An Investigation of the Measurement Accuracy and Productivity of a Waratah HTH 625c Processor Head

A dissertation submitted in partial fulfilment of the requirements for the degree of Bachelor of Forestry Science with Honours by:

D. A. Saathof

New Zealand School of Forestry
University of Canterbury
Christchurch
New Zealand
2014

1. Abstract

Log processor heads have become increasingly used in New Zealand (NZ) forest harvesting operations to increase productivity and improve worker safety. Information regarding the measurement accuracy and productivity of new model processor heads is limited. As a result, log quality control (QC) is carried out on logs that have been merchandised by a processor head. This task can have a high risk for injury from man – machine interaction. A trend between studies was that older model Waratah's did not have sufficient measurement accuracy to alleviate the requirement for log QC. In this study, a Waratah HTH 625c processor head operating in NZ was analysed for measurement accuracy and productivity.

Measurement accuracy was considered by measuring logs for length, diameter and branch size. A comparison of two methods of processing was also considered to determine measurement accuracy, productivity and production efficiency for the way logs are delimbed and merchandised. Once gathered, the data was then analysed to identify significant effects, trends and relationships between variables.

Length measurements were highly accurate but diameter measurements were under-estimated. It was also evident that although there was absolute accuracy, there was a high variability in measurements with underestimating and overestimating. Branch size was also found to have a significant impact in reducing length measurement accuracy and productivity. Single pass processing has significantly higher production efficiency than two pass processing, although single pass processing had a higher length error associated with it.

The Waratah HTH 625c processor head has better measurement accuracy than older model Waratah's. However, logs are still cut out-of-spec which will require a log QC to identify. As measurement technology is further improved in processor heads, and improvements to NZ's plantation resource (improved form and smaller branching) are realised at harvest age, measurement accuracy and productivity of log processor heads will further improve.

Key Words: Processor Head, Waratah HTH 625c, Log Quality Control, Measurement Accuracy, Branch Size, Productivity, Production Time, Tolerances.

Table of Contents

2. Acknowledgements

I would like to first thank Rien Visser for supervising this project, the guidance and help that I received, and mostly for his precious time he made for me. Special thanks must go to Raffaele Spinelli and Natascia Magagnotti from Ivalsa, Italy, who in their time spent in New Zealand aided me in the project through measuring logs at the harvesting operation, I am very grateful for your time.

I would like to thank Rayonier – Matariki Forests for funding and making this project available for me to complete with special thanks to Jason Syme and Rob McGregor for their help in organising and setting up this project.

I would like to thank R F Davis Logging and their crew 97 for working in with my study and allowing me to gather the data from their Waratah processor head.

Lastly, I would also like to thank and acknowledge my parents Ed and Maureen for the encouragement and the support in completing this project and also to the rest of the class for driving each other to complete our projects and the good times we have shared together throughout this time.

3. Introduction

3.1 General Introduction

Log processing is a fundamental task in forest harvesting. Stems are delimbed and then cut into logs based on different log grades and their specifications. This can be done manually with a man and a chainsaw or with an excavator with a specially designed ‘processor head’. A processor head will delimb, measure stem dimensions and cut a stem into logs with an inbuilt chainsaw in a process referred to as merchandising.

Log processor heads are commonly used in New Zealand forest harvesting to process trees into logs at the stump or on a skid site. Increasing mechanisation by processing stems with a machine can increase productivity and improve worker safety (Murphy, 2013). Increased measurement accuracy and productivity has become achievable through improved measurement and optimising technologies built into log processors and forestry machines (Marshall & Murphy, 2005). Currently, skid workers using chainsaws are still the most common log processing option as it is perceived that they obtain better value recovery through higher accuracy. Potential improvements in measurement accuracy and productivity are often the focus of the re-design and introduction of new model processing heads.

Waratah processor heads are commonly used in NZ to merchandise radiata pine trees into logs. However, there is a lack of information about the measurement accuracy of the new model Waratah HTH 625c. As a result, a crew member works alongside the Waratah processor head and a fleet loader on the skid site to log Quality Control (QC); ensuring logs are within the specifications of their respective grade. With the task of log QC, there is potential risk of injury from man – machine interaction because the log QC works alongside two to four operating machines. By quantifying the measurement accuracy of the Waratah 625, justification of the requirement for a log QC position to quality control merchandised logs can be established. However, because of updated technology and design, this may enable a level of measurement accuracy within a threshold that deems the log QC position unnecessary.

3.2 Problem Statement and Objectives of the Study

Forest harvesting in New Zealand has recently been the focus of the media for having an insufficient commitment to safety which is resulting in unnecessary injuries and fatalities (WorkSafeNZ, 2014). This has prompted a greater focus on mechanisation to remove workers from dangerous tasks on the hillside and place them within the safety of a machine.

Mechanised log processing with processor heads attached to excavators has replaced the need for motor manual processing by workers with chainsaws. However, as the accuracy and productivity of new model log processors is unknown, one man is still commonly employed to QC logs that the processor head has merchandised. Unfortunately, the QC position exposes a worker to a highly mechanised operation where there is a high risk of injury through man – machine interaction.

Radiata pine trees often have large sized branches which may be affecting the measurement accuracy and productivity of processor heads. There is a need for research to quantify the effects of branch size on measurement accuracy and productivity. There is also a need to determine if alternative methods of processing stems are more efficient than the common practice of delimbing stems prior to merchandising to improve production efficiency.

There are three main objectives of this study:

1. To determine length, Small End Diameter (SED) and Large End Diameter (LED) measurement accuracy for a Waratah HTH 625c processor head;
2. To determine the effect of branch size on measurement accuracy and productivity for a Waratah HTH 625c processor head;
3. To determine the effect of processing technique (delimbing and merchandising simultaneously vs. delimbing prior to merchandising) on processing time and measurement accuracy for a Waratah HTH 625c processor head.

4. Literature Review

4.1 Waratah HTH 625c

The Waratah HTH 625c processor head is designed and manufactured by Waratah NZ Limited based in Tokoroa. This Waratah is a harvester/processor that has been designed specifically for harvesting and processing radiata pine. The processing head weighs 4,200 kg and requires a minimum carrier size of 29 tonne (Waratah, 2014). In this study, the Waratah 625 was mounted on a 36 tonne Caterpillar 336D excavator (Figure 1).

Stems are driven through the Waratah's two sets of delimbing knives by two spiked feed rollers that have full hydraulic synchro-drive at a feeding speed of 4.2 m/sec. The processor has two hydraulic chainsaws; a butt saw and a top saw, which have bars 102 cm and 73 cm long respectively (Waratah, 2014). The butt saw has a maximum cutting diameter of 90 cm and the top saw has a maximum cutting diameter of 50 cm. The processing head is capable of delimbing stems with diameters up to 85 cm large-end diameter. It has the TimberRite™ control and measurement system inbuilt into the processing head and the excavator.

Figure 1: Waratah HTH 625c processor head attached to a Caterpillar 336D excavator

Mechanical processors/harvesters use inbuilt sensors for measuring length and diameter in order to optimise and buck stems into correct log grades (Strandgard & Walsh, 2012). The processor head measures length with an encoder coupled to a measurement wheel and the feed rollers as shown in Figure 2 (Anderson & Dyson, 2001; Strandgard & Walsh, 2012). Each time the wheel is turned, the encoder generates a fixed number of pulses. Diameter is measured with a potentiometer or pulse encoder that uses the delimbing knives and feed rollers to measure deflection. The processing head measures diameter from three points of contact on the stem. These are the delimbing knives and the feed rollers (Figure 2).

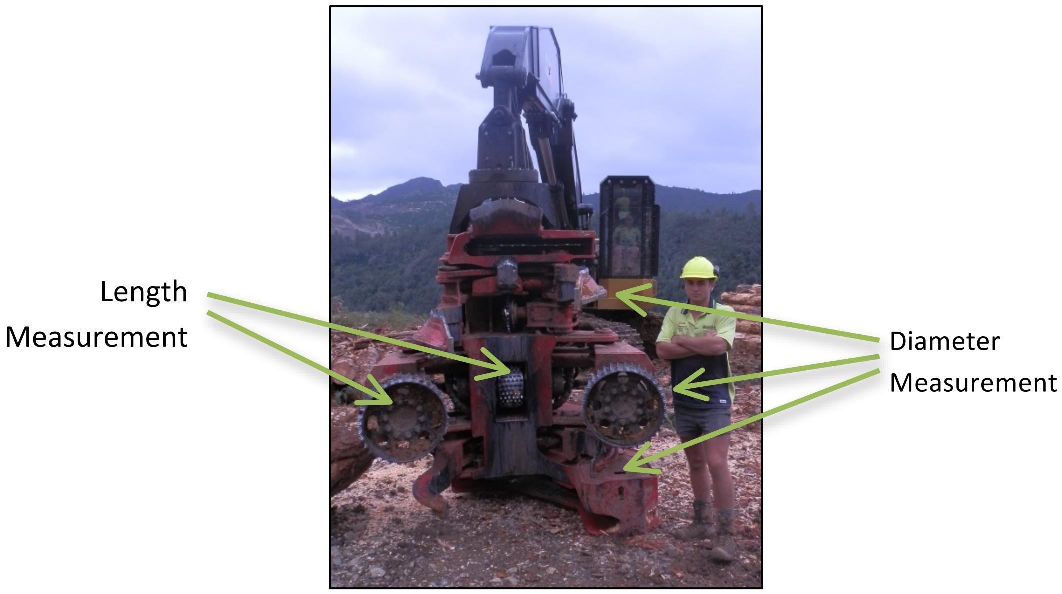


Figure 2: Waratah HTH 625c processor head with length and diameter measurement sensor locations identified.

