Evaluation of Processing Head Measurements in Merchandizing Southern Yellow Pine in the Southeast US

by

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Abstract

Today's timber market in the Southeast US demands a specific size log; thus, the harvested trees need to be processed at the landing. The utilization of a processing head in the logging industry is encouraged due to the presence of technological advancement on the machine that allows the loggers to merchandize and top the logs by specifying the desired measurements into the processing head's computer program. This study evaluated the accuracy of processing heads in merchandizing logs by analyzing the bias and precision of measurement differences. The results showed that the processing heads resulted in a biased measurements but very low precision in measuring length, butt diameter, and top diameter. The majority of produced logs (62% of the observed data) were on acceptable length as they were produced between trim allowance. It was also found that processing heads showed better performance in measuring top diameter than butt diameter (0.55 inches and 0.71 inches of overall measurement differences respectively). Butt diameter measurement differences that were equal to zero were found on 25% of total observation, while it was found that 42% of the total top diameter measurements were showing equal reading with the post-measurements. In addition, it was found that the measurement difference had a positive correlation with the length of merchandized logs with an R-squared of 3%. Longer logs were likely to contribute to a higher difference between processing head and manual measurement.

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Chapter 1. Introduction

1.1 Project Background

As a subsequent result of the Great Recession, sawmills' production capacity in the U.S. South fell to under 17 billion board feet in 2010. However, this decline has recovered in the last few years, where the capacity reached 21 billion board feet in 2017 (Tyson 2018). This number is expected to grow even further, with an expected production capacity of 23.5 billion board feet by 2020, due in part to the expected completion of 20 new sawmills by 2022 (Beck 2019). This growing presence of sawmills across the Southeast US has provided new challenges as well as opportunities for loggers around the area. The requirements to transport the specific size of logs to these mills is strictly enforced. Therefore, the loggers need to process the harvested trees to meet mill specifications before they are transported. On the other hand, the loggers' ability to merchandize the stems is providing them the opportunity to gain a higher income compared to selling the harvested trees as tree length.

The practice of merchandizing is commonly conducted by the loggers using a pull-through delimber and a slasher saw that are attached to a knuckleboom loader. The knuckleboom operator delimbs and tops the harvested trees using the delimber and merchandizes them by length using the slasher saw. These processes rely on the operator's subjectivity in estimating the top diameter; hence, the result of topping and merchandizing are susceptible to measurement errors.

To avoid this subjectivity, the utilization of a processing head in the logging industry is encouraged due to the technological advancement in the machine. This technology allows the loggers to merchandize and top the logs by specifying the desired measurements into the processing head's computer program. Therefore, the incorporation of a processing head in logging operations is expected to provide the exact measurements of the logs by removing the operator's subjectivity. However, with such an effective measurement, its accuracy needs confirmation.

The ability to produce logs into accurate dimensions as desired using a processing head would likely depend on the operator. An adequate amount of experience in operating a machine provides the operator with the skill to run the operation in the most efficient way, which results in maximum production. Kärhä et. al (2004) reported that an experienced operator performed 40% higher productivity compared to an inexperienced operator. Despite higher production, the experience level would also likely to affect the accuracy of processed logs. As the machine operator gains familiarity with the computer system and panel controls that are installed on the processing head, improved accuracy on the processed logs is expected. Purfürst (2010) examined 16 beginner forestry machine operators to understand their learning curves. These operators showed a low performance level as they started operating a new machine. However, they were reaching a constant performance where they were able to roughly double the performance after eight months of operating a logging machine.

In addition to operator experience, calibration is also an important element in producing the desired log dimensions. Even though a processing head is designed to handle heavy objects (trees) in the field, the machine's accuracy could be compromised after a certain amount of usage. Therefore, it is important to keep the machine calibrated to ensure that the products are measured correctly. As reported by Nieuwenhuis and Dooley (2006), conducting harvester calibration regularly could reduce the difference between harvester measurements and manual measurements which resulted in higher accuracy in the length measurement. Additionally, when a harvester is regularly calibrated, the accuracy on the volume of timber produced can be increased up to 6% (Dooley et al, 2006).

1. 2 Project Objectives

This thesis is intended to evaluate the accuracy of utilizing processing heads to merchandize southern yellow pine in the Southeast United States. This research will help to better understand the accuracy of the machine in measuring logs' dimensions, and identify factors related to their accuracy. Specific objectives included:

1. Investigate the difference of processing head measurements and manual measurements.
2. Analyze the difference of measurement differences between machine operators studied.
3. Analyze the correlation between log lengths measured by processing head and the measurement differences to find if a longer log results in higher measurement error.

Chapter 2. Literature Review

2.1 Tree-Length Operation Transformation to Merchandizing

Ground-mechanized forest operations are divided into three logging techniques, tree-length (TL) operations, cut-to-length (CTL) operations, and whole-tree (WT) operations (Kellog et al. 1993; Rummer 2002). These three techniques are distinguished by how the harvested trees are delivered to the roadside. TL operations utilize a felling machine, skidder, and a loader to complete the operation. A CTL operation is a harvesting system that uses a harvester head to cut and delimb the trees as well as buck them into certain length and diameter right on the stump. Then, the logs are transported to the roadside with a forwarder. In WT operations, the trees are cut and transported from a timberland without removing the limbs and top of the tree. This timber harvesting method is incentivized when timber residues (limbs and tops) are desired by the market, such as for the bioenergy market (Briedis et al. 2011).

Harvesting techniques in southern US are established to produce tree length materials. These emerged as the preferred way to harvest timber when the loggers wanted to move from a labor-intensive manual harvesting operation in order to increase their productivity (Cubbage 1982). In addition, TL forest operations have been adapted since the 1980s in the region to process southern pine logs (Cubbage & Granskog 1982) as a consequence of the market availability around the area. The market prefers to purchase the delimbed tree-length logs. In this logging operation, a logging crew utilizes the combination of a feller-buncher, a skidder and a knuckleboom loader to harvest mature trees. Equipped with a stroke or gate delimber, this type of timber harvesting produces logs that are cut to a specific top diameter that will be delivered to mills.

Recently, Canadian lumber companies have expanded their enterprises to the southern US because these timber manufacturers had begun to experience a slower production rate in Canada. It is reported that the top 10 timber companies in Canada recorded a roughly 1% drop in production in 2014 compared to 2013 (Taylor 2015). In addition, these Canadian timber producers encountered this decline because of the export taxes and quota limitations that were enacted under the Softwood Lumber Agreement, (Hoover & Fergusson 2015; Parfitt 2008) and followed by the collapse of the US housing market during the Great Recession (Hayter et al. 2015; Coiteux et al. 2014). Further, the production also declined due to restricted fiber availability as a result of mountain pine beetles attacks on the pine forest stand. This outbreak led to a considerable amount of timber losses. In 2011, the province of British Columbia encountered the mortality of 53% of merchantable pine (Walton 2012). This situation vitalized the investment of Canada's companies to migrate to other areas that have steady timber resources, such as the southern US. The emergence of Canadian lumber manufacturers' investment in the southern US region began in 2005 by upgrading their existing mills and taking over several US mills (Parfitt 2008). South timber resources are known to produce 55% of total timber harvested in the US in 2002 (Haynes et al. 2007) and retains 40% of the nation's timberland (Oswalt & Smith 2014). Furthermore, the rising demand for the US housing market recovering from the Great Recession also contributes to their aggressive expansion due to proximity to this market.

The expansion of Canadian lumber companies to the southern US has provided a new challenge as well as the opportunity for the loggers around the area. It contributed to the changes in the wood market, where these companies exclusively accept logs that are of certain sizes (diameter and length) and it is strictly enforced. Logs that are under specification result in wastage as the manufacturers will only be able to produce lumber to the next-shorter length. Usually, a 5 cm dispensation is given for under-length logs (MacDonald 1999). Therefore, to accommodate this demand, the loggers need to process the harvested trees at the landing before they are loaded onto the truck. On the other hand, the loggers' ability to merchandize the stems is providing them the opportunity to gain a higher income compared to selling the harvested woods as tree-length when the log buyers provide various economic returns following the lengths of the logs (Sessions et al. 1989). May et al. (1994) reported that in-woods merchandizing allows the loggers to supply multi-products (e.g. pulpwood, sawlogs, and veneer) that can be marketed to different mills, and it has the potential to increase the economic return to them.

2.2 The Addition of a Processing Head for Merchandizing Trees

This changing demand from mills has resulted in the modification of conventional tree length operations in the South. The harvested trees need to be bucked to size at the landing before they are hauled to the mill. However, the TL operations are not completely shifted to CTL operations. It is modified using the machines they have, and add a merchandizing process at the landing to process the logs to a particular length or top diameter.

Harvested trees may be merchandized into different products, such as poles, ply logs, saw timber, chip-n-saw, and pulpwood. The requirements for a log to be merchandized into these products vary from type to type with poles having the strictest requirements and pulpwood having the least strict. Poles, the highest valued products, are produced from healthy, straight stems with 10-20 inches DBH and a minimum length of 30 feet. Meanwhile, pulpwood production does not require the same strict size requirements as logs that would be merchandized into poles. Trees with 6-9 inches DBH could be processed into pulpwood (Timber Apps, LLC n. d.).

The use of a knuckleboom loader with its attached pull-through delimber and a slasher saw has become a common merchandizing practice for loggers. In this practice, the trees are merchandized first by having the operator delimb and top the tree, then by using the slasher saw to buck the delimbed tree to specific lengths (Rummer 2002). However, using this type of machine, estimation of diameter relies highly on the operator's subjectivity since there are no measuring devices to provide the information of diameter size. Therefore, the result of topping and merchandizing are prone to measurement error.

Imprecision when merchandizing logs using a knuckleboom loader with its attachments would likely result in products that do not meet specifications. This inaccurate measurement will contribute to value loss to the loggers (MacDonald 1999). When the logs are below the mill's specification, it may be downgraded which results in the reduced payments to the loggers. In addition, if the loggers are making logs that are above the mill's specification, they are losing profit for selling higher value trees for a lower price. With susceptibility to diameter measurement error, there are chances that the loggers are supplying larger logs to the mills. Meanwhile, they could have processed the tree to the mill's requirement to obtain more value.

