Investigating Factors that Influence Processor Productivity

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

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1. Abstract

In the last decade, there has been a transition from motor-manual processing to mechanised processing. This transition occurred rapidly over the past eight years due to increased awareness of health and safety, with some 33% mechanisation (ground-based) in 2009, increasing rapidly to 88% in 2017. Understanding factors that influence processor productivity is important to better estimate contractor rates and production targets.

A time study was completed on behalf of Hancock Forest Management at five crews in six locations within Kinleith forest estate over the summer of 2018/19. Data was collected from detailed video footage and STICKS woodflow management system.

Three factors were compared against processor productivity within this study, those being piece size, tree form, and skid size.

Cycle times analysing processor work tasks demonstrated that the majority of time was spent processing stems (59%). An overall utilisation rate of 91% for all crews was estimated; however, this only accounted for delays less than ten minutes. The average productivity for these six locations ranged between 34.8 m^3/hour and 79.1 m^3/hour, with average productivity of 62.7 m^3/hour. Statistically significant differences were identified between locations, suggesting that crew productivity cannot be assumed to be uniform.

A positive relationship could be observed between piece size and productivity for all crews in this study, suggesting that a larger piece size will yield a higher average productivity. Tree form categorised stems into one of three groups; 0 (Good), 1 (Poor) and 2 (Bad). A stem in category 1 took 54% longer and a stem in category 2 took 84% longer to process than a ‘good’ stem (0). A negative trend between tree form and productivity was observed. Larger skid size reduced the average delay per stem while also increasing the productivity of the processor, but with only 6 skids this result is not statistically significant.

Keywords: processor productivity, piece size, tree form, skid size.

2. Acknowledgements

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3. Introduction

3.1 Background

The way in which stems are processed at skid sites has changed significantly over the past decade from motor-manual to mechanised processing. This rapid transition came from improvements in technology, skill shortages impacting on harvest companies, an increased drive to improve productivity and health and safety performance in the forestry industry. In 2009, only 33% of processing was mechanised. By 2017, this had increased to 88% (Visser, 2018).

The use of mechanised processors has significantly improved the productivity of crews and provided better quality assurance and information on harvested stems. However, with increasing mechanisation came other challenges – high purchase costs, increased running costs and maintenance, and process challenges caused by machine unavailability, breakages and maintenance down time.

Most productivity studies in a forestry context, investigate the entire harvesting system or study specific aspects of the operation, i.e. the entire crew or machinery involved. Many studies have investigated the productivity of felling, forwarding and skidder machinery. However, there is a lack of literature investigating processor machinery in New Zealand. Forest processor machines are used to delimb and cut stems into defined log grades typically operating in either in the cut-over or on the skid site. This is the stage in the harvesting operation where value is gained from the stem.

Productivity incorporates both the cycle time of the machine and the volume of material that is handled in that time. The productivity of such machinery will influence contractor rates ($/ton) as well as the production targets for the crew (Visser, 2009a).

With the changes in capital and operational costs, has come the need to clearly understand the factors that influence the productivity of the mechanised processor. This report provides a case study to identify and analyse these factors.

3.1 Mechanisation

Harvesting operations have rapidly transitioned from predominantly motor-manual to mechanised machines over the past 20 years (Riddle, 1995). Health and safety of forestry workers when processing stems (delimbing and log grading) and difficulties attaining skilled forest workers has accelerated the mechanised processing transition (Riddle, 1995). Increased log production is an unintended benefit associated with the forest processing mechanisation.

Mechanisation in both ground-based and cable-based harvesting systems continues to increase throughout New Zealand. The task of log-making where stems were cut and processed into defined log grades using motor-manual chainsaws has been substituted mainly for mechanised machines (Riddle, 1995). This is evident with some 33% mechanised processing in 2009, increasing to 88% mechanised processing in 2017 (Visser, 2018). This represents a significant increase in mechanisation in a short eight-year window of time.

The determination of log grades cut was previously done based on personal measurements and experience, which was both labour intensive and time-consuming. With the transition to mechanised processing, most of these log-making decisions are made using onboard computers to eliminate log grade error and reduce cost (Riddler, 1995).

Processor machinery operating in New Zealand typically consists of an excavator base with a boom, to which the processing head is attached. Stems are seized and run through the processing head to attain length and diameter data; this is used to determine the appropriate cut to make. An onboard computer inside the cab of the machine displays the ‘suggested’ log grades to be cut, to which, the operator can change based on characteristics of the stem which the computer does not take into consideration.

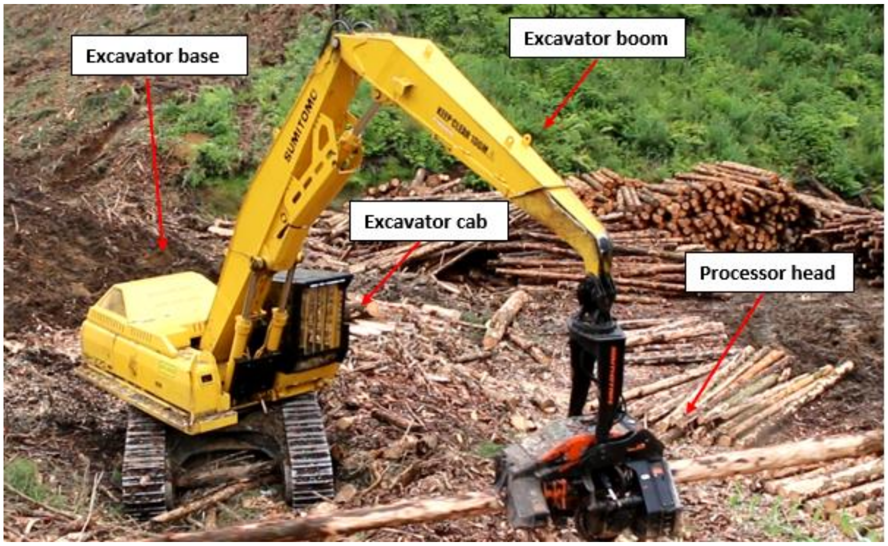

Figure 1*: Image of a processor in operation at crew F with identification of key machine components.*

The New Zealand forestry industry has been using mechanised processing machinery since the late 70's and early 80's (Riddle, 1995). The popularity of processing machinery has increased significantly over the past 40 years in both ground-based and cable-logging operations. Approximately 1,100 processing machines are operating in domestic forestry operations; this is assuming a total of 9,500 full-time workers in crews of 8 (Nixon *et al*. 2017), with 88% using mechanised processing (Visser, 2018).

However, there is high variability in the assortment of processing machines in New Zealand operations. Crew owners must evaluate the economics; purchase, maintenance and running costs, available labour; skilled workers to operate machinery, technical restrictions; ability to process stems, and machine availability (Castro *et al*. 2016). In addition, there is a large variety of processing manufacturers selling into the New Zealand market; Southstar, Waratah, Satco, and Woodsman, to name a few. Machinery selection is generally made according to economic constraints and fitness for purpose for the harvesting operation.

3.2 Productivity Studies

The relationship between influential variables with work inputs and work outputs describes the intention of work measurement (Magagnotti & Spinelli, 2012). Time and motion studies are the most common and most accurate method to collect detailed data on forestry machinery, which examines production cycles (Olsen *et al.* 1998). For a processor, this would be the time taken to select, delimb and process a stem, considering any delays incurred. The use of comparative studies investigates the potential effects of fixed factors (covariates or continuous variables) on time consumption or productivity (Magagnotti & Spinelli, 2012). Such studies are commonly used in the forestry industry to better understand and improve on-site operations (Visser & Spinelli, 2008). However, the collection of data for time-motion studies can be hazardous due to the proximity needed to observe forest machinery (Strandgard & Mitchell, 2015).

In order to attain accurate time-motion values, nuisance variables and other factors that are not being investigated need to be controlled or eliminated. To achieve this, variables should be kept constant or in perpetuity (e.g. ensuring that the same operator is performing the task). Alternatively, randomization or inclusion techniques could be used (Magagnotti & Spinelli, 2012).

3.3 Previous Studies

The use of time studies to analyse processor productivity and utilisation are standard practice in many forest harvesting studies. Many of these studies assess factors that influence productivity, including operator experience (Ovaskainen *et al,* 2004; Spinelli *et al,* 2007; Visser, 2009b), machinery used (LeDoux & Huyler, 2001; Spinelli *et al* 2011), piece size (Nakagawa *et al*, 2010; Puttock *et al*, 2005; Spinelli *et al,* 2010; Tufts, 1997), tree form (Evanson & McConchie, 1996; Tolan, 2014; Ramantswana *et al*, 2012) and number of grades cut (Tolan, 2014). The comparability of these studies in a New Zealand context is challenging as many of the studies were carried out in forests with different characteristics to those found in New Zealand.

Operator Skill

The influence of operator skill and experience when operating machinery is well documented within the forestry industry. Differences in productivity values for feller-buncher machinery may be due to the varying skill level of operators between sites (Spinelli *et al.* 2007). Mechanised harvesting productivity was found to be influenced by operator experience, with variation in machine productivity of 20-50% due to human performance (Murphy & Vanderberg, 2007). A similar conclusion was made in a study by Ovaskainen *et al.* (2004) stating that productivity levels between harvester operators varied up to 40% in a similar stand because of operator experience, motoric skills, decision processes and environmental effects.