4.2 Measurement Error

Emphasis on achieving accuracy in length measurement is important as out-of-spec log lengths are a common reason for log rejection (Strandgard & Walsh, 2012). There is a larger emphasis placed on achieving length accuracy over diameter accuracy because length measurement is important for every log, as it has to meet a certain length requirement (e.g. A-grade: 3.75, K-grade: 5.95, S30: 7.3). Achieving diameter accuracy is only important for logs with diameters that are near the minimum or the maximum diameter limits for a grade.

The NZ Logging Industry Research Organisation (LIRO) completed several studies on early model processor heads operating in New Zealand pine forests. Evanson, Riddle and Fraser (1994) found that approximately 76-88% of logs measured by a Waratah HTH 234 were within a length tolerance of +/- 5 cm. They found a relationship where length measurement accuracy decreased with log length but found no significant relationship with length measurement accuracy and diameter. A later study by Evanson (1995) found that a Waratah HTH 234 cut 90% of logs within +/- 5 cm. However, measurement accuracy of processed pulp logs was not considered in this study. A trial conducted by Evanson and McConchie (1996) showed that the accuracy of a Waratah HTH 234 was within +/- 5cm for 93% of logs measured. Differences in accuracy between these studies were not apparent but may be due to different stand characteristics. A more recent study in South Africa found that 98% of logs were within spec and that the out-of-spec logs were overcut for length by a Waratah HTH622, Tigercat TH575 and a Log max 7000B processor head. (Eggers, McEwan, & Conradie, 2009).

Diameter measurements are fundamental for optimising a stem into the highest value combination of log grades (Clark, Wynne, & Schmoldt, 2000). Alongside studies examining length error, diameter measurement accuracy has also been considered. Anderson and Dyson (2001) completed a study of 31 harvesters for measurement accuracy. They found a large variation between harvesters for diameter measurement accuracy and that 34% and 57% of logs measured per machine had a diameter error within ±4mm and ±8mm, respectively. However, they discussed that diameter was not often used for bucking decisions but more commonly used to find the topping diameter of stems (10cm) which has influenced their results to indicate highly accurate measurements. This study does not indicate the diameter errors that could be associated with larger log diameters. Evanson (1995) also measured SED error and found that 0-8% of log processors had SED measurements out of spec. It was also discussed that processors were often calibrated to underestimate diameter in order to cut well above the minimum SED tolerance.

In measurement accuracy studies, taking representative manual measurements of length and diameter is fundamental in evaluating processor head measurement accuracy. Strandgard (2009) completed a study considering the manual measurements and the errors associated for processor accuracy studies. It was recommended that length was measured at the same position that the measuring wheel measured along the stem with a standard loggers tape. This method provides the most precise representation of the processors length measurements. Diameter was recommended to be measured with a diameter tape as it removes the variability of stem eccentricity (Strandgard, 2009). Measuring diameter with callipers has a higher variability than diameter tape as callipers have less points of contact with the stem.

4.3 Causes of Measurement Error

Errors that occur in the measurement of log dimensions can be caused by inaccuracies in measurement process, human error and instrument limitations (Strandgard & Walsh, 2012).

The environment and work that a processor operates in is rough and can cause length inaccuracies from multiple factors. Large branches have been associated with reduced length measurement accuracy (Anderson & Dyson, 2001). Branching can result in the processor head losing its known position on the stem when it has to make several delimbing passes (Strandgard & Walsh, 2012). This is caused by the processor head losing contact or slipping along the stem on the bark (Marshall & Murphy, 2005). Another important factor is re-zeroing the length measurement at the end of a stem with the chain bar. At times, contact is not made with the bar and the log end as the operator has narrowly missed the stem end, causing over-estimations of log length (Strandgard & Walsh, 2012).

Damage to the processor head can occur through normal operation causing length and diameter measurement errors. In addition to resetting length with the saw blade, a photocell is used to identify the stem end. The photocell can be damaged from impact or dust and saw chips. The photocell can cause length error when there is a slab uncut from the end of the stem which the photocell measures as being part of the log. This can be overcome by the operator cutting a narrow disc from the stem end to re-set the length measurement (Strandgard & Walsh, 2012). The measurement wheel can also be damaged by having the stem twist against it or can become clogged with soil and bark.

Accurate diameter measurements are obtained when full contact can be made with the stem. However, nodal swelling and knots cause the drive rollers and delimbing knives that measure diameter to deflect resulting in an overestimation of diameter (Strandgard & Walsh, 2012). A function programmed into the processor head averages diameter measurements periodically along the stem to filter out irregular measurements that would indicate the diameter increases towards the head of the stem. The level of pressure applied to the delimbing knives and drive rollers also has an impact on diameter measurements (Marshall & Murphy, 2005). Too much pressure applied to the log will cause under-estimations of log diameter but too little pressure and the opposite occurs.

Manual log measurements in processor head measurement accuracy studies are assumed to be accurate and representative of the logs true dimensions (Strandgard, 2009). However, measurement techniques that will lead to manual measurement errors include measurement over branch stubs, misalignment and the application of incorrect tension to callipers and tapes. Another constraint is that logs often have an irregular shape. Variability and measurement errors are caused by stem eccentricity and non-square log ends. In order to minimize variability in manual measurements, Strandgard (2009) recommended measuring length at the same location along the stem that the processor head measured and measure diameter with a diameter tape to have better contact with the stem surface.

4.4 Impacts of Branch Size on Measurement Accuracy and Productivity

Research of processor heads working in harvesting operations have focused on tree form, volume and delimbing quality but there is little research on the effects of branch size on measurement accuracy, processing time and productivity. This may be because stems often reach the landing pre-delimbed from felling, extraction and being stacked. However, not all stems are pre-delimbed through earlier activities and it is common for a processor to process stems with branches of various sizes.

A study completed by Anderson and Dyson (2001) discussed that branch size appeared to influence the measurement accuracy. Increasing the size and frequency of branching resulted in a larger variation in length error of the processed logs. They further discussed that branch characteristics from different parts of the stem and between different species may explain why measurement performance of processor heads varied between different operations, stands and log grades. However, they did not provide any measurement accuracy value to these comments.

4.5 Processing Efficiency

The trend for increased mechanisation in harvesting operations is to improve productivity and worker safety. There have been many studies that analysed the productivity of processor heads within the harvesting system but no time studies that evaluated the productivity of alternative delimbing and merchandising methods for processing stems in New Zealand production forests. It is common for processors to merchandise while delimbing in stands where branch sizes are small. New Zealand radiata pine trees tend to have large branches which has made delimbing prior to merchandising a more favourable method for operators. As a large proportion of forests in New Zealand are moving into second rotation with higher quality genetics and higher crop stockings, this favours smaller branching (Mason, 2005). There is a need to research new methods of log processing for increasing productivity whilst retaining measurement accuracy.

New Zealand time studies that have examined a processor head operating within the harvesting system have recorded the time taken to process where delimbing is completed prior to merchandising. A Waratah HTH 234 in a ground-based operation processed a stem at 0.67 (min) and the same model machine in a yarder-based operation processed stems at 1.28 (min) (Evanson & McConchie, 1996). Another study found that the same model of Waratah processed stems at 1.06 (min) (Evanson, Riddle, & Fraser, 1994). There is a high variability between these time-studies. The variability may be due to different levels of experience as Evanson and McConchie (1996) suggested that it took two years of experience before a processor operator was deemed fully competent.

5. Methods

5.1 Test Site and Stand Description

The test site was located in Rayonier's Tairua forest, Bay of Plenty.

This site was chosen because the landing was of a sufficient size to complete the study without negatively affecting the logging crew's production and so that the study could be completed in accordance with New Zealand forest harvesting health and safety regulations.

The stand the crew was harvesting was in its second rotation. Stand details are shown in Table 1 below:

Table 1: Stand Details

Age (Years)	27
Mean Top Height (m)	38.9
Stocking (stems/ha)	335
Mean BA (m^2)	58.6
Mean Piece Size (m^3)	1.72

5.2 Operation Description

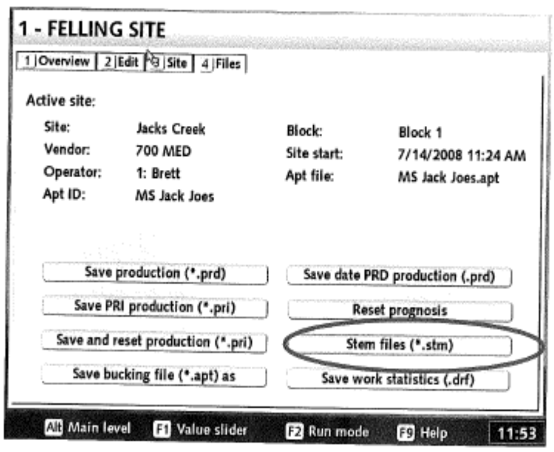
The site was harvested by a cable logging contractor; R F Davis Logging. The operation consisted of a Madill 172 tower yarder which hauled stems to the landing, a Caterpillar 329D fleet loader and a Caterpillar 336D with a Waratah HTH 625c processor head attached. A log QC worked together with the fleet loader operator and the Waratah operator in quality controlling all of the logs that the Waratah head processed.