For these reasons, accuracy in merchandizing has become a concern in the South logging industry. Therefore, loggers are starting to invest in a processing head to replace the merchandizing task of a knuckleboom loader. The function of a processing head is incorporated into to the TL logging operations in South US. Unlike its purpose to fell and buck trees at the stump in a CTL operation, a processing head is attached to a tracked processor and utilized at the landing to accurately measure the dimensions of logs so that the merchandizing process could be conducted effectively. Meanwhile, the felling and skidding processes are still conducted with a feller-buncher and a skidder. Substituting the loader with a processing head could avoid the subjectivity issue, and enhance the bucking optimization process (Nieuwenhuis & Dooley 2006). The processing head is equipped with measuring technology that allows the loggers to merchandize and top the logs by specifying the desired measurements into its computer program. With this bucking optimization system, incorporating a processing head in logging operations is expected to provide the exact measurements of the logs.

2.3 Challenge in Using the Processing Head

Mechanized logging operations involving a processing head have been shown to bring benefits, as productivity increases, and product dimensions are more accurate (Conrad & Dahlen

2019). However, to bring a corresponding benefit in terms of net profit, this harvesting technique needs recognition from the mills to compensate for the high investment in adding a processor head to the operation (May et al. 1994; Conrad & Dahlen 2019). In addition, the utilization of processing heads in the logging operation also raises arguments regarding its precision to merchandize logs (Bembenek et al. 2014; Beaudoin & LeBel 2019) and the side effect of processing the trees to physical properties of the logs (Jorgensen et al. 1975).

Another feature of processing heads that affect the products, besides its computerized optimization process, is the delimbing arms and the feed rollers (Figure 1). These parts of the machine are able to remove limbs and bark as the stem is roll-fed through the machine (Levesque 1976). These functions are giving both desired and undesired results to the operation. The debarking and delimbing functions of a harvester head are beneficial as the removed limbs and bark will be left in the woods, and will eventually decompose which will provide nutrients to the soil (Jorgensen et al. 1975). In addition, bark removal should be performed soon after the tree is felled because debarking is easier to achieve on a freshly cut tree (Grobbelaar & Manyuchi 2000). In the case of eucalyptus trees, bark has the potential of being more adhesive as the logs get drier (Wingate-Hill et al.1989); therefore, it is better to remove the bark when it still has moisture. On the other hand, debarked logs as a result of bucking them with a head processor would likely suffer from damage and eventually lower the quality of fiber. Damage resulting from the contact between stem and feed-rollers and delimbing arms have been identified for both softwood and hardwood species (Karaszewski et al. 2016). A study in a eucalyptus plantation in South Africa also showed that the use of harvester a head resulted in reduced bark content but lower quality of chips in terms of its uniformity, accepted chips produced, and the number of pins produced during chipping (van der Merwe et al. 2016).

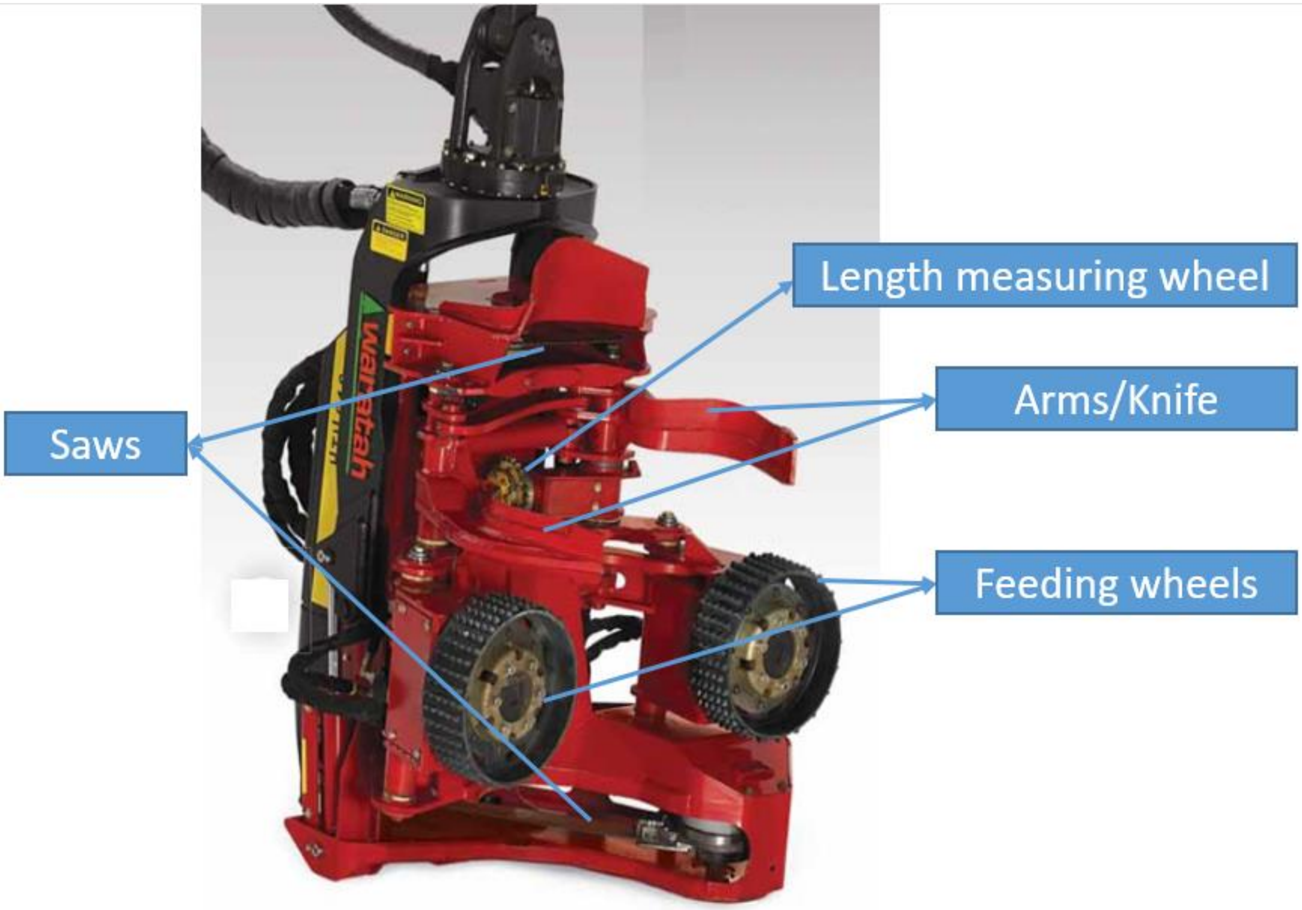


Figure 1. Waratah Processing Head (John Deere n. d.)

Processing pine logs has another consequence due to its bark removal. Depending on the customers' requirements, the loggers need to provide logs that are of the mills' specifications. Southern sawmill companies usually decide to purchase logs based on their outside-bark diameter (DOB). However, the utilization of processing heads in the merchandizing of logs results in the unavoidable debarking as the delimbing arms and feed rollers help to remove some of the bark. This removed bark signifies that the diameter of the processed logs is not completely measured on their outside bark. For this reason, as part of the bark is removed, the logging crews are supplying logs with larger top diameters to the mills. In addition, if this removed bark is accounted for, loggers can supply smaller top diameter logs to the mills. Keeping the logs produced at the mills' specifications, even though there is evidence of removed bark, results in missing some sawtimber material for the loggers.

As mentioned before, precision in measurement is important in producing bucked logs. Out-of-specification products result in losses for the loggers. Therefore, with such an effective optimization system in a processing head, precise measurements are expected. However, logging operations that are using a processing head may still see products that are out of specification, which will ultimately lead to fiber losses. Inaccurate crosscutting of *P. elliottii* and *P. patula* with harvester heads has resulted in a wood volume loss of 1.5% and a total revenue reduction of 3.4% (Williams and Ackerman 2019).

The ability to produce logs into accurate dimensions as desired using a processing head would likely depend on the operator. An adequate amount of experience in operating a machine provides the operator with the skill to run the operation in the most efficient way, which results in maximum production. Kärhä et. al (2004) reported that an experienced operator performed 40% higher productivity compared to an inexperienced operator. Despite higher production, the experience would also likely affect the accuracy of processed logs. As the machine-savvy operator becomes more familiar with the computer system and panel controls that are installed on the processing head, a higher accuracy on the processed logs is expected. Purfürst's 2010 study found that operators of harvesting machines have decisive influence on those machines' performance. In this study, the performance of 16 new operators were examined to understand their learning curves in running harvester heads. Forestry machine operators showed a slow performance level as they start operating the machine and reached a constant performance after eight months. These operators' performance level began at 0.56 on average, and by the end of learning phase (after eight months operating harvester heads), they are able to roughly double their performance to 1.10 on average. A processing head is a machine that has complex components; therefore, it requires proficiency to effectively operate it to its maximum potential. According to Gellerstedt (2002), an operator needs five years of experience to entirely master and be able to run a harvester head efficiently.

In addition to experience, the calibration is an important element in producing the desired log dimensions. Even though a processing head is designed to handle a heavy object (trees) in the field, the machine's accuracy could be compromised after a certain amount of usage. Therefore, it is important to keep the machine calibrated to ensure that the products are measured correctly. As reported by Nieuwenhuis and Dooley (2006), conducting harvester calibration regularly could reduce the difference between harvester measurements and manual measurements. Additionally, when a harvester is regularly calibrated, the accuracy of the volume of timber produced can be increased up to 6% (Dooley et al. 2006).

Harvester head is a technology that was developed in Scandinavian forestry to accommodate their logging practice, which has operated with CTL method to produce shortwood logs since the 1960s (Hakkila 1989; Björheden 1998; Harstela 1999). Along with ergonomic, environmental, and economic reasons, silvicultural management adopted by loggers in this region also contributed in the adaption of CTL operation. For example, the rotation period in Finland takes between 70 and 120 years which requires several thinning operations during one rotation period (Hakkila 1989). Therefore, CTL operation is more suitable to use due to less damage to remaining trees because CTL machine's size is smaller. This technology then was introduced in North America since this method can be used to harvest trees on a clear-cut, thinning and individual tree selection logging (Pulkki n. d.). Mostly, the use of a machine that has an automatic log measuring is intended to produce short logs.