Piece Size

The relationship between forests of a low stocking per hectare and an increased piece size is well documented in scientific literature (Muñoz *et al.* 2008; Pinkard & Neilsen, 2003). The advantages of increased piece size is that larger logs typically attain a higher price in the marketplace (Cassidy *et al.* 2012). However, it should be noted that with increased spacing between trees the diameter of branches increased (Hébert *et al.* 2016). There is a trade-off between having a lower stocking with fewer larger stems compared to having a higher stocking with a greater number of small trees (D'Amato *et al.* 2011).

Stem piece size is defined as being the average size (m^3 or tonnes) of felled trees or extracted sections. A positive relationship can be observed between piece size and productivity in feller-buncher machinery with piece size being identified as an influential factor (Visser & Stamper, 2003). Likewise, a positive relationship can be observed between productivity and piece size in felling operations (Hånell et al. 2000; Ramantswana *et al.* 2012) as well as when crosscutting into log grades and delimbing (Tufts 1997; Puttock et al. 2005). Harvesting operations in an Italian setting found that the time to process increased linearly with piece size to a point where tree size reached the capacity of the machine (Spinelli *et al*. 2010).

The time taken to process larger trees is longer than that when processing smaller trees in respect to piece size (Nakagawa *et al.* 2010). Increases in piece size will result in increased production levels due to less work required to drag a given volume of stems to the landing (Anon, 2005). However, if stem piece size is too large for the processor head, it is expected to take longer to process and result in lower production (Nakagawa *et al.* 2007). This is phenomenon is known as the 'piece size law' (Visser & Spinelli, 2012).

Number of Grades Cut

The number of log grades being cut in forest harvesting operations can vary depending on wood availability and market conditions. The number of log sorts produced in New Zealand forests is a result of both domestic and international requirements; more grades result in higher value recovery per stem (Cossens, 1991). With a higher number of log grades, processing operations can become more complicated, influencing machine productivity. This is demonstrated in a negative trend between productivity and the number of log grades (Tolan, 2014).

Tree Form

Variability in tree form can arise as a result of stocking (Hébert *et al.* 2016), site and soil characteristics and a range of environmental factors (Zobel & Buijtenen, 1989). Deformations including stem forking, multi-leaders, sweep and large branchings can negatively influence processor productivity due to increased time required to process stems (Evanson & McConchie, 1996; Muhummad *et al.* 2013; Tolan, 2014). Research conducted in South Africa identified that tree form was a significant influencing factor in a*cacia mearnsii* felling operations (Ramantswana *et al.* 2012). From this research, a relationship was established, describing how productivity decreases with worsening tree form (Ramantswana *et al.* 2012).

Skid Size

A skid site or forest landing is described as a cleared flat piece of land used to process stems, store logs and load out trucks (Visser *et al*. 2010; Stokes *et al.* 1989). Considerable costs can be incurred to construct skid sites, making their location and size crucial for efficient harvest operations. Skid layout and size is dependent on woodflow, extraction system, and other restrictions of the harvest area – e.g. nearby waterways, site access (Anon, 2005). The size of the skid site is influenced by the total and/or daily production for the crew and the number of log grades being cut (Visser *et al*. 2010). Skid sites with a poor layout or of insufficient size can result in delays which reduce productivity (Anon, 2005).

3.4 Problem Statement

The transition from motor manual processing to solely mechanised processing over the last decade in Hancock Forest Management (HFM) estates has provided a number of productivity benefits. These include reductions in operator-machine interactions, improved performance in health and safety and increased production. However, there is a lack of analysis of what factors most influence processor machinery due to the unique stand characteristics and forest structure found in New Zealand; prior international studies have limited relevance.

For HFM, identification and quantification of factors that influence processor productivity is key to understanding constraints to harvesting operations and improving productivity. By setting production targets that exceed crew capabilities, there are increased safety risks and overworking crew and plant equipment. However, setting targets too low will result in higher costs and overpayment of logging rates. Getting the balance right is the key to efficient harvest management and this HFM case study will investigate three factors to better understand their effect and significance on HFM processor productivity:

1. Piece size
2. Tree form
3. Skid size

In doing this research, HFM forest managers may better understand what factors they should focus on to influence the processor and machine productivity, allowing more accurate estimations for logging rates and production targets. Two research questions have been addressed for this study:

1. What is the average production level for processors in Kinleith forest estate?
2. Do piece size; tree form; and skid layout affect processor productivity?

3.5 Hypothesis

In order to answer these questions, the following hypotheses have developed to test for statistically significant differences:

1. H_0: There is no statistical difference in processor productivity between crews.

   H_1: There are statistical differences in processor productivity between crews.

2. H_0: The effect of factors measured are found not to influence processor productivity.

   H_1: The effect of factors measured are found to influence on processor productivity.

4. Methods

Study Sites

The processor works on the skid site or in the cut over and is used to cut stems into defined log grades. For this study, all processor machines were operating on a skid site. A representation of how the processor fits into a harvesting operation is provided in *Figure 2*, below.

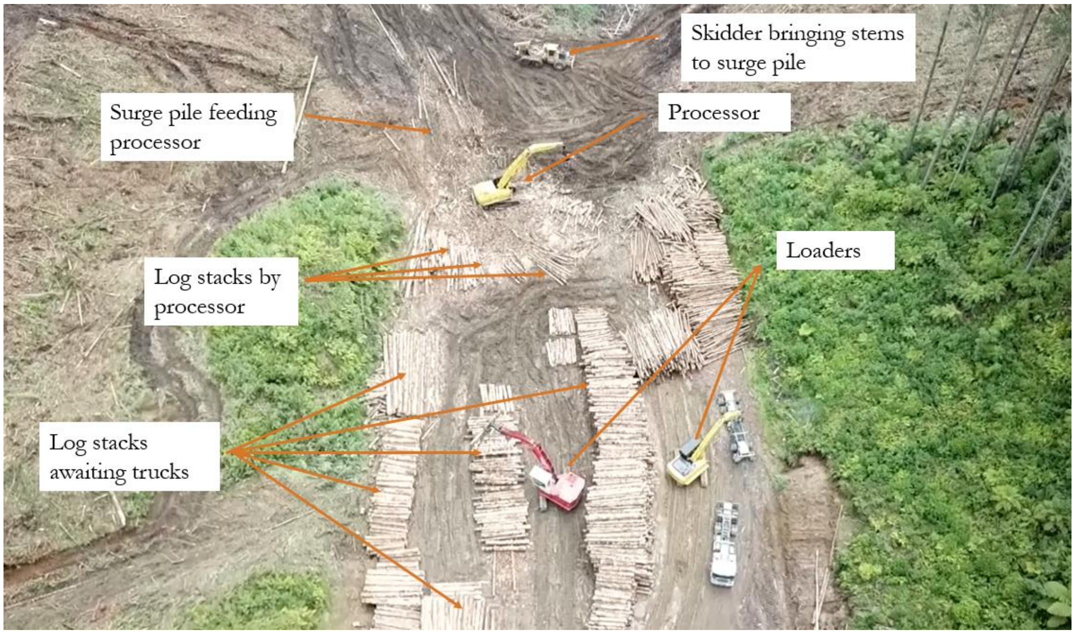

***Figure 2**: Illustration of a typical skid site investigated as part of this study.*

Crews can operate with a range of different equipment depending on the characteristics of the stand and the production target set. Stems are felled in the cutover by a forestry worker via motor-manual chainsaw or mechanised machine. A skidder then retrieves these stems and transports them back to the skid site where they are stacked into surge piles for subsequent processing. The processing machine then picks up a stem and cuts it into logs, arranging logs into graded groupings for the loader to sort and stack.

For this study, all processor machines operated with surge piles; a collection of stems brought to the landing by the skidder. This pile acts as a buffer to prevent delays, in case the felling machine or skidder breaks down. Processing machinery is typically operational every working day (subject to breakdowns).

To analyse factors that influence processor productivity, data was collected from five crews operating at six locations in the Central North Island. All crews were operating on behalf of HFM in the Kinleith forest estate. Machine configurations, skid site size and layout varied amongst crews; however, all machinery was deemed to be ‘fit for purpose'. The characteristics for each crew location have been summarised in *Table 1*, as shown below. Estimated skid size, area to be harvested, stand age and volume throughput was gathered from pre-harvest documentation for each location. Number of crew members, average piece size and site descriptions were collected from surveys collected by crew members at each study location (*Appendix 1*).

***Table 1**: Summary of characteristics for each crew location investigated within this study.*

Crew	**Skid size (m^2)**	**Area to be harvested (ha)**	**Volume throughput (m^3)**	**Number of crew members (#)**	**Stand age (years)**	**Average piece size (m^3)**	**Description**
A	3,600 m^2	11 ha	7,172 m^3	8	26 years	1.81 m^3	Operating in harvest area for two weeks.
B	3,150 m^2	5.6 ha	3,617 m^3	8	26 years	2.05 m^3	Operating in harvest area for four weeks.
C	2,800 m^2	8.8 ha	4,980 m^3	8	25 years	1.35 m^3	Operating in harvest area for one week.
D	2,800 m^2	10.8 ha	6,870 m^3	6	28 years	1.8 m^3	Operating in harvest area for three weeks.
E	2,750 m^2	3.8 ha	2,580 m^3	5	29 years	1.7 m^3	Operating in harvest area for seven weeks. Skid was split across a secondary road.
F	3,500 m^2	10.8 ha	7,333 m^3	5	29 years	2.05 m^3	Operating in harvest area for five weeks.

Operator

The experience of each operator varied slightly. However, all individuals had been working with processor machinery for at least two years, as described in *Table 2*, below.