5.3 Data Collection

In a designated area on the landing the Waratah or the fleet loader shovelled 3-5 stems into a stack. The Waratah then processed each stem into logs, laying the logs out in sequential order from when they were cut while keeping logs from each stem in individual piles (Figure 5).

Prior to commencing processing, the Waratah's on-board computer was re-programmed to save individual stem files (Figure 3). Stems files were saved individually to avoid ambiguity with stem ID from physical measurements. The stem files are a record of each stem processed which includes a measure of each logs length, diameter, volume, quality and the log grade. The stems files were then further selected to be saved as separate files; recording each stem file separately and showing the date and the time the stem was processed (Figure 4). The time stamp is crucial for matching physical measurements of each log to the Waratah stem files.

Individual stem files were downloaded from the processor computer at the end of each working day and matched to physical measurements by using the file time stamp.



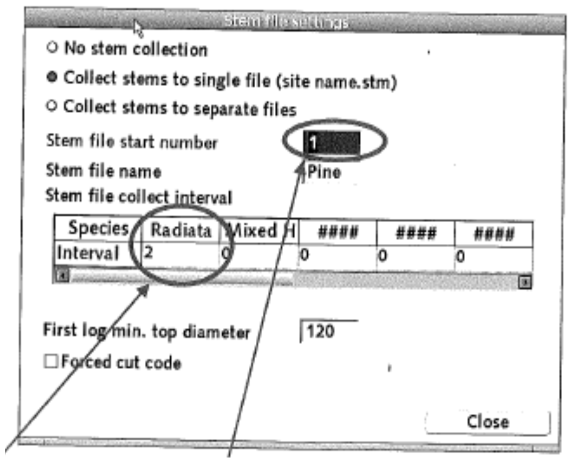


Figure 3 (Left): TimberRite™ screen display for reprogramming stem files (Waratah, 2010)

Figure 4 (Right): Further TimberRite™ screen display indicating the correct program function to save stems to individual stem files (Waratah, 2010)

5.4 Manual Measurements

Manual measurements were taken to determine the actual length and diameter of a log. Once the operator had processed several stems, the length, SED and LED were measured for every log with a loggers tape for length and a builders tape for diameter (Figure 5). It was recommended by Strandgard (2013) that a processors diameter measurement was best represented by a diameter tape and length was best represented by a loggers tape. However, under the time constraint and within the parameters of a functioning harvesting crew, diameter tape could not be used as the logs would have had to been placed on bearers.

Measurements were taken over-bark for both the Waratah and the manual measurements. Each log was measured in the same sequence as it was merchandised and attributed a unique ID (tree number/log number). For each tree number, a time stamp was recorded at the time when the last cut was performed. In order to avoid ambiguity with the time stamps, each tree was manually scaled directly after processing or after 2-5 stems had been processed, so that in the meantime the processor could process more trees (outside of the study) and subsequent time stamps where several minutes apart.

Figure 5: Measuring processed logs for length and diameter

5.4.1 Branch Size Measurement

Branch size was visually assessed by the researcher as each log was merchandised. The branch categories are defined in the following classes:

0. No branching: The log is free of branches or has previously been delimbed
1. Small branching: All branches have diameters less than 50 mm
2. Medium branching: Two or more branches have diameters that are greater than 50 mm but are less than 100 mm
3. Large branching: Two or more branches have diameters that are greater than 100 mm

5.4.2 Processing Time Measurement

The processing time measurements were taken with a Husky Hunter handheld computer running the dedicated Siwork 3 time-study software. Two methods of processing by the Waratah were measured in seconds. The first method of processing involved the Waratah delimbing and merchandising logs simultaneously (One Pass method) where the second method involved the Waratah making a delimbing pass prior to merchandising logs from the delimbed stem (Two Pass method). For each stem, the following time elements were measured:

- Time to pick up the tree (seconds)
- Time to pre-delimb the tree - if working in two-pass mode (seconds)
- Time to delimb and merchandise the whole stem (seconds)
- Any delay, caused by the study or not (seconds)

5.5 Study Design

Completing research in a production harvesting operation required carefully planned work routines and designated areas for measurement and safe retreat zones. Prior to commencing research at the beginning of each day, a health and safety plan was created and implemented with all crew members being briefed on the plan. The work routine adopted for this study was:

1. Designate an area on the landing to process the stems that was away from operating zones and in accordance to the New Zealand harvest operation regulations.
2. Operator began by picking up the study stem and processing it, dropping the logs in sequential order from when they were cut, and in groups from the stem they were cut. Once finished, the operator moved back to his normal processing zone, resuming work.
3. From the safe zone, a researcher recorded the stem ID, time stamp, branch class and processing time on the handheld computer
4. On receiving the OK signal from the operator, researchers moved in from the safe zone to the row of logs and measured each log for length, SED, LED together with the stem and log ID
5. Researchers then retreat to the safe zone and signalled the fleet loader to remove the logs. Once the fleet loader had finished, the process was repeated.

5.6 Data Analysis

A computer software program Silvia was used to open and view the stem files. This program was used to read the TimberRite^{TM} stem files and obtain the Waratah's log measurements. The time stamp recorded during the merchandising phase was used to match the correct stem files to the stems that were physically measured in the study. These measurements were then matched to the manual measurements for each log. Length and diameter errors were calculated by subtracting the Waratah's log measurements from the physical measurements:

$$E = y - \tilde{y}$$

Where:

E = error

y = physical measurement

$\tilde{y}$ = value measured by the Waratah

Individual log errors were then used to create histograms to visualise the distribution of errors. The error distributions indicate whether the processor is under-estimating or over-estimating the actual measurement. A positive error indicates that the processor under-estimated the actual measurement where a negative error indicates that the processor over-estimated the actual measurement. The error distributions also indicate the variability and spread of the errors associated with measuring length and diameter.

Basic exploratory data analysis was carried out on the length and diameter error data sets to become familiar with the dataset, explore relationships between variables and identify any outliers present in the dataset. For all statistical analysis completed, the statistic program R was used. A Student's T-test was used on the length and diameter error datasets to determine if they were significantly different from zero error. Regression analysis was then completed to determine whether stem characteristics could explain the length and diameter errors. The dependent and independent variables that were tested in the regression analysis are presented in Table 2 below:

Table 2: Dependent and independent variables tested with regression analysis

	Dependent Variable	
	Length Error	Diameter Error
Independent Variables	Branch Class	Branch Class
	Log Length	Log length
	SED	SED
	LED	LED

The branch class categorical variable was then considered for the effect of branch size on measurement error. This was initially explored with a basic statistical summary. Further regression analysis was completed on the effect of branch size on length error, SED error and LED error to determine if branch size had any significant effect on measurement error. Finally, the effect of branch size on productivity was considered. An analysis of variance (ANOVA) and a Tukey HSD test was used to determine if branch class had an overall affect on productivity and if there was any significant difference in productivity between the branch classes and their size.

Stem processing time was compared for the two methods with an independent sample T-test with the assumption of equal variances. Further ANOVA and regression analysis was completed to determine if there was any difference in measurement error between the two processing methods. Finally, a Generalised Linear Model was used to create a log processing time function.

All significance values where considered at a 95% confidence level.

6. Results

6.1 Measurement Accuracy

6.1.1 Error Distributions

Measurement accuracy was considered through error distributions. Length error is normally distributed (Figure 6), with a mean length error of -0.17 cm and a standard deviation of 1.9 cm. This indicates that on average, the Waratah is measuring logs longer than their actual dimensions by 0.17 cm. However, there is variability in log length errors as illustrated in Figure 6 where logs are both under-cut and over-cut. There is a wider skew towards negative length errors with the largest overestimated length measurement at -15 cm. The Waratah also underestimated length measurements with the largest underestimated log measured 8 cm shorter than the logs actual length. A Student's T-test established that length measurements are statistically significantly different from zero error (P-value = 0.013). This may be attributed to the variability of the dataset.

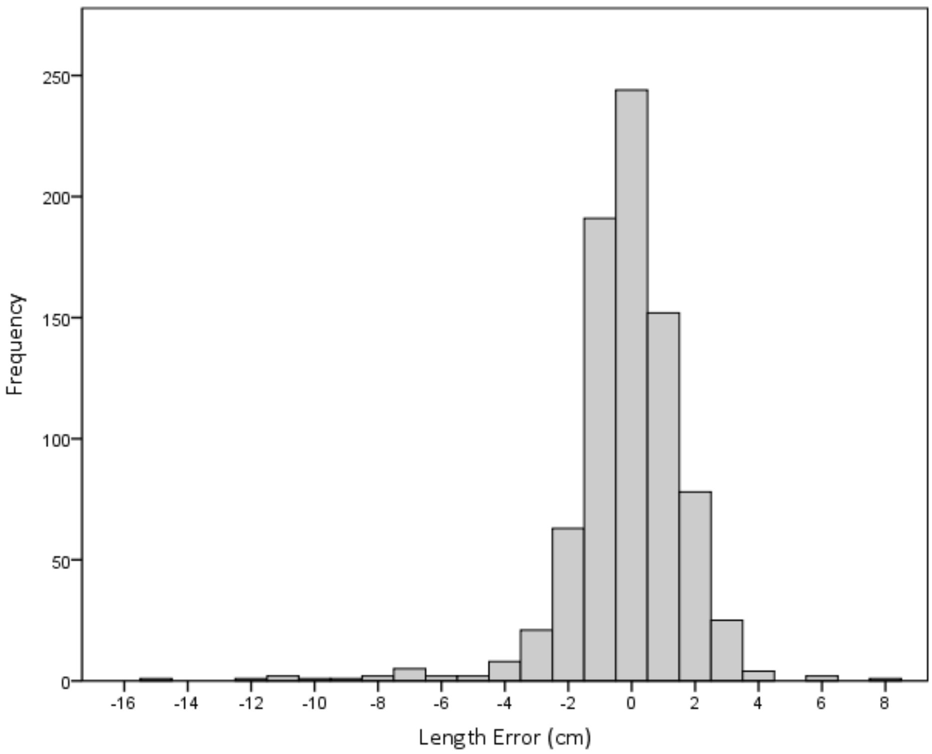


Figure 6: Length error distribution

The small end diameter error distribution (Figure 7) has a positively skewed distribution with a mean of 1.6 cm and a standard deviation of 2.2 cm. The SED distribution indicates that the Waratah is generally underestimating each logs actual SED dimensions. Unlike the length error distribution, there is a skew towards positive SED errors with the largest underestimated error of 12 cm. There is a small frequency of overestimated SED measurements with the largest overestimation of 3 cm. A Student's T-test established that SED measurements, alike length measurements are statistically significantly different from zero error (P-value < 0.001).