Harvester heads are mostly used in areas where the harvesting operation produces short logs. In this type of logging operation, the subsequent process of transporting these logs to the roadside is conducted by a forwarder that is designed to load shortwood. Even the hauling process of transportation to the mill uses a tailored truck for short-bucked logs. On the other hand, the overall practice of harvesting in the South has long been performed using a skidder, and the existing truck transportation has also been designed to haul the TL materials. The southern loggers are still using current practices and equipment, and because of this, they are continuing to produce longer logs than what are produced in the area that usually use a harvester head. As this machine is normally used to buck shorter logs, there are concerns as to whether this machine would perform as it should when measuring longer logs.

Chapter 3. Methods

During the course of this study, we observed eight operations located in the Southeast US (Georgia, Louisiana, and Alabama) where the loggers used processing heads at the landing (Figure 2). Seven of the eight operations had only a single operator, with the remaining operation having two, bringing the total number of operators studied to nine. The observed machines (Figure 3) include the processing heads manufactured by Waratah (HTH 622B and HTH 623C) and Tigercat (575 Harvesting Heads). It should be noted that the results of this study are not intended to be a promotion of any manufacturer over another.

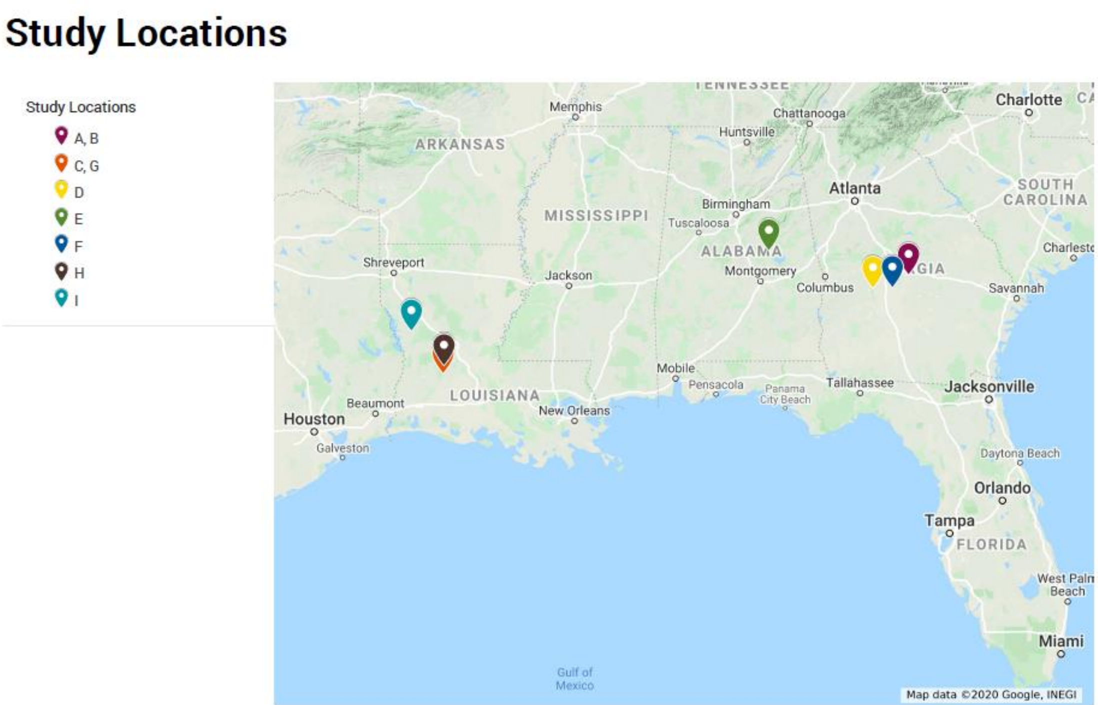


Figure 2. Study Locations

Logs were processed based on nearby mill specifications. The required sizes vary from mill to mill, but generally, the logs produced ranged from 16 to 49 feet in length. Few exceptions were found when the loggers decided to process longer logs ($\geq$ 50 feet) if the stems were straight and healthy and the top diameter met the minimum specification. Shorter logs (< 16 feet long) were also found as a result of defects on the stem. Additionally, the loggers usually provided a trim allowance of 3 inches (0.25 feet) to avoid downgrading to account for end injuries or uneven cuts. In terms of diameter, the loggers needed to cut the logs that were measured on their DOB. The smallest acceptable top diameter was 5 inches. For every operator, the aim was to collect data from 100 harvested trees. To maximize the observation, either for the processing heads' screen recording and the post measurement, the data was collected in every 25 trees; therefore, there were 4 groups of 25 trees each that were processed by each operator. However, this data collection grouping had nothing to do with statistical analysis.

Of the nine operators studied, two operators (E and I) were processing trees to a certain top diameter without length restriction whereas the remaining seven were processing the tree into bucked-to-length products. Even though they utilized a processing head, these two operators were not processing trees into bucked-to-length products as the market for their products did not require fixed lengths.

(a)

(b)

Figure 3. Images of processing heads used in the study: Waratah HTH 622B on a John Deere tracked loader (a) and Tigercat 575 Harvesting Heads (b)

To confirm the measurement accuracy, two types of measurements were gathered in this study. The processor's measurements were obtained by recording the processor's monitor inside the cab and were finalized by reviewing the recordings. Meanwhile, the researcher collected post measurements by measuring the length and dimeter of the logs using a caliper and cloth tape. The logs were numbered directly after they were cut by the machine, to keep them in order in the post measurement stage. The measurements collected in this research include the butt diameter, top diameter, and length of the logs. At the post-measurement, the diameter was measured as the inside-bark diameter.

In this study, measurement error was defined as the difference between the measurement by processing head and the result of manual measurement after the logs were processed. Positive measurement differences were the result of processing head overestimating the log's dimension from its actual size. On the other hand, measurement differences lower than zero were caused by an underestimated measurement by the processing head compared to the manual measurement of the logs.

$$Measurement\ difference = Processing\ head\ measurement - Post\ measurement$$

3.1 The Analysis of Processing Head's Measurement Accuracy

The tendency of measurements to systematically shift from the true value is known as bias (Stephanie 2013), while true value is defined as the actual value of an object that is obtained from a perfect measurement (Fuentes-Arderiu 2019). In this study, we hypothesized that the measurement differences between processing head's measurements and post measurements were equal to zero; therefore, we assume that the true value of the difference is 0. Then, the actual measurement differences that were obtained by subtracting the processing head's measurement to post measurements were evaluated statistically using z-test to understand their bias from zero. Meanwhile, precision is the measure of the variability (proximity or dispersion) of observed values to each other (Arachchige et al. 2019). In this study, descriptive statistics of every log dimension measured were used as the measure of variation to evaluate the precision of processing head measurements. The descriptive statistics used include range, interquartile range, mean, and standard deviation (Langley & Perrie 2015).

Accuracy is defined as the closeness of measurements of an object to its true value (Walther & Moore 2005), and determined by evaluating the bias and precision (ASTM International 2009). Combining bias and precision provides the information regarding the accuracy of an estimator or measurement. The more biased and the less precise an estimator is, the worse its overall ability to make an accurate point estimation.

3.2 Measurement Differences between Loggers

Log merchandizing in each operation in this study was performed by different loggers who work in the area. Each operation had their own operator who run the processing head. Therefore, in order to understand the significance of log measurement differences resulting from the effect of different operators, the data was grouped by operator and statistically analyzed. An analysis of variance was run on the entire dataset to assess the significance of measurement differences between the logging operations that were studied. The ANOVA test was followed by Fishers Least Significant Difference (LSD) test to compare the mean of measurement differences between loggers.

3.3 Correlation between Measurement Difference and Log Length

The third analysis conducted was to evaluate if the measurement differences increase as the length of logs that were measured using the processing head increase. A regression analysis was conducted to figure out the correlation between measurement differences and processing head measurements. In this analysis, log length measured by processing head’s measuring tool was the variables considered to contribute to the length measurement differences.

3.4 Statistical Methods

The data of processing head measurements and post-measurements were input to Excel spreadsheet and loaded into statistical packages. The measurement differences for length, butt diameter, and top diameter were analyzed for the mentioned statistical tests (z-test, descriptive statistics, ANOVA, and regression analysis) using R and JMP Statistical Software. In addition, a significance level of 0.05 was used to determine the significance of the tests.

Chapter 4. Results and Discussion

4.1 Measurement Differences

The study was conducted by observing nine operators in eight logging operations in the Southeast US (Georgia, Louisiana, and Alabama) who were utilizing processing heads to merchandize harvested trees into bucked logs. The study was designed to obtain an identical number of observations from each logger. However, due to several constraints, the total number of measurements gathered were different from logger to logger (Table 1). After removing incomplete data, the smallest number of data were obtained from Logger E, whereas data from the other eight operators were around 70 and above with the highest number of observations was found on the measurement of length from Logger F.

Table 1. Number of samples at each observation

Logger	Number of Samples		
	Length	Butt Diameter	Top Diameter
A	94	100	93
B	72	73	70
C	75	73	73
D	100	98	94
E	42	42	38
F	102	98	97
G	99	98	98
H	99	98	95
I	98	97	95
Total	781	777	753

The extreme lower data count at operation E was the result of not enough harvested trees at the time of the visit; only 42 trees were available to be processed and measured. The quality of video recording also became a factor that resulted in unusable data which in turn resulted in the loss of data from 1 group of trees at operation B. Another group of data from Logger C also was not obtained as a result of an inclement weather after the third group of harvested trees. Some constraints that resulted in omitting a small number of measurements was the difficulty at the time of post measurement. Logs were stacked on each other, which resulted in difficulty in reaching the logs on the bottom of the stack. In addition to stacked logs, another poor video recording occurred as a result of high vibration in the machine at the time of recording. This resulted in the loss of several processing head measurements. Meanwhile, the most number of data points were found on the length measurement from Operator F. He had prepared 100 harvested trees in 4 groups, some of which were processed into more than one log; therefore, we had 102 counts of length measurement data from this operator.