__Table 2__: Summary of the number of years operating processor machinery by each crew.

Crew	Years' operating processor
A	4 years
B	4 years
C	2 years
D	2 years
E	4 years
F	4 years

HFM harvest managers were approached to determine the experience of processor operators. As the managers had an in-depth knowledge of the skill of each operator, their insight provided suitable individuals for this study. This was reinforced by an operator interview in which information concerning the time spent in the harvest area, experience, formal and informal training was gathered (The questionnaire is shown in *Appendix 1*).

As well as many years' experience operating the machine, all operators possess the appropriate qualification/documented competencies to operate the machine. In harvesting operations, the person operating the processor is typically one of the most highly paid employees as the conversion of stems into logs maximises value recovery. Because of this, workers typically progress 'through the ranks' with experience across a wide range of site machinery before becoming the processor operator. As a result, operators have multiple years working with heavy machinery before working with the processor.

STICKS Data

An integral part of a forest harvester's role is to monitor and assess each crew with respect to their performance. One tool used to analyse this is STICKS harvest wood flow management and reports (provided by Interpine). This provides a system for receiving, processing, and examining Standard for Forest and Data Communication Data (StanForD). This is used to aid in managing forest woodflow and production. StanForD is the standard for communication between both machine computer and office analysis, providing a crucial link for information analysis.

STICKS data provided a .PRI file for the daily production of the machine. This file was sourced from the processor's onboard computer which provided details surrounding the grades, volumes, small end diameter (SED), large end diameter (LED), log length and a forced cut description (manual or automatic). Data is typically uploaded at the end of the working day to a mediatory company who decrypts the code and reformats it into a structure for forestry companies to analyse. Using this data, harvest managers can compare the percentage and volumes of different log grades cut as well as comparing weekly or daily production to the agreed rate.

Time and Motion Study

A video camera was set up to attain footage concerning the time spent by the processor performing work tasks. Detailed video recordings were taken in grouped twenty-minute segments giving roughly two hours of footage per shift. The video footage had an associated timestamp which was used to calculate the time taken to perform each work task and therefore providing the total time associated with processing each stem. Documentation of this time was recorded and entered into a Microsoft Excel spreadsheet.

Number of Replicates

The number of replicates used when undertaking a time study experiment will influence the accuracy and variability of the study (Illumina, 2010). The number of replicates must be specified with the definition of the observational unit (Magagnotti & Spinelli, 2012). The traditional equation used to determine the sample size for cycle level analysis of harvesting operations are defined by Murphy (2005):

$$\text{Number of replicates} = t^2 * V/E*Mean/100)^2$$

Where: t = Student's t-value (=1.96 for a 95% confidence interval -> $t^2 = 3.842$)

V = expected variance of work cycle time

E = level of precision required (e.g. 5%)

Mean = expected mean of work cycle time

However, using this methodology can exaggerate the number of replicates needed, which can make it infeasible due to time constraints. The scope and purpose of the study must be considered when estimating the required number of replicates. As a result, determination of the number of replicates for a study is often estimated on an educated guess or through a pilot study (Magagnotti & Spinelli, 2012).

Segregation of operational tasks into clear groups allows the calculation of time consumption for production steps or work tasks within a harvest operation. The most common example of classification of forest work is taken from the Nordic Research Council, which were harmonised by the IUFRO (1995). However, some level of variation from this template will occur for unique production studies.

Task classification for harvesting operations can vary depending on the scope and the machinery studied. For felling and felling/processing machinery, work tasks performed can be divided into six categories (Visser, 2009b):

Table 3*: Classification and definition of work tasks performed by felling or felling/processing machinery.*

Work Task	**Description**
Fell	Severing the tree and bringing it to the ground.
Delimb	Removing branches from the whole tree.
Bunch	Aggregating stems for subsequent extraction.
Move	Travelling to a new location or tree.
Clear	Removing slash and woody debris from delimbing or felling.
Delay	Operational and mechanical delays

In order to evaluate the time spent by the processor, the specification of work tasks performed was needed (*Table 4).* The work tasks used were a variation of those used in literature published by Visser (2009b), as described in *Table 3*, above.

Table 4*: Quantification of work tasks performed by the processor for subsequent timing.*

Category	**Description**
Boom swing	The time between the final cut and grappling next stem.
Delimbing	Time taken to Removing branches from the whole tree.
Processing	First cut made to stem until the final cut.
Delays	Machine not processing or performing unrelated tasks, delays <10 min.

With definitions of processor work tasks, the associated times could be recorded based on detailed video footage.

Tree Form

Categorical number-based systems can be used to characterise differences in tree form and branch sizes (Puttock, 2005; Ramantswana *et al.* 2012). Evaluation of tree form was completed using a categorized numerical system which specified stems between 0-2 with quality decreasing with an increasing category. In order to quantify the quality of each stem, several factors were evaluated: branch size, frequency of branches, tree sweep, and the absence or presence of multi-leader or forking of the stems. Taking these into consideration, the following classification system was developed (*Table 5*):

Table 5*: Description of tree form categories used to classify tree form.*

Category	**Description**
0 (Good)	No deformations.
1 (Poor)	Some large branching and/or slight sweep.
2 (Bad)	Large branching and/or severe sweep and/or multi-leader and/or forked stem.

Determination of tree form was completed in the office and on-site using both recorded video footage as well as written notes while the machine was operational; these were assigned to the specific stems later. Example of stems in each of the three tree form categories are shown in *Appendix 2-4*.

Calculating Productivity and Utilisation

To estimate the productivity of the processor for a given stem, the time to process each stem needed to be matched with the corresponding piece size (m^3). STICKS data provided the piece size of each log rather than for each stem. The logs cut from each stem were combined in order to give the overall piece size for a given stem. With the time to process and piece size for each stem, the productivity could be calculated.

For this study, productivity was calculated in m^3/hour. Productivity was calculated based on the time to process and piece size for each stem; this was then scaled to give a m^3/hour value. This scale factor divided 3,600 (the number of seconds in an hour) by the time to process for each stem, to demonstrate how many stems could be done per hour. The associated piece size for the stem would then be multiplied by this scale factor to calculate the cubic meters per hour.

<u>*Example*</u>:

Time to process: 158 seconds

Piece size: 2.5 m^3

3,600 seconds / time to process = scale factor

3,600 seconds / 158 seconds = 22.8 cycles of that stem per hour

22.8 cycles * piece size = productivity (cubic meters per hour)

22.8 cycles * 2.5 m^3 = 57 m^3/hr.

The productivity of each stem was calculated using this methodology to give a spread of values for each crew. This method took into consideration the fact that smaller stems take less time to process on average, resulting in more cycles per hour. However, this would ultimately be cancelled out as the piece size was smaller, resulting in a reduced productivity value.

Utilisation rate denotes the ratio of productive machine hours (PMH) against the scheduled machine hours (SMH) to estimate the percentage of productive time for a given machine. As such, PMH is the sum of all machine time spent performing work tasks, for this study tasks include time to swing the boom to collect stem, delimbing time, and time to process each stem into logs. The SMH uses the same ‘productive' times, however, includes downtime where the machine is not operational; such as delays or non-productive tasks. Calculation of the utilisation rate (%) is done using the following equation:

Utilisation rate (%) = (PMH/SMH) * 100

Forest managers and contractors can use this utilisation rate to better estimate associated running costs or evaluate the potential of buying or selling the machine. However, as this study is only considering delays less than ten minutes, the application of the utilisation rate is limited.

Data Analysis

RStudio statistical software was utilised to complete analysis of variance (ANOVA). Models within ANOVA were used to determine whether there were statistically significant differences between mean values. These tests were used to evaluate the presence or absence of statistically significant differences between average crew productivity. This was completed assuming a p-value of 5%, or $P \leq 0.05$. Factors with p-values higher than this were deemed to be non-significant.

Data analysed in RStudio was sourced from Microsoft Excel spreadsheets which contained data associated with time per stem and piece size. Microsoft Excel served as the template for the collection and recording of raw data from video footage and STICKS files. Data was input into spreadsheets for preliminary sorting, and values were subsequently transferred to RStudio for data to be further filtered. This data was used to develop graphs and tables to illustrate observed trends within the study.

5. Results

Data for this study were collected over the summer of 2018/19 from five crews operating in six locations within HFM Kinleith forest estate. Ten hours of detailed video footage was collected and analysed using approximately two hours of footage recorded at each site.

5.1 Utilisation

The analysis of video footage provided a means to identify and assess work tasks performed by the processor machine operator. The time spent was categorised into four groups: time to process, boom swing time, time to delimb and delay time (*Table 4*). The time associated with each task for all crews is shown in *Figure 3*, below.