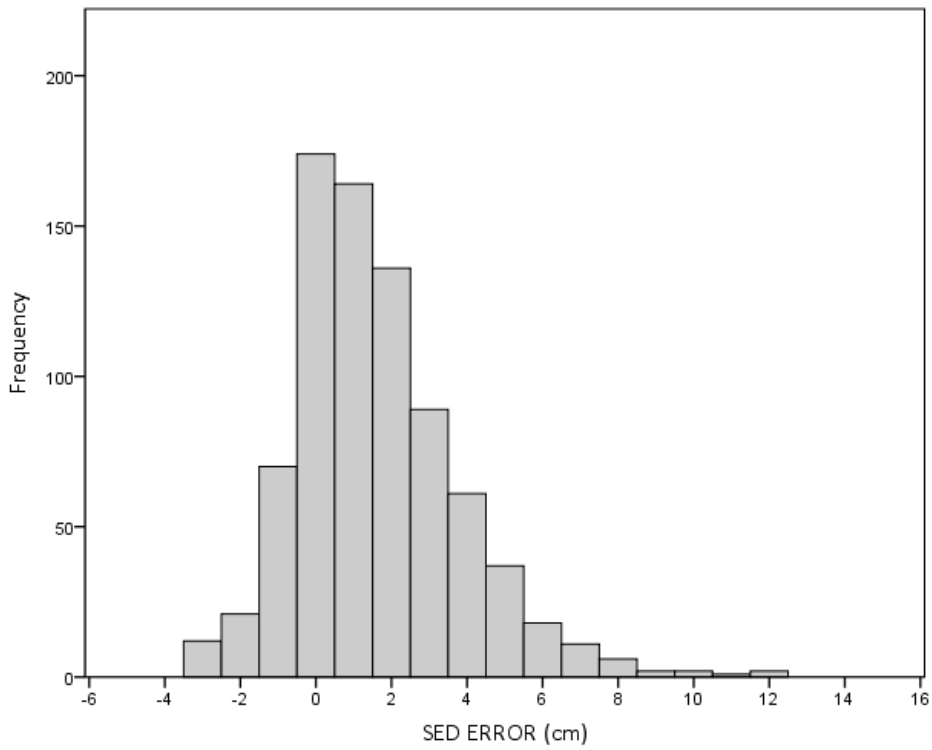


Figure 7: Small end diameter error distribution

The Waratah is also underestimating large end diameter as there is a positively skewed error distribution (Figure 8). The mean LED error is 4 cm with a standard deviation of 3.1 cm. This analysis indicates that the Waratah is on average measuring large end diameter 4 cm smaller than the true diameter. The error distribution has a strong skew towards positive errors and consequently underestimating LED. Alike the SED error distribution, the negative tail of the distribution is less obvious. However, the Waratah measures a small frequency of LEDs larger than their actual dimensions with the largest overestimated LED at -9 cm. At the other end of the distribution, the Waratah has measured LED up to 16 cm smaller than the logs actual diameter. A Student's T-test further established that alike length and SED error, LED error is also statistically significantly different from zero error (P-value < 0.001).

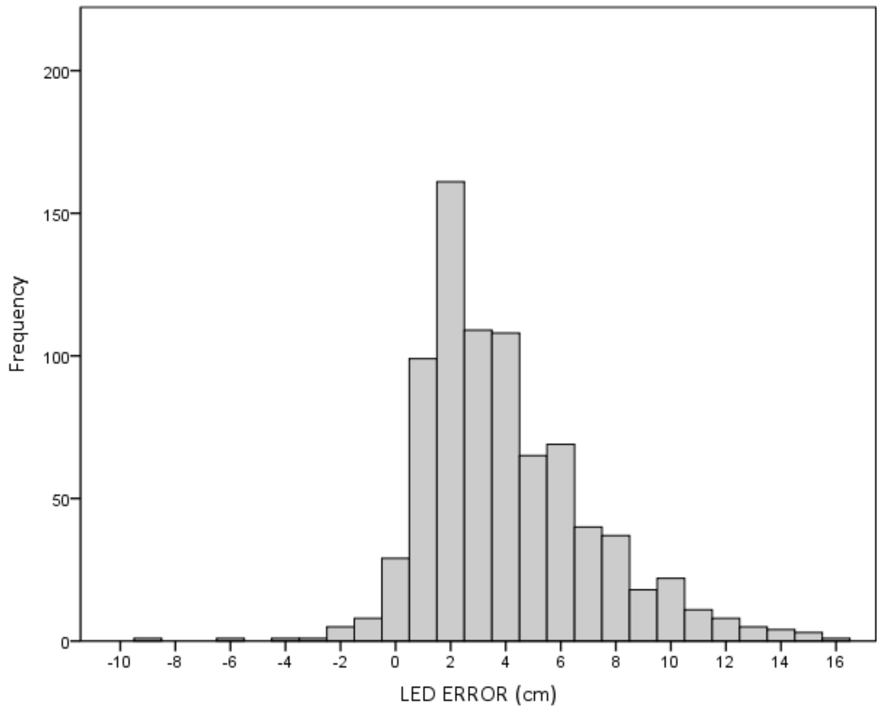


Figure 8: Large end diameter error distribution

Each of the error distributions has a bell shaped curve which indicates that the sample distributions have been taken from populations with a normal distribution (Marshall & Murphy, 2005). The sample size for each distribution is the same at n = 806. Ten outlier log length measurements were removed from the dataset because of the large difference between physically measured logs and the Waratah's log measurements. These length measurement errors are described by Jules Larson (2014) (CEO Waratah Ltd) as 'ghost lengths'. How or why the Waratah measures these lengths is unknown.

LED is the least accurate measurement made by the Waratah which is indicated and illustrated from the mean error and wide error distribution (Figure 8). LED has the widest distribution with a standard error of 0.109 cm while SED has a smaller standard error of 0.078 cm. Length measurement error has the smallest standard error of 0.067 cm. The increasing standard errors from Length to SED and then LED can be visualised through the distributions of Figure 6, Figure 7 and Figure 8. This further supports the results in that length measurements are the most accurately measured.

6.1.2 Waratah Measurement Accuracy by Grade

The Waratah's on-board computer recorded the grade for each log to the stem files as logs were merchandised. The average and standard deviation for length error, SED error and LED error for each log grade is presented in Table 3. Log grades with high average errors and large standard deviations make up the tails for each of the error distributions. However, there is no particular log grade that consistently has the greatest average error and standard deviation between the dependent variables length error, SED error and LED error.

Table 3: Length, SED and LED error by log grade

Log Grade	Variable: Length Error		SED Error		LED Error		No. of Logs Measured
	Average (cm)	St Dev (cm)	Average (cm)	St Dev (cm)	Average (cm)	St Dev (cm)	
A	-0.9	1.9	2.8	2.6	5.2	2.8	60
K	0.1	2	1	1.6	3.4	2.8	152
KM	-0.3	1.1	1.1	1.8	2.7	2	171
M20	-0.6	1.7	1.8	1.8	3.3	2.2	72
P35	0.4	1.3	2.4	2.3	5.5	3.8	64
S30 RL	0.3	1.8	2.3	2.4	6	3.1	193
UA	-0.9	3	0.6	2.4	2.1	2.2	89

The percentage of logs in specification as percentages for different tolerances of length, SED and LED are shown in Table 4, Table 5 and Table 6. These tables indicate the percentage of logs that would meet a specific tolerance as forestry companies have different tolerances applied to their log specifications. Length measurements have the highest percentage of logs in specification at zero error and at a ±5 cm tolerance.

