THE IMPACTS OF SAWMILL PROCESSING VARIANCES ON LUMBER TARGET SIZES AND PRODUCTION REVENUE

by

YINGZHONG LIN

B. Sc., Fujian Forestry Institute, China, 1983
M. Sc., Northeast Forestry University, China, 1986

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Department of Wood Science

The University of British Columbia
Vancouver, Canada

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Abstract

Although the statistical quality control technique has been applied in the lumber manufacturing industry for more than two decades, many sawmills are still severely over-sizing their lumber due to the inefficiency of their lumber target size control programs in which only the sawing variation is controlled. The shrinkage variation and planing variation which may also contribute significantly to lumber target sizes in the current sawmills are usually not the controlled subjects. This study evaluated the traditional target size control programs and investigated the impacts of all the three processing variances (sawing, drying and planing) on lumber target size control and production net revenue. This was done by: 1) thorough examination of the system variances of an interior B. C. softwood sawmill, and 2) developing a target size estimation program which considers all the three processing variances.

The results of empirical study indicated that the variation in drying shrinkage was even larger than total sawing variation and the planing variation of the test mill was more than half of the total sawing variation. The shrinkage variation caused by drying operations other than material itself was found significant. Therefore it was found to be essential to control the drying and planing processes along with controlling the sawing process.

The evaluation of traditional target size estimation method showed that this method over-estimates lumber target sizes. The results also showed that the target sizes currently used

in the test sawmill were much larger than the necessary target sizes. There is great opportunity for the mill to reduce its target sizes. If the variances of the three sub-processes are strictly controlled, the test mill could expect to realize about three million dollar net revenue per year without reducing current system variation level.

The study of the impact of system variation on the target size reduction showed that the reduction in planing variation had greatest impact among the three processing variances. The impact of sawing and drying variation on the target size reduction were similar. In general, it was the variation which was larger in value had larger impact on target size reduction.

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1 Introduction

As concerns for the environment and future wood supply increase, the available wood resources for industrial, construction and home use are decreasing. At the same time, wood demand has increased and will continue to increase as the wood consumption per person and the world population both increase. More efficient use of the available wood resources is an important part of the solution to this current problem.

Canadian statistics shows that the cost of raw material and supplies in the lumber manufacturing industry accounts for far more than half of the total lumber production cost, and it has been increasing steadily. For example, in British Columbia, the cost of material and supplies of saw mills in 1988 was 75 per cent of the total cost of lumber manufacturing and 59.6 per cent of lumber value (Macklin, 1992). Furthermore, the increased stumpage prices and environmental restrictions lead to further increase in raw material cost. Logging cost alone has been increased by 50 per cent in the past two years (Hamilton, 1995). Again, increasing raw material conversion efficiency is a key to the survival of a sawmill.

The products and waste products of cutting a log include lumber, chips, saw dust and planer shavings. Lumber is the most valuable product and the increase of lumber recovery rate is always an important objective of lumber manufacturing. The results of "Study of Softwood Sawlog Conversion Efficiency and the Timber Supply Problem" in 1973 showed that the

average lumber recovery rates in United States' band mills and circular saw mills were 48.5% and 42%, respectively, which means that only less than half of the log volume was converted to lumber in the 1970s. The sum of saw kerf and planing shavings was about 30% of raw material volume. The rest was converted to wood chips.

Basically, there are three categories involved in increasing the lumber recovery rate, i.e., reducing saw kerf, optimizing cutting patterns and reducing system processing variance. Reducing saw kerf reduces the volume of sawdust; optimizing cutting patterns reduces both the volumes of saw dust and chips; reducing processing variance reduces planing shavings, over-drying, and average finish lumber sizes.

The processing variance of a sawing system producing dry, dressed lumber mainly consists of sawing variation, shrinkage variation and planing variation. A lot of studies have been devoted to the control of sawing variation and as a results, the average sawing variation has been greatly reduced in the past two decades. In the 1960s, sawing variation was simply accounted for by a constant, "tolerance", the average of which was 0.2 inches for US west coast sawmills. In the 1970s, the average sawing standard deviation of US sawmills was reduced to 0.146 inches (Sawmill Improvement Program, 1973). The average sawing standard deviation of 22 sawmills in B. C. was 0.132 inches (Bremhall, 1973). In the 1990s, the average sawing standard deviation of Canadian sawmills has been further reduced to 0.039 inches (Lister, 1995).

However, the shrinkage variation caused by the drying operation and its impact on lumber target sizes and mill profitability has not received its deserved attention in the past. Few studies on variance control in lumber drying related to lumber target size control and sawmill production profits have been reported. How the drying variation impacts on the lumber target sizes and conversion efficiency is not clear yet to the industry. The fact of unclear relationship between the lumber target size and sawing variation shows that the factors other than sawing variation, such as planing variation, shrinkage variation and production requirements, may contribute significantly to green lumber target sizes (Lister, 1995). A better understanding of the variation in the whole sawing system (including sawing, drying and planing) and its impact on lumber conversion efficiency is critical to further improvement of lumber conversion efficiency.

A green target size is the expected green size set by a sawmill in order to cut lumber which yields dry dressed lumber of the sizes not less than the corresponding minimum dry, dressed size required by the grade rules. As it is shown in Figure 1, extra fiber is added to the required dry dressed lumber size to allow for sawing variation, drying shrinkage and lumber surfacing in sawing rough green lumber. Each of these process has a variance, which must be accounted for. The smaller the system processing variance (sawing, shrinkage and planing variation) the smaller the target size is required. Smaller target sizes result in less raw material consumption in producing the required dry, dressed sizes of lumber. The green target sizes of a sawmill very well reflect the level of the processing variation of the whole processing system or the production profit of the sawmill.

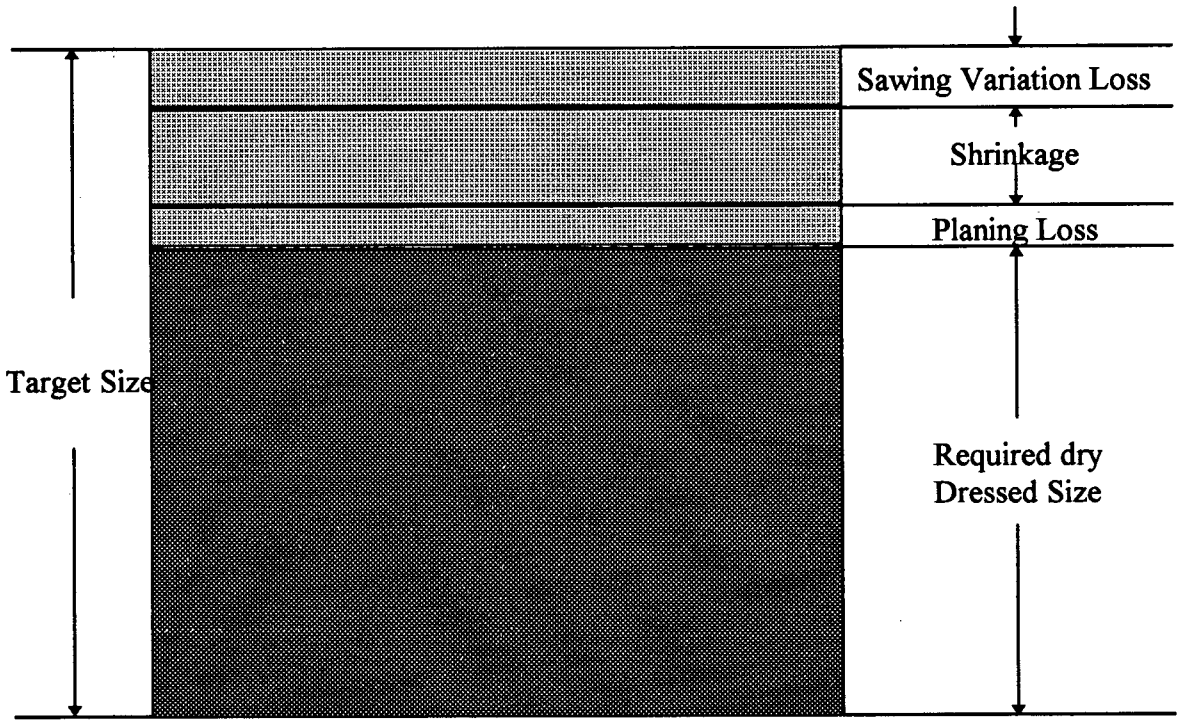

Figure 1 The Composition of the Green Target Size

The average target size has been consistently reduced in the last two decades as the average sawing variation has been reduced. For example, in the 1960s the average green target size of 2 inch thick boards was 1.876 inches when the sawing variation was accounted for by a "tolerant" in US west coast sawmills. In the 1990s, the average target size has been reduced to 1.69 inches when the sawing standard deviation was 0.039 inches in Canadian sawmills (Lister, 1995).

Though the target size depends on all the three processing variations (sawing variation, shrinkage variation and planing variation), the attention of the target size control

programs has been restricted to the control of sawing variation. In the current target size estimation methods, only sawing variation is treated as a random variable, the drying shrinkage and shrinkage variation are accounted for by a constant shrinkage allowance and the fiber needed for dressing is accounted for by a constant planer allowance. The result of a computer simulation study showed that these target size estimation methods may not yield correct target sizes (Cassens and Gibson, 1993).

Studies show that due to the high percentage of material costs in lumber manufacturing, target size reduction (reduction of total system processing variation) has great impact on sawmill revenues. The result of a complete sawmill simulation showed that the reduction of green target sizes by 5.9% results in 7.2% increase in lumber recovery factor (LRF) (Maness and Lin, 1995). Lumber size quality control is essential to maximizing mill efficiency and profitability. However, to take full advantage of the information gained in a lumber size QC program, a correct method of sampling and estimating sawing and drying variation and calculating correct target sizes must be devised.

The purpose of this study is to improve raw material conversion efficiency by a detailed examination of the factors which influence lumber target sizes. The information of the three processing variations (sawing, drying and planing) of an interior B. C. softwood sawmill will be collected through field testing. The current target size estimation methods and the impacts of each processing variation on lumber target sizes and mill production profit was evaluated by incorporating a computer simulation technique and the statistical analysis technique based on the data collected at the test mill. A new target size estimation method

which reflects the processing variation of the whole sawing system will be developed. The study has the following objectives:

1. Identification of total system variation in the sawing, drying and planing processes by detailed field studies,
2. Developing a target size estimation method which takes account of all the processing variations of the three sub-processes,
3. Comparison of current target size estimation method with new target size estimation method,
4. Identifying the impact of system variations on lumber target sizes and volume recovery, and
5. Identifying the impact of target size reduction on mill net revenue.

2. Literature Review

The process of converting saw logs to dry, dressed lumber consists of three main processes: sawing, drying and planing. There is processing variation in each of the three processes due to operator variability, mechanical play, lack of repeatability and many other factors. In the sawing process, there is variation among the sizes measured at various points of a piece of lumber and also variation among the piece averages. These two size variations are called within-board variation and between-board variation, respectively. In the drying process, the variation of lumber shrinkage can be caused either by material variation or the variation in the drying operation. An example of drying operation variation is the uneven airflow in a drying kiln. Boards in some locations of the kiln dry quicker than boards in other locations. An example of variation in the raw material is the orientations of a piece of lumber in a log. Wood tangential shrinkage is about twice that of wood radial shrinkage in most wood species. In the planing process, there is planing variation.

As shown in Figure 1, the green target size has traditionally been decided by four factors: the minimum dressed size required by grade rules, drying shrinkage, the fiber required to off-set sawing variation and the fiber needed for surfacing. The larger the processing variations are, the larger the target size is required to insure the satisfied dry, dressed lumber size. Reducing the system processing variation will reduce lumber target sizes, thus increases raw material conversion efficiency.

The statistical process control method applied in sawmills to reduce sawing , drying, and planing variations, thus reducing lumber target sizes is called the lumber target size control program. The tasks of these programs include data collection and evaluation, variation estimation, target size estimation and process monitoring by control charts.

The lumber industry had been slow to embrace the concept of formal quality control (Mason, 1973). It was probably at the beginning of the 1970s when statistical analysis methods were first applied in the lumber manufacturing industry to study lumber size variation. In a survey of 22 B. C. sawmills in 1973, the variation of rough green lumber thickness was presented by a variability index, the variance (in^2) multiplied by 10,000. At each mill 25 boards were measured in thickness at four places, 1 inch from each edge of the piece at 1 foot from each end. The variability index was further broken down to two components: the between-board index attributed to errors in the set-works, and the within-board index due to variation in thickness from side to side and from end to end of a board. The latter may be partly due to saw-blade vibration, wandering and, in case of double-arbor circular saws, by misalignment of the saws. The survey found that the variation between boards was responsible for most of the variability in thickness. The set-works was therefore the prime target for the improvement in control at that time.

Warren further developed the concept of treating rough-sawn boards as non-uniform thickness in the same year (Warren, 1973). The variation among the sizes in a board was given by the within-board standard deviation and the variation among board averages was given by between-board standard deviation. The two standard deviations and the total sawing standard

deviation were estimated by analysis of variance. Two phases were required to complete the estimation of sawing standard deviation. The sawing standard deviation was firstly estimated with 50 samples to estimate proper sample size for correct sawing standard deviation estimation. Four random measurements were taken from each sample. Then with the sample sizes determined by the first phase, the sawing standard deviation could be estimated at the required precision. The relationship between sample sizes and the sawing standard deviation (between-board and within-board standard deviations) estimated with the first sampling phase was presented in a table. The algorithm of estimating between-board and within-board deviations starts from computing the sum of squares of all measurements, SS and grand total of the measurements GT. Then the total sum of squares SS_t is computed by

$$SS_t = SS - GT^2 / N \qquad [1]$$

where N is the number of total measurements. The between-board sum of squares (SS_b)

$$SS_b = SSB / n - GT^2 / N \qquad [2]$$

where SSB is the sum of squares of the board totals and n is the number of measurements in each board. The within-board sum of squares (SS_w),

$$SS_w = SS_t - SS_b \qquad [3]$$

The means of the within-board sum of squares and between-board sum of squares are calculated by

$$M_w = SS_w / (N - m) \qquad [4]$$

and

$$M_b = SS_b / (m - 1) \qquad [5]$$

respectively, where m is the number of boards. Then the within-board and between-board standard deviations are estimated by

$$S_w = \sqrt{M_w} \qquad [6]$$

and

$$S_b = \sqrt{(M_b - M_w)/N}, \qquad [7]$$

respectively.