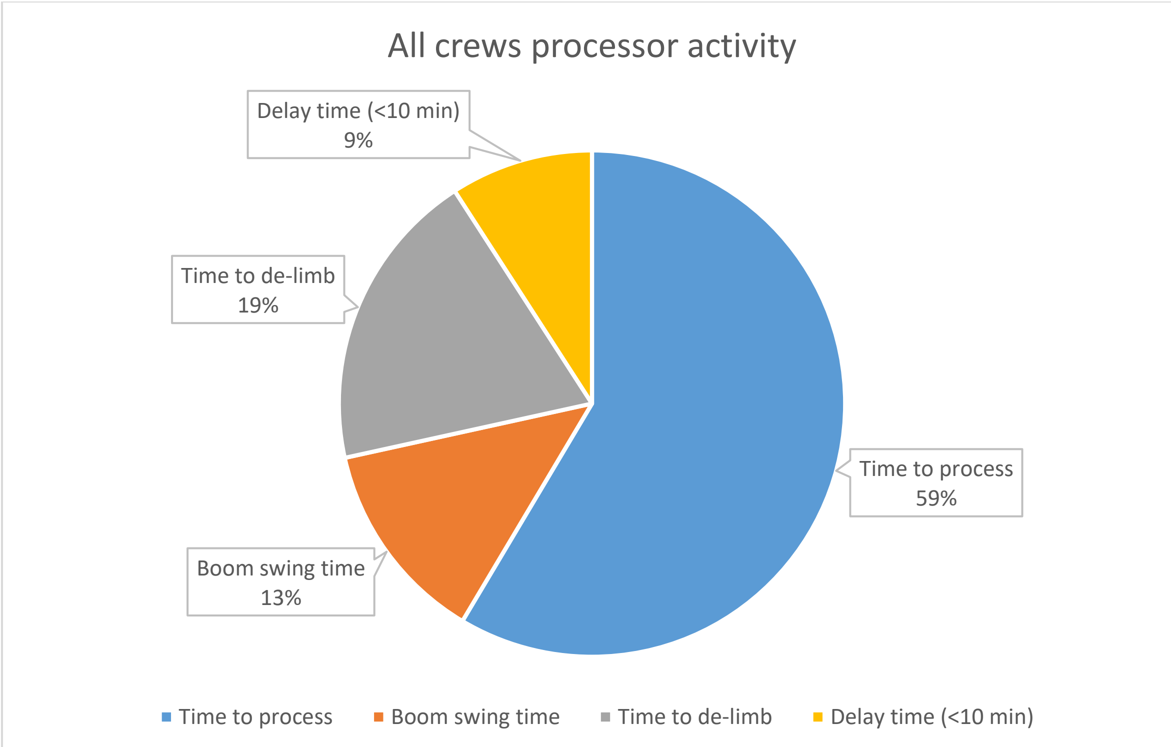

***Figure 3**: Percentage of time spent by a processor performing work tasks for all crews.*

Aggregation of this data shows the 59% of time was spent processing stems into logs. This is to be expected as this task is where the value is added from stem assessment, to ensure that the optimal logs are cut. The time to delimb stems was 19% of the time. Delay time of 10 minutes or less accounted for 9% of all time spent by the processor. Based on this delay time, the utilisation rate estimated for all crews was 91%, suggesting that the processor is performing work tasks 91% of the time. It should be noted that only delays less than ten minutes were used in this analysis as detailed video footage was used.

There was considerable variability in the time spent performing tasks for each crew. The results from this analysis are demonstrated in *Appendix 5-10.*

5.2 Productivity

Productivity takes into account both the time taken to perform work tasks for a stem and the associated piece size. The average productivity estimated for each crew was derived from the average of all individual stems given in cubic meters per hour. There was significant variability within crews concerning their productivity, as demonstrated in *Table 6*, below.

Table 6: *Productivity statistics calculated for investigated crews.*

Crew	Average Productivity (m^3/hour)	5^{th} Percentile (m^3/hour)	95^{th} Percentile (m^3/hour)
A	79.1	11.2	149.3
B	62.8	14.3	128.2
C	34.8	4.3	82.1
D	51.8	5.7	137.3
E	73.4	9.2	189.2
F	65.4	21.0	115.8

The overall average for all crews was 62.7 m^3/hour, however the range varied between a low of 34.8 m^3/hour at crew C, to a maximum of 79.1 m^3/hour observed at crew A. This represents a maximum difference of 44.3 m^3/hour between crews investigated in this study. The 5^{th} and 95^{th} percentiles demonstrate significant variability in the productivity values attained at each crew. This is further supported when looking at the 'box and whisker' distribution as shown in *Figure 4*, below.

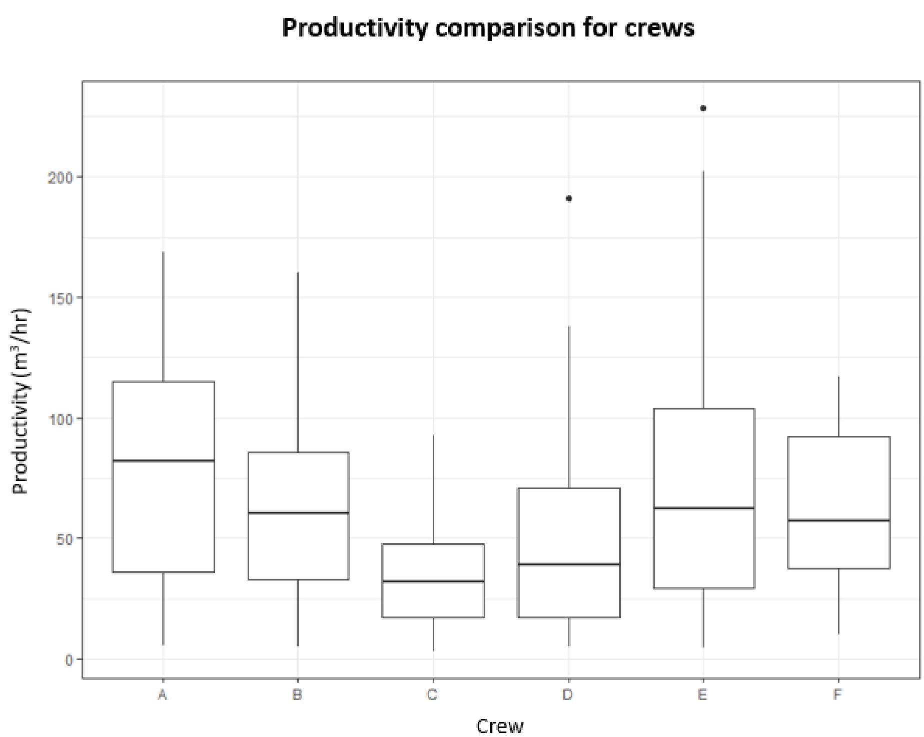

Figure 4: *Box and whisker graph comparison of processor productivity values for crews studied.*

The broad distribution of productivity values achieved at each crew is highlighted in *Figure 4*, above. These trends suggest that there may be statistically significant differences in the mean productivity values for crews. To test this theory, an analysis of variance (ANOVA) test was completed in RStudio, assuming a p-value of 0.05 (5%). The ANOVA tested the following null (Ho) and alternative (Ha) hypotheses:

H_0: There are no statistically significant differences in average productivity between crews.

H_1: There are statistically significant differences in average productivity between crews.

For the null hypothesis to be rejected, the p-value associated with the relationship would need to be less than 0.05.

The ANOVA test established that there were statistically significant differences in average crew productivity. The relationships that demonstrated p-values of less than 0.05, and therefore reject the null hypothesis, are shown in *Table 7*, below. It can be assumed that if the ANOVA test demonstrated a p-value greater than 0.05 between crews that the relationship or difference in means is not statistically significant, accepting the null hypothesis.

Table 7*: ANOVA analysis demonstrating statistically significant differences (P<0.05).*

Crew	P-value
A-C	0.0001
A-D	0.0438
B-C	0.0016
C-E	0.0001

Statistically significant differences between average crew means occur when either crew A or C are involved. As shown in *Figure 4* above, these crews demonstrate the highest average mean (crew A) and the lowest average mean (crew C).

Furthermore, follow up analysis using an 'emmeans' (estimated marginal means) test was completed and graphed to demonstrate differences between crews (*Appendix 11*). Red arrows are for comparisons between crews, whereas the blue bars represent the associated confidence intervals. If an arrow from one crew fails to cross that of another crew, then the relationship is statistically significant. The graph illustrates that there are statistically significant differences between crews A-C, A-D, B-C, and C-E (these were between means of 79.1 – 34.8 m^3/hour, 79.1

- 51.8 m^3/hour, 62.8 – 34.8 m^3/hour, and 34.8 - 73.4 m^3/hour respectively). These coincide with results produced from ANOVA testing (*Table 7*).

5.3 Productivity and Piece Size

Piece size was derived from STICKS data associated with the cumulative logs cut from each stem by the processor. The piece size study aimed to investigate to what extent (if any) piece size has on processor productivity. With this knowledge, productivity estimates can be tailored based on the piece size found within harvest areas.

Machine productivity was derived from the time to process individual stems, scaled up to give a cubic meters per hour value. The average piece size for each crew varied from between 1.35 m^3 (crew C) to 2.05 m^3 (crew B and F), quite large for New Zealand standards. However, there was considerable fluctuation in piece size around the mean; a maximum observed piece size of 4.45 m^3 with a minimum piece size of 0.045 for the crews studied. Productivity calculations considered the time to swing the machine boom, delimb the stem, process into logs and average delay per stem. The relationship between productivity and piece size for all crews (colour coded for each crew) is illustrated in *Figure 5*, below.