Table 4: Logs in specification (as percentages), for different tolerances of length

Log Type	0cm	± 1cm	± 2cm	± 3cm	± 4cm	± 5cm	± 7cm	± 10cm	± 15cm
A	25	61	84	90	97	98	98	100	100
K	34	71	89	98	99	99	99	99	100
KM	38	88	96	99	99	99	100	100	100
M20	35	76	93	96	97	97	99	100	100
P35	30	78	95	98	100	100	100	100	100
S30 RL	22	68	91	97	99	99	99	99	100
UA	29	58	79	88	88	89	96	98	100

Table 5: Logs in specification (as percentages), for different tolerances of SED

Log Type	0cm	± 1cm	± 2cm	± 3cm	± 4cm	± 5cm	± 7cm	± 10cm	± 15cm
A	2	15	33	52	66	84	95	100	100
K	5	55	82	95	98	98	99	99	100
KM	2	45	78	90	96	98	98	100	100
M20	1	35	54	75	90	96	99	100	100
P35	0	22	39	50	77	91	100	100	100
S30 RL	2	32	51	68	78	87	96	99	100
UA	2	55	76	88	92	96	97	99	100

Table 6: Logs in specification (as percentages), for different tolerances of LED

Log Type	0cm	± 1cm	± 2cm	± 3cm	± 4cm	± 5cm	± 7cm	± 10cm	± 15cm
A	0	0	11	26	36	51	79	95	100
K	1	14	39	58	74	80	91	96	99
KM	1	13	39	74	87	94	96	98	99
M20	0	13	33	53	71	82	94	99	100
P35	2	8	9	19	31	45	63	89	100
S30 RL	1	3	8	13	26	39	69	90	99
UA	0	26	54	73	83	92	99	99	100

6.1.3 Variable Interactions

Analysis of log length and log LED regressed with length error indicated that both of these variables had a significant relationship with length error (both p-values < 0.001). However, they both had weak relationships with an $R^2 = 0.04$ and $R^2 = 0.02$ for length error regressed on log length and length error regressed on LED respectively. The trend in Figure 9 illustrates that for shorter logs, the Waratah processor head tends to overestimate length measurements, but at longer lengths the processor head underestimates length measurements. However, there is also a large spread of length error at each point on the x - axis where a log grade is cut. The relationship between actual LED and length error has the same trend and has been included in Appendix 1.

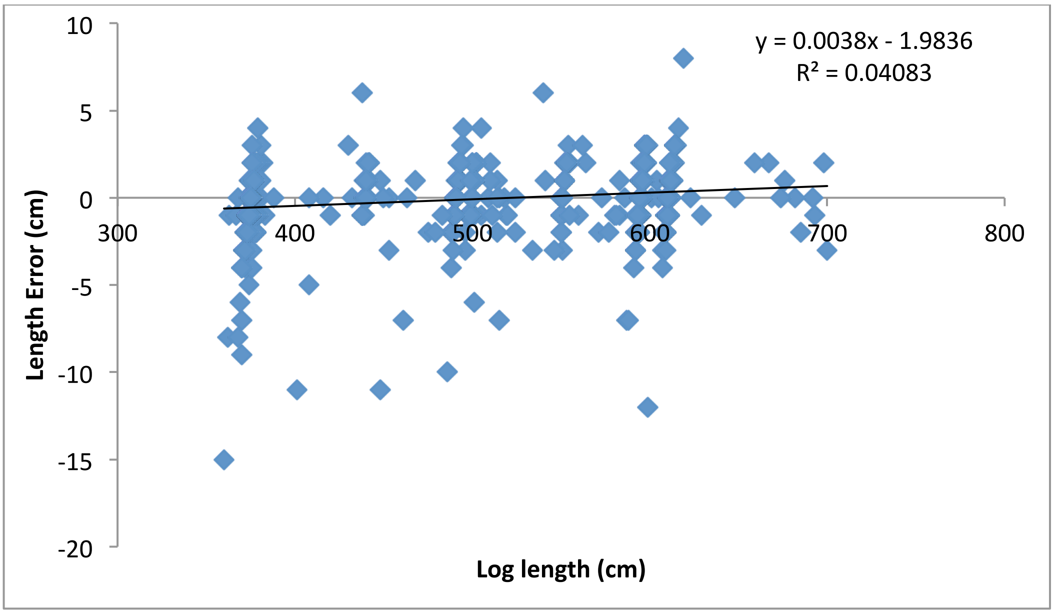


Figure 9: Length error regressed on log length

Regression analysis of SED error and LED error with actual SED and LED are highly significant (both p-values < 0.001) and have strong relationships. Both regressions have a trend where increasing SED and LED resulted in higher error and an increasingly under-estimation of actual diameter. This is evident in both Figure 10 and Figure 11 where SED error and LED error is regressed against the actual diameter. These relationships have a good fit at $R^2 = 0.27$ and $R^2 = 0.35$ respectively. These regressions further support the error distributions (Figure 7 and Figure 8) where the Waratah is measuring and cutting logs at smaller diameters than the actual log diameters.

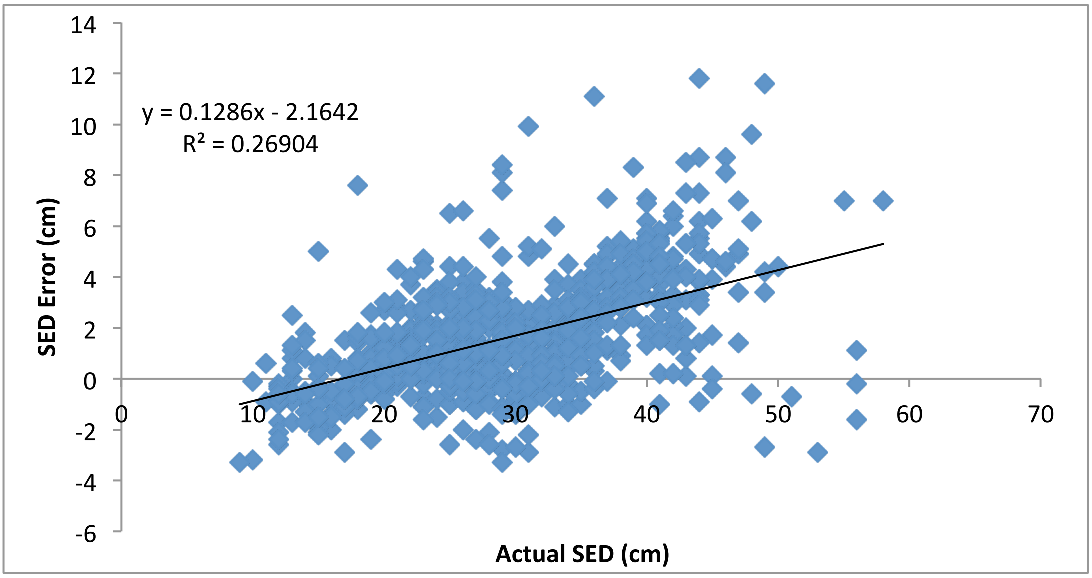


Figure 10: SED error regressed on actual SED

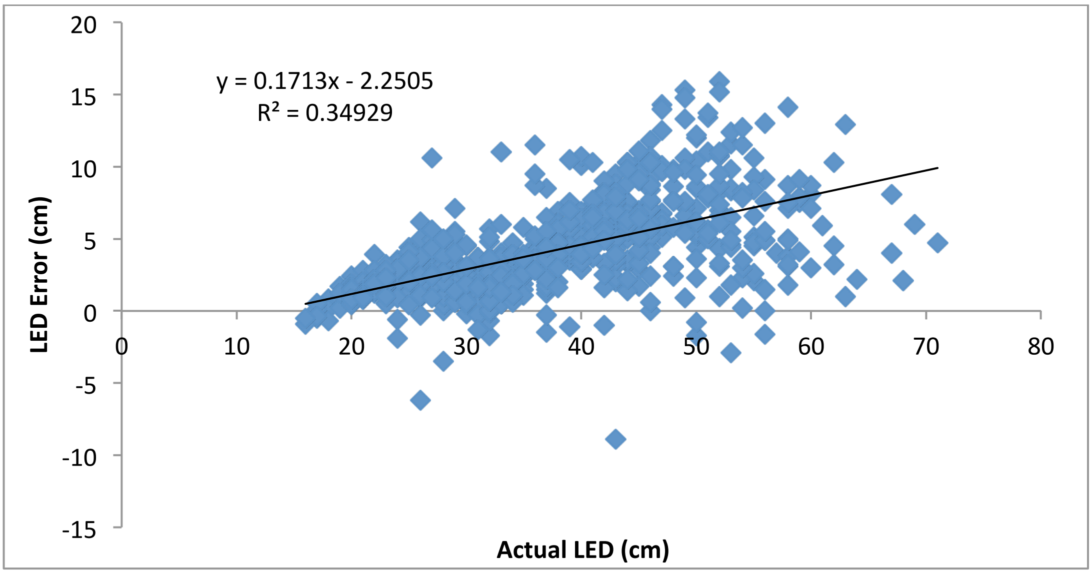


Figure 11: LED error regressed on actual LED

6.2 Branch Effects

6.2.1 Effect of Branch Size on Measurement Accuracy

The forest this research was carried out in was second rotation with high quality genetics and a narrow spacing which resulted in a high frequency of trees with smaller sized branching. Trees that had branches with diameters greater than 50 mm were low in frequency and only occurred when an edge tree was hauled in. A contributing factor to the low frequencies of logs in the larger branch categories was that branches were knocked off the stem during in-haul by the yarder and when the stem was shovelled to the processing area from the chute.

The average length error increases from branch class 0 (no branches) through to branch class 3 (two or more branches greater than 100 mm in diameter) as indicated in Table 7. The branch classes 1 and 2 have lower average errors than the branch class 0 for both SED error and LED error. This may be because of the interaction with diameter, displayed in Figure 10 and Figure 11, as logs without branches are usually the pruned butt log with the largest diameter. The large average errors encountered with branch class 3 may be in part due to the low number of logs measured causing bias. The large standard deviation for length, SED and LED support this. However, this class has been presented to provide an indication to the likely errors associated merchandising logs with large branches.