The target size is the sum of required dry dressed size, a fixed allowance for shrinkage and dressing, and the fiber needed for sawing variation. The shrinkage and dressing allowance

were treated as deterministic values in this size control program. Only the sawing variation is the object of the lumber size control program.

Due to bad size quality control in most British Columbia sawmills (indicated in the studies by Valg (1978), Bramhall (1973) and Dobie (1975)), Whitehead (1978) presented a systematic statistic quality control program, believing that improvements in size quality control could increase lumber yield by as much as 6.5%. The program includes data collection and evaluation, sawing variation estimation, target size estimation and process monitoring. In data collection, twelve subgroups of four are selected and six measurements in each board are taken at fixed board positions. The between-board and within-board standard deviations are estimated by range statistics and the total sawing standard deviation is computed by

$$S_t = \sqrt{S_w^{\,2} + S_b^{\,2}} \qquad [8]$$

where S_w is within-board standard deviation and

S_b is between-board standard deviation.

Three control charts for each machine center are used to control process: $\bar{X}$ bar chart, within-board range chart and between-board range chart. The process is controlled by taking at least one subgroup each shift. The target size consists of four factors: finished or marketable size, planing allowance, shrinkage allowance and dimensional variation allowance.

Again, only sawing variation was the control objective. Identifying sawing problems was an important part of this quality control program.

The concept of target size estimation is similar to that used by Warren (1973). Target sizes vary only with sawing variation. The shrinkage and planer allowance are again assumed to be constants. Target sizes (t) were estimated by the following formula:

$$t = (S_t \times K) + F \qquad [9]$$

where S_t is the total sawing standard deviation,

K is the skip allowance factor which determines the amount of lumber that is allowed to be undersized and

F is the predetermined value which was the sum of dry dressed size, shrinkage and planer allowance.

A statistical method was applied to measure sawing variation in a sawmill of St. Regis Paper Company in 1979 (Eagon and Huber, 1979). The operation included a dimension mill that produced 60 million board feet of lumber per year and a stud mill that produced 55 million board feet of studs per year. The study showed that an estimated reduction of 0.008 inches (0.20 mm) in the target size was possible without reducing the sawing variation. A reduction of sawing standard deviation to 0.015 inches (0.38 mm) by improving the mill provided an opportunity of 0.019 inch (0.48 mm) reduction in the target size. The revenue

increase due to this reduction in one machine center of the mill was estimated to be $112,500 per year.

In the later 70s, thanks to the great effort of quality control practitioners and researchers, the lumber size quality control principle described by Whitehead (1978) was further developed to a complete and practicable lumber size control program and became popular in the lumber manufacturing industry. However, the objective of these target size control programs was still controlling only the sawing variation. In Brown's early works on lumber size control programs (1978), the estimations of sawing variation and target sizes were not much different from those published by Whitehead. The sawing standard deviation was estimated by range statistics and target sizes were only affected by sawing variation. The shrinkage and planer allowance were assumed to be constants. In his later works , the within-board standard deviation of a board is estimated by

$$S_{wi} = \sqrt{\sum_{j=1}^{n}\left(Y_{ij} - \overline{Y}_{i.}\right)^2 / (n-1)} \qquad [10]$$

where S_{wi} is the estimated within-board standard deviation of board i ,

Y_{ij} is the jth measurement of board i ,

$\overline{Y}_{i.}$ is the average of all measurements of board i ,

n is the number of measurements in each board, suppose that the numbers of measurements in every board are equal.

The squared root of the average of S_{wi}^2 over all samples ($i = 1,2,...,m$), S_w, is an estimation of the within-board standard deviation of all boards of the same dimension. The between-board standard deviation (S_b) is estimated by

$$S_b = \sqrt{\sum_{i=1}^{m} \left(\overline{Y}_{i.} - \overline{Y}_{..}\right)^2 / (m-1)} \qquad [11]$$

where $\overline{Y}_{..}$ is the average of all measurements in all samples,

m is the number of sampled boards.

The total sawing standard deviation is computed by

$$S_t = \sqrt{S_w^2 + S_b^2}\,. \qquad [12]$$

The current statistical methods for target size estimation are not much different from those developed by Warren (1973), Brown (1979) and Whitehead (1978). One typical formula of these target size estimations is:

$$t = \frac{t_f + t_p}{1-\omega} + S_t \cdot z_\alpha \qquad [13]$$

where t is the estimated target size,

t_f is the required minimum dry dressed size,

t_p is the planing allowance, which is very often assumed to be 0.08 inches,

ω is the percent of shrinkage determined by the species, initial and final moisture content,

σ_s is the total sawing standard deviation and

z_α is the critical value of normal distribution with α% allowable under-sized lumber.

In the formula, the allowable percentage of under-sized boards is assumed to be less than $100\alpha\%$ and the green sizes are assumed to be normally distributed. The planing variance is not explicitly considered but included in the deterministic value, the "planing allowance". The drying shrinkage is determined by wood species, initial and final moisture content. Because lumber shrinkage is not uniform but varies from board to board, it is recommended to use the maximum shrinkage of the species in determining target sizes. For example, if the maximum shrinkage of a certain species is 7% and the lumber is dried from 30% MC to 19% MC, the shrinkage used should be 2.57%.

Obviously, the shrinkage variation and planing variation are not controlled in these target size control programs. The sawing variation is the only variation of the three which is controlled. The limitations of the current target size estimation method and why it would be

necessary to control lumber target sizes based on all the three processing variations are discussed in the following three portions:

- The finished size is actually not a deterministic value. There is size variation in the final dressed sizes. The larger the dressed size variation, the larger the average dressed sizes are required in order not to under-sized boards, requiring larger target sizes. Larger dressed size variation can also result in larger interaction between dry size variation and dressed size variation.

- The planing allowance used in practice is determined by past experience or experimental approaches. These approaches are not only time consuming, expensive and a barrier to the real-time size control techniques, but they are also not much help in controlling the planing variation and understanding the impact of the planing variation on target sizes. Actually, the planing allowance should vary with dry size variation, planing variation and minimum fiber needed for surfacing which is determined by the planing heads. Figure 2 shows the required planing allowance with zero minimum fiber required for surfacing. Clearly, the planing allowance depends on both the drying and the planing variations.

- Deterministic assumption of shrinkage does not allow for shrinkage variation control. The possible interaction between green size and dry size variations in determining target sizes is ignored.

In general, because of the deterministic assumptions and the ignorance of the interactions between variations, the current target size estimation method may not yield correct target sizes. If this is the case, the following problems are apparent. Firstly, an estimated target size can be used only as a starting point for searching a correct target size by field experiments. This is a very expensive and slow responding procedure, and a barrier to the successful implementation of real-time quality control systems. Secondly, whether the mill is over-sizing its lumber or not can hardly be evaluated. The over-sizing can cost several million dollars in mill revenue without the mill being aware of it. Lastly, the information on mill operation capability is not clear. Does the mill work properly? Is there any variation which can be reduced? And what is the reward of this reduction? All these questions can not be answered properly.

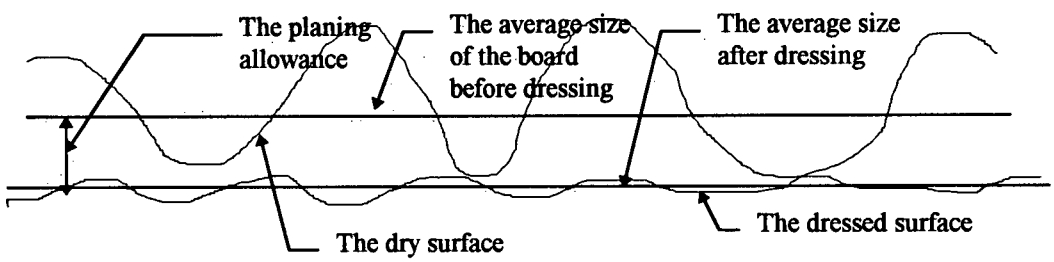

Figure 2 The Planing Allowance

Some studies have already questioned this target size estimation method. According to Equation [13], a sawmill with smaller sawing variation is expected to have small target sizes. However, a survey of 47 Canadian softwood sawmills found that this is not necessarily true. Some sawmills use larger target sizes, even though their sawing variations are smaller. The lack of a clear linear relationship between sawing accuracy and target sizes may indicate that some sawmills are using target sizes that are larger than that required for the sawing accuracy of their machines. It may also indicate that sawing variation is not the most important factor controlling target sizes. Other factors, such as planer allowances, lumber shrinkage and product requirements, may be more significant (Lister, 1995).

A computer simulation study of sawing process (Cassens and Gibson, 1993) also challenged the traditional target size estimation methods. Because the traditional target size estimation methods were developed on the assumption that shrinkage, planer allowance, and finished lumber size are all deterministic values, they do not allow for any interaction between various processes including green lumber variation, shrinkage, planer allowance and finished sizes. The objective of their computer simulation study was to develop a method to account for interrelated stochastic processes found in lumber manufacturing. In this study the green sizes, dry sizes and dressed sizes of a set of samples and the percentage of planer skips were measured first. Then the percentage of planer skip was estimated with both the computer simulation program and the current target size estimation method. The study found that the computer simulation method predicted much better than the current target size estimation method which greatly under-estimated the percent of skip dress lumber. In the computer simulation study, all the three size distributions were assumed to be normally distributed.

It is understandable that the objective of the early lumber target size control program was to control sawing variation, because the sawing variation was the major variation at that time. However, as the sawing variation is continuing to be reduced, other processing variances may become more significant, and eventually may become the controlling variation of target sizes. Developing target size control programs which consider all the three system processing variances is necessary to further reduce lumber target sizes and increase lumber conversion efficiency.

3 Methods

The first part of this study is to estimate the variation in the three sub-processes (sawing, drying and planing). This was done through field testing and statistical analysis. The second part of the study is to devise a correct target size estimation method and evaluate the current target size estimation method based on the variation information obtained in the first part of the study. The last part of the study is to estimate the impact of the three process variations on lumber target sizes and mill production revenue.

3.1 Estimation of the System Processing Variation

For the sawing process, because many studies have been done on sawing variation control, the objective of this study is to correctly estimate the within-board standard deviation, between-board standard deviation, total sawing standard deviation, and green size distributions.

For the drying process, because not many studies have been done in investigating the variation in the drying operations on account of lumber target size control, detailed information of the variation in the drying practice is to be collected. Apart from the within-board and between-board shrinkage variations, the shrinkage variation among the locations of boards in a drying package and the shrinkage variation among the locations of drying packages in a drying kiln is to be estimated as well. This information tells us how much of the

shrinkage variation is contributed by wood material and how much is contributed by drying operations. The moisture content of sample boards before drying and after drying also provides import information on the drying variation.

For the planing process, only the within-board standard deviation, between-board standard deviation and the total planing standard deviation was estimated. The variation estimation process is the same as that used for estimating variation in the sawing process.

The mill chosen for the study has two sawing lines, a headrig bandsaw line for sawing large logs and a chip canter line for sawing small logs. It produces 160 million board foot dry, dressed SPF dimension boards per year. A total of nine hundred 2" by 4" 16 foot boards was randomly selected from the green chains of the sawmill as samples, three hundred boards from each shift. Each selected board was marked with a lumber crayon on one end of the board to distinguish the shift, the end, side and surface of the board. The green sizes, dry and planed thickness and width of all the samples were measured for estimating the process variations.

Size Measurement

In the current size control programs, lumber sizes are normally measured with calipers. In order to measure lumber dimensions more precisely and efficiently, a laser displacement scanner system was used as the size measuring equipment. Figure 3 shows the working principle of the laser scanning system.

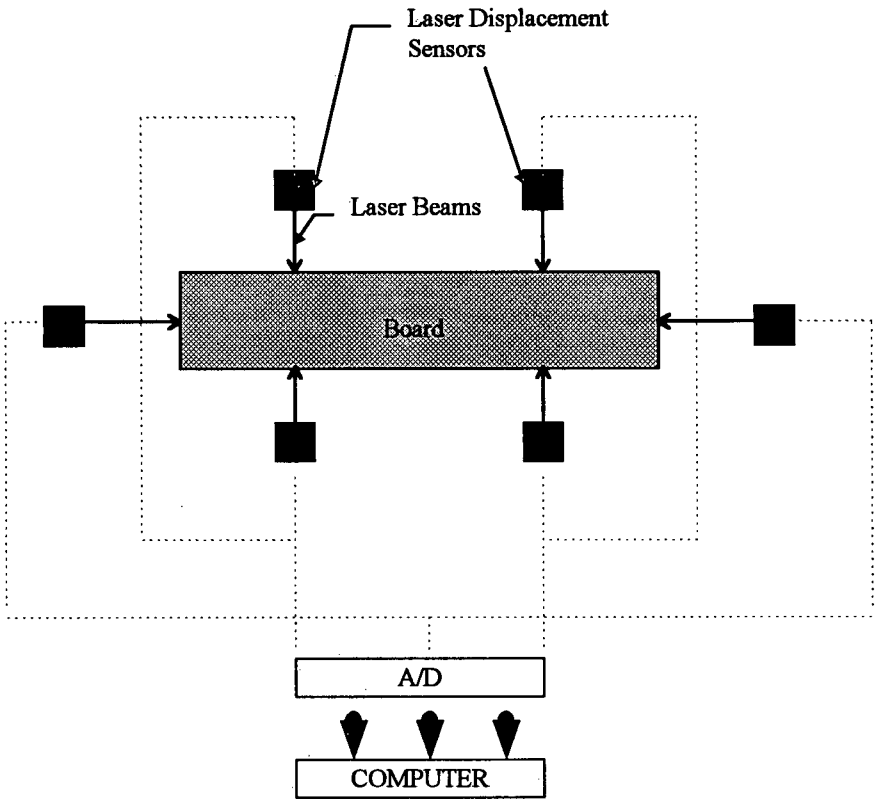

Figure 3 The Working Principle of the Scanning System

The system has six laser displacement sensors, two as a pair, each pair measuring one size. If a piece of lumber is placed properly in the scanner, the scanner will measure its right thickness, left thickness and width. A laser sensor sends out a beam which hits the surface of the lumber and is reflected back to the sensor. The displacement is measured on a photo sensitive chip in the scanning head and transformed to a voltage. The sum of the voltage values of the two opposite sensors represents the total distance of the two scanning heads to

board surfaces. The lumber size is measured by subtracting this distance from the distance between the two scanning sensors.