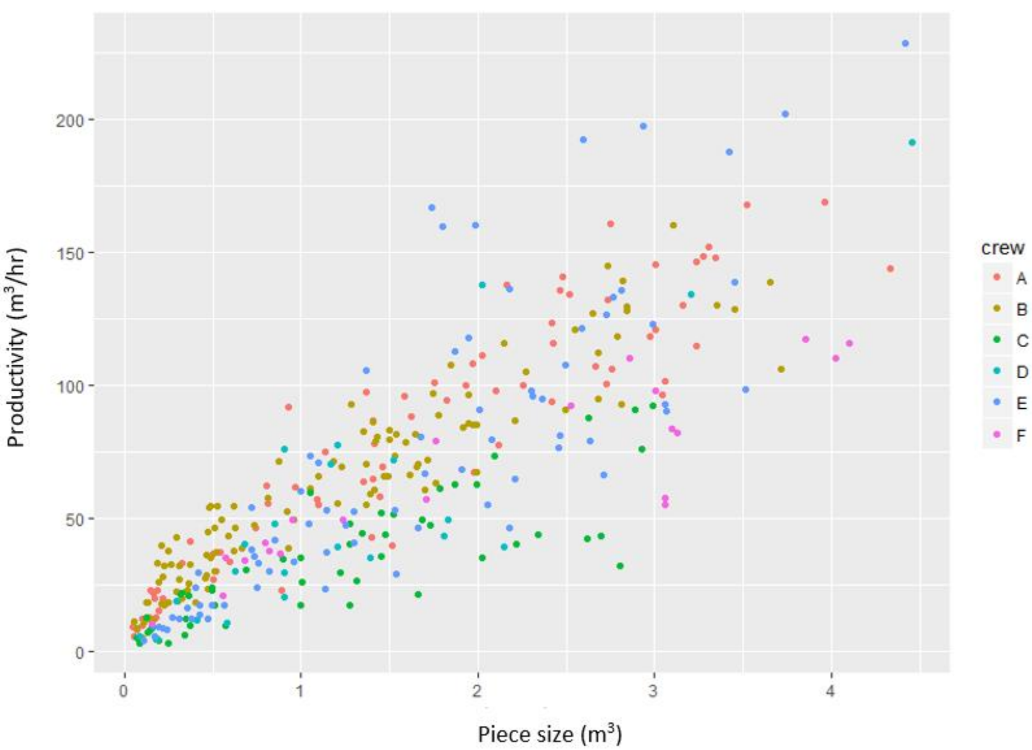

Figure 5*: Illustration of productivity against piece size for all crews investigated in this study, colour coded to segregate crews.*

A clear positive trend between piece size and productivity can be observed in *Figure 5*, above. The trend suggests that a larger piece size corresponds with increases in productivity; demonstrated in the associated equation below.

$$\mathbf{y = 34.7x + 11.3}$$

$$\mathbf{R^2 = 0.70}$$

This equation demonstrates that with every cubic meter increase in piece size, the expected productivity of the processor increases by 34.7 m^3/hour. The intercept of 11.3 has limited use for this study as productivity is dependent on piece size; when piece size is zero, there will be no productivity. The r-squared value or coefficient of determination explains the amount of variability in the dependent variable that is explained by the independent variable. An r-squared value of 0.70, a moderate to a strong relationship, means that the piece size can explain 70% of the variation of residuals from the mean.

The individual relationships between productivity and piece size for each crew is difficult to identify from *Figure* 5. To further investigate these trends, *Figure 6* illustrates the relationships between productivity and piece size for study crews.

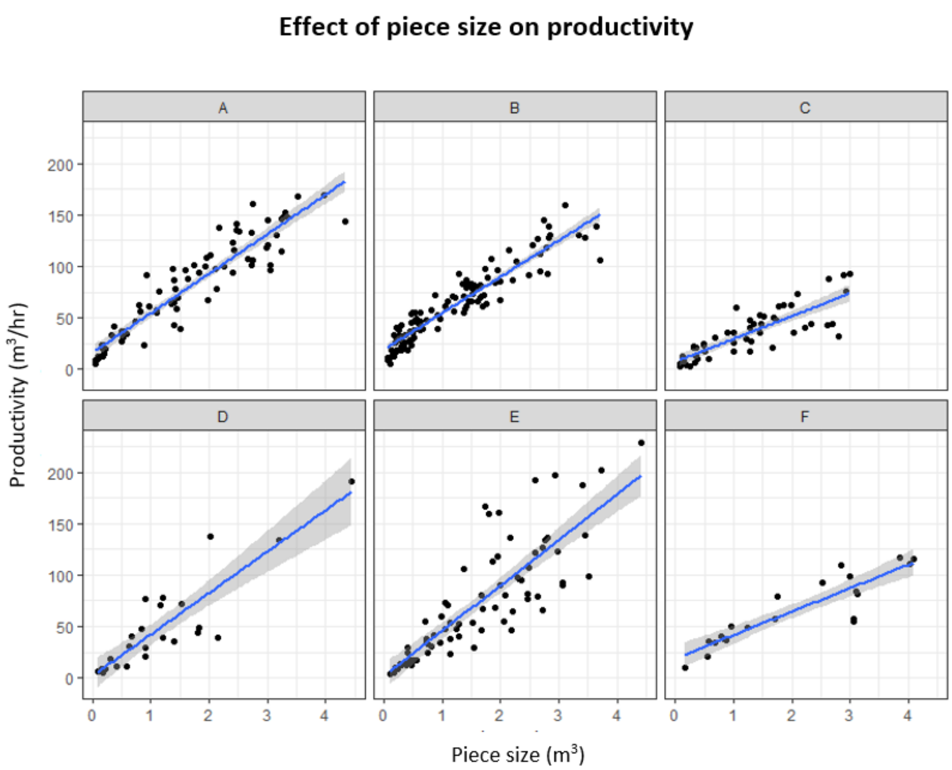

Figure 6*: Relationship between piece size and productivity observed for each crew studied.*

For all crews investigated, the same positive trend can be observed between piece size and processor productivity (*Figure 5*). However, the relationship of this increase is variable; the increase in productivity relative to the piece size is different for each crew. As a result, different productivity values for a given piece size are achieved by different crews. For example, using a piece size of 1.5 m^3, the expected productivity based on the associated trend line will vary depending on the crew *(Table 8*). An average of 62.7 m^3/ha was used to estimate differentiations from the mean; this average represents the expected productivity for all data at a piece size of 1.5 m^3.

Table 8: *Estimations of productivity using associated crew slope relationship assuming a piece size of 1.5m3 for each crew.*

Crew	**Expected productivity m^3/hour**	**% Differentiation from mean**
A	75	16%
B	72	13%
C	50	-25%
D	58	-8%
E	70	10%
F	52	-20%

It becomes clear that due to the unique relationship for each crew, the estimated productivity value can change considerably (*Table 8*). This is graphically illustrated in *Figure 7*, as shown below.

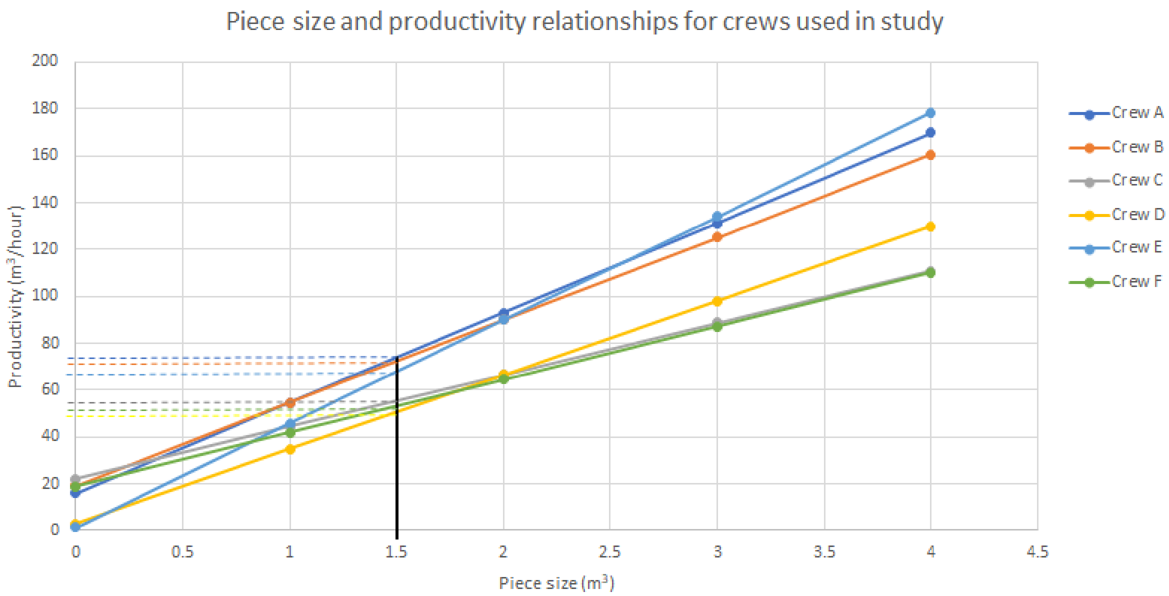

***Figure 7**: Illustration of the expected productivity associated with the piece size and productivity relationship for each crew.*

There was considerable variability in relationships between piece size and productivity for each crew as demonstrated by the corresponding slope gradient. This indicates that although all processor operators were deemed to be 'competent', there was still variability in the expected productivities, with some operators being more 'productive' than others. This relationship demonstrated that assuming a piece size of 1.5 m^3, the most productive operator would process 50% more than that of the least productive operator (75 m^3/hour and 50m^3/hour respectively).

5.4 Tree Form

To investigate the effect of tree form on time to process and productivity analyses were completed on Crew D. Approximately 42% of all stems observed at this crew had some form of tree deformation; non-straight stem, double leader, branching, sweep, and forking. Other crews were not analysed due to a lack of different stem form (the majority of stems in category 0). Review of detailed video footage taken of crew D allowed each stem to be assessed individually, to which, the respective tree form category was assigned based on specifications in *Table 5*. The processing time associated with each stem was compared to the allocated tree form category (*Figure 8*).