Table 7: Log Error Measurements by Branch Category

Branch Class	Variable: Length Error		SED Error		LED Error		No. of Logs Measured
	Average (cm)	St Dev (cm)	Average (cm)	St Dev (cm)	Average (cm)	St Dev (cm)	
0	-0.03	1.89	2.81	2.06	4.57	3.19	231
1	-1.00	1.61	2.40	2.22	3.69	2.41	72
2	-1.76	3.45	2.76	2.50	3.71	2.51	21
3	-5.33	4.04	6.57	3.05	7.33	5.75	3

Regression analysis of branch class on length error, SED error and LED error indicated that branch size only had a significant effect on length measurement (P-values < 0.001). However, the regression of length error and branch class has a weak relationship at R^2 = 0.11 (Figure 12). Further ANOVA analysis of the effects of branch size on length error indicates that there is a significant difference in length error between the different branch classes. The Waratah can more accurately measure length when there are no branches or only small branches in comparison to logs with large branches.

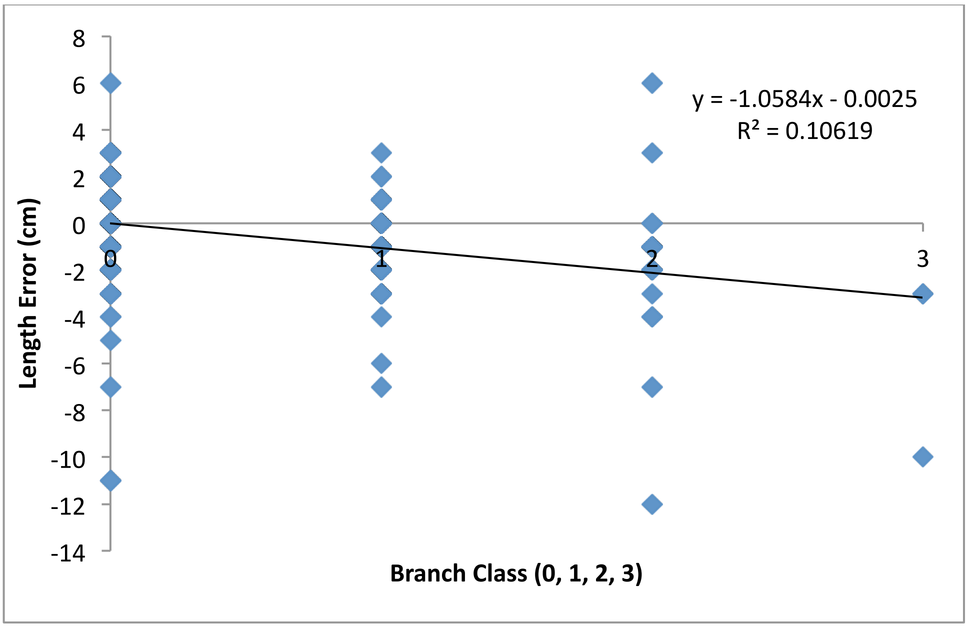


Figure 12: Length error regressed over branch class

6.2.2 Effect of Branch Size on Productivity

The effects of branch size on productivity was analysed to examine whether larger branches reduced the productivity of the Waratah. This is because larger branches require more power from the drive rollers to pull/push the stem through the delimbing knives and hence are more of an impedance to the processor than smaller branches. The average productivity (Productive Machine Hour – m^3/PMH) for logs with different branch sizes is indicated in Table 8. The average productivity for logs without branches is higher than logs with branches in class 1 and 2. However, there is a large reduction in productivity from branch class 1 to branch class 2 where average productivity reduces by $20m^3$/PMH.

Branch class 3 has the lowest average productivity. Logs with large branches require additional time to process because the processor can be stopped in the path of the branch, which requires a re-run with more momentum and power to drive the delimbing knives through the branch. However, only 3 logs with two or more branches greater than 100 mm were measured which may produce bias in this average productivity. Average productivity for branch class 3 can be taken as an indication of the likely productivity for logs with large branches. The low frequency of logs measured for branch size in branch class 2 and 3 was out of the control of the study as working in a production environment, what stem was hauled in from the setting with different branch sizes was completely random.

Table 8: Summary statistics of processing logs with different branch sizes

Branch Class	Av. Productivity m^3/PMH	St Dev m^3/PMH	No. of Logs Measured
0	83.6	44.5	231
1	76.2	43.0	72
2	56.1	20.7	21
3	53.2	24.9	3

Branch class had an overall significant effect on productivity with a p-value of 0.018. A log being processed that has branches has a significantly lower productivity than a log that has already been pre-delimbed. Tukey's method determined that branch class 0 (no branching), was significantly different to branch classes 1 (small branches), 2 (medium size branches) and 3 (large size branches). A pre-delimbed stem can be processed faster than a stem that still has branches.

A generalised linear regression for predicting the productivity of the Waratah 625 by branch size and log volume was not significant. The branch factor was non-significant for inclusion in the model with a p-value of 0.086. This may be because of the small sample size for branch class 2 and 3. However, although non-significant, considering an alpha value of 0.1, this regression can be considered significant. The regression further indicated a reduction in productivity when a log had larger branches on it. This regression has been included for reference in Appendix 2.

6.3 Processing Method Analysis

6.3.1 Stem Processing Time

Two different methods of processing stems were analysed for production time and level of measurement accuracy. Single pass processing involved delimbing and merchandising in one pass. The processor head has a function that predicts the likely taper and length of a stem based off the last 20 trees measured. This allows the processor head to optimise and merchandise the stem as it delimbs without measuring the whole length of the stem and the diameter profile for log optimisation. However, when merchandising while processing, the processor head would struggle to begin delimbing after cutting each log. The two pass processing method begins with the processing head completing an initial delimbing pass whilst measuring the log length and diameter profile and then comes back to the butt end to merchandise the stem into log grades. The two pass processing method is favoured in stands with large branch sizes as the processor often needes the momentum of a single fluent pass to remove all of the branches.

The single pass processing method takes a shorter average time to process stems than the two pass processing method (Table 9). A total of 42 stems where timed for each processing method, with each method being staggered throughout the study days. A single factor ANOVA and an independent sample T-test were used to determine whether there was any significant difference in production time between the two methods. Both tests returned significant differences in the processing methods with both p-values = 0.005. This significant difference indicates that it takes less time to process stems with a single pass than to do an initial delimbing pass to remove the branches and measure the stem dimensions before merchandising.

Table 9: Processing Method Time Study Summary

Processing Method	Av. Time (min)	St Dev. Time (min)	No. stems Processed	Av. Stem Vol. m^3
Single Pass	1.58	0.60	42	1.99
Two Pass	2.03	0.79	42	2.07

6.3.2 Processing Method Measurement Accuracy

Determining alternative ways of processing stems to improve productivity and efficiency is important, but the level of accuracy between the two methods is also fundamental in retaining measurement accuracy during production. As there was a significant difference found between the single pass and two pass processing method; with single pass processing taking the shortest time, the accuracy of the length, SED and LED measurements for merchandising logs were compared between the two processing methods.

An ANOVA was performed to determine whether there was any significance between processing method with length error, SED error and LED error. A significant difference was found between single pass processing and two pass processing for length error (P-value < 0.001), but no significant difference between the two processing methods for both SED error and LED error with p-values at 0.339 and 0.968 respectively. The single pass processing method had the highest length error (Table 10) in comparison to the two pass processing method. Length was overestimated when the processor merchandised and delimbed simultaneously whereas the Waratah underestimated lengths when completing a delimbing pass prior to merchandising. This means that the Waratah was undercutting logs when processing via the single pass method but then overcut logs when processing via the two-pass method. The favoured two-pass processing method retains the highest measurement accuracy, but is the slower processing method.

Table 10: Length error, SED error and LED error statistics differentiated by processing method

Processing Method	Variable: Length Error		SED Error		LED Error		No. of logs
	Average (cm)	St Dev (cm)	Average (cm)	St Dev (cm)	Average (cm)	St Dev (cm)	
Single Pass	-0.81	2.12	2.86	2.37	4.35	3.03	169
Two Pass	0.04	2.00	2.63	1.91	4.34	3.07	158

6.3.3 Log Processing Time Function

A generalised linear model, with moderate accuracy ($r^2 = 49\%$), was developed to predict the time required to process individual logs from the measured variables. The variables with the highest significance determined for inclusion in this model was the branch class factor, processing method and the volume of the log. The significance (p-values) for the intercept, branch class factor, processing method and the volume of the log are < 0.001, 0.022, < 0.001 and < 0.001 respectively. Prediction of production time is as follows:

Branch Class

0	*Processing time (secs) = -4.64 + 11.16 (delimb first) + 47.62 (m^3)*
1	*Processing time (secs) = 0.34 + 11.16 (delimb first) + 47.62 (m^3)*
2	*Processing time (secs) = 5.79 + 11.16 (delimb first) + 47.62 (m^3)*
3	*Processing time (secs) = 12.58 + 11.16 (delimb first) + 47.62 (m^3)*

Where

- *Delimb first =*

  ***0** if processing method is 'single pass' and;*

  ***1** if processing method is 'two pass'*

The regression indicates that an increase in one or a combination of the variables considered will result in an increase in production time for individual logs. A log with a high branch class increases production time as larger branches take longer to delimb. The type of processing method also determines production time. This is because when stems are delimbed prior to merchandising, this takes a significantly longer time than delimbing while processing. There is a significant relationship between the volume of each log and the production time required for each log. The variable log volume has the highest weighting on production as an increase in 1 m^3 significantly increases processing time by 47.62 seconds.