In practice, a board is carried by a conveyor belt through the scanner. The scanning sensors continuously scan the board to generate voltages which correspond to the size of the lumber. A computer is connected to the scanning sensors via an analog-to-digital converter to convert the voltages to the board sizes and record the data to a text file. The measuring frequency (signal sampling time interval) of the board sizes can be adjusted on the computer. By adjusting the sampling frequency and the conveyer speed, the number of measurements per unit length can be adjusted.

One of the advantages of this scanning system is the high measuring precision (the measurement variance in long run). Since the readings of the scanner system are proportional to the voltage measured in the sensors, the precision of the scanning system is greatly affected by the voltage stability of the system power supply. A voltage stabilizer was built in the system to supply high quality voltage for the scanning sensors. And since the reading of each measurement is determined by the displacements of the two opposite sensors, the positions of a board between the sensors do not affect the readings as long as they are within the measuring ranges of the sensors. The change of the position of the board increases the displacement of one sensor and decreases the displacement in the other. The total effect on the displacements is zero. Thus, the feeding system does not have much impact on the system measuring precision. We do not have to worry about the variation in the conveyor and the belt. The precision of this laser scanning system is less than 0.01 millimeter.

Another advantage of the scanning system is its measuring efficiency. Laser scanning is thousands of times faster than manual measuring with calipers. When a piece of lumber is put through the scanner in a few seconds, thousands of measurements of the three dimensions along the length of the lumber can be measured and recorded into a computer file.

In this study the scanner was adjusted to take about 120 measurements of thickness and width, respectively, along the length of each sample. The green, dry, and planed sample boards were measured exactly the same way.

Moisture Content Measurement

Because there is a high correlation between moisture content and drying shrinkage, the objective of measuring the moisture content is just to collect the information of the average moisture content and the variation of the moisture content. The variance of moisture content among the locations of the samples in a drying package and among the locations of a drying package in a drying kiln was not studied.

The green and dry moisture content was measured with a Wagnor Moisture meter at 16 points along the length of each sample board (one inch distance between each two adjacent points) and uploaded to a computer file for analysis.

3.1.1 Estimation of Sawing Variation and Planing Variation

Because the estimation of planing variation and sawing variation are exactly the same, the following discussion of sawing variation estimation also applies to the estimation of planing variation. Suppose that n sample boards are randomly selected from the sawmill and m random points in each board are measured for the estimation of within-board and between-board variations and that the measuring error is negligible when it is compared to the within-board variation, then we have the following mathematical model for estimating the two sawing variations,

$$Y_{ij} = \mu + \alpha_j + \varepsilon_{i(j)} \qquad [14]$$

where Y_{ij} is the values of i th measurement of j th sample board,

μ is true mean of the sizes,

α_j is the contribution of the size difference between boards and

$\varepsilon_{i(j)}$ is the contribution of within-board variance.

The bracket in $\varepsilon_{i(j)}$ indicates that the m measurements of each sample board are nested in each sample board. The analysis of variance of this experiment is showed in Table 1.

Table 1 The ANOVA of Sawing Variance Estimation

Source	df	SS	MS	EMS
Between-board α_j	$n-1$	$m\sum_{j=1}^{n}(\bar{Y}_{.j}-\bar{Y}_{..})^2$	$m\sum_{j=1}^{n}(\bar{Y}_{.j}-\bar{Y}_{..})^2/(n-1)$	$\sigma_w^{\ 2}+m\cdot\sigma_b^{\ 2}$
Within-board $\varepsilon_{i(j)}$	$(m-1)\times n$	$\sum_{j=1}^{n}\sum_{i=1}^{m}(Y_{ij}-\bar{Y}_{.j})^2$	$\sum_{j=1}^{n}\sum_{i=1}^{m}(Y_{ij}-\bar{Y}_{.j})^2/[(m-1)\times n]$	$\sigma_w^{\ 2}$

In Table 1 df stands for the degree of freedom, SS for the sum of squares, MS for the mean of the sum of squares and EMS for the expected mean of the sum of squares. From the table we can see that the within-board variance can be obtained directly from the mean of the within-board sum of squares, but the between-board variance does not equal the mean of the between-board sum of squares. The between-board variance can be computed by the following equation .

$$\sigma_b^{\ 2}=\frac{MS_b-\sigma_w^{\ 2}}{m}. \qquad [15]$$

The estimate of between-board variance,

$$S_b^{\ 2}=\frac{\sum_{j=1}^{n}(\bar{Y}_{.j}-\bar{Y}_{..})^2}{n-1} \qquad [16]$$

used very often in the current lumber size control programs, is actually not an unbiased estimate of σ_b^2 because according to SS_b in Table 1 and Equation [16],

$$S_b^2 = \frac{\sigma_w^2}{m} + \sigma_b^2. \qquad [17]$$

Only when the number of measurements in each single board is large or the within-board variance is small compared to the between-board variance, then does

$$S_b^2 \approx \sigma_b^2. \qquad [18]$$

If both within-board and between-board variances are the variances of the normal distribution and they are independent of each other, according to the statistics theorem regarding the linear combination of random variables, the total variance of the samples will be

$$\sigma_t^2 = \sigma_w^2 + \sigma_b^2 \qquad [19]$$

The mean of the total sum of squares

$$\frac{\sum_{j=1}^{n}\sum_{i=1}^{m}\left(Y_{ij} - \bar{Y}_{..}\right)^2}{mn-1} \qquad [20]$$

is, again, not an unbiased estimate of total sawing variance, because the expected mean of the total sum of squares is

$$EMS_t = \frac{m(n-1)\sigma_b^{\ 2} + (mn-1)\sigma_w^{\ 2}}{mn-1}. \qquad [21]$$

This does not comply with the unbiased estimate of total sawing variation of Equation [19]. This can be explained by careful examining Formula [20]. When the between-board variation and the within-board variation do not have the same value, the contributions of between-board and within-board variations to the total sum of squares will vary as m and n are changed while the total number of measurements mn remains unchanged. Hence the mean of the sum of total squares will not be the same with different m and n and constant mn.

The within-board and between-board variations of the test mill were computed according to Table 1. The total sawing variation was computed according the Equation [19].

3.1.2 Estimation of Drying Shrinkage Variation

The shrinkage variation caused by the variation in wood material can be measured with within-board shrinkage variation and between-board shrinkage variation. These two variations can be reduced only by better sawing technologies. The shrinkage variation among the positions of boards in a drying package and among the positions of drying packages in a drying kiln can be reduced by better drying operations. The estimation of all these variations is

essential to better understand the impact of drying procedure on lumber target sizes and sawmill conversion efficiency.

In order to study the shrinkage variation among the locations of a drying package in a drying kiln, all sample boards in each of the three shifts were evenly distributed to 36 drying packages, the same size of the normal drying packages, with 12 packages per shift. Each drying package had 25 sample boards. The locations of experimental packages in the drying kiln were randomly selected. In order to study the variation among the locations of boards in a drying package the sample boards in each drying package were evenly divided to the five zones of the drying package (Figure 4). Each zone had five sample boards. The placement of the sample boards in each zone was random. The orders of sample boards in the experiments were random as well.

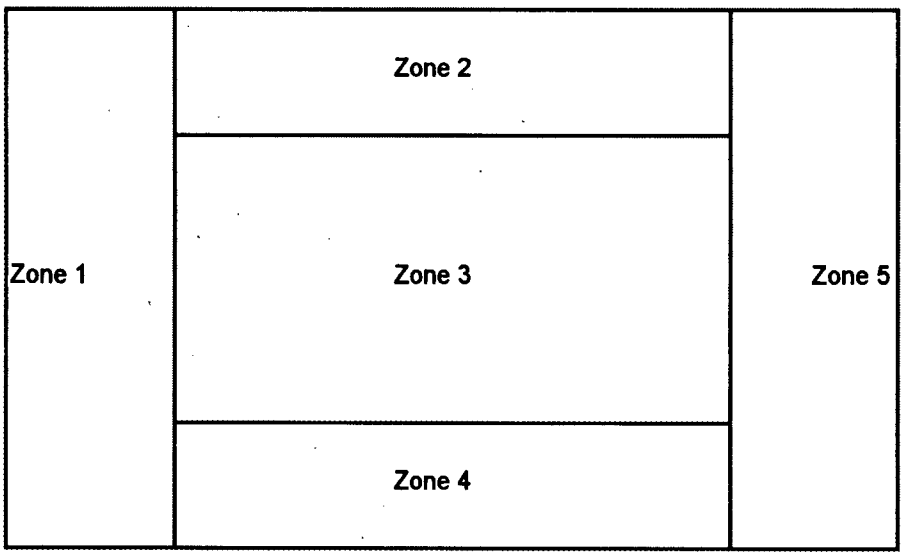

Figure 4 Zones in a Drying Package

The drying schedules of the three runs were exactly the same as those used for non-experimental purposes. No intentional changes were applied. The target dry moisture content was 19%.

The mathematical model for this drying experiment can be expressed as:

$$Y_{ijkmn} = \mu + R_n + P_{(n)m} + Z_{(nm)k} + B_{(kmn)j} + W_{(jkmn)i}. \qquad [23]$$

where μ is the mean thickness (or width),

R_n represents shift effect, a random blocking effect, ($n = 1,2,3$).,

$P_{(n)m}$ represents package location effect, another random blocking effect, $(m = 1,2,3,4)$,

$Z_{(nm)k}$ represents board location effect, a fixed blocking effect, ($k = 1,2,3,4,5$ since there are five zones in each drying package),

$B_{(kmn)j}$ represents between-board variance, ($j = 1,2,3,4,5$ since there are five sample boards in each zone. The sample boards are nested in zones),

$W_{(jkmn)i}$ represents within-board variance, ($i = 1,2,\ldots,9$ since nine measurements will be randomly selected from the measurements of each board for the purpose of analysis of variance) and

Y_{ijkmn} represents the measured value at the point expressed by the subscript.

The expected means of the sum of squares of the experiments are shown in Table 2. Each variance can be computed from this table and whether a variance is significant can be tested by its corresponding F-test.

Table 2 The ANOVA of the Drying Experiments

Source		df	EMS	F Test
Shift	σ_r^2	2	$900\sigma_r^2 + 225\sigma_p^2 + 9\sigma_b^2 + \sigma_w^2$	EMS_r / EMS_p
Package	σ_p^2	9	$225\sigma_p^2 + 9\sigma_b^2 + \sigma_w^2$	EMS_p / EMS_b
Zone	φ_z^2	48	$45\varphi_z^2 + 9\sigma_b^2 + \sigma_w^2$	EMS_z / EMS_b
Between	σ_b^2	240	$9\sigma_b^2 + \sigma_w^2$	EMS_b / EMS_w
Within	σ_w^2	2400	σ_w^2	
Total		2699		

In Table 2,

σ_r^2 represents the shift variance,

σ_p^2 represents the variance caused by the locations of drying packages in the drying kiln,

φ_z^2 represents the variance among the five zones,

σ_b^2 represents the between-board variance and

σ_w^2 represents the within-board variance.

What we have discussed until now is the analysis of dry size variation of the dry samples which is not the drying shrinkage variation we want to study, due to the presence of sawing variation in the green samples. Only when the sawing variation equals zero, does the shrinkage variation equal to the dry size variation. However, it is possible to find out the relationship among green size, dry size and shrinkage distributions. Then the shrinkage distribution can be derived from this relationship since the green size and dry size distribution are known.

It is always true that at any point of a board, we have

$$T_s = T_g - T_d \qquad [22]$$

where T_d is the dry size,

T_g is the green size and,

T_s is the shrinkage due to drying.

Theoretically, the correct way to estimate the shrinkage variation from equation [22] should be

$$\sigma_s^2 = \sigma_g^2 + \sigma_d^2 - 2\sigma_{gd} \qquad [23]$$

where σ_d is the dry size standard deviation,

σ_g is the green size standard deviation,

σ_s is the shrinkage standard deviation and

σ_{gd} is the covariance between g and d.

Unfortunately, in this study it is impossible to measure the paired green size and dry size at exactly the same point. Then the covariance term in the equation [23] can not be proper estimated.

However, a statistical theorem (Wadsworth, 1960) regarding the distribution of derived functions states that if $x_1, x_2, \ldots x_n$ are independent, normally distributed variables with respective parameters $(\mu_1, \sigma_1), (\mu_2, \sigma_2), \ldots, (\mu_n, \sigma_n)$, then the weighted sum $x = a_1 x_1 + a_2 x_2 + \cdots + a_n x_n$ (where at least one of the coefficients $a_1, a_2, \cdots a_n$ is not zero) is normally distributed with parameters (μ, σ) where

$$\mu = a_1 \mu_1 + a_2 \mu_2 + \cdots + a_n \mu_n \qquad [24]$$

and

$$\sigma = \sqrt{a_1^2 \sigma_1^2 + a_2^2 \sigma_2^2 + \cdots + a_n^2 \sigma_n^2}. \qquad [25]$$

Now if we rewrite Equation [22] as

$$T_d = T_g - T_s \qquad [26]$$

and assume they are normally distributed. Theoretically, the shrinkage and the green size are dependent to each other. However, when we express the green size as the sum of the green size mean and the deviation,

$$T_g = t_g + \varepsilon \qquad [27]$$

where t_g is the mean of the green sizes and

ε is the deviation from the mean.

The shrinkage can be written as

$$T_s = T_g \cdot \omega = t_g \cdot \omega + \varepsilon \cdot \omega \qquad [28]$$

where ω is the percentage of shrinkage at this point.

Because $\varepsilon \cdot \omega$ is negligible when it is compared with $t_g \cdot \omega$, practically we can assume

$$T_s \approx t_g \cdot \omega \qquad [29]$$

Thus T_s and T_g can be assumed to be independent in this problem. Then we can apply Equation [24] and [25] to get

$$t_d = t_g - t_s \qquad [30]$$

and

$$\sigma_d^2 = \sigma_g^2 + \sigma_s^2 \qquad [31]$$

where t_d is the mean dry size,

t_g is the mean green size,

t_s is the mean shrinkage,

Because the sawing variation and dry size variation can be estimated from the drying experiment, the shrinkage variation can be computed from Equation [31]. The shrinkage variation obtained this way may over-estimate the actual shrinkage due to the assumption of Equation [29]. The dry size variations among the locations of boards in drying packages and locations of drying packages in a drying kiln were the corresponding shrinkage variations.

3.1.3 Size Distribution Normality Test

If the size distribution can be assumed to be normally distributed, the estimation of system variation and target sizes will be greatly simplified. The normality tests of green, dry and planed size distributions were carried out with "Goodness of Fit" tests.