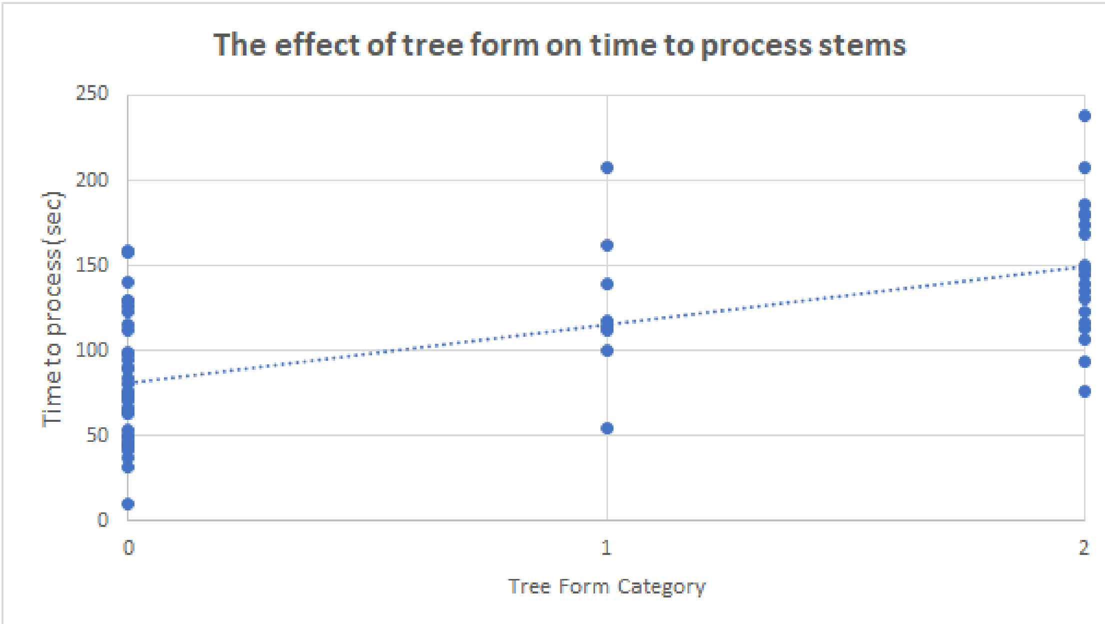

Figure 8*: Comparison of time to process stems against assigned tree form category.*

There is a positive relationship between the time to process and tree form category, as shown by the trend observed in *Figure 8*, above. These results show that as tree form worsens (tree form category increases), the time to process those stems increase. The associated equation and r-squared value summarise the trend:

$$\mathbf{y = 34.2x + 81.6}$$

$$\mathbf{R^2 = 0.39}$$

This demonstrates that as the tree form category increases by one, the time to process will also increase by 34.6 seconds. The intercept of 48.6 seconds explains the average time to process a stem, given that it has a tree form category of zero. The r-squared value of 0.39, a moderate/weak trend, demonstrates that the tree form category can explain 39% of the variation of residuals from the mean.

Assuming the average values are representative of the tree form category, the percentage differences were calculated. Given a stem was in category 1 (Poor), it would take 56% longer to process than a stem in category 0 (Good). Similarly, a stem that was in category 2 (Bad) would take 84% longer (almost double the time) to process than a stem in category 0 (Good).

It is crucial to understand the relationship between tree form and productivity as shown in *Figure 12*, below. This demonstrates a negative correlation between tree form category and productivity.

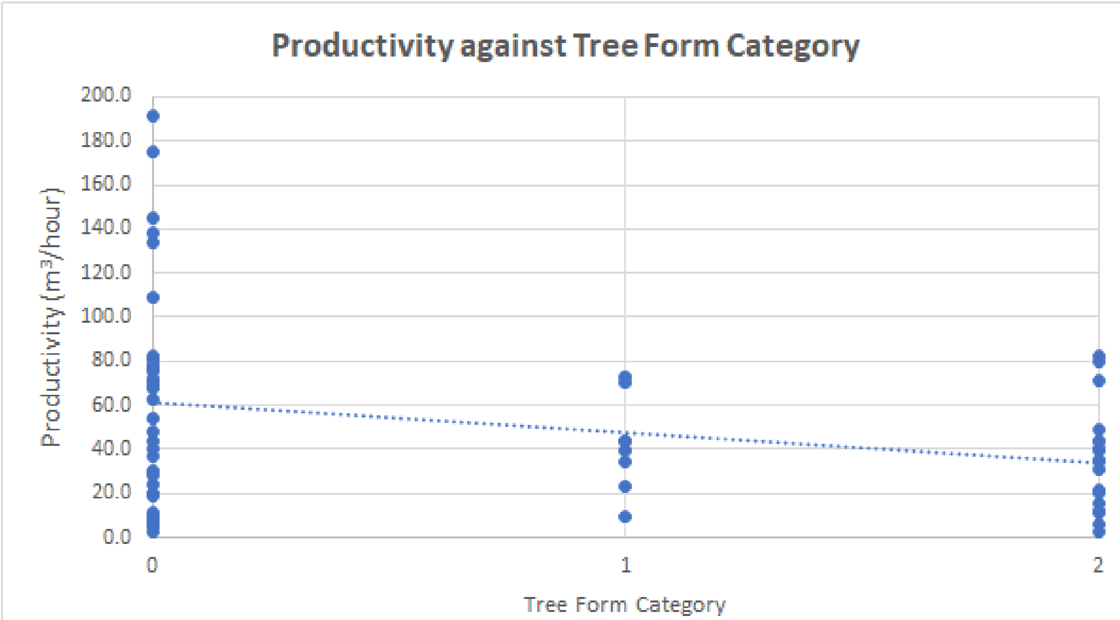

Figure 9*: Comparison of tree form categories against the associated productivity for that stem.*

The negative relationship between tree form category and productivity indicates that as tree form worsens (increase in category), the expected hourly productivity decreases (*Figure 9*). However, there is considerable variability within each tree form category, demonstrated by the associated r-squared value of 0.09 (the trend can explain 9% of variability). The reason for this relates to the broad spread of productivity values within each tree form category as a result of large branches, forked stems and multi-leaders which make processing the stem more difficult to perform.

Comparing the average productivity of category 0 against that of category 2 there is a 26.8 m^3/hour decrease (61.5 m^3/hour and 34.7 m^3/hour respectively). For crew D, some 13% of stems were in tree form category 1, and 30% of stems in tree form category 2 (the remaining 57% in category 0). Using the percentage of stems in each tree form category, the average weighted productivity was calculated to be 51 m^3/hour. Therefore, it is expected that due to tree form crew D would have a lower productivity on average, coinciding with results demonstrated in *Table 8* (productivity 8% less than average for all crews).

5.5 Skid Size

Throughout the data collection process, delays and times when the machine was not performing work tasks were recorded. The delay study aimed to evaluate how skid size influenced both the crew delay and productivity. In order to compare the delay times against the skid size, the average delay per stem was calculated; scaling the overall delay by the number of stems processed over that period. These delay values were plotted against the skid size (m^2), as shown in *Figure 10*, below.

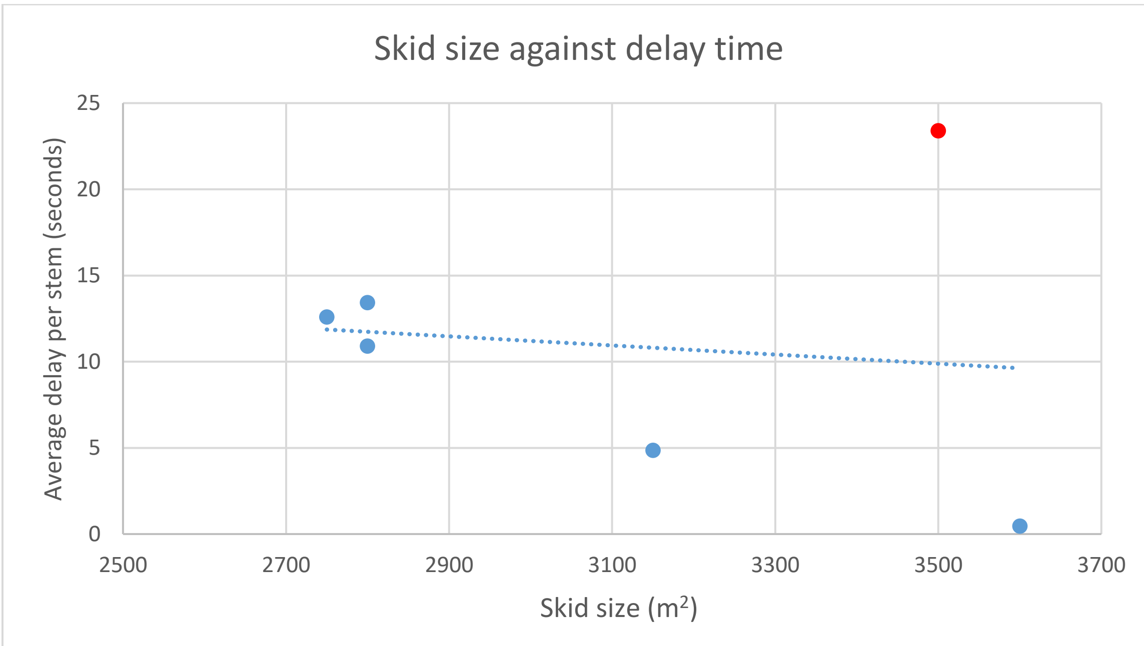

Figure 10*: Comparison of average delay per stem against skid size.*

The horizontal trend observed in *Figure 10* is level with delay time staying relatively constant regardless of skid size. This indicates that there is no relationship between the size of the skid and the average delay per stem. However, one point has been highlighted (red) due to the high average delay per stem associated with a larger landing. This result was unexpected as the associated delay appeared to be much higher than what was assumed by the trend. As a result, an outlier test was performed to test this theory.