The different number of data of the three logs' dimensions were sometimes found from the same operator due to constraints we encountered in the field (e.g. stacked logs). We were able to collect measurements for length and butt diameter but had difficulties to reach the top diameter because it was below other logs. However, this discrepancy in the number of data does not mean that logs without all three dimensions were not included in the analysis of the dimension(s) that we had data for. These three dimensions were analyzed separately; therefore, having an unequal number of data for different dimension(s) is acceptable.

In spite of this variation of the number of data collected from each operation, the analysis of the difference of measurement errors between loggers was conducted with an ANOVA. Since the sample size of the lowest number of observations was more than 30, ANOVA was appropriate to use in order to understand the difference of measurement error for the nine operators studied (LaMorte 2016).

4.1.1 Length Measurement Differences

4.1.1.1 Length measurement accuracy

Maintaining the accuracy of processed logs in an operation where the buyer restricts the length of logs they purchase is very important. Poor measuring accuracy that resulted in over measuring or under measuring brought their own consequences. Loggers who produce lower log lengths than the mill's specification will be on the risk of downgrading and possible deduct. On the other hand, over measuring, which produces logs longer than they should, is also undesirable as the mill cannot efficiently use the additional wood.

After removing incomplete data, there were 781 collected observations of length measurements from nine operators. Overall, the processing head had a tendency to over measure the manual length measurements by 0.18 feet (Table 3). This meant that the actual length of logs were 0.18 feet shorter on average. The length measurement differences ranged from -10.17 to 11.66 feet where negative results signified that processing head measurements were shorter than manual measurement, whereas positive results indicated that measurements by processing were longer than the actual length of logs.

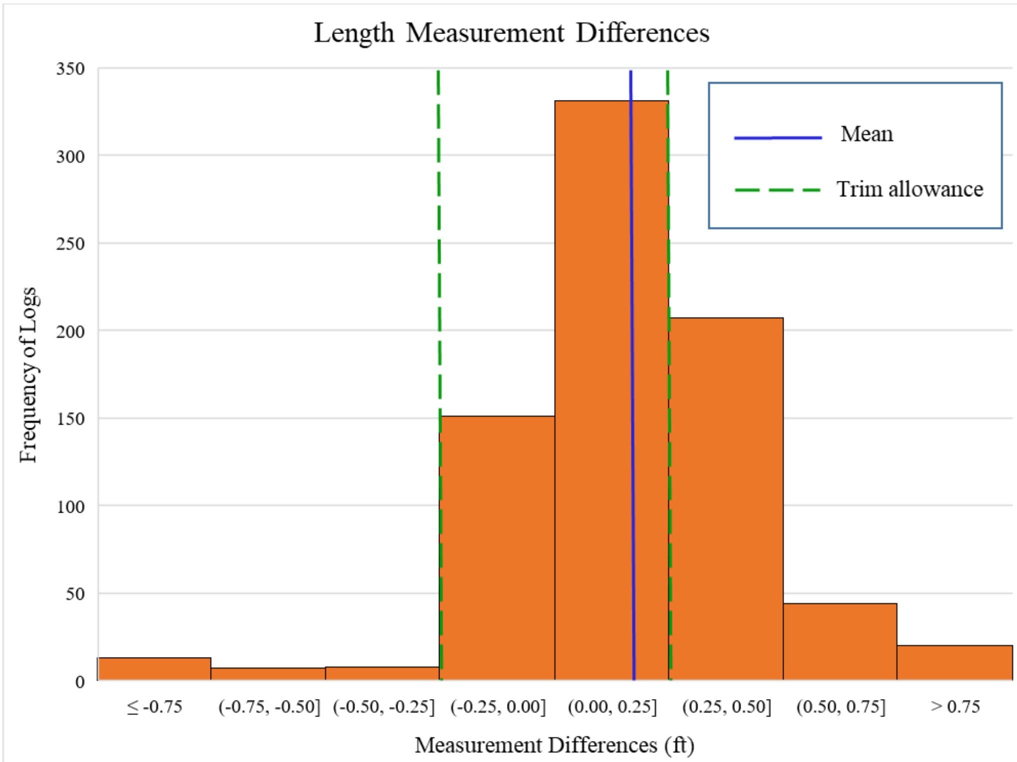


Figure 4. Data distribution of length measurement differences

Remarks:

- Mean of length measurement differences = 0.18 feet
- Logs that fell within length trim allowance (62% of produced logs) were acceptable
- Positive measurement difference signifies that processing head measurement is longer than post-measurement, and negative measurement difference suggests that processing head measurement is shorter than post-measurement

Trim allowance is used by log buyers and loggers in order to accommodate mismeasurements, uneven cuts, or defects. This allowance provides loggers with the flexibility that allows them to deliver logs even if these logs would fall outside of the exact length specification wanted by mills. With these allowances, merchandized logs were considered acceptable if they fall within a 0.25-foot window, either above or below the length specified by the buyers. Considering the concept of trim allowances defined above, the results of this study showed that the majority of the merchandized logs were within mills' specifications (Table 2). Of the logs produced in this study (n=781), it was found that most of the produced logs (62%) fell within this trim allowances window. Meanwhile, a very small percentage of produced logs were cut too short (3%), and the remaining 35% of produced logs were cut too long.

Table 2. The proportion of logs that were within and outside the trim allowance

Measurement differences (ft)	n	Percentage (%)	Remarks
< -0.25	28	3	outside the trim allowance
-0.25 to 0.25	482	62	within the trim allowance
> 0.25	271	35	outside the trim allowance
Total	781	100	

Having the log measured shorter could result in consequences. Loggers could face a downgrading of their products if they do not meet the minimum length required. Longer logs produced than the required size also brings disadvantages if there is no compensation for loggers for supplying longer logs than they should. However, these consequences would be different if the market has different approaches to compensate the loggers. In a market where loggers are compensated by the tonnage of wood delivered, producing longer logs than the required length would not be an issue as the extra length is still paid by the mills. If this is the case, then the results of this study which showed that 35% of produced logs were longer than the trim allowance would not be disadvantageous to the loggers.

It should be noted that, while in the process of collecting the data for this study, the researcher was only able to collect post measurements to the nearest 0.10 of a foot, whereas the trim allowance is 0.25 feet (3 inches). Therefore, the exact 0.25 or -0.25 feet differences could not be completely recognized. In order to account for this, when the researcher encountered a 0.25-foot measurement difference in the data points, the number of logs that have this amount of mismeasurement will be divided into two, where half were considered as within trim allowance and the others were considered outside trim allowance.

Table 3 shows the analysis of bias and precision to find the accuracy of processing heads in measuring the length of logs. The Z-test that was run to understand the accuracy of the length measurement differences resulted in a p-value < 0.001. Meanwhile, the precision of measurement differences is explained by the descriptive statistics shown in Table 3. With a mean of 0.18 feet, the differences in length measurement varied from -10.17 to 11.66 feet resulted in a range of 21.82 feet. In addition, the standard deviation (1.23 feet) of the dataset was larger than its mean. This indicates that there is a high variation in the length measurement differences. A higher standard deviation is also an indication that the data points were highly dispersed around the mean. The lower quartile of length measurement differences was 0.03 feet, and the upper quartile was 0.31 feet resulted in an interquartile range (IQR) of 0.28 feet. This means that 50% of length measurement difference data points were found between 0.03 and 0.31 feet. The analysis of precision, through analysis of the descriptive statistics, suggested that processing heads’ measuring tools gave low precision in measuring the length of logs as data points of measurement differences were highly dispersed around the mean, though the majority of produced logs fell within the trim allowance.

Table 3. Analysis of length measurement accuracy (bias & precision)

n		781
Collected Measurements		
	Processing head measurements (ft)	34.22
	Post-measurement (ft)	34.03
Descriptive Statistic of Measurement Differences		
	Mean (ft)	0.18
	SD (ft)	1.23
	Std Error (ft)	0.04
	Variance (ft^2)	1.52
	Minimum (ft)	-10.17
	Maximum (ft)	11.66
	Range (ft)	21.82
	1st Quartile (ft)	0.03
	Median (ft)	0.17
	3rd Quartile (ft)	0.31
Z-test of Length Measurement Differences		
	p-value	< 0.001*

Remarks: * significant at 95%

4.1.1.2 Length measurement differences between loggers

Loggers tended to overestimate the length of logs they processed (Table 4). Processing heads from seven loggers were showing higher length measurement readings compared to the manual measurements, which meant that the logs' actual lengths were shorter than processing head measurements. Meanwhile, Logger G and C were the only loggers who produced longer manual length measurements compared to the length estimated by the measuring tool of the machine (0.05 feet and 0.34 feet respectively).

Table 4. Summary of Length Measurement Differences for All Loggers

Logger	n	Mean	Std Error
A	94	0.10	0.13
B	72	0.18	0.14
C	75	-0.34	0.14
D	100	0.22	0.12
E	42	0.68	0.19
F	102	0.17	0.12
G	99	-0.05	0.12
H	99	0.39	0.12
I	98	0.46	0.12

From the table above it can be seen that the highest overestimation was found on logs processed by Loggers E, I, and H. Processing head measurements at these operations tended to overestimate the length of logs by 0.68, 0.46, and 0.39 feet on average respectively. This result means that the actual length of logs measured after they were processed were shorter by 0. 68, 0.46, and 0.39 feet. Meanwhile, the smallest overestimation was found with Logger A. The processing head length measurements were slightly longer than the post length measurements, which resulted in an average of measurement differences of 0.10 feet.