3.2 A Computer Simulation Method for Lumber Target Size Estimation

Computer-based simulation modeling is a practical technique to experiment with various designs for a complex system in manufacturing and other fields, especially in fields where uncertainty exists. A lumber manufacturing simulation model which simulates the three processes of a lumber manufacturing system, sawing, drying and planing, was developed. The green target thickness and width of 2" by 4" boards of the test mill were estimated with this method based on the mill processing information obtained in the empirical field study and the results were compared with those estimated with the traditional target size estimation method.

The simulation procedure is exactly the same as the actual lumber processing procedure. It starts with a pre-estimated target size. The sawing, drying and planing processes are simulated with this target size and the percent of under-sized boards with the pre-estimated target size under the present system processing variation is computed from the simulated results. When this percentage is larger than the allowable under-sized percentage, the target size is reduced and the simulation is repeated, and when this percentage is smaller than the allowable under-sized percentage the target size is increased. The iteration is repeated

until the percentage of under-sized board equals or is considered equal to the allowable percentage of under-sized board. Figure 5 is the flow chart of the simulation procedure. This simulation procedure is explained step by step in the following paragraphs.

Step 1: Traditional Target Size Determination

A target size is determined by the traditional target size estimation method (Equation 13). This target size is used as the initial target size in the simulation.

Step 2: Sawing Simulation

Green sizes are sampled from the green size population described by the green size distribution (green sizes vary due to sawing variation). n measurements (sizes sampled from the population) form a sample board. m pieces of sample boards are randomly selected.

Step 3: Drying Simulation

$m \times n$ samples of drying shrinkage are randomly selected from the drying shrinkage population and subtracted from their corresponding green sizes to yield dry sample sizes. The variation of dry sample sizes is the combined effect of the sawing variation and the shrinkage variation as explained above.

Step 4: Planing Simulation

Because there is also planing variation, in order to insure that the percentage of under-sized boards is less than the required α% of the total boards, the planing target size $t_{pl.ta}$ (the

size where the planer is set) must be larger than the required minimum dressed size t_r. The planing target size

$$t_{pl.ta} = t_r + z_\alpha \cdot \sigma_{pa}$$

where t_r is the required minimum dressed size,

σ_{pa} is the planing standard deviation and

z_α is the coefficient decided by the planing variation and the dressed distribution.

Again $m \times n$ dressed sizes are sampled from population $f(t_{pl.ta}, \sigma_{pa})$.

Step 5: Computing the Percent of Under-sized boards

The differences between each corresponding dry size and dressed size are computed. If any of the n dry measurements in a board are smaller than its corresponding dressed size, this board is considered to be under-sized. The percentage of under-sized boards under the present target size is calculated. Then the difference of this percentage minus the allowable under-sized percentage is compared with a predetermined value based on the intended simulation precision. If the absolute value of the difference is larger than the predetermined precision value, the target size is adjusted according to the difference and Step 2 to Step 5 is repeated. If the difference is positive, the target size is reduced, and if the difference is negative, the target size is increased. This procedure is repeated until the absolute value of the difference is less than the predetermined precision value. The target size estimation is then completed.

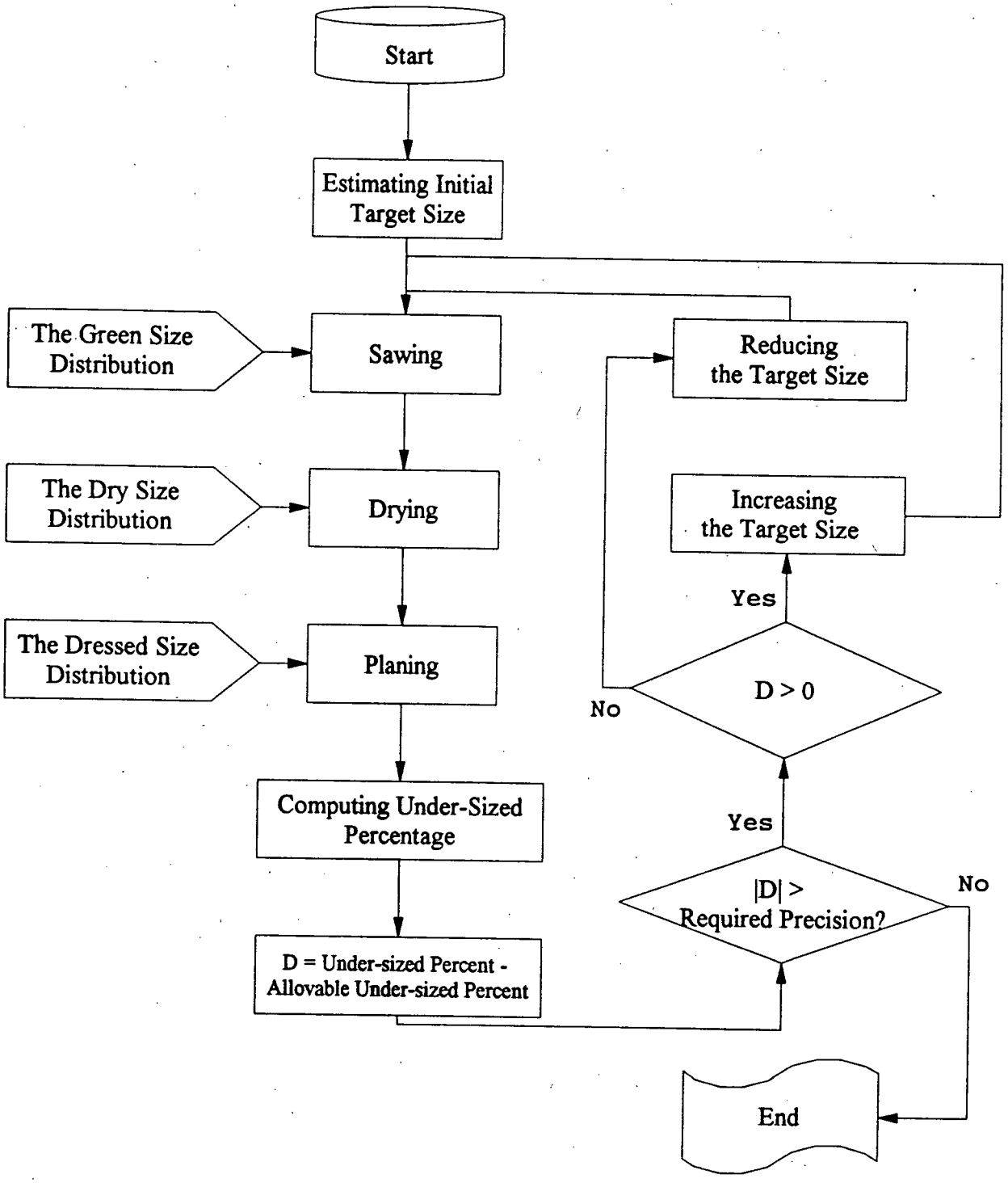

Figure 5 The Flow Chart of the Computer Simulation Program for Target Size Estimation

The reliability of the simulation results depends largely on the reliability of the estimated system parameters and processing variance. Both the normal distribution and actual size distribution obtained in the field study were used in the computer simulation to study the appropriateness of the normal distribution assumption in the computer simulation program for target size estimation.

Apart from the system processing parameters, the number of measurements and the number of boards simulated also affect the reliability of the simulation study. The larger the sample size, the more reliable the simulated results are, but longer time is needed for the simulation. Information on how the sample size used in the simulation study affects the simulation precision is important to determine proper sample sizes and obtain reliable simulation results.

One way to test the validity of the simulation program is to make use of the relationship among green, dry size distributions, and shrinkage distribution. The dry size distribution was derived from the green size distribution and the shrinkage distribution obtained from the field study with the computer simulation program. If the simulated dry size distribution equals the actual dry size distribution, the simulation program is considered reliable.

The simulation precision under various sampling sizes was studied by estimating the mean and the standard deviation of the mean estimations of the dry size standard deviation

from known green size and shrinkage distributions. The smaller the standard deviation of the mean estimations and the closer the estimated mean is to the actual dry size standard deviation, the higher the simulation precision is.

The target thickness and width of 2" by 4" SPF boards were estimated with the new computer simulation program. The required minimum dressed thickness and width used in the simulation were 1.5" and 3.5" respectively and the allowable maximum undersized boards was supposed to be 5% of the total boards. The target moisture content was assumed to be 19%. The simulated target sizes were then compared with those estimated with the traditional target size estimation method and the actual target thickness and width.

The relationship between the target size and the percentage of under-sized boards under the current mill processing variances was also studied with the simulation program. The under-sized percentage was computed with target thickness from 1.5 to 2.0 inches and target width from 3.5 to 4.0 inches at the interval of 0.5 millimeters.

3.3 The Impact of System Processing Variance on Target Size Reduction and Production Net Revenue

Once target sizes can be correctly estimated, the study of the impacts of reducing system variances (any or all of the three sub-process variances) on the target size reduction and mill production net revenue is possible. This study provides critical information to the mill in making decision on where and how to improve the processing system.

One of the most important problems of sawmill quality improvement programs is to find which variance should be reduced for the least investment and fastest dollar return. The impact of reducing one of the three processing variances on target size reduction, while the other two were held unchanged, was studied by reducing the variance in study at interval of 0.1 millimeter.

To complete the study, the impacts of system variance reduction or target size reduction on the net production revenue of the studied sawmill was estimated with a Sawmill Production Control Model developed by Maness (1993), which allows the simultaneous analysis of the effect of all five of the changes in sawing strategies on value recovery due to the reduction in lumber target sizes. This technique uses combined optimization of bucking and sawing, which optimizes manufacturing decisions based on the raw material input, marketing conditions, and sawmill technology facing the mill, thus permitting a better estimate of the net revenue change of the mill due to target size reduction.

To quantify the combined effect of target size reduction on the mill revenue, SPCM was run under the current mill parameters with the three target size sets: the actually target sizes (the measured average green sizes of the mill), the target sizes estimated with the traditional target size estimation method and the target sizes estimated with the new computer simulation program.

The sawmill is producing 160 million board foot SPF lumber per year. Raw material input to the mill is in the form of long-length stems, ranging from 4.0-inch to 15.0-inch small end diameter by 0.5-inch increments, and from 8 to 60 feet long by 2-foot increments (Table 3). Raw material cost is $45 per cubic meter.

Table 3 Raw Material Input Parameters

Parameter	Minimum	Maximum	Increment	Average
Stem small end diameter (in.)	4.0	15.0	0.5	7.0
Nominal stem length (ft.)	8.0	60.0	2.0	34.0
Taper: 1 inch in 8 feet				
Sweep: none				

There are two primary breakdown lines in the sawmill: a band saw breakdown line for sawing large logs and a chip-n-saw line for sawing small logs. The sawing method used was split-taper sawing at headsaw and full taper sawing at gangsaws. All production parameters concerning the equipment used in the simulation are shown in Table 5.

The sawmill produced random-length dimension lumber from 8 to 20 feet in length. There were four dimensions: 2 by 4, 2 by 6, 2 by 8 and 2 by 10. Lumber prices used in the simulation were taken from *Random Length* and are shown in Table 4.

The target widths of 6, 8 and 10 inches were estimated based on the assumption that the shrinkage variation, sawing variation and planing variation do not vary with lumber width. With this assumption, we have

Target Width = Required Dressed Width + Shrinkage
+ Additional Fiber Required by Variation and Planing

The percent of shrinkage was taken from the measured shrinkage of 4 inch wide boards which was 3%. The additional fiber required by variation and planing was also estimated from 2 by 4 boards because the target sizes of 2 by 4 boards of the three sets were already known.

Table 4 Product Prices ($US) per Thousand Board Feet Used in the Simulation

Product	8 ft.	10 ft.	12 ft.	14 ft.	16 ft.	18 ft.	20 ft.
2"x4"	355	360	310	340	405	370	375
2"x6"	265	258	250	270	300	375	375
2"x8"	325	310	310	335	360	400	400
2"x10"	320	320	355	445	410	390	360

Source: *Random Lengths*, May 6th, 1994

Table 5 Mill Productivity Information

Sawmill information	Line 1	Line 2
Operating hours	360	360
Headsaw chain speed (fpm)	110	110
Gap between logs (ft.)	9.9	9.9
Downtime	10%	10%
Sawmill cost per hour	$2,033	$950

4. Results and Discussions

4.1 Processing Variations

Table 6 is the summary of the average green sizes and sawing standard deviations. The F-test was applied to test the differences among the total sawing variations of the three shifts. The test results are shown in Table 7. For the thickness, the total sawing standard deviation of Shift 1 did not equal the total sawing standard deviation of Shift 2 and 3, but the difference between the total sawing standard deviation of Shift 2 and Shift 3 was not significant at 95% confidence level. For the width, the total sawing standard deviation of Shift 2 did not equal the total sawing deviations of Shift 1 and Shift 3, but the difference between the total deviations of Shift 1 and Shift 3 was not significant at 95% confidence level.

These results indicated the important fact that when a sawing system is not in statistical control, sawing variations of the system may vary from time to time. The target size estimated with the sawing standard deviation from one production point may not be the proper target size required at another production point due to the variation of the sawing standard deviation, even if the target size estimation method properly predicts the required target size.

Table 6 Green Sizes and Sawing Standard Deviations

(mm)

Size	Item	Shift 1	Shift 2	Shift 3	Average
Thickness	Average	43.06	43.48	43.62	43.39
	Within-board Standard deviation	0.29	0.27	0.29	0.28
	Between-board Standard deviation	0.34	0.23	0.28	0.28
	Total sawing Standard deviation	0.45	0.36	0.40	0.40
Width	Average	99.66	99.84	99.41	99.64
	Within-board Standard deviation	0.65	0.79	0.71	0.72
	Between-board Standard deviation	0.60	0.73	0.58	0.64
	Total sawing Standard deviation	0.88	1.08	0.92	0.96

Table 7 The F-test on the Equality of Sawing Variances of the Three Experiment Runs

	S_1 / S_2	S_1 / S_3	S_2 / S_3	$F_{0.025}(300,300)$	$F_{0.975}(300,300)$
Thickness	1.563	1.266	0.810		
				1.255	0.797
Width	0.664	0.916	1.378		

Table 8 shows analysis of drying shrinkage variation. The F-test results show that all the blocking effects were significant except the effect of the location of lumber in packages (zone effect) on thickness. The breakdown of the total drying standard deviation of the dry size are shown in Table 9. The sum of shift standard deviation, package standard variation and zone standard variation in thickness and width were, respectively, 33% and 23% of the total dry size standard deviation. This means that around one third of dry thickness standard deviation and one quarter of dry width standard deviation were contributed by drying practices. This part of the variation can be reduced by better drying practice. The rest of the drying variance is comprised of within-board sawing and shrinkage variation, and between-board sawing and shrinkage variation. Within-board and between-board shrinkage variation can only be partially reduced by better sawing technology.