For a point to be deemed an outlier, the suspected point must be greater than the mean plus one and a half times the interquartile range (IQR). The equation demonstrates the test used:

Outlier = Mean + (1.5 * IQR)

IQR = Upper Quartile – Lower Quartile

Where:

Upper Quartile = Mean of Upper 25%

Lower Quartile = Mean of Lower 25%

For this study, the following values were estimated, as shown in *Table 9*, below:

***Table 9**: Summary statistics for average delay time per stem for determination of outlier points.*

Variable	Seconds
Q1	6.4
Q3	13.2
IQR	6.9
Average	10.9
Outlier if	> 21.2 or < 0.3

As the point in question demonstrates an average delay per stem of 23.4 seconds, which is above the upper outlier threshold of 21.2 seconds, it should be removed from the analysis. With the exclusion of the outlier point, *Figure 11* illustrates the relationship between skid size and average delay per stem.

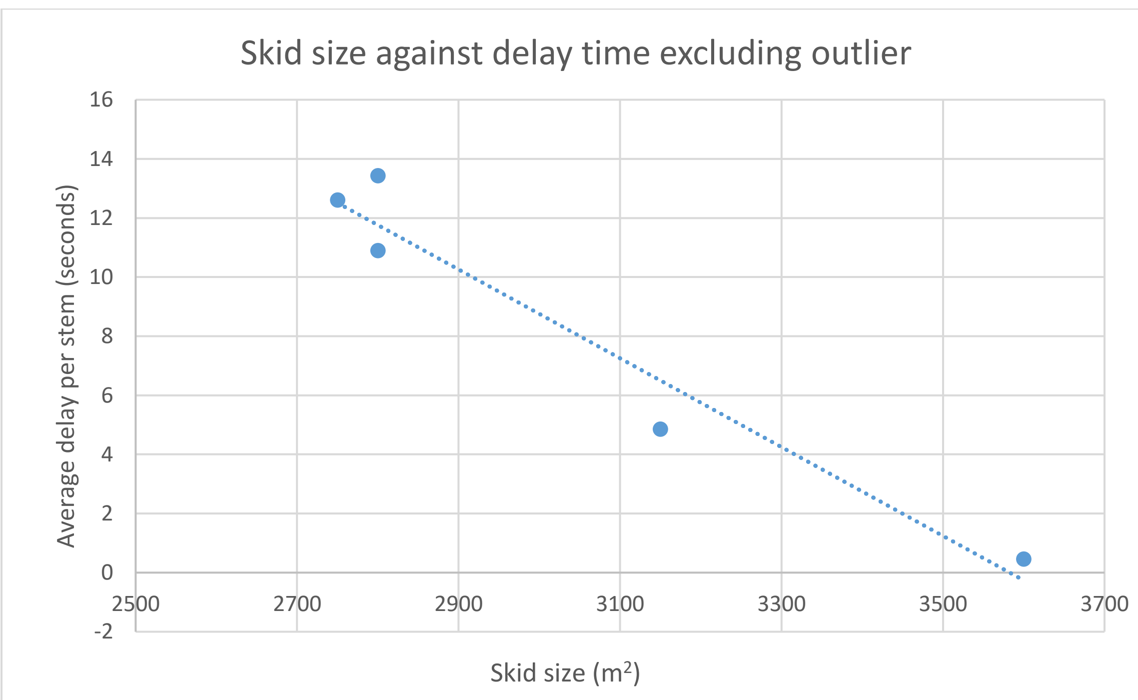

***Figure 11**: Comparison of average delay time per stem against skid size with outlier point removed.*

A pronounced negative trend can be observed between the average delay per stem and skid size, demonstrated in *Figure 11*, above. The trend suggests that as the size of skid decreases in area, the average delay per stem increases. The corresponding equation and r-squared value summarise this relationship:

$$y = -0.015x + 53.$$

$$R^2 = 0.94$$

The equation states that every 53 m^2 decrease in skid size will equate to a one-second increase in average delay time per stem. The high r-squared value demonstrates that the average delay per stem can explain 94% of the variation in residuals from the mean.

The relationship between average crew productivity and skid size was also investigated within this study. The results of this analysis are shown in *Figure 12*, below.

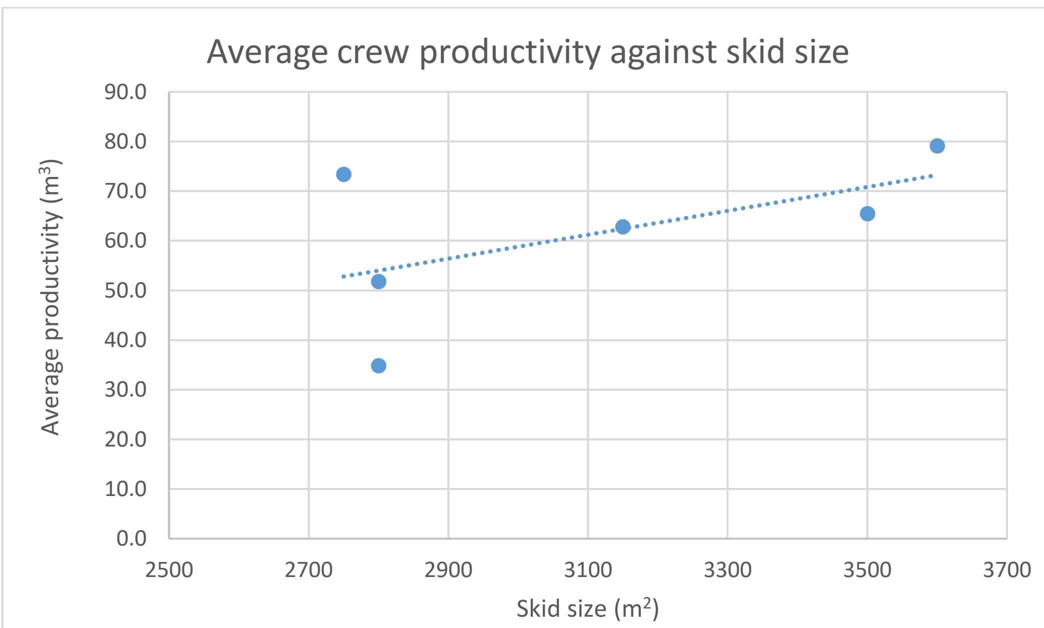

Figure 12*: Comparison of average productivity against skid size.*

A positive trend can be observed between skid size and productivity, as shown in *Figure 12*, above. This suggests that as skid size increases, so too does the average productivity of the crew. The following equation and r-squared value summarize this relationship.

$$y = 0.024x - 13.3$$

$$R^2 = 0.32$$

The equation states that for every ten meters squared increase in skid size, the expected productivity increases by 2.4 m^3. However, as the r-squared value is only 0.32, a weak relationship which suggests that the size of the skid can explain only 32% of the variation in residuals from the mean. As a weak r-squared value is observed, it suggests that predictions made using the linear equation may be imprecise or non-representative of the actual value. This should be taken into consideration for the application of this relationship.

5.6 Processing Time of Log Grades

Time data in respect to the grades cut by the processor were calculated based off detailed video footage. This denoted the time it took to cut a defined log grade; this measured the time between the first and final cut. In total, some 1,657 individual log were cut with the corresponding times recorded. The average time to process each log grade is shown in *Figure 13*, below.

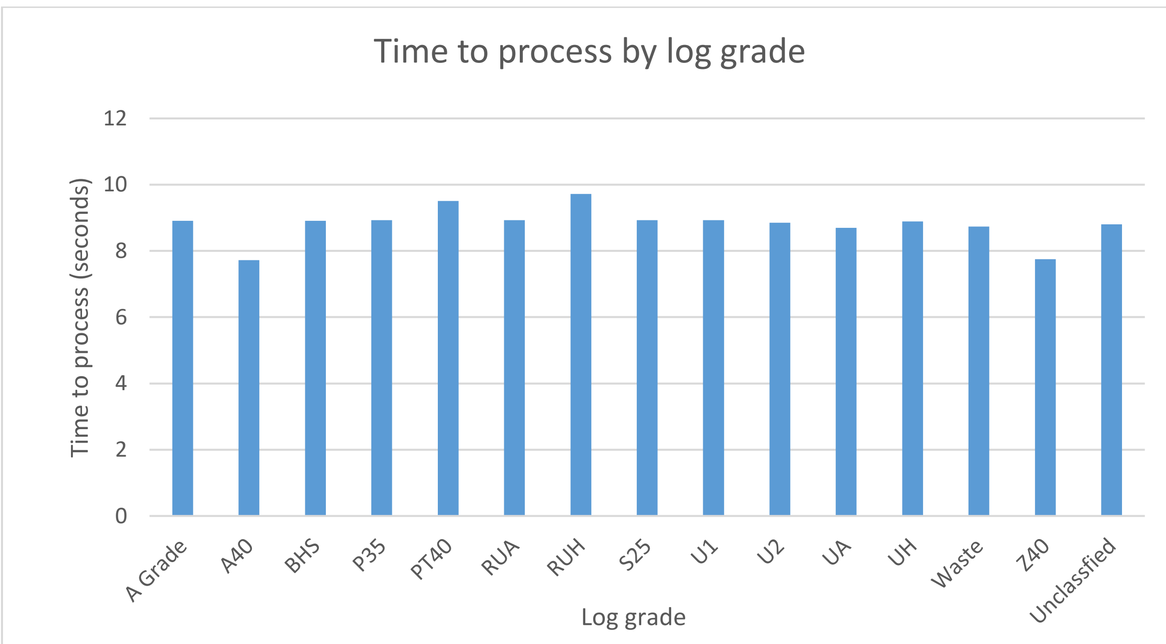

Figure 13*: Average time to process for all log grades observed in the study.*

There is considerable variability in the time taken to process different log grades, as shown in *Figure 13*, above. The log grade that took the longest time to process on average was UH at 13.22 seconds, whereas, the shortest time was BHS (bin grade) at 6.60 seconds.