The comparison of measurement differences between loggers in this study is depicted in Figure 5. The high length measurement overestimation by Logger E who possessed 1 month of experience was not significantly different from the overestimation of the length measurement logs produced by H (60 months of experience) and Logger I (6 months experience). In addition, the underestimation of length measurement by Logger C (1 month of experience) was not significantly different from the underestimation of length measurements by Logger G (24 months of experience). The performance of length measurement of the least experienced operators (C and E) was only significantly different from the performance of operator A (24 months of experience), operator B (192 months of experience), operator D (30 months of experience), and operator F (30 months of experience). In terms of length measurement, experience proved to be a factor in providing measurements that were equal to manual measurements. Although the statistical analysis shows a non-significant result with some operators that had more experience, the least experienced operators (C and E) were found to provide the least favorable length measurements.

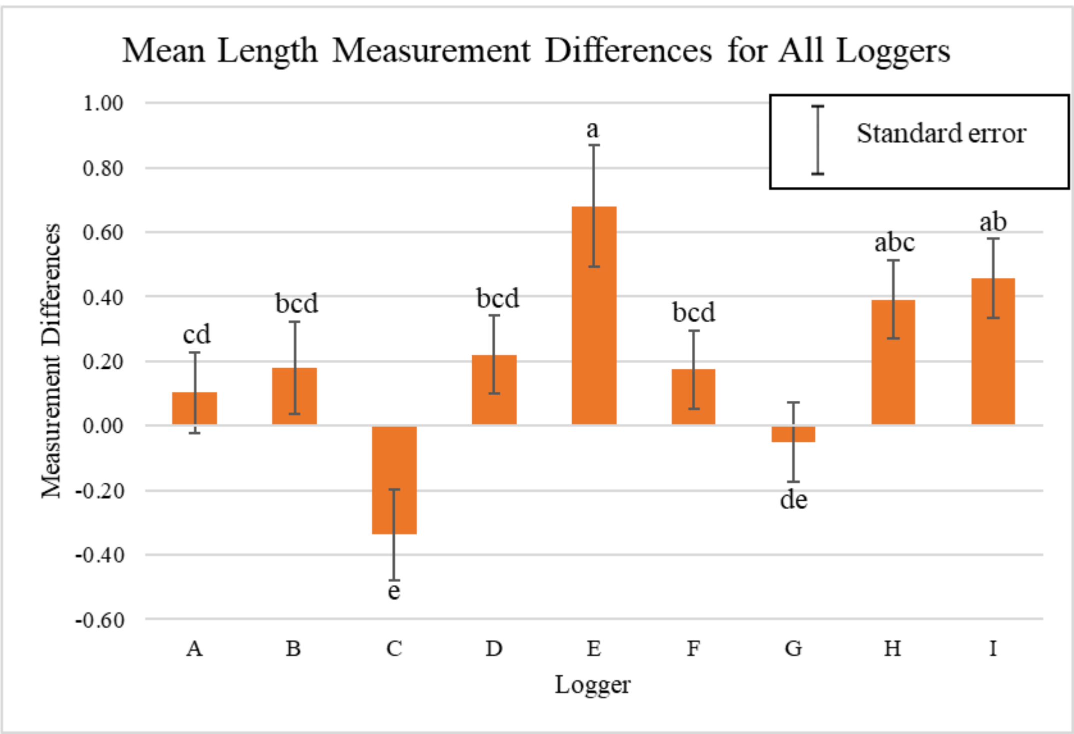


Figure 5. Mean length measurement difference (ft) comparisons between loggers

Remarks: Means of measurement differences followed by the same lowercase letter are not significantly different at $P < 0.05$

This study revealed that logs produced by Logger G and C were longer than what the machine measured. The average length of processed logs was underestimated by these loggers; therefore, the actual length of the logs was 0.05 and 0.34 feet longer respectively. However, loggers are usually provided trim allowance where the logs are still acceptable if they are below or over 0.25 feet of the mill's specified length. This trim allowance has allowed more loggers to be able to provide logs with the appropriate lengths to the mills.

4.1.1.3 Factors contributing to length measurement differences

Several factors contributed to the differences in length between the processing heads' measuring tools and post measurements. The first of these was that the shape of the logs contributed to the differences between these two measurements. Crooked logs (Figure 6 (a), (b)) would provide a longer processing head measurement. This was because as the machine processed the stem, it followed the shape of the log. However, the post-measurement, which was measured horizontally with a measuring tape from one end of the crooked log to the other, resulted in a shorter length measurement as compared to the processing heads' measurements which measured along the surface of the log. On the other hand, straight stem (Figure 6 (c)) would likely result in similar output between processing head measurement and post-measurement.

(a)

(b)

(c)

Figure 6. Crooked stem that was processed by a processing head (a), post measurements of crooked (b) and straight stems (c)

During the data collection process, it was observed that some of the loggers did not start to process logs from the butt of the stem. As the processing head grabbed the stem, these operators did not run the machine from the butt. Rather, without considering the untouched part of the stem, they directly ran the stem through the machine. There were also instances in which they used the electronic eye in the machine to estimate the length of the untouched part of the stem. This resulted in shorter length readings by the processing heads. These measurement differences could have been anticipated by the loggers by bucking the butt, which would mitigate the degree of differences for both measurements but it would have taken more time to process. Despite the potential benefits of using an electronic eye to assist in length measurement, there are certain situations where using an electronic eye could result in measurement errors. The working conditions at the landing might not be conducive to use this technology effectively. There could be dirt or debris that interferes with the electronic eye's capability to accurately measure log length. In addition, in rainy conditions, the loggers are usually still working, but there is the chance that raindrops could interfere with the electronic eye performance.

The removal of knots and limbs might also contribute to the measurement differences. Depending on the size of the knots and limbs, a processing head may require multiple passes to be able to completely remove them. In this case, there could be errors in the measurement as the machine makes multiple passes over the stem. In addition, unremoved knots can cause a loss of traction between the measuring wheel and the log's surface. In order to ensure that a proper measurement is obtained from a processing head, it is of the highest importance that proper traction between the measuring wheel and stem is maintained.

4.1.2 Butt Diameter Measurement Differences

4.1.2.1 Butt diameter measurement accuracy

In a modified tree-length operation, another concern is the size of the logs’ butt diameter. The size of a log’s butt diameter will be one of the determining factors that decides to which market it may go. Therefore, to provide a correct butt diameter measurement, it is important to analyze and evaluate the performance of a processing head when it measures butt diameter and to understand the factors contributing to its performance, so that it can assist the logger appropriately in merchandizing activity.

The data distribution of butt diameter measurement differences can be seen in Figure 7. This figure depicts 777 observations of butt diameter measurement differences after removing incomplete data. On average, the machine measurements were 0.71 inches smaller than their actual diameter measurements, with values ranging from -18.90 to 5.50 inches. Negative results indicated that processing head measurements were smaller than the actual diameter, and positive measurement differences represented higher processing head measurements compared to post measurements.

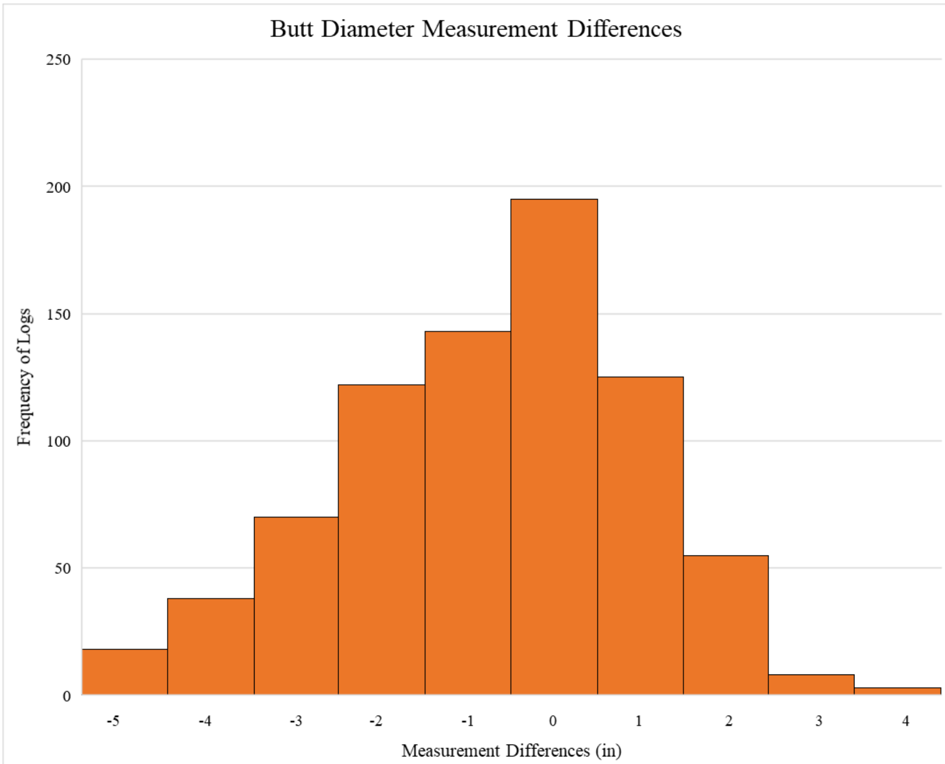


Figure 7. Data distribution of butt measurement differences

Remarks:

- Mean of butt diameter measurement differences = -0.71 inches
- Positive measurement difference signifies that processing head measurement is larger than post-measurement, and negative measurement difference suggests that processing head measurement is smaller than post-measurement

Similar to length measurement, there was another limitation encountered in measuring logs' diameter after they were processed. At the post-measurement, the log's diameter was collected to the nearest 0.5 of an inch, whereas the processing heads were able to obtain diameter measurements to the nearest 0.1 of an inch of every processed log. Therefore, in this study, the measurement differences found between -0.5 and 0.5 inches were considered equal to 0, which means that the processing head measurements were equal to the post-measurements.

In all operations observed in this study, the majority of the processing heads' measurements have smaller butt diameter readings by processing heads compared to the actual diameter size (Table 5). Of these observations of 777 logs, half (50%) were measured smaller than their actual measurements. Meanwhile, of the observed data, equal readings and bigger butt diameter readings from the processing heads showed a proportion of 25% each.