The average dry thickness and width were 41.81 and 96.65 mm respectively and the average thickness and width drying shrinkage were 1.58 and 2.99 mm respectively.

The total thickness and width shrinkage standard deviation shown in Table 10 were derived from total dry size standard deviation and total green size standard deviation with Equation [28]. There were, respectively, 0.50 mm and 0.75 mm. It should be noticed that the thickness shrinkage standard deviation was larger than the thickness sawing standard deviation and the width shrinkage standard deviation was 78% of the width sawing standard deviation. This result indicates that controlling the variance in the drying process is at least as important to the sawmill as controlling sawing variation.

Table 8 The ANOVA of the Drying Experiments

A. Thickness (mm)

Source	df	MS	EMS	F	$F_{0.05}$
Shift	2	94.72117	$900\sigma_r^2 + 225\sigma_p^2 + 9\sigma_b^2 + \sigma_w^2$	11.267	4.257
Package	9	8.406389	$225\sigma_p^2 + 9\sigma_b^2 + \sigma_w^2$	4.764	1.919
Zone	48	2.180879	$45\varphi_z^2 + 9\sigma_b^2 + \sigma_w^2$	1.236	1.411
Between	240	1.764511	$9\sigma_b^2 + \sigma_w^2$	20.316	1.164
Within	2400	0.086854	σ_w^2		
Total	2699				

B. Width (mm)

Source	df	MS	EMS	F	$F_{0.05}$
Shift	2	172.3459	$900\sigma_r^2 + 225\sigma_p^2 + 9\sigma_b^2 + \sigma_w^2$	9.211	4.257
Package	9	18.7102	$225\sigma_p^2 + 9\sigma_b^2 + \sigma_w^2$	3.496	1.919
Zone	48	10.6701	$45\varphi_z^2 + 9\sigma_b^2 + \sigma_w^2$	1.994	1.411
Between	240	5.3522	$9\sigma_b^2 + \sigma_w^2$	8.752	1.164
Within	2400	0.6116	σ_w^2		
Total	2699				

Table 9 The Breakdown of Total Dry Size Standard Deviation

(*mm*)

Standard Deviation	Thickness	Width
Shift	0.310	0.413
Package	0.172	0.244
Zone	0.096	0.343
Between-board	0.432	0.726
Within-board	0.295	0.782
Total	**0.639**	**1.219**

Table 10 Shrinkage and Its Variation

(*mm*)

	Average Thickness	Thickness Standard Deviation	Average Width	Width Standard Deviation
Green	43.39	0.40	99.64	0.96
Dry	41.81	0.64	96.65	1.22
Shrinkage	**1.58**	**0.50**	**2.99**	**0.75**

The average dressed sizes and standard deviation are shown in Table 11. Because there were virtually no planer skip in the test samples, the dry size should have little impact on the variation of the dressed sizes. All extra fiber will be planed off. The size variation was completely due to planing and wood property, making it unnecessary to distinguish the sample

in the three shifts. The thickness and width standard deviations were 0.28 mm and 0.75 mm respectively. They were more than half of the corresponding sawing standard deviations. It seems improper to ignore the planing variation in estimating target sizes. The planing variance may need control as well. Larger planing variation requires larger average dressed sizes and thus larger target sizes if the same percentage of under-sized boards is to be maintained.

The summary information of the system variance is shown in Figure 12.

Table 11 The Averages of Dressed Sizes and Their Standard Deviations

(mm)

Item	Thickness	Width
Average	38.13	90.01
Standard Deviation	0.28	0.75

Table 12 The Summary Information of the System Variance

(mm)

Process	Sawing	Drying	Planing
Thickness Standard Deviation	0.40	0.50	0.28
Width Standard Deviation	0.96	0.75	0.75
Thickness Average	43.39	1.58	38.13
Width Average	99.64	2.99	90.01

4.2 Lumber Size Distributions

Figure 6 to 11 are the distributions of green, dry and dressed thickness and width. The results of the distribution normality tests (test for goodness of fit) are shown in Table 13. Only the dry size distribution could be correctly assumed to be approximately normally distributed. The error in the normality assumption on both the green size and planed size distribution were significant according to the test results.

Table 13 Distribution Test for Normality

Lumber Status	Size	χ^2	$\chi_{0.05}{}^2(\upsilon)$
Green	Thickness	54.58	43.77(30)
	Width	59.22	55.76(40)
Dry	Thickness	45.08	52.19(37)
	Width	69.36	69.83(52)
Dressed	Thickness	47.26	31.41(20)
	Width	81.35	42.56(29)

