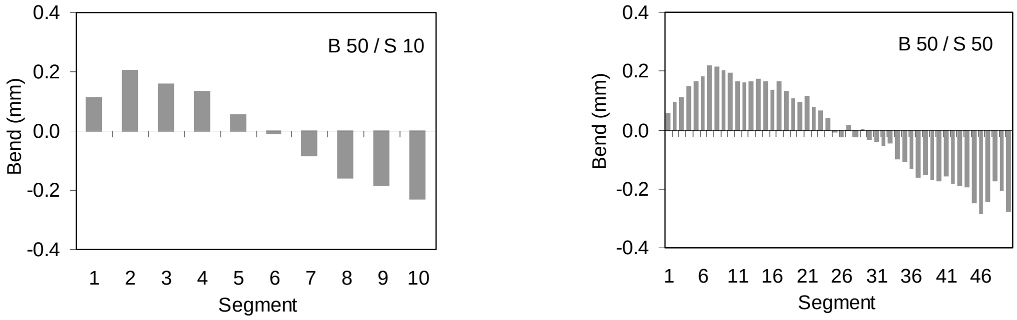


Figure C.9. *Sawblade bend within board segments. Presented results are calculated for 10-segment method (B50/S10), on the left side, and with 50-segment method (B50/S50). Both bends indicate top end thick and butt-end thin sawing.*

The 10% trim percentage does not have a negative effect on the accuracy or size of the process descriptors. Furthermore, the data indicates that the sample descriptors calculated and the graphical presentations drawn, using fifty boards and either ten or fifty segments, are for all practical purposes identical. Based on the comparison of the two methods, the method of fifty boards and ten segments (B50/S10) is used to produce data for saw centre benchmarking and analysis. This method has an effective capacity to average out random local variations, due to both large sample population and strong averaging of data readings. The 10-segment calculation with 10% trim is chosen for this study.

Appendix D: Data Readings and Trimmed Means

Table D.1 presents an example of data readings collected from one single board. The length of the measured board was such that each segment contains 31 individual data readings. These readings are used to calculate the trimmed means for each segment in the board, Table D.2.

Table D.1. *Original data for the left centrepiece number nine sawn in a single-arbor circular saw. The target size is 49.3mm. Values are in mm.*

	Segment									
Reading	1	2	3	4	5	6	7	8	9	10
1	49.5	49.9	49.2	49.6	49.9	49.9	49.6	49.9	49.2	49.9
2	49.5	49.9	49.2	49.6	49.9	49.6	49.6	49.6	49.6	49.9
3	49.5	49.9	49.5	49.2	49.9	49.9	49.6	49.6	49.6	49.9
4	49.5	49.9	49.5	49.6	49.6	49.9	49.6	49.6	49.6	49.9
5	49.5	49.5	49.5	49.2	49.9	49.9	49.6	49.2	49.6	49.9
6	49.5	49.5	49.2	49.6	49.9	49.9	49.6	49.2	49.6	49.9
7	49.5	49.5	49.5	49.6	49.6	49.9	49.6	49.6	49.6	49.6
8	49.9	49.9	49.2	49.6	49.9	49.6	49.9	49.6	49.9	49.9
9	49.5	49.9	49.5	49.6	49.9	49.9	49.6	49.6	49.9	49.6
10	49.9	49.5	49.5	49.2	49.9	49.6	49.6	49.6	49.6	49.6
11	49.9	49.9	49.5	49.6	49.9	49.9	49.6	49.6	49.6	49.6
12	49.5	49.5	49.5	49.6	50.3	49.6	49.6	49.6	49.6	49.9
13	49.9	49.9	49.2	49.9	49.9	49.6	49.6	49.6	49.6	49.9
14	49.9	49.5	49.2	49.6	49.9	49.6	49.6	49.2	49.6	49.6
15	49.9	49.5	49.5	49.9	49.9	49.6	49.6	49.2	49.2	49.6
16	49.9	49.5	49.5	49.6	49.9	49.6	49.6	49.2	49.6	49.6
17	49.9	49.5	49.5	49.9	49.9	49.6	49.6	49.6	49.6	49.6
18	49.9	49.2	49.5	49.9	49.9	49.6	49.9	49.6	49.6	49.9
19	49.9	49.5	49.5	49.6	49.9	49.6	49.6	49.6	49.6	49.9
20	49.9	49.2	49.2	49.9	49.9	49.6	49.6	49.6	49.6	50.3
21	49.9	49.5	49.2	49.6	49.9	49.6	49.6	49.2	49.6	49.9
22	49.9	49.5	49.2	49.6	50.3	49.6	49.6	49.6	49.6	49.6
23	49.9	49.5	49.5	49.6	49.9	49.9	49.6	49.6	49.6	49.2
24	49.9	49.5	49.5	49.6	49.6	49.6	49.6	49.6	49.6	49.6
25	49.9	49.5	49.6	49.9	49.6	49.6	49.9	49.2	49.2	49.6
26	49.9	49.2	49.6	49.9	49.9	49.6	49.6	49.2	49.6	49.2
27	49.5	49.2	49.6	49.9	49.9	49.6	49.6	49.6	49.9	49.6
28	49.5	49.5	49.6	49.6	49.6	49.6	49.6	49.6	49.9	49.6
29	49.9	49.2	49.6	49.6	49.9	49.9	49.6	49.6	49.9	49.2
30	49.9	49.5	49.6	49.9	49.9	49.9	49.9	49.6	49.6	49.2
31	49.5	49.5	49.2	49.9	49.6	49.9	49.6	49.2	49.9	49.2

Table D.2. *Trimmed segment means calculated from data in Table D.1. Trim percentage is 10. Values are in mm.*

	Segment									
	1	2	3	4	5	6	7	8	9	10
Mean	49.76	49.56	49.43	49.68	49.86	49.71	49.61	49.50	49.64	49.69

The mean size of the left centrepiece number nine is 49.64mm. It deviates 0.03mm from the sample average of 49.67mm. The total standard deviation of the board is 0.13mm. It is small compared with the total standard deviation of the fifty board sample, 0.30mm.

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