7. Discussion

7.1 Measurement Accuracy

Attaining accurate length measurement by the Waratah HTH 625c processor head is important because of the requirement for every log to be within a certain length tolerance. The measurement accuracy of log length by the Waratah 625c processor head has improved from older model Waratah processors that operated in New Zealand radiata pine stands. Of the logs measured, 98% of logs processed by the Waratah were within a ±5 cm length tolerance. This is higher than the Waratah HTH234 Evanson (1995) researched where 90% of logs measured were within ±5 cm and also higher than a study completed by Evanson and McConchie (1996) who found 93% of logs measured were within ±5 cm for a Waratah HTH 234. A more recent study on a different model of log processor found similar length accuracy at 98% within ±5 cm in a Chilean *Pinus radiata* stand (Carey & Murphy, 2005). This indicates that the Waratah 625 is achieving a similar level of measurement accuracy as other new model log processor heads.

The diameter calibration for the Waratah 625 processor head has been set to measure log diameters conservatively (Nieuwenhuis & Dooley, 2006). This effect is highlighted by the diameter measurement error distributions (Figure 7 and Figure 8), where the distribution has a positive skew towards underestimated diameters. The diameter sensors on the Waratah are calibrated to underestimate a logs diameter to ensure that a log with a diameter close to the minimum SED specification for a log grade is well within this requirement. This has implications for value recovery as the maximum value of a log may not be achieved because of underestimated diameter measurements (Conradie, Greene, & Murphy, 2003) (Boston & Murphy, 2003). However, the underestimated diameter measurements ensure that logs are correctly optimised into the grade when they are near the minimum specifications and limits rejection.

Retention of log QC based on this measurement accuracy research will depend on health and safety priorities by forest companies and a shift in the focus of the whole forestry supply chain. Currently, it is common for New Zealand forest companies to apply a ±5 cm length tolerance to their logs which the Waratah HTH 625c is not achieving 100%.

However, the difference between this tolerance and the length of the sawn lumber that is cut from a log grade is often greater than ±5 cm. As the difference between the log grade spec and the length of timber that is to be cut from the log is greater than the commonly accepted length tolerance, this may mean that a high percentage, if not 100% of logs are sufficiently long enough for the final timber length. The implication to this is that if a consistent tolerance level is adopted throughout the supply chain, and log specification tolerances can be relaxed, the risk of a man working around 2-5 heavy machines can be alleviated. With the current tolerances, the Waratah HTH 625c processor head cannot meet this standard for length and diameter and hence log QC is still required. What needs to be addressed is whether the risk of 1 in 50 logs being out of spec at the current tolerance level has a higher cost than the daily employment cost and reduced efficiency with a QC man on the skid site.

A change in the tolerances allowed for log specs negotiated throughout the forestry supply chain could benefit health and safety, reduce costs and improve productivity but will require new processes and performance measures implemented. New model processors have the ability to stencil log grades on log ends, so have the potential to carry out each task of the log QC. Without a log QC, the fleet loader does not have to double handle stems but can fleet logs straight into stacks so operational costs could be reduced. By way of discount to the log purchaser, this may incentivise the relaxing of log spec tolerances. The reduction in costs could further spread throughout the supply chain as harvesting costs could be reduced for the forest company.

Continuous tracking of length and diameter measurement accuracy through a Statistical Process Control (SPC) chart may be sufficient to replace log quality control. Samples of logs processed by the processor head are measured over a defined interval to track measurement accuracy. SPC charts can provide a measure of compliance to the log specifications the log processor is cutting to. The chart has the potential to provide a history of the machines accuracy and identify trends where the processor is working within the company specified tolerance or whether there is some factor influencing measurement accuracy (Boston & Murphy, 2003). SPC charts can be updated daily, or within a defined interval that ensures trends are captured. Future research can be completed in this area to identify a method of tracking measurement accuracy of a log processor that can be readily taken up by forest companies and harvesting contractors working with log processors.

Production radiata pine forests in New Zealand are physically demanding on machines. This is because of large diameters, large piece sizes and large branch sizes. The simplest way to reduce measurement error is to regularly maintain, calibrate and check the processor head (Marshall, Murphy, & Boston, 2006). Machines that are regularly checked for length and diameter accuracy at the logging operation retain the highest accuracy as the processor can be calibrated and corrected for measurement errors (Anderson & Dyson, 2001; Nieuwenhuis & Dooley, 2006). As Marshall and Murphy (2005) suggest, training and communication are also important for maintaining measurement accuracy. The operators of these machines need to understand how the measurement system of the log processor works and the importance of accurate length and diameter measurements to the operations profitability.

A limitation to the diameter accuracy measurements of this study arises from the way the Waratah processor estimates diameter and the method of physical measurement. The Waratah's diameter measurement technology filters diameter measurements to ensure that diameter decreases from the butt end to the head of the stem. What can occur to create a large difference between physical diameter measurement and the diameter calculated by the Waratah is when the physical measurement is taken over a whorl or branch stub at the log end. This then creates excessively large errors. Diameter measurements are further limited in that a builders tape was used to measure diameter instead of a diameter tape. As stems are eccentric in shape, the diameter measurements taken with the builders tape may have introduced bias.

7.2 The Effect of Branch Size

As discussed earlier, the forest resource in New Zealand has trees with large piece sizes and large branches which place a high physical demand on the log processor heads operating with them. These machines have intricate measurement technology that is required to calculate highly accurate measurements in a rough operating environment. This research determined that based on visual assessment, branch size has a significant effect on length measurement accuracy. The larger the branches are on a log being processed, the greater the measurement inaccuracy. This result is contrary to that reported by Anderson and Dyson (2001), and Eggers, McEwan and Conradie (2009) who found no significant relationship with branch size and measurement error. However, these measurement accuracy studies were completed in different countries with production forests that have smaller branches, different branch frequencies, piece size and species.

Logs without branches have the lowest measurement error (Branch class 0 had an average error of -0.03 cm) because the processor can make one pass over the length of the log, where there is less chance for slippage on the log by the measurement wheel to cause measurement error. Large branches require more power applied to the processor head, and consequently more strain on the processor head to delimb. At times, the processor is impeded from delimbing a branch, so is required to have a second attempt to force the delimbing knives through the branch. However, the consequence of making several passes with large impacts may cause length error as the measurement wheel can lose contact or slip along the stem and as a consequence lose its known position.

Branch size has a negative relationship with productivity in that the presence of branches significantly reduces the productivity of the processor to process logs. The processor head is often impeded by large branches which increases the time taken to process a log, consequently reducing productivity. However, it is important to note that within a harvesting operation, branches are removed when logs are hauled in from the hillside by the yarder and when logs are subsequently shovelled to the landing and stacked. This effect is to the advantage of improving productivity, in that the more branches that are removed, the lesser impact on productivity they will impose.

A limitation to the branch size analysis is that only three logs with large branches were measured for productivity and measurement accuracy. This small sample size may have bias in larger inaccuracies than the true measurement accuracy the Waratah 625 can attain with large branches. However, regression analysis without the large branching factor was still significant. Further work is required for a more in-depth study that assesses branch size and frequency. Instead of visually assessing logs for branch size, a sample or the largest branches identified would be measured for diameter prior to processing. This could provide a more comprehensive study and in-depth understanding of the effect of branch size on measurement accuracy and productivity.

7.3 Processing Method

Increasing productivity and efficiency of machines operating within production harvesting crews is important for reducing costs and increasing profitability. The one-pass processing method was significantly faster (1.58 min) than the two pass processing method (2.03 min). Both of these processing times are longer than those reported by Evanson and McConchie (1996) who found that a Waratah HTH 234 was two-pass processing at 0.67 min in a ground-based operation and 1.28 min in a yarder-based operation. Another study completed by Evanson, Riddle and Fraser (1994) measured the same model processor at 1.06 min for processing stems by the two-pass processing method. The reason for the large difference between these studies and the Waratah HTH 625c may be in part due to the 625c working in larger piece size. The Waratah 625 is designed for 'Big Wood' with large diameters, whereas the Waratah 234 is a smaller processing head designed for smaller diameter stems.

One-pass processing; albeit having a significantly faster processing time, had a larger associated length error. There is a trade-off then, where faster production comes at the cost of lower length measurement accuracy. Length measurement is highly important for every log. Diameter measurements are only a concern when the logs diameter is near the cut-off minimum SED for the log grade specification. However, the decision to one-pass process or two-pass process depends on length and diameter tolerance.

Given that the profit margins within the forest industry can be small when log prices are down, the trade-off for high production versus high value recovery is a decision each forest company has to implement. The production function created indicates that production time will increase with two pass processing, larger branches and increased log volumes. However, as the forest resource in New Zealand moves into subsequent rotations with higher quality genetics and smaller branching from narrower spacing (Mason, 2005), this will aid in improving production time for processing logs because of inherently better form and small branches that are easy to delimb. As branch size is further decreased, this may then enable higher accuracy measurements for length to be obtained for single-pass processing which then would enable high value recovery (Conradie, Greene, & Murphy, 2003) coupled with higher production and higher profitability to the forest industry.

8. Conclusions

The primary objective of this study was to determine the measurement accuracy of a Waratah HTH 625c processor head for length, SED and LED. Based on this research, the Waratah is highly accurate at measuring length but still undercuts and overcuts logs from the target length for a log grade. Diameter measurements are also accurate, except that diameter sensors underestimate actual diameter. Based on the length measurement accuracy, only 1 in 50 logs are outside of the ±5 cm length tolerance commonly imposed by forest management companies. This level of rejection can be reduced if grade specification tolerances are relaxed which may also alleviate the need for log QC. Also, as the diameters are calibrated to underestimate diameter, this further reduces the instances of rejection where a log has a diameter close to the min SED.