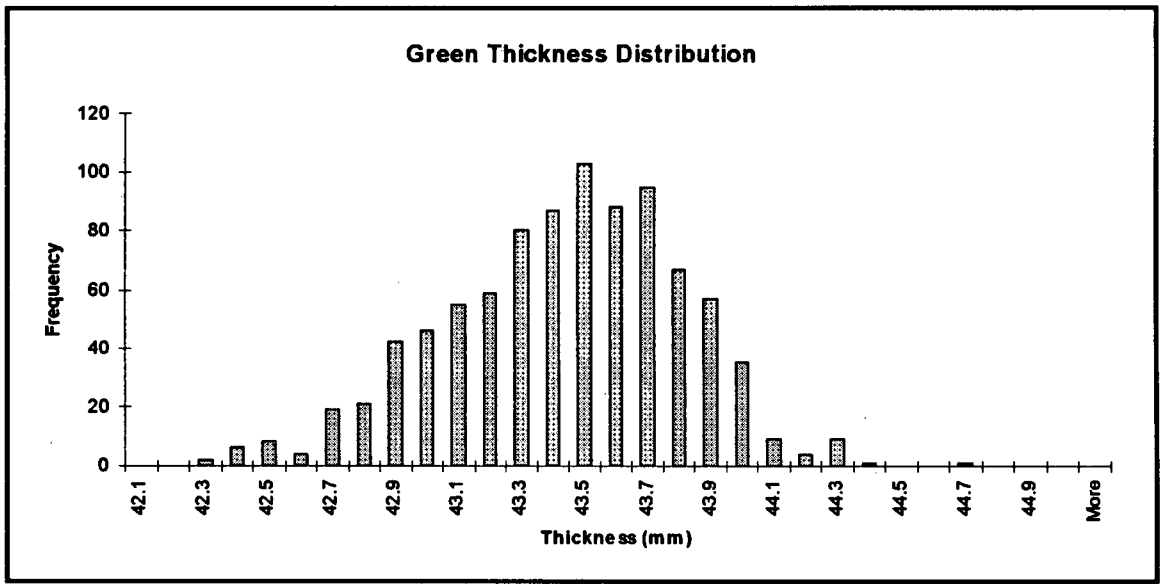

Figure 6 The Green Thickness Distribution

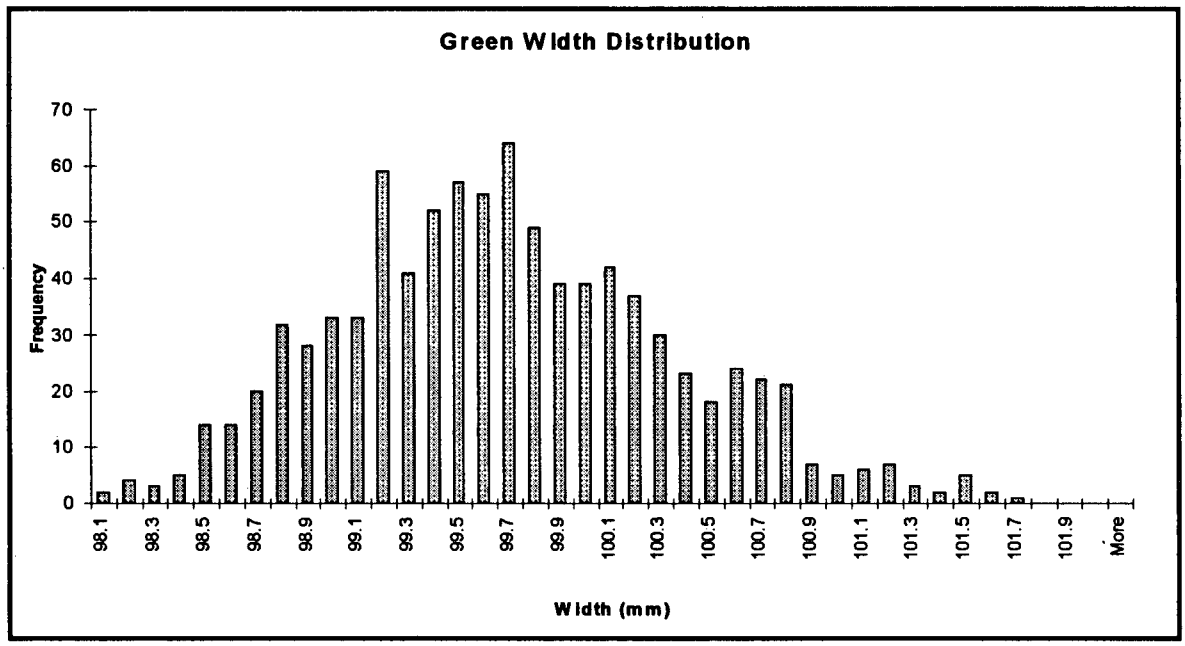

Figure 7 The Green Width Distribution

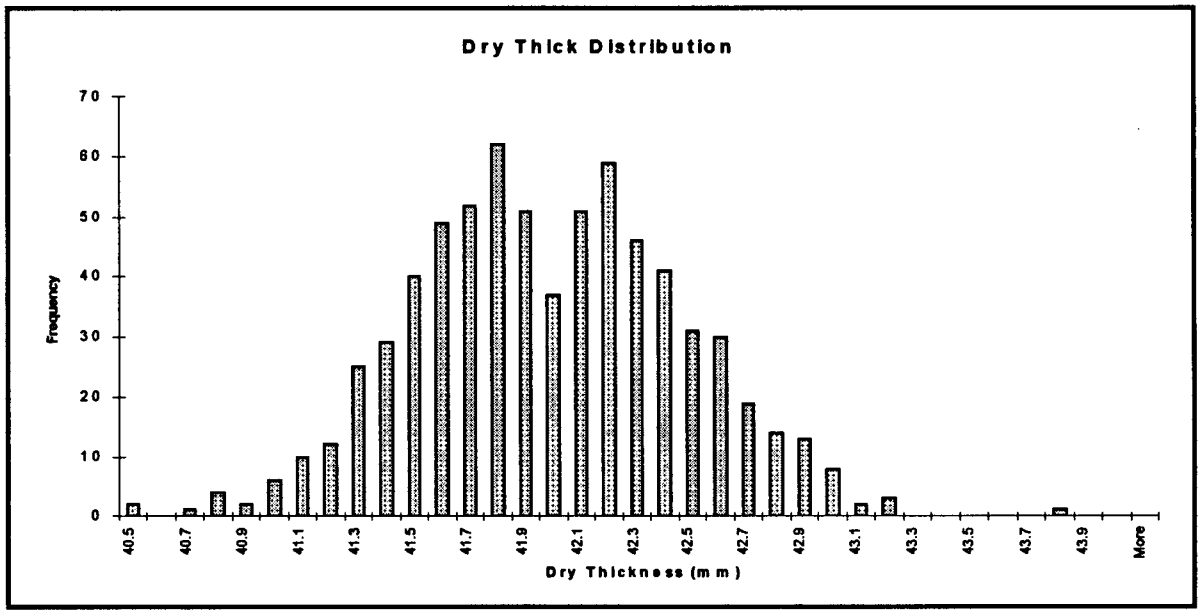

Figure 8 The Dry Thickness Distribution

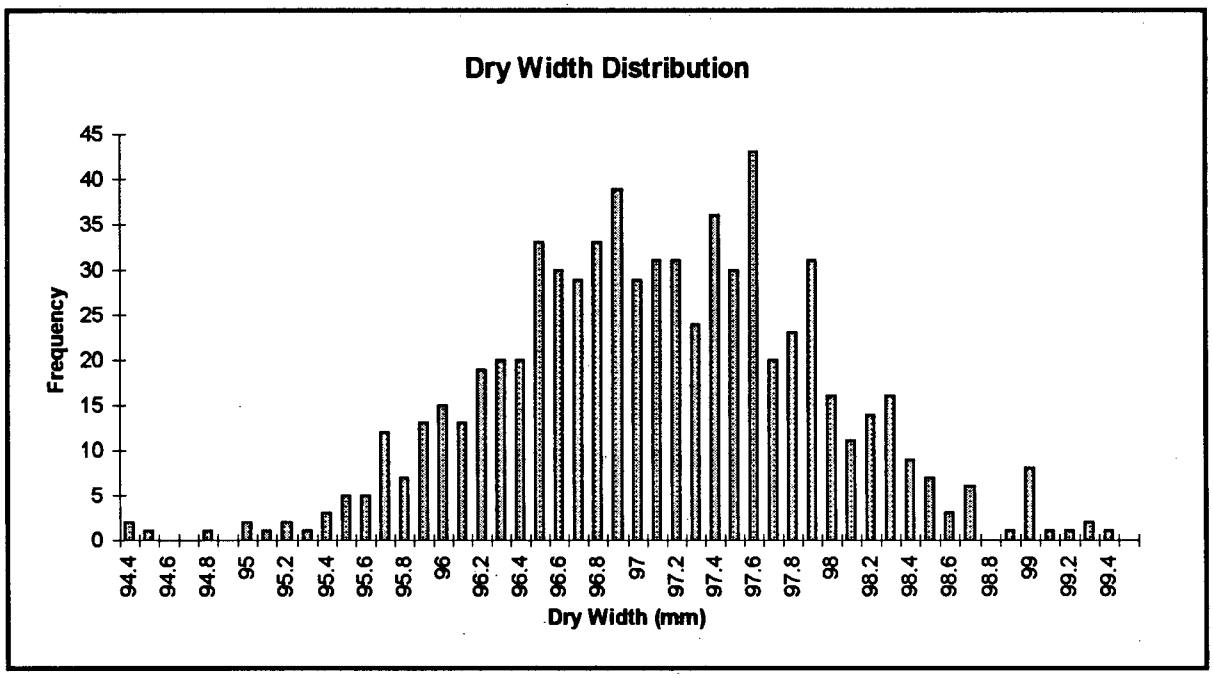

Figure 9 The Dry Width Distribution

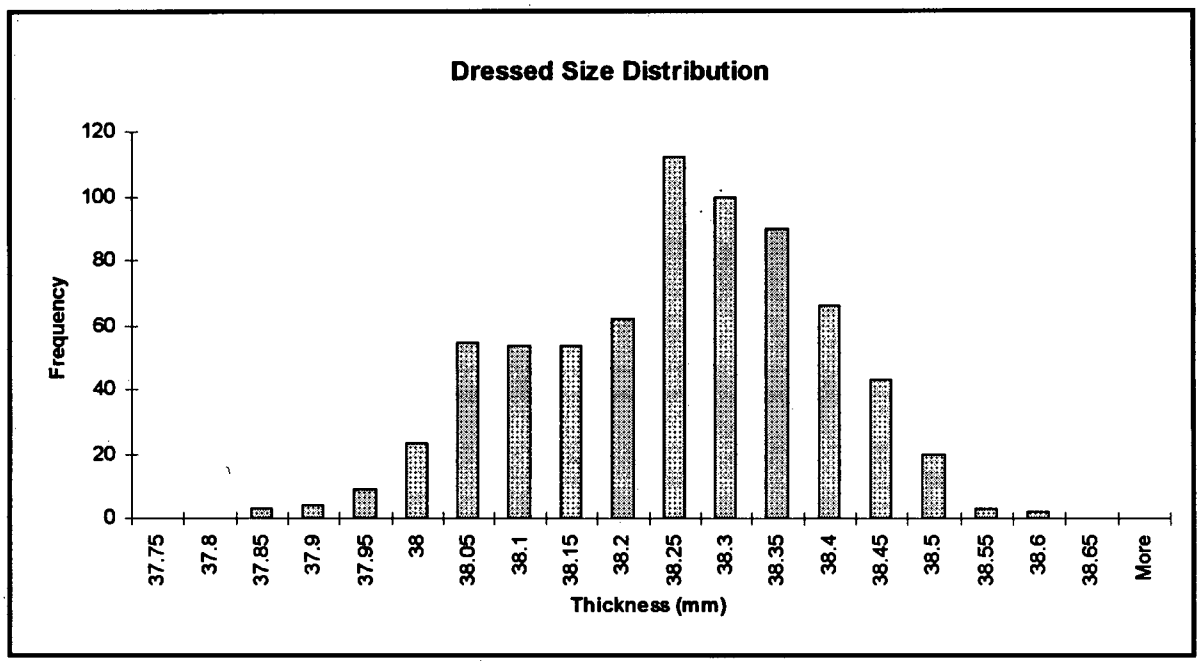

Figure 10 Planed Thickness Distribution

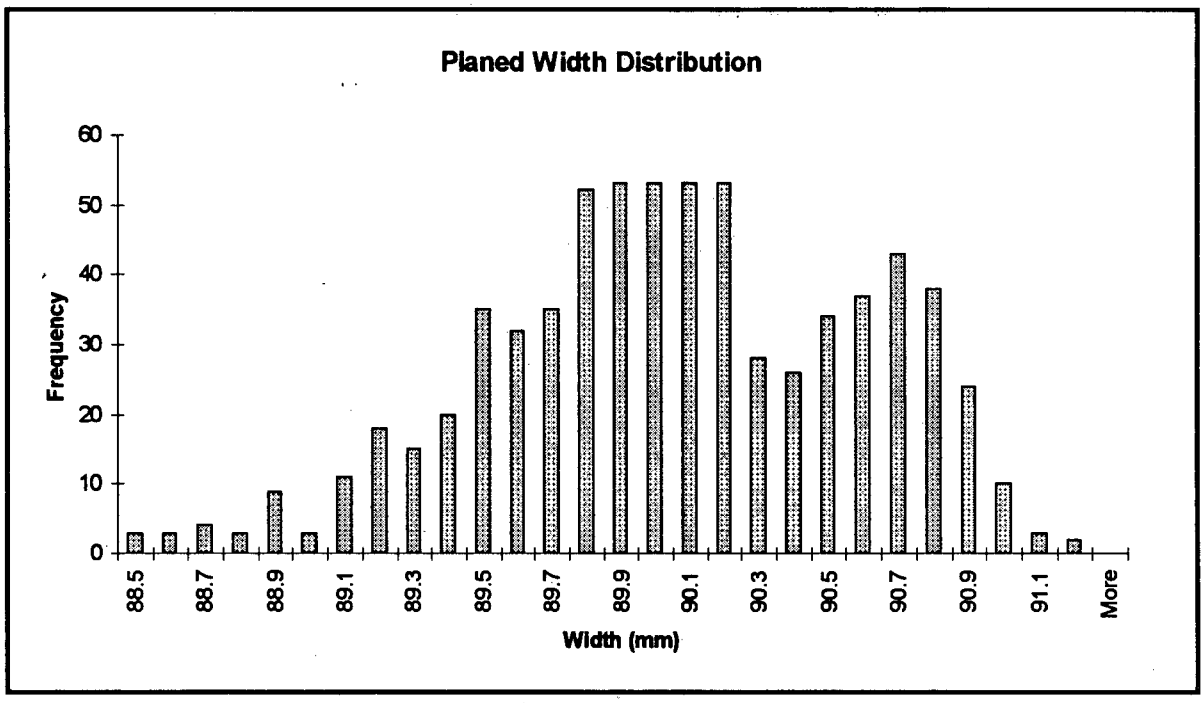

Figure 11 Planed Width Distribution

4.3 Variation in Moisture Content

The summary of green moisture content information is presented in Table 14. The actual moisture content of the samples may be much higher than the values shown in Table 14, because the measuring range of the Wagner moisture meter is between 2 to 30 %. Any moisture content higher than 30% will be shown on the meter as some thing around 30%. However, the data in Table 14 at least show us that the average moisture content of the green samples is higher than the moisture saturation point of SPF.

Table 14 Green Moisture Contents and Their Standard Deviations

(%)

Item	Shift 1	Shift 2	Shift 3	Average
Average	31.82	32.36	32.34	32.17
Within-board Standard Deviation	1.16	0.65	0.68	0.83
Between-board Standard Deviation	1.19	0.78	0.87	0.95
Total Standard Deviation	1.66	1.02	1.10	1.26

Table 15 shows the summary information of dry moisture contents and their variation. The average moisture content was 14.22%, a value much lower than the target dry moisture content, 19%. The mill was obviously over-drying its lumber. If the amount of lumber with moisture content higher than 19% was required to be less than 5% of the total lumber, the necessary target moisture content should have been 16.38% under the current final moisture

content standard deviation, 1.59%. The increase of the final moisture content from 14.22% to 16.38% only will reduce the target size by 0.5%.

Table 15 Dry Moisture Contents and Their Standard Deviations

(%)

Item	Shift 1	Shift 2	Shift 3	Average
Average	13.15	13.64	15.86	14.22
Within-board Standard Deviation	1.17	1.23	1.55	1.32
Between-board Standard Deviation	0.68	0.88	1.12	0.89
Total Standard Deviation	1.36	1.51	1.91	1.59

The average dry moisture content standard deviation was 1.59%, which was 11 percent of the average dry moisture content. The variation of the final moisture content could be explained either by the variation in raw material or by the variation in drying operation. Again it proves that the drying variance caused by the drying operation could contribute significantly to the drying shrinkage variance.

4.4 Target Sizes Estimated with the Traditional Target Size Estimation Method

The required finished thickness and width are not less than 1.5 and 3.5 inches (38.1 and 88.9 mm), respectively, for 2" by 4" boards. The average sawing standard deviations in thickness and width were 0.40 and 0.96 mm (Table 6). The allowable under-sized boards were supposed to be less than 5%. The critical value, z_α in the Equation [13], was 1.65 according to the normality distribution. The target final moisture content of the mill was 19%. The shrinkage of SPF lumber dried from green to 19% moisture content is 3.5%[1]. The total planer allowance was assumed to be 0.08 inch (2.03 mm) for the two opposite sides of a board, a number used by most sawmills. Then according to Equation [13], the target thickness of the mill was computed as:

$$\text{Target Thickness} = \frac{38.1 + 2.03}{1 - 3.3\%} + (1.65 \times 0.40) = 42.16 \quad mm,$$

and the target width was computed as:

$$\text{Target Width} = \frac{88.9 + 2.03}{1 - 3.3\%} + (1.65 \times 0.96) = 95.62 \quad mm.$$

The measured average green thickness and width were 43.39 and 99.64 mm which were larger then the estimated target sizes.

4.5 Target Sizes Estimated with the Computer Simulation Model

4.5.1 Simulation Precision via Sampling Sizes

Table 16, Figure 12, 13 and 14 show the simulated results of the relationship between sample size and simulation precision. From Table 16, we can see that when the sample size is high enough the simulated average dry size and dry size standard deviation were 41.81 and 0.61 mm, respectively, which were equal to the actual field test average size and standard deviation. As expected, the higher the sampling size the closer the estimated lumber size is to the actual lumber size. For example, when the sample size is 10,000, the standard deviation among each simulated dry size was only 0.013% of the average dry size and the standard deviation among the simulated dry size standard deviations was 0.627% of the dry size standard deviation. These results prove that the simulation model can correctly estimate the sawing and drying processes.

Figure 12 shows the relationship between the sample size in the simulation and the error in estimating dry size standard deviation. The relationship is obviously not linear. When the sample size is small, the change of sample sizes has much greater impact on the estimation error than when the sample size is large.

[11] 3.5% was used in target size estimation by the test mill referred later on. If the maximum shrinkage is to be used in target size estimation, the shrinkage of drying SPF to 19% would be 3.3% because the maximum green to oven-dry tangential shrinkage of Canadian SPF is 8.9%.

Figure 13 and 14 are the $\pm 3\sigma$ limits of the errors in estimating dry size and dry size standard deviation, respectively. When the sample size is less than 2,000, the error in the estimated dry size is increased sharply and when the sample size is less than 3,000, the error in the estimated dry size standard deviation is increased sharply. So the proper sample size for dry size distribution simulation should be more than 3,000.

Table 16 The Relationship between the Sample Size and the Simulation Precision

(mm)

Sample size	Average Estimated Dry Size Standard Deviation	Standard Deviation of the Estimated Dry Size Standard Deviation of the 20 Iterations	Average Estimated Dry Size	Standard Deviation of the Estimated Dry Sizes
1000	0.6104683914	0.0125816862	41.8173615000	0.0206717344
2000	0.6098981427	0.0097118749	41.8155992500	0.0089097558
3000	0.6101817718	0.0064532702	41.8169038333	0.0076965804
4000	0.6096367183	0.0059695199	41.8154810000	0.0069807745
5000	0.6093991828	0.0061621361	41.8141586000	0.0062663235
6000	0.6098417000	0.0062622658	41.8128296667	0.0050588920
7000	0.6095381837	0.0056681360	41.8137718571	0.0059002653
8000	0.6099947545	0.0053670251	41.8134500625	0.0067001676
9000	0.6102794064	0.0044025645	41.8124697778	0.0057747738
10000	0.6102139053	0.0038290180	41.8122795000	0.0055657700