Table 5. The proportion of logs that fell between 0.5 inches of diameter measurement differences

Measurement differences (in)	n	Percentage (%)
$x \leq -0.5$	391	50
$-0.5 < x \leq 0.5$	195	25
$x > 0.5$	191	25
Total	777	100

Remarks: x = Butt diameter measurement differences

The analysis of bias and precision of processing heads' measurements was presented in Table 6. The analysis of the former was using a z-test and resulted in a p-value of < 0.001. This meant that processing heads showed bias in measuring butt diameter. Meanwhile, the precision analysis of butt diameter measurement differences can be explained by the descriptive statistics on the table. The butt diameter measurement difference between processing head and manual measurements had 24.40 inches of range from -18.90 to 5.50 inches. The first quartile of data points was at -1.80 inches and the third quartile was at 0.50 feet. This means that half of the observed measurement differences were found between -1.80 and 0.50 feet. In addition, with a mean of -0.71 feet, the data set had 1.87 feet of standard deviations. These descriptive statistics explain that there is a high variation in the dataset. Therefore, the precision analysis suggested that the processing heads' measuring tool gave low precision in measuring the diameter of logs as data points of measurement differences are highly dispersed around the mean.

Table 6. Analysis of butt diameter measurement accuracy (bias & precision)

n		777
Collected Measurements		
	Processing head measurements (in)	12.91
	Post-measurement (in)	13.63
Descriptive Statistic of Measurement Differences		
	Mean (in)	-0.71
	SD (in)	1.87
	Std Error (in)	0.07
	Variance (in^2)	3.48
	Minimum (in)	-18.90
	Maximum (in)	5.50
	Range (in)	24.40
	1st Quantile (in)	-1.80
	Median (in)	-0.50
	3rd Quantile (in)	0.50
Z-test of Measurement Differences		
	p-value	< 0.001***

Remarks: *** significant at 95%

4.1.2.2 Butt diameter measurement differences between loggers

Overall, the measuring tool of processing heads tended to have smaller butt diameter measurements. Exceptions were found on three loggers (Table 7). Loggers A, B, and D had higher average processing heads' butt diameter measurements than their manual measurements. It was also found that there were four loggers identified as having butt diameter measurement differences of less than 1 inch, whether they were positive or negative (Loggers B, D, E, and F). The biggest under measurement was found with Logger I, where the machine measured the butt diameter 2.20 inches smaller on average. Meanwhile, butt measurement differences that were closest to zero were observed with Logger B, wherein the machine measured butt diameter for 0.41 inches larger than the actual size, on average.

Table 7. Summary of Butt Diameter Measurement Differences for All Loggers

Logger	n	Mean	Std Error
A	100	1.13	0.15
B	73	0.41	0.17
C	73	-1.67	0.17
D	98	0.63	0.15
E	42	-0.74	0.23
F	98	-0.70	0.15
G	98	-1.68	0.15
H	98	-1.61	0.15
I	97	-2.20	0.15

Figure 8 shows the comparison of measurement differences between loggers. The highest mismeasurements of butt diameter size were shown by Logger I with 6 months of experience, and it is significantly different from the measurement difference from the other eight loggers in the study. On the other hand, one of the least experienced operators (C) showed non-significant butt diameter measurement differences with two other loggers who had higher amounts of experience (G and H). Similarly with Logger C, Logger E, who also only had 1 month of experience, revealed non-significant measurement differences of butt diameter with logger F that had 30 months of experience. Meanwhile, loggers with a similar amount of experience (A, D, F, and G) were showing significant differences in butt diameter measurement differences with each other. This result suggests that the operator’s experience did not contribute to butt diameter measurement performance using processing heads. Instead, the performance of butt diameter measurement might be a result of how an operator merchandizes logs (e.g. start processing a tree from the butt end of a stem).

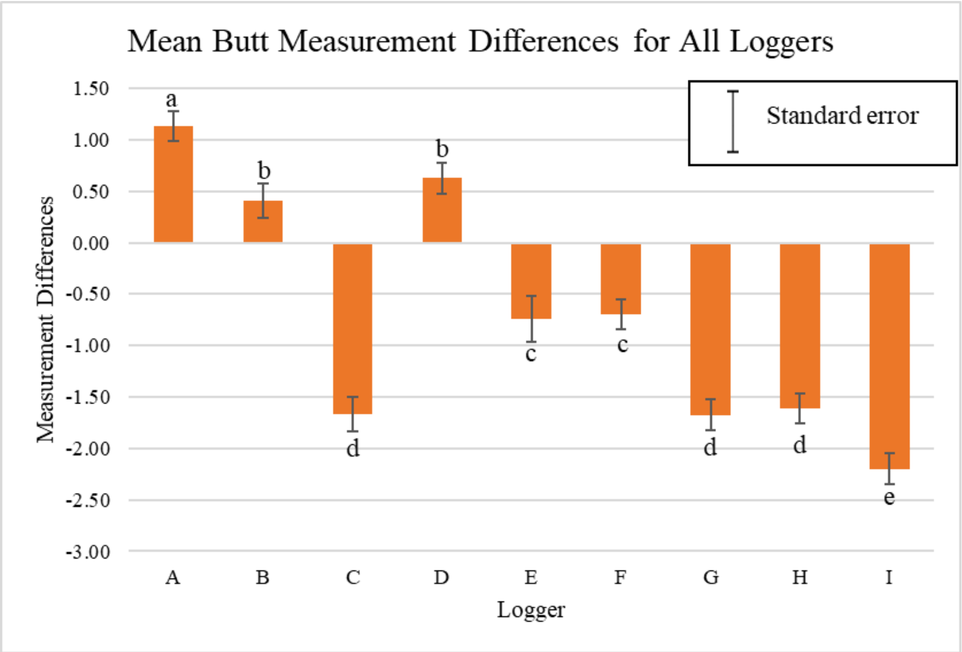
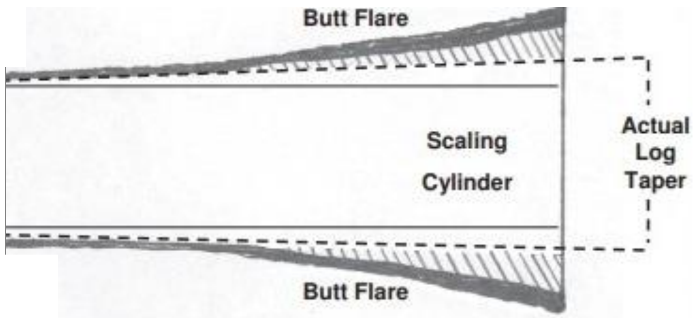


Figure 8. Mean butt diameter measurement difference (in) comparisons between loggers

Remarks: Means of measurement differences followed by the same lowercase letter are not significantly different at $P < 0.05$

4.1.2.3 Factors contributing to butt diameter measurement differences

It is important to note the exact part of logs measured, especially for the butt diameter measurement. At the beginning of processing a tree, a processing head grabs the tree where the arms and feed rollers pick the stem several feet from the butt. Often, when the operator considers that the stem is healthy and without defects, a jump butt is not performed. Therefore, the measurement of butt diameter is made a few feet from the butt, and any butt swell is still intact (Figure 9 (a), (b), (c)). Meanwhile, the post measurement was taken by using a caliper on the butt of each log. This situation contributed to smaller processing heads' butt diameter measurements. Measurements conducted by the processing head were located on the round area of the log, whereas post measurements were measuring the average of the flared butt area (Figure 9 (b), (c)).



(a)

(b)

(c)

Figure 9. Visualization of butt flare (Lowell 2010) (a), Logs with butt flare in the study (b), (c)

Even when a jump butt was performed, the position where the machine measures the log's diameter was different from the position where the post-measurement was taken. Diameter size is estimated by a potentiometer that takes measurements from how wide the feeding wheels open when holding a tree (Figure 10). These feeding wheels are located around 3 feet from the saw that is used to trim the butt, which means that the processing head's diameter reading was taken 3 feet from the butt end. Meanwhile, post measurements were taken from the butt end of each log. As expected, different results of diameter measurement could be encountered due to this difference in measurement location on the log.

Figure 10. Waratah HTH622B that depicts the location of trimming saw and feed wheels (Waratah n. d.)

On the other hand, a result of higher processing head reading is also possible. The measuring tool in the processing head is likely to measure a log on its DOB as the bark on the butt of the logs was intact from the processing head's debarking tools (arms and feed rollers). Even when the stem is bucked to remove butt flare or defects, the bark would likely remain on the butt area since the bottom area of the logs has only the initial contact with the processing head (Figure 11). Multiple passes are only required when the loggers need to remove the knots and limbs, which are typically located near the end of the tree. While the processing head measures DOB, the manual measurement was designed to determine the DIB of a log. Therefore, the intact bark provides higher butt diameter readings from the processing head when compared to post butt diameter measurements.

Figure 11. Bucked defects/butt flare with bark remains on the stem

However, some logs were found with removed bark on the butt area. This is because there were incidents when a log was subjected to multiple passes. These happened when an operator started to merchandized a log and then encountered large limbs or knots on the way to the top of the log. This sometimes resulted in an incorrect length measurement, an error that loggers want to avoid. Therefore, the operator would need to return the processing head to the butt part of the log in order to obtain a better length measurement. Being exposed to processing head arms and feed wheels for more than one pass results in a considerable amount of removed bark.

From the data collected in this study, the average of butt diameter measured by the processing head was 12.91 inches. Therefore, it was expected to see a difference of approximately 0.9 inches between processing head and manual measurement (Table 8). Henceforth, the expected post measurement should be 12.01 inches. However, the results from this study showed that the average post measurement butt diameter of the logs was 13.63 inches, which was higher than the expected post measurement from the literature. Most of these larger processing head diameter readings can be attributed to butt swell.

Table 8. Loblolly pine bark thickness

Tree dbh		Single bark thickness	
cm	in	cm	in
10	3.94	1	0.39
15-20	5.91-7.87	1.3	0.51
25-30	9.84-11.81	2	0.79
35-40	13.78-15.75	2.3	0.91
45-50	17.72-19.69	2.5	0.98
60	23.62	3	1.18
75	29.53	3.8	1.50
90	35.43	4.3	1.69

Source: (Schultz 1997)

Another measurement difference came from the shape of logs that were not perfectly round. Given that a log may have an irregular shape, there are potential difficulties in ascertaining an objectively accurate measurement from the processing head because this measurement may differ depending on where the processing head holds the log. Meanwhile, the post measurement was tailored to take the average diameter by taking two readings. This situation could result in either lower or higher diameter readings, depending on which part of the diameter the machine measured (Figure 12).