The analysis of Branch Class indicates that branch size has a significant effect on length measurement accuracy and productivity. The presence of branches reduces both length measurement accuracy and productivity. It was found that single pass processing was significantly faster than two-pass processing but that single pass processing had significantly larger length measurement errors associated. There is then a trade-off between having higher production but lower accuracy and lower value recovery.

The overall aim of this study was to quantify the measurement accuracy of a new model log processor head. With a trend towards mechanisation in forest harvesting, this research provides evidence to the improvement in measurement technology inbuilt into the new model specialist forestry machines. The Waratah HTH 625c is highly accurate at measuring length and diameter but still cannot meet the current grade specification tolerances. For this reason, log QC is still required. As the Waratah processor heads are continually improved and the NZ plantation resource improves in form with smaller branches, this will continue to improve measurement accuracy and productivity of log processor heads.

9. References

Anderson, B., & Dyson, P. (2001). Log Measuring Accuracy of Harvesters and Processors. *2001 Council on Forest Engineering (COFE) Conference Proceedings: "Appalachian Hardwoods: Managing Change"* (p. 5). Snowshoe, July 15-18: Forest Engineering Research Institute of Canada, Vancouver, British Columbia.

Boston, K., & Murphy, G. (2003). Value Recovery from Two Mechanized Bucking Operations in the Southeastern United States. *South. J. Appl. For. 27(4)*, 259-263.

Carey, P. B., & Murphy, G. E. (2005). Mechanised versus Manual Log-Making in Two Chilean Pinus Radiata Stands. *New Zealand Journal of Forestry Science 35(1)*, 25-34.

Clark, N. A., Wynne, H. R., & Schmoldt, D. L. (2000). A Review of Past Research on Dendrometers. *Forest Science 46(4)*, 570-576.

Conradie, I. P., Greene, W. D., & Murphy, G. E. (2003). Value recovery with harvesters in southeastern USA pine stands. *Forest Operations Among Competing Forest Uses*, (pp. 1-6). Bar Harbor.

Eggers, J., McEwan, A., & Conradie, B. (2009). *Pinus saw timber tree optimisation in South Africa: A comparison of mechanised tree optimisation (harvester/processor) versus current manual methods.* George: Nelson Mandela Metropolitan University.

Evanson, T. (1995). A Survey of the Quality of Mechanised Log-Making in New Zealand. *Logging Industry Research Organisation 20(6)*, 1-5.

Evanson, T., & McConchie, M. (1996). *Productivity Measurements of Two Waratah 234 Hydraulic Tree Harvesters in Radiata Pine in New Zealand.* Rotorua, New Zealand: New Zealand Logging Industry Research Organisation (LIRO).

Evanson, T., Riddle, A., & Fraser, D. (1994). An Evaluation of a Waratah Model HTH 234 Harvester in a Cable Hauler Operation. *Logging Industry Research Organisation New Zealand*, 1-10.

Larson, J. (2014, July). Waratah HTH625c. (R. Visser, Interviewer)

Marshall, H. D., Murphy, G. E., & Boston, K. (2006). Evaluation of the economic impacts of length and diameter measurement error on mechanical harvesters and processors operating in pine stands. *Canandian Journal Forest Reasearch (36)*, 1661-1673.

Marshall, H., & Murphy, G. (2005). Optimal log merchandizing on mechanical processor/harvesters: Opportunities and challenges.

Mason, E. G. (2005). *A brief review of the impact of stand density on variables affecting radiata pine stand value.*

Murphy, G. (2013). Procedures for Scanning Radiata Pine Stem Dimensions and Quality on Mechanised Processors. *International Journal of Forest Engineering*, 91-101.

Nieuwenhuis, M., & Dooley, T. (2006). The Effect of Calibration on the Accuracy of harvester Measurements. *International Journal of Forest Engineering 17(2)*, 25-33.

Strandgard, M. (2009). Evaluation of Manual Log Measurement Errors and Its Implications on Harvester Log Measurement Accuracy. *International Journal of Forest Engineering 20(2)*, 9-16.

Strandgard, M., & Walsh, D. (2012). *Assessing measurement accuracy of harvester heads in Australian pine plantations.* Tasmania: Cooperative Research Centre for Forestry.

Waratah. (2010). *TimberRite 30H Measuring and Control System Ver 2.8.3.* Tokoroa, New Zealand: Waratah NZ Limited.

Waratah. (2014, October 7). *HTH625c Harvester Head Quick Specs.* Retrieved from NZ Waratah Web site: http://nz.waratah.net/hth625c.html

WorkSafeNZ. (2014). *Response to the indpendent forestry safety review.* Work Safe New Zealand.

10. Appendices

10.1 Appendix 1

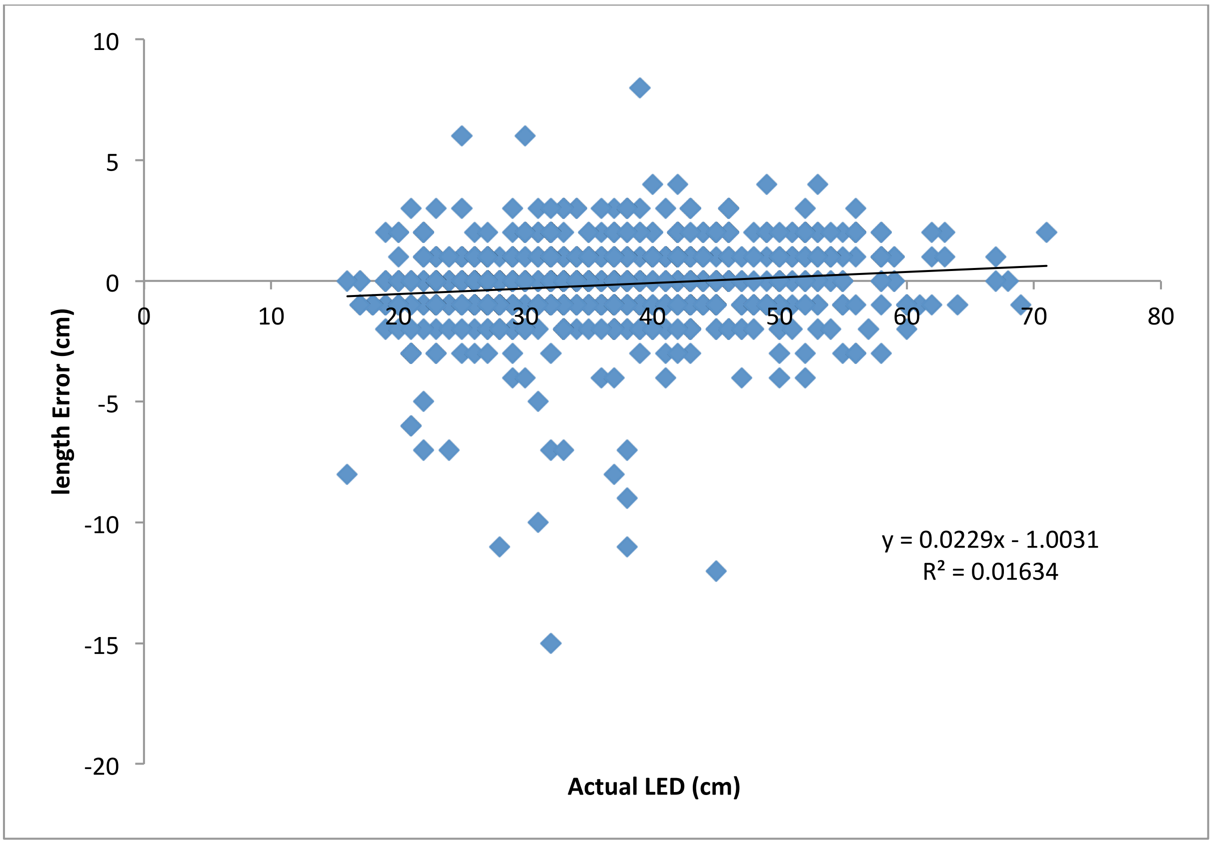


Figure 13: Length Error regressed over large end diameter

10.2 Appendix 2

General Regression Analysis: Productivity vs LED, Branching

Regression Equation

Branching

0	productivity	= 40.1117 + 1.10126 LED
1	productivity	= 38.9842 + 1.10126 LED
2	productivity	= 19.4533 + 1.10126 LED
3	productivity	= 5.84593 + 1.10126 LED

Table 11: Regression coefficients

Coefficients				
Term	Coef	SE Coef	T	P
Constant	26.098	10.372	2.516	0.012
Branch Class 0	14.012	6.862	2.042	0.042
1	12.885	7.480	1.722	0.086
2	-6.645	9.215	-0.721	0.471
LED	1.101	0.216	5.091	0.000

Summary of Model

S = 41.5583   R-Sq = 10.27%   R-Sq(adj) = 9.16%

Analysis of Variance

Table 12: Analysis of variance for the regression equation

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	63676	63676	15919.0	9.2172	0.0000005
Branching	3	18901	11331	3777.1	2.1870	0.0894643
PhysLED	1	44775	44775	44774.7	25.9249	0.0000006
Error	322	556123	556123	1727.1		
Lack-of-fit	95	225478	225478	2373.5	1.6295	0.0017035
Pure Error	227	330624	330645	1456.6		
Total	326	319799				