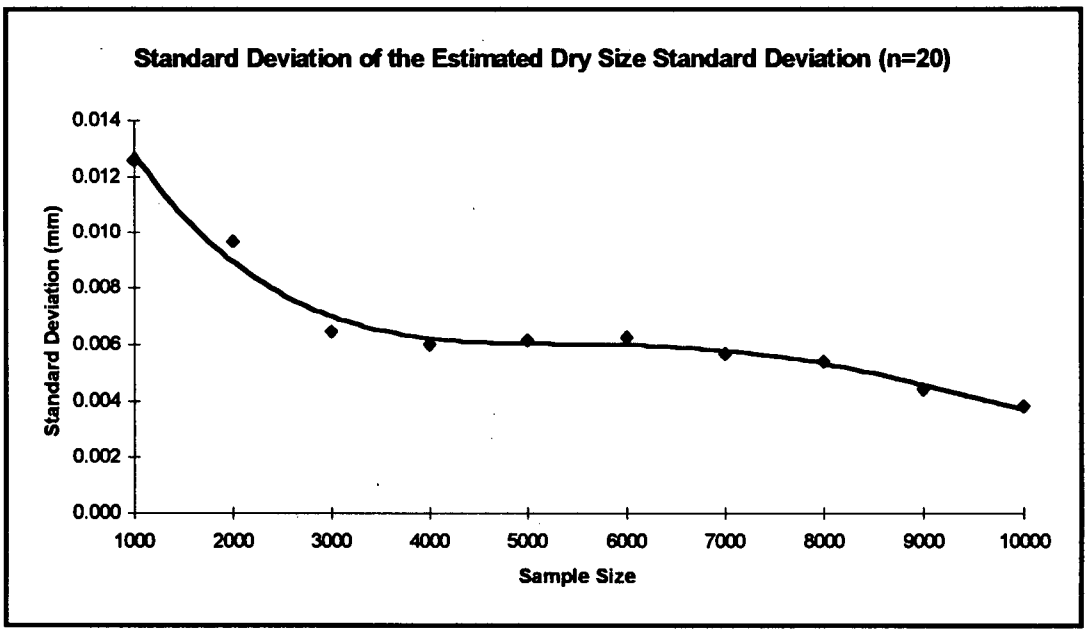

Figure 12 The Relationship between the Sample Size and the Simulated Precision

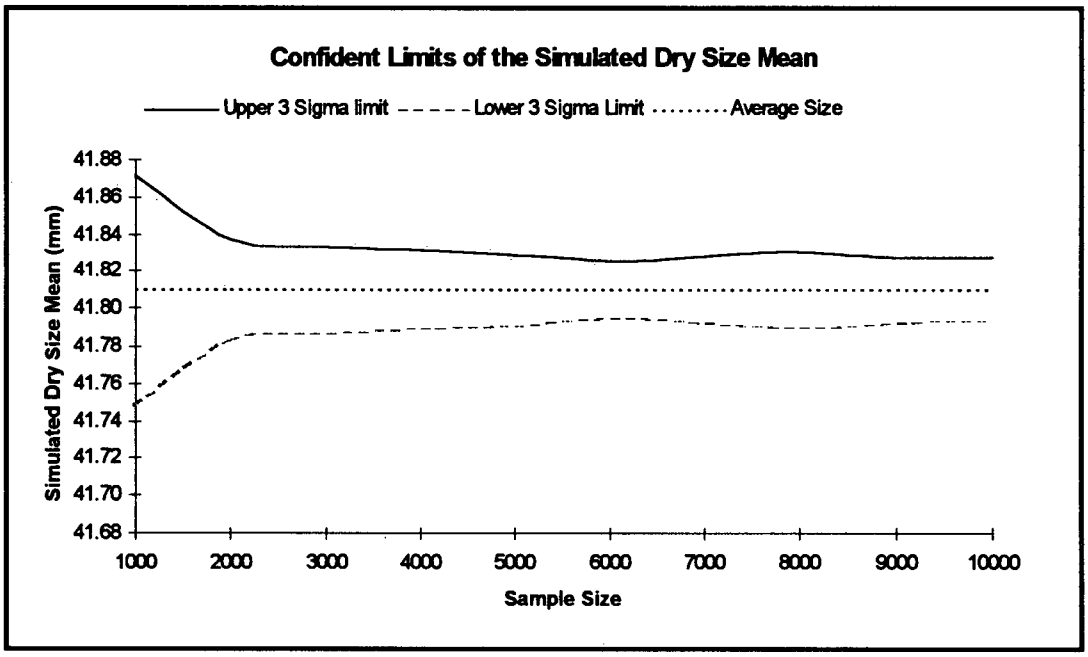

Figure 13 $\pm 3\sigma$ Limits of the Estimated Dry Size

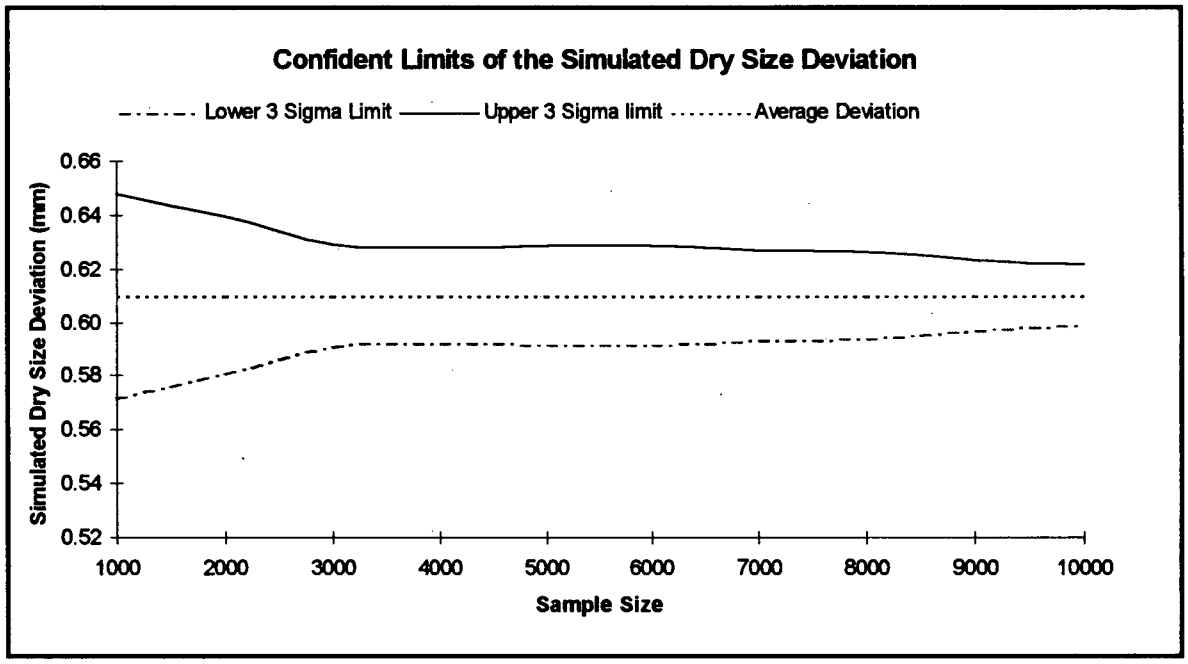

Figure 14 $\pm 3\sigma$ Limits of the Estimated Dry Size Standard Deviation

4.5.2 Simulation with Normal Size Distributions

The initial estimated target thickness and width were 42.16 and 95.62 inches respectively [Section 4.4]. The planing target thickness and width were determined to be 38.57 and 90.13 as illustrated in Figure 15, assuming normal dressed size distribution. If a minimum amount of dressing fiber is required in the planing, this amount of fiber should be added to the planing target size in the simulation. In this example, the minimum fiber required

for the dressing is assumed to be zero. The simulated target thickness and width were 41.27 mm and 94.47 mm respectively. Both were smaller than the targets estimated with the traditional target size estimation method.

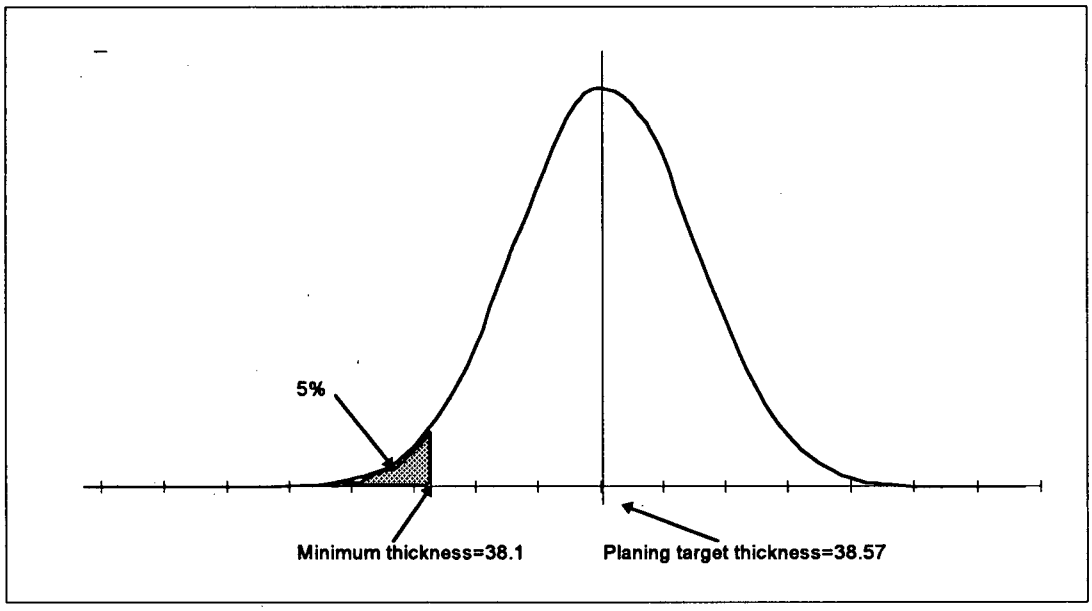

Figure 15 Determination of Target Planing Size

4.5.3 Simulation with Actual Size Distributions

Then the actual dressed thickness and width distributions were used in the simulation to estimate green target sizes. The planing target thickness and width were determined to be 38.33 and 89.81 mm, respectively. Both were a little bit smaller then the target planing sizes estimated with normal distribution which were 38.57 and 90.13 mm. This means that the planing target sizes estimated with normal dressed size distribution are larger than the

necessary sizes. The planing target thickness and width were 0.24 and 0.32 mm , respectively, larger than their correspondents estimated with the actual dressed size distribution. The actual green size distribution was also used in the simulation. However, the actual shrinkage was not available in the study. Only the derived shrinkage distribution based on the normal green and dry size distributions was used in the simulation. The correctness of the results will certainly depend on the correctness of the derived shrinkage variation.

The target thickness and width of the simulattion results were 40.97 and 94.73 mm, respectively. The green target thickness was 0.30 mm smaller than the green target thickness estimated with normal assumption, but the green target width is 0.26 mm larger than that estimated with normal assumption. The result showed that the normality assumption of dressed size distribution results in error in target size estimation and the actual dressed size distribution should be used in the simulation.

This result also showed that the target thickness and width estimated with the traditional target size estimation method were 1.19 mm and 0.89 mm larger than the target thickness and width estimated with the simulation method. The traditional target size estimation method over-estimates target sizes.

The actual average green thickness and width were 43.39 and 99.64 mm which were larger than the target sizes estimated both by the current target size estimation method and the simulation. The sawmill is obviously over-sizing its lumber. There is plenty room for the test mill to reduce its target sizes.

The simulated percentage of under-sized thickness and width in respect to various green target thickness and width is shown in Figure 16 and 17. The relationship between the target sizes and the percent of under-sized boards is not linear.

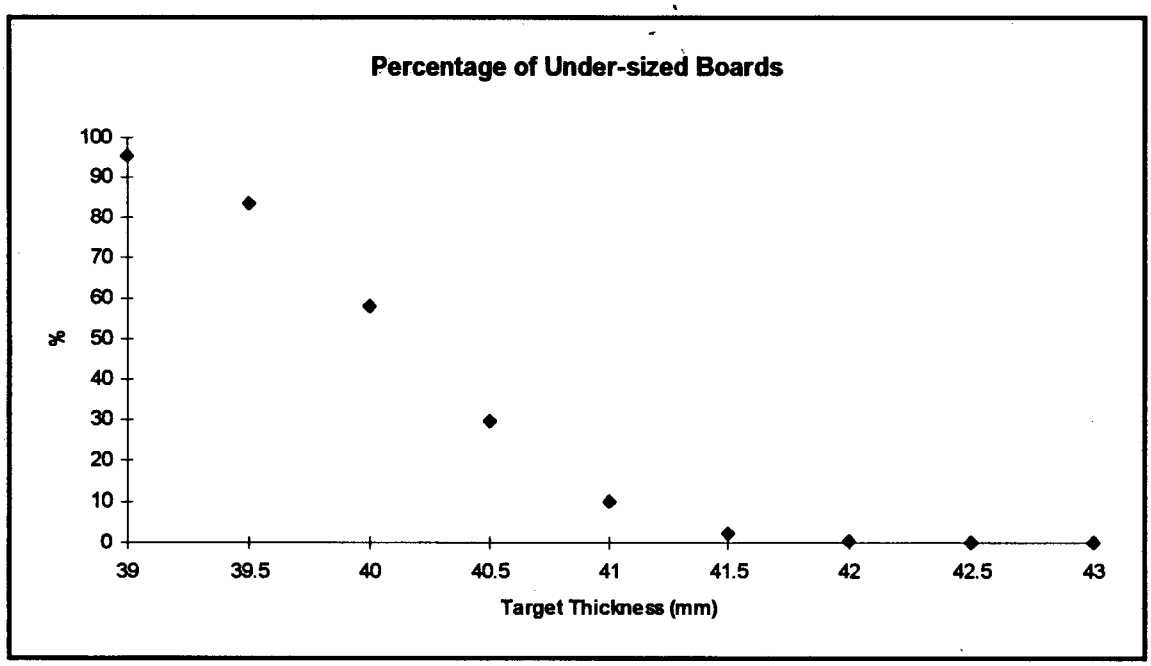

Figure 16 Percent of Under-sized Thickness

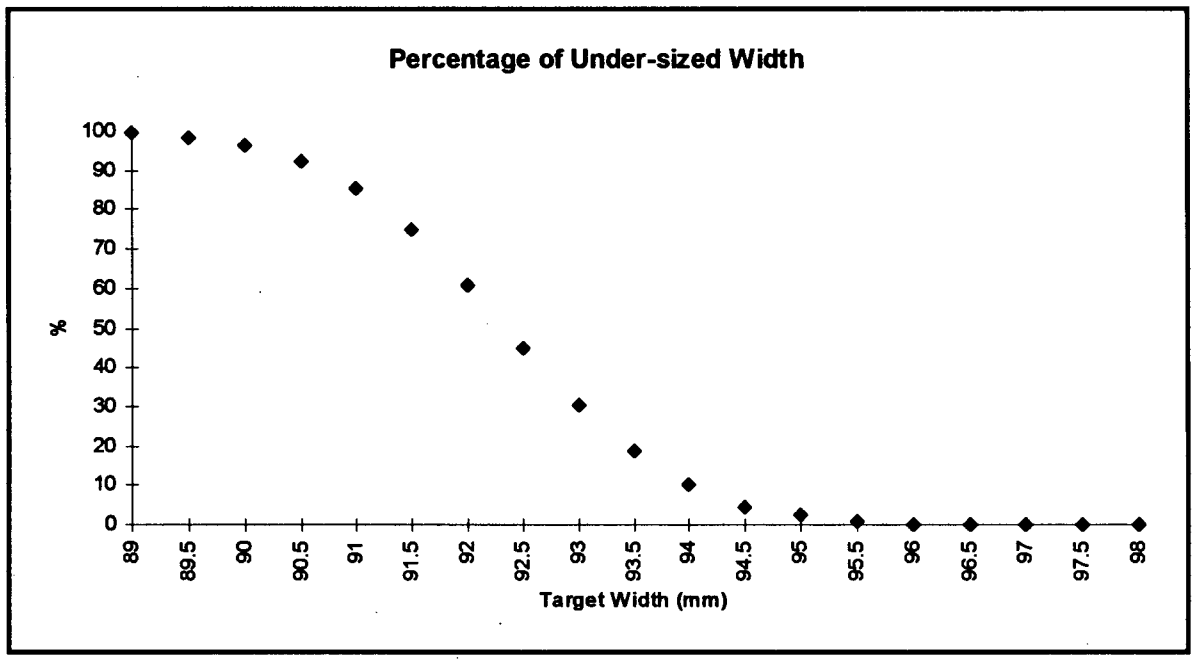

Figure 17 Percent of Under-sized Width

4.6 The Impacts of Variance Reduction on Lumber Target Sizes

The target sizes resulting from reducing one of the three variations, while the other two variations were held unchanged, were obtained with the simulation program. The estimated target sizes are shown in Table 17 and 18 and Figure 18 and 19. Reducing planing variation has much higher impact on target sizes than reducing sawing variation and shrinkage variation.