Figure 12. Two different diameter readings from the same log

4.1.3 Top Diameter Measurement Differences

4.1.3.1 Top diameter measurement accuracy

Sawmills have an optimization system that is able to maximize sawing classes by using the top diameter as the control (Lundahl & Grönlund 2010). Therefore, in addition to specified length of logs, top diameter is another dimension of logs that is needed to be a certain size in order to meet the mill's requirements. In this study, generally, the loggers were required to supply logs with a minimum top diameter of 5 to 8 inches, depending on the market.

Figure 13 depicts the data distribution of top diameter measurement differences from 765 observations, where diameter measurement differences ranged from -6.10 to 6.60 inches. The data showed an approximately normal distribution with an average of measurement differences of 0.55 inches (Table 10). Similar with butt diameter, negative measurement differences showed a smaller processing head measurement compared to manual measurement, and positive results revealed a higher processing head measurement than their actual diameter size. Therefore, the processing heads were measuring top diameter of logs 0.55 inches larger than their actual size on average.

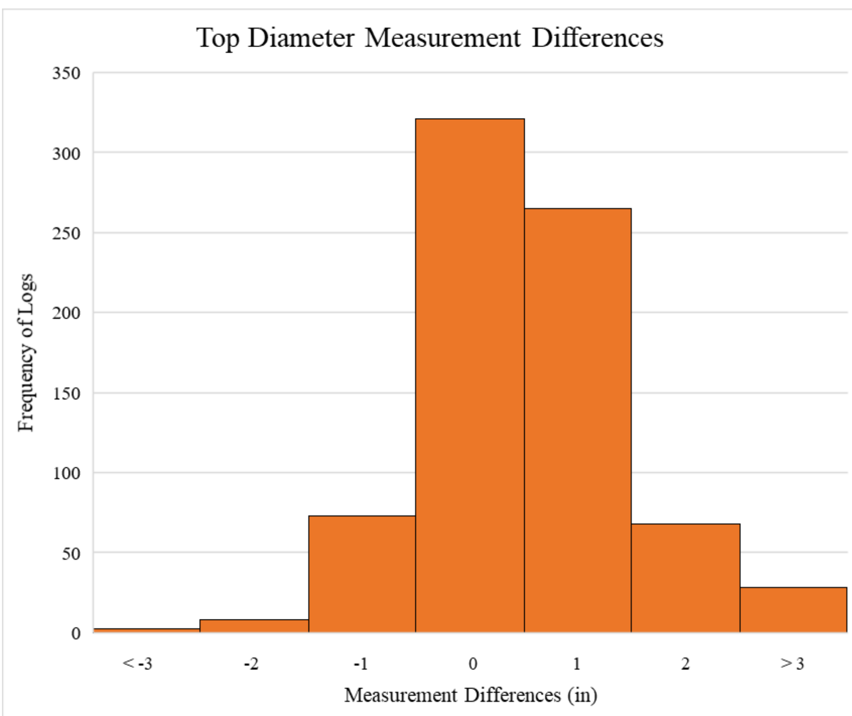


Figure 13. Data distribution of top measurement differences

Remarks:

- Mean of butt diameter measurement differences = 0.55 inches
- Positive measurement difference signifies that processing head measurement is larger than post-measurement, and negative measurement difference suggests that processing head measurement is smaller than post-measurement

Unlike the butt measurement overall result, the processing head measurement of the log's top diameter was mostly smaller than its post-measurement for all observed data (Table 9). The larger processing head readings were found on 47% out of 765 observations. It was found that there was an improvement in measuring the top diameter. The measurement differences that were considered equal to 0 were found on 42% of the total logs measured. Meanwhile, only 11% of the observed data were measured smaller by processing head than their actual size.

Table 9. The proportion of logs that fell between 0.5 inches of diameter measurement differences

Measurement differences (in)	n	Percentage (%)
$x \leq -0.5$	83	11
$-0.5 < x \leq 0.5$	321	42
$x > 0.5$	361	47
Total	765	100

Remarks: x = Top diameter measurement differences

Bias and precision analysis of measurement differences between processing head and post-measurements are presented in Table 10. A z-test was conducted to determine the significance of measurement differences from zero, and it resulted in a p-value of < 0.001, representing a biased top diameter measurement of the processing heads' measuring tool. In addition to bias analysis, summary statistics were used to evaluate the precision test processing heads' measuring ability. The data points of top measurement differences dispersed from -6.10 to 6.60 inches resulted in a range of 12.70 inches. Half of the observations were found between -0.10 inches (first quartile = -0.10 inches) and 1.00 inch (third quartile = 1.00 inch). Furthermore, the average of measurement differences of top diameter was 0.55 inches with 0.97 inches of standard deviation. These summary statistics indicated a very high variability; henceforth, the precision of processing heads was very low in measuring logs' top diameter.

Therefore, the analysis of bias and accuracy of the processing heads' measuring tool show low measurement accuracy.

Table 10. Analysis of top diameter measurement accuracy (bias & precision)

n		765
Collected Measurements		
	Processing head measurements (in)	9.16
	Post-measurement (in)	8.61
Descriptive Statistic of Measurement Differences		
	Mean (in)	0.55
	SD (in)	0.97
	Std Error (in)	0.04
	Variance (in2)	0.95
	Minimum (in)	-6.10
	Maximum (in)	6.60
	Range (in)	12.70
	1st Quantile (in)	-0.10
	Median (in)	0.50
	3rd Quantile (in)	1.00
Z-test of Measurement Differences		
	p-value	< 0.001***

Remarks: *** significant at 95%

4.1.3.2 Top diameter measurement differences between loggers

When merchandizing logs, processing heads' measuring tools from the nine operators studied tended to have a larger reading in measuring logs' top diameter compared to its actual value. There were six loggers (B, C, D, E, F, and H) that were identified to have larger processing heads' measurement readings of less than 1 inch. Meanwhile, the processing heads for two other loggers (A and G) had larger top diameter measurements of more than 1 inch on average. The remaining logger (I), was the exception as the only logger to have a smaller processing head measurement than the actual value, being on average 0.19 inches smaller (Table 11).

Table 11. Summary of Top Diameter Measurement Differences for All Loggers

Logger	n	Mean	Std Error
A	93	1.49	0.09
B	72	0.47	0.10
C	73	0.22	0.10
D	95	0.94	0.08
E	40	0.22	0.13
F	97	0.28	0.08
G	98	1.06	0.08
H	99	0.21	0.08
I	98	-0.19	0.08

The comparison of measurement differences between loggers in this study is shown in Figure 14. The highest top diameter measurement difference was shown by Logger A (24 months of experience), and it is significantly different from the results of top measurement differences from other loggers in the study. Similarly, Logger I (6 months of experience), the only operator who measured logs' diameter smaller than the actual diameter, showed a significant mean of top diameter measurement differences from the mean of top diameter measurement differences from other loggers. Meanwhile, the means of top diameter measurement differences from the least experienced operators (C and E) were not significantly different from the means of top diameter measurement from operators with more experience (Operator B, D, F, G, and H). This result suggests that the operators’ experience did not have any effect on the performance to measure log’s top diameter.

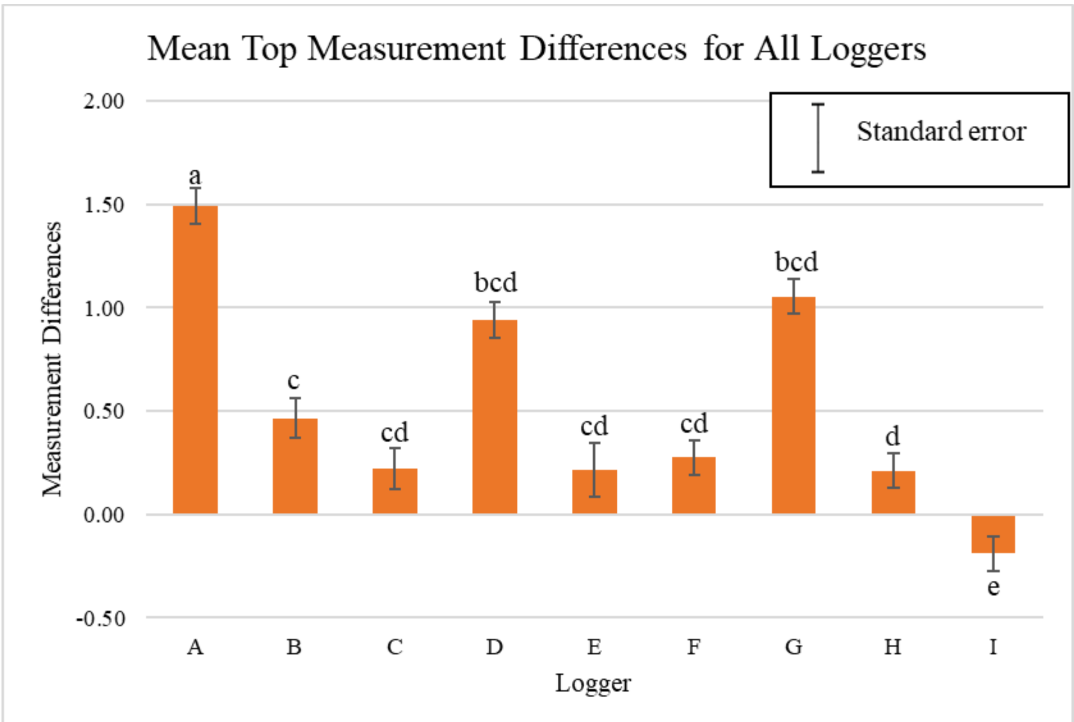


Figure 14. Mean top diameter measurement difference (in) comparisons between loggers
Remarks: Means of measurement differences followed by the same lowercase letter are not significantly different at $P < 0.05$

4.1.3.3 Factors contributing to top diameter measurement differences

The results of the measurement differences between processing head and manual measurement study showed an overall higher top diameter measurement by processing head, which suggested that the actual diameters were smaller than the processing heads' readings. The presence of knots in the top diameter would result in similar consequences as would be expected with the presence of butt flare in the butt diameter. As the location of both measurements on a log are different, the sizes of diameter obtained were different. A higher processing heads' diameter measurement is possible due to the presence of knots. This would be the case when the section of the log that has knots is measured by the machine, whereas the post measurement was conducted on the round part of the log.