Table 17 Target Thickness after Reducing One of the Three Process Variations

(*mm*)

Standard Deviation Reduction	Target Thickness		
	Sawing	Drying	Planing
0.0	41.27	41.27	41.27
0.1	41.18	41.17	41.05
0.2	41.12	41.08	40.85
0.3	41.08	40.99	N/A
0.4	N/A	40.96	N/A

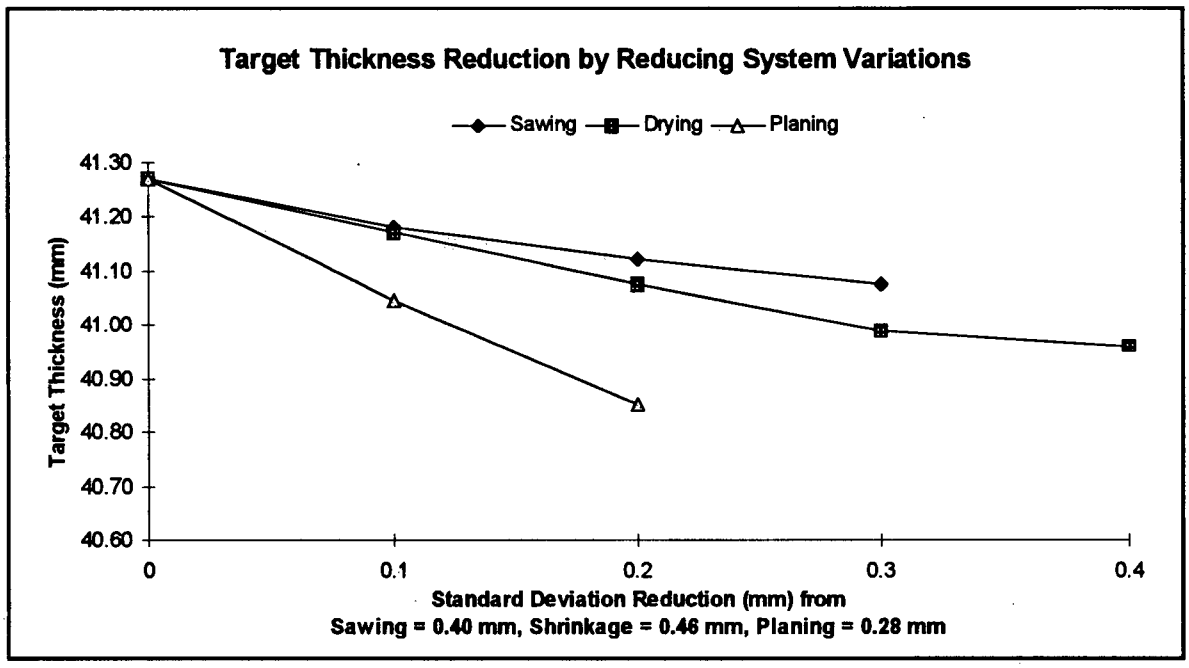

Figure 18 Target Thickness after Reducing One of the Process Variations

Reductions of sawing variation and shrinkage variation have similar impacts on target sizes. The more efficient way of reducing the target size is to reduce the one which is larger in value. For example, in this case study, since the shrinkage variation in thickness is larger than sawing variation in thickness, the target thickness can be reduced more by reducing shrinkage variation than by reducing sawing variation. In contrast, target width can be reduced more by reducing sawing variation than by reducing shrinkage variation since the sawing variation in width is larger than shrinkage variation in width.

Table 18 Target Width after Reducing One of The Three Process Variations (mm)

Standard Deviation Reduction	Target Thickness		
	Sawing	Drying	Planing
0	95.24	95.24	95.24
0.1	95.12	95.19	94.99
0.2	95.00	95.15	94.74
0.3	94.90	95.13	94.51
0.4	94.80	N/A	94.28
0.5	94.72	N/A	94.07
0.6	94.65	N/A	93.89
0.7	94.61	N/A	93.70
0.8	94.55	N/A	N/A
0.9	94.52	N/A	N/A

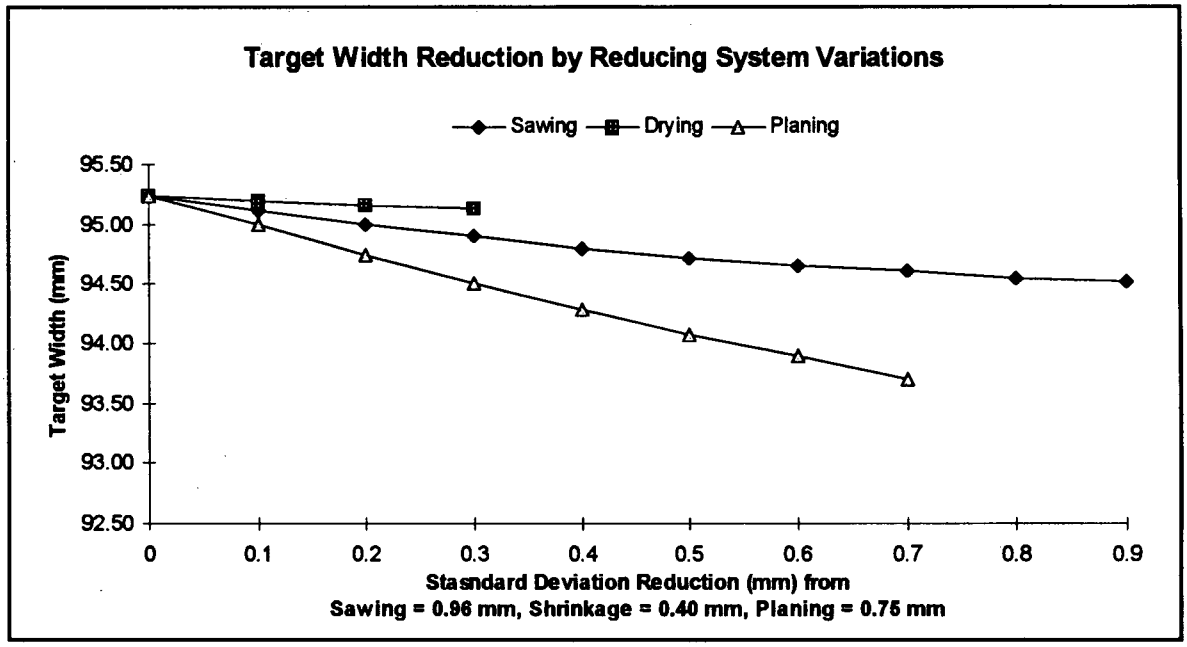

Figure 19 Target Width after Reducing One of the Process Variations

4.7 The Impacts of Target Size Reduction on Production Net Revenue

Assuming that the mill operates at the simulated target sizes, 40.97 and 94.73 mm, the possible target thickness and width reductions from the targets currently used in the sawmill are 2.42 mm and 4.91 mm, respectively. The annual net revenues were estimated with three sets of target sizes: Target sizes estimated with the traditional method, target sizes estimated with the computer simulation model and the actual target sizes.

The target sizes other than the 2" by 4" boards were estimated and shown in Table 19.

The net revenues of the three simulations are shown in Table 20. If the mill operates at the target sizes estimated with computer simulation, the mill net revenue can be increased $3,303,972 per year. The profit is increased by 38.8% while the target size is only reduced by 5.2%. This result showed how important the target size reduction is to the mill net revenue increase. The net revenue difference between the target sizes estimated with current target size estimation method and the computer simulation method is 10%.

The relationship between target size and the mill revenue is shown in Figure 20. The two have very good linear relationship. With this relationship and the target size reduction due to the reduction of any mill variation, the net revenue change of the variation reduction can be found.

Annual Net Revenue ($) = 5,000,000 - 951,077 Target Thickness (mm.)

This equation shows that the mill net revenue can be increased nearly one million dollars if the target size is reduced by one millimeter.

Table 19 Estimated Target Widths for Boards Other Than 4 inches wide

Nominal (in.)	Required dry dressed size (mm.)	Target used in the current mill (mm.)	Target estimated with current methods (mm.)	Target estimated with simulation (mm.)
4	88.90	99.64	95.62	94.47
6	139.70	151.96	147.94	146.79
8	184.15	197.75	193.73	192.58
10	234.95	250.07	246.05	244.90

Table 20 The Mill Production Profit of Simulations with Different Target Sizes

Target Size	**Production Profit ($)**
Used in the current mill	8,520,972
Estimated with current target size estimation method	10,746,612
Estimated with Simulation method	11,824,944

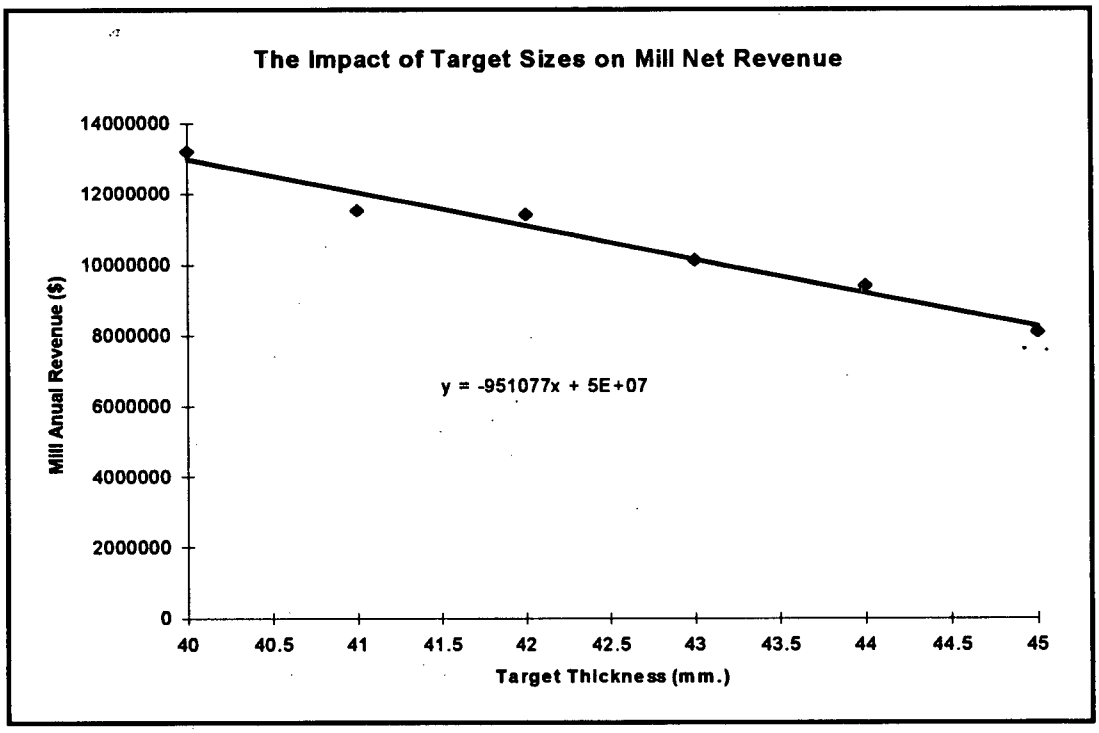

Figure 20 The Impact of Target Sizes on the Mill Net Revenue

5. Conclusions

The mill field test results confirmed the suspicion that the shrinkage variation could be a controlling factor in determining target sizes, because the shrinkage variation was almost equal to the sawing variation. The test results also showed that the standard deviation among the positions of boards in drying packages and packages in a drying kiln accounted for almost 1/3 of total shrinkage standard deviation. Therefore, the quality control program in lumber drying is as important as quality control program in sawing.

It was found that the sawing variation of the mill was not in statistical control because it varies from shift to shift. This causes difficulty in target size estimation. Normally, target sizes have to be set according to the worst situation in order not to under-size lumber. This could be one of the major reasons of lumber over-sizing. The mill needs to improve its lumber size quality control program in order to establish control in sawing variation as well as other processes.

Only the dry size distribution was found to be approximately normally distributed. The normal assumption of green size and dressed size distributions could result in error in target size estimation with the computer simulation. In order to increase the reliability of computer simulation, actual lumber size distribution estimated from field tests should be used instead of the normal size distribution.

A computer simulation program for target size estimation was developed which takes account of all the three processing variances of the sawing system and the interactions between all the three processing variances. This simulation program can take actual lumber size distributions or normal size distributions. The simulation results show that for the processing variance of the test mill (not normal distribution), the use of normal distribution assumption will results in error in the target size estimation.

The target sizes estimated with this new target size estimation method shows that the current target size estimation method does not yield correct target sizes due to constant assumption of shrinkage and planing allowance. Actually, drying shrinkage is not only affected by raw material, but also by the sawing and drying operation. The planing allowance is affected by planing operation and dry size distribution. The shrinkage variance and the planing variance need to be controlled as well. The error in the current target size estimation method could result in severe loss to a sawmill.

The three process variances have different impacts on target sizes. The priority of reducing any of the variances should be awarded to the one which has the largest impact on target size and the least effort needed for the variance reduction. Of the three process variances, the planing variance has greatest impact on the target sizes. However, customers are least likely to detect problem in planing variation. The impact on target sizes of the sawing variation and shrinkage variation is about the same. The process which has larger variance has larger impact.

The relationship between target size reduction and mill net revenue was found to be approximately linear. In this case study, the mill will gain nearly one million dollars per annum per millimeter by reducing target sizes. It was also found that the mill is currently seriously over-sizing its products. The loss due to this over-sizing could be more than 3 million dollars per year which is 38.8% of its annual net revenue. A better quality control program will greatly improve the profitability of the sawmill.

The estimation of net revenue increase of lumber target size reduction was based on the average sawing and drying variation. However, actual sawing and drying variations of the test mill were different from shift to shift. The drying shrinkage variations vary from one location to another location in a drying package and in a drying kiln. These uncertainties in operation variation undermine the target size reduction opportunity. Measures of better quality control should be brought in order to achieve the expected target size reduction.

In the target size estimation by computer simulation, the minimum fiber needed for surfacing was assumed to be zero on account of the fact that there is a size variation in dry rough surfaces. From the theoretical point of view, there is no problem in this assumption. However, in practice, a planer head may not be able to cut off fiber which is too thin for its knife edges. Further study on the minimum fiber needed for surfacing has to be done in order to confirm the computer simulation method for target size estimation.

Recommends to the Test Sawmill

1. The mill should be able to tighten its green target sizes immediately because there is essentially no planer skips in the current final products even though the final moisture content is much lower than the target moisture content. The results of the simulation program also show that the mill is currently severely over-sizing its lumber. Tightening the target sizes will significantly increase the mill production profit.
2. The average final moisture content in drying should be increased to 16.38%. This will result in lumber target size reduction by 0.5% while the moisture content still satisfies the grading rules.
3. More efficient quality control program should be applied in all the three processes of the mill because it was found that the variations in the current sawmill are not in statistical control. If this is not done, it will be very difficult for mill to estimate correct lumber target sizes and further reduction in target sizes is impossible.
4. The mill should pay more attention to the variation among the initial moisture content, because it was found that the between-board shrinkage variation was much larger than the within-board shrinkage variation, which is probably caused by the variation in the initial moisture content in the drying.
5. More attention should be paid to the variation in the planing because it was found that the planing variation has the greatest impact on mill production profit and the current dressed size variation is quite large.

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