On the other hand, the presence of knots could also result in a larger manual top diameter measurement compared to the processing heads' reading. Knots result in an irregular shape of the top diameter (Figure 15) that results in a different outcome between processing heads and manual measurements. The result of manual measurements were obtained by aggregating two top diameter measurements, whereas the processing heads' top diameter reading might be conducted on a perfectly round section of the log. Therefore, it is likely to see a smaller diameter reading by processing heads.

Figure 15. Knots on the section of a log where post measurement was taken

Processing heads are equipped with two saws, one at each end of the head. The butt part of the log is always processed with the bottom saw, while the log's top can be processed using either saw. During data collection, we did not consider recording which saw the operator used when processing harvested trees, and whether diameter readings were adjusted by the machine to measure the top ends of logs when the operator uses the top saw to cut logs' tops. This could be a factor that resulted in the processing head providing different top diameter measurements compared to post-measurements.

Contrary to butt diameter, the top diameter is exposed to the processing head's arms and feed rollers, which results in an effective debarking while it processes a harvested tree. Without bark remains on the stem, the measuring tool estimates the DIB instead of DOB. Therefore, processing head measurement and post measurement were measuring the same dimension of the log, which ideally results in similar measurement outcomes. Consequently, this results in measurement differences that were close to zero. The results from this study found that the number of logs that had zero measurement differences of top diameter (n=321 or 42% of the total observation) was higher than butt diameter (n=195 or 25% of the total observation). Having the bark removed could increase the accuracy of processing heads' measuring tool.

Even though the top section of logs were mostly exposed to the debarking tools of a processing head, we still found many produced logs that had bark remaining (Figure 16). For many of the logs in this study, the processing head measures their DOB; whereas the post measurement measured their DIB, as described in the methods section of the study. Therefore, higher measurement readings by processing heads were also explained by the unpulled bark from the stem.


Figure 16. Merchandized logs with remaining bark at top diameter

4.2 Operators Experience

Differences of measurement between nine processing head operators in eight logging operations were compared. These measurement differences included three different dimensions of a log (length, butt diameter and top diameter). These nine operators were different in terms of the amount of experience each operator had in running a processing head (Table 12). As suggested by Purfürst (2010), an operator requires a certain amount of time to be able to run a forestry machine until proficiency is obtained. Theoretically, this should also apply to the operator of processing heads. In fact, operating processing heads are relatively more arduous compared to other forestry machines such as a knuckle boom loader. Sophisticated components of the head and the computer program, as well as the intricate joystick and buttons, require a certain period for an operator to be conversant with the whole part of a processing head, and then be able to effectively operate it to its maximum potential.

Table 12. The amount of experience of each operator

Logger	Operator's experience
A	24 months
B	192 months
C	1 month
D	30 months
E	1 month
F	30 months
G	24 months
H	60 months
I	6 months

Generally speaking, of the three log dimensions measured, the study revealed that the best results of measurements were achieved by Operator F, who had 30 months of experience operating a processing head. The average length of logs produced by this operator was mismeasured by 0.17 feet longer than the actual length. In addition, this operator's measurement of logs' butt diameter was 0.70 inches smaller than their actual size, and the logs' top diameter was measured 0.28 inches larger than their actual size. With the same 30 months of experience, Operator D also produced better measurements as compared to all operators, excluding Operator F. Length, butt diameter, and top diameter measurements of logs from Operator D were off by 0.22 feet, 0.63 inches, and 0.94 inches respectively, where all of these log dimensions were over measured by the processing head. On the other hand, operator I (6 months of experience) displayed the least favorable measurement of length (0.46 feet) and butt diameter (-2.20 inches), whereas the highest top diameter mismeasurements were presented by Operator A (24 months of experience) with a result of 1.49 inches of measurement difference. This high variation in measuring performance suggests that regardless of the experience, the performance of merchandizing logs is not necessarily related to the operator's experience. However, it should be noted that production performance of these operator was not addressed by this study.

The multiple comparison analysis of measurement accuracy between loggers for all three dimensions suggests that the only significant difference of the least experienced operator was only found on the length measurement dimension. Operators C and E resulted in significantly different length measurement differences from the other loggers. Meanwhile, the analysis shows that there is no significant difference in the performance of measuring diameter (butt and top) regardless of the amount of experience. Instead, the difference of measurement performance of butt diameter was found to be significant among loggers with the same amount of experience (A, D, F, and G). This result could be attributed to the shape of logs (e.g. butt flare) and the practice conducted by the loggers when merchandizing trees, such as not processing trees from the butt of the log. In regards to the top diameter, experience also did not result in a statistical significance of measuring performance. The performance of loggers with the least experience (C and E) was not statistically different with the most experienced operator (B) and with several other loggers with more experience (D, F, G, and H).

4.3 Overall Accuracy Analysis

The results of processing heads' accuracy analysis, obtained by analyzing the bias and precision of measurement difference for all of the logs' dimensions (length, butt diameter, and top diameter), showed similar results. The results of the bias analysis suggested that the processing heads had a bias in measuring the logs and the precision analysis showed a very low precision of processing heads' measuring ability for all log's dimensions. This result was obtained due to the high variability of collected data in the operations studied.

The study was conducted in various locations and consisting of nine different personnel to operate the machine. Not only can the variability of measurement differences be very high in one logging operation, but combining data from nine operators into one analysis also made the data variability even higher. That was because some loggers were overestimating the measurement of a log's dimension, but other loggers were underestimating the same dimension. Therefore, the data points of measurement differences from all operations were highly dispersed around the ideal mean of measurement differences (0) resulting in a bias measurements and very low precision.

In this study, the imprecision of log measurements by processing heads was different for each of the log's dimensions. Length and top diameter measurements from operators utilizing processing heads tended to result in higher readings compared to their actual size; whereas processing heads' measurement of butt diameter tended to result in smaller measurement values compared to their actual bottom diameter measurements. With regards to diameter measurements, it was found that processing heads gave a better reading for top diameter (0.55

inches) than butt diameter (0.71 inches). As explained in each section of the measured log dimensions, it was observed that, for some logs, the processing heads were not in contact with the exact butt part of the log when a jump butt was not required. However, for the top diameter measurement the machines were always in contact with this part of the log, as they needed to trim the top. This explains why the top diameter measurements by processing head were more accurate than the butt diameter measurements by processing head relative to their actual measurements.

4.4 Log Length and Length Measurement Differences Relationship

To assess the interaction between the measurement difference and the length of the processed log, a regression model was developed. The regression analysis resulted in:

$$y = -0.468 + 0.019x$$

$$R\text{-squared} = 0.03,\ p\text{-value} < 0.001^*$$

Where: y = Length measurement difference (ft),
x = Processing head length measurement, and
* significant at 95%

Table 13. ANOVA table of regression model for length measurement differences

Coefficients	Estimate	Std. Error	t value	p-value
(Intercept)	-0.468	0.138	-3.393	0.0007*
x	0.019	0.004	4.983	<0.001*

Remarks: * significant at 95%

The resulting regression model revealed that there was a positive relationship between measurement difference and log length. As the length of processed logs increased, so did the measurement differences. However, this regression model resulted in an R-squared of 3%; this means that the length of processed logs explained only 3% of the total variation in length measurement differences in the model. Although the R-squared is very low, the size of processed logs that were measured by processing heads still provides a statistically significant explanatory power to the length measurement differences (Table 13).

Chapter 5. Conclusion

Modification of tree-length operation by adding a processing head to buck the tree to size is expected to eliminate the operator's subjectivity as this machine is equipped with a computerized optimization system to effectively measure the length and diameter of a log. The effectiveness of utilizing this machine in measuring the length and diameter of logs was evaluated in this study.

Accuracy of processing head measurement was evaluated by analyzing the bias and precision of measurement differences for each log dimension (length, butt diameter, and top diameter). The result of log merchandizing from nine logging operators showed that the processing heads resulted in biased measurements and very low precision in measuring length, butt diameter, and top diameter. Processing heads' tendency to mismeasure length and top diameter were similar, where processing heads provided higher readings compare to their actual measurements. However, the processing heads tended to give a smaller measurements of butt diameter compared to the actual measurements.

The result of length measurement differences showed that 62% of the observed data were produced within typical mill trim allowance. In addition, processing heads were found to give better performance in measuring top diameter (0.55 inches of overall measurement differences) than butt diameter (0.71 inches of overall measurement differences). Additionally, the data shows that the comparison between machine and manual measurements was similar in 25% of butt diameter observations, whereas 42% of top diameter observations were similar.

With regard to the length contribution to the measurement difference, it was found that there is a positive correlation. As the length of long increased, the measurement difference also increased. The regression model shows that the length of processed logs accounts for only 3% of the total variation in length measurement differences with processing head length measurements as a variable that contributes significantly to the measurement differences.

Looking forward to future research on this topic, there are three possible approaches to improving the result of this study. The first of these is the accounting for additional collected data that might be useful to the whole observation, such as recording the remained bark and the but swell. The amount of bark remains on the logs after merchandizing is important to obtain an in-depth understanding of how much bark can affect the accuracy of the machine. It is also important to record the butt flare and categorize them for the same reason. Secondly, it is important to be able to compare the types of machines used by each operator to understand if different machines are contributing differently to measurement accuracy. However, this needs thorough data collection, including not only obtaining observations from more loggers but also collecting other useful information such as machine hour, machine's age, and general maintenance records. Lastly, to be able to compare the performance of loggers in terms of measurement accuracy performance, data from more loggers is needed so that the effect of experience in measurement accuracy can be better analyzed using categorical statistics.

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