Statistically significant differences where the p-value was less than 0.05 were observed between multiple log grades (*Appendix 12*). This indicates that there are significant differences in the times to cut and process specific log grades. Estimated marginal means (emmeans) test found that there were indeed statistically significant differences between log grade means; failure of red arrows to intersect (*Appendix 13*). The graph illustrates that there are statistically significant differences in the time to process log grades, coinciding with ANOVA tests.

6. Discussion

The main objective of this study was to identify factors that influenced the productivity of processor machinery.

Three factors; piece size, tree form and skid size, were studied in detail to evaluate their effect on processor productivity. Data was collected from five crews at six locations through the recording of detailed video footage. Stem characteristics, including piece size, lengths, and grades cut, were provided by STICKS harvest woodflow management system. Through cross-referencing this data with detailed video recordings, the productivity associated with each stem could be calculated. This ensured that operator-machine interactions were kept to a minimum with automated data collection reducing health and safety risks associated with operating on an active skid. The use of automated processor data collection has the potential to be used in further related studies while aiding forest managers in monitoring and reconciliation of operations (Roth, 2016).

Processing stems into log grades represented 59% of the total time the processor was undertaking work tasks. This was slightly higher than the 49% found by Tolan (2014) who was investigating the effect of the number of log sorts on processor productivity. This study found that the time spent in delays (less than 10 minutes) equated to 9% of total time, slightly less than the 16% reported by Tolan (2014).

Delays less than 15 minutes in duration represent some 94% of all delays observed in a harvesting operation (Spinelli & Visser, 2008). This study found an average utilisation rate of 91% for all six investigated crew locations. Similarly, a utilisation rate of 89% was observed when investigating harvest operation delays (Spinelli & Visser 2008), coinciding with results found in this study. This report assumed that only delays less than 15 minutes were included.

Productivity

A detailed productivity study was undertaken over the summer months of 2018/19 to understand factors that influence processor machinery. Productivity is defined as the number of outputs (m^3) over a defined time frame (hour), derived from the time to process each stem.

Productivity was calculated based on the total processing time per stem and the associated piece size. The average productivity for all crews of approximately 62.7 m^3/hour was slightly less than the 66 m^3/hour to 74 m^3/hour range observed by Tolan (2014) assuming a piece size of 1.5 m^3; the approximate average observed in this study. ANOVA identified that there were statistically significant differences between average crew productivities (assuming p-value of 0.05). These differences involved the maximum (crew A) and minimum (crew C) productivity values and other crews. This highlights that even processor machinery operating in the same forest estate may have varying productivities.

Productivity and Piece Size

A positive relationship was found between piece size and productivity for all crews investigated within this study. This suggests that increases in piece size correspond to increased processor productivity. Alternative studies investigating feller-buncher machinery in Australia (Ghaffariyan & Acuna, 2012) and mechanised cut-to-length systems in Ireland (Jiroušek *et al.* 2007) demonstrated similar relationships between piece size and productivity. This trend was also observed in prior studies investigating processor productivity, however, above a piece size of 3.5 m^3 there was a plateau then decline in processor productivity (Tolan, 2014; Ramantswaba *et al*. 2012). This trend is recognised as the "piece size law" in which piece size increases to the point that is too large for the processor resulting in decreased productivity (Visser & Spinelli, 2011). Results within this study failed to demonstrate this law as no plateau occurred, suggesting that the optimum productivity was greater than 4 m^3.

However, the results demonstrated that the relationship between piece size and productivity vary among crews (differing gradients). Assuming a piece size of 1.5 m^3, the expected productivity ranges from between 50 m^3/hour to 75 m^3/hour. This suggests that the most productive operator would process 50% more volume than the least productive operator. Assuming that 62.5 m^3/hour is the average of all operators, this study demonstrates that there is some 20% variation in processor productivity around the mean. This variation may be due to operator factors which coincide with the 20 to 50% productivity range observed by Murphy and Vanderberg (2007). This demonstrates that for ‘competent' processor operators, there was a level of uncertainty in productivity.

Tree Form

Individual stems were classified into one of three tree form categories; 0 (Good stem), 1 (Poor stem), and 2 (Bad stem). The classification was made taking into consideration branch size, sweep, presence/absence of multi-leaders and stem forking. Some 64 stems were used in this analysis; 37 stems in category 0, 8 stems in category 1 and 19 stems in category 2 (42% of stems in category 1 or 2).

This study found a positive trend between tree form category and time to process. This demonstrates that as tree form worsened, the time to process increases at a rate of 34.2 seconds per tree form category. Quantification of these results showed that a stem in category 1 took 56% longer and a stem in category 2 took 84% longer to process than a stem in category 0. This knowledge can then be applied by harvesting managers when estimating contractor rates.

Furthermore, the relationship between tree form category and productivity suggests that as tree form worsens, the expected productivity decreases. This relationship coincides with findings from Ramantswana *et al.* (2012), who observed a similar trend in South African harvesting operations. However, the relationship between productivity and tree form category is weak as demonstrated with an r-squared value of 0.09.

Skid Size

Skids are used for the processing and storage of logs from a defined harvest area. Their size is determined from production targets, the number of log sorts and area constraints (Tolan, 2014; Visser *et al*. 2010). A strong negative relationship was observed between the average delay per stem and skid size, suggesting that as skid size decreases, the average delay per stem increases. When analysing the relationship between skid size and productivity, a positive trend was observed; higher productivity estimated at larger skids. However, this relationship is moderate/weak, as demonstrated with an r-squared value of 0.32. Crew interviews that were undertaken in a study by Visser *et al.* (2018) discussed how skid size might be a limiting factor to crew performance.

Processing Times of Log Grades

The UH log grade took the longest time to process, whereas, the BHS log grade took the shortest time to process (13.2 and 6.6 seconds respectively). ANOVA tests identified that there were statistically significant differences between the average time to process many of the log grades investigated. However, the application of this information is limited as grade selection is driven by both market demand and stem characteristics, including maximum sweep, diameter, and branch size (Whiteside & Manley, 1986). Instead, this information could act as a lead on from research published by Tolan (2014) who investigated the effect of the number of log sorts on log processor productivity.

Benefits of this study

Hancock Forest Management has undergone a transition from motor-manual processing to almost completely mechanised processing in the past decade. This both improved health and safety in the forestry workplace while also providing increased production. The results from this study provide information concerning the broad range of factors that can influence mechanised processing productivity, with a particular focus on the extent that piece size, tree form and skid size influence processor productivity.

Quantification of the effect of these factors on productivity provides benefits to both HFM harvesting operations as well as the wider New Zealand forestry industry. The benefits of this study have been summarised and are as follows:

- A greater understanding of the key factors that influence processor productivity and possible areas for improvements in productivity.
- Quantification of the effect that piece size, tree form and skid size have on productivity.
- Information to better estimate harvesting operation contractor rates and characteristics of the harvest area that could influence those rates.
- A greater understanding of processor operations and how how tasks performed by processor machinery influences productivity.

The results of this study may prove to be useful for other forest management companies and contractors alike, as harvesting operations become increasingly mechanised.

Limitations

This study aimed to analyse three factors that influence processor productivity, these were piece size, tree form and skid size. However, due to the scope of the investigation, it was not feasible to investigate all factors that may influence productivity. During the planning phase of this study, attempts were made to identify many other factors that may influence productivity. There is a vast array of such factors that can influence processor productivity. These were not considered within this study - human behavioural factors, processor manufacturer, and processor power, to name a few. Future research may investigate these factors further to determine their level of influence (if any) on processor productivity.

This study identified that piece size, tree form and skid size influenced processor productivity. However, the strength of these relationships varied. The r-squared value explained the amount of variability in the dependent variable that could be explained by the independent variable - the higher the value, the better the trend represents the data. The relationship between tree form and productivity could only explain 9% of the variation in the results, meaning that the trend may not be representative of the entire data set.

The processor was the only machine that was observed in this study as it was identified as a key bottleneck to the harvesting operation. Members of the harvesting team reinforced that the processor machine was the bottleneck to the harvesting crew. However, this assumption may not apply to all crews in operation, with potential for other machinery operating, trucking frequency, and the cohesion of crew members to also be bottlenecks in the system.

Before the automation of stem data collection, researchers were required to attain physical measurements. However, if these systems are not operating correctly, it can lead to difficulties in data analysis. For this study, STICKS data only provided information for each log grade rather than for each stem. As a result, log grades cut from each stem needed to be combined to provide the piece size for each stem with all times being provided from detailed video footage. This process took considerable amounts of time to complete and authenticate data. Due to these time constraints, the study was only able to investigate five crews in six locations.

Future Research

Given the limitations of this study, there is an opportunity for future investigations looking into processor productivity. These studies should take into consideration the following aspects:

- Investigate other factors that influence processor productivity, i.e. Operator experience - comparing an experienced operator to one that is new to the machine, processor head manufacturer – are there any differences in productivity between manufacturers? And, processor power – what is the relationship between power and productivity?
- Study machines throughout New Zealand – benchmark against other regions.
- Increased length of the investigation in order to gain a larger data pool from which conclusions are made.
- Investigate productivity for other species and countries – how does processor productivity compare against Canadian operations, or when processing *E.bosistoana* species.

Research into these fields will help to identify additional influential factors to processor productivity allowing for greater knowledge about the limits of the machine.

7. Conclusion

This study aimed to investigate three factors and their effect on processor productivity: piece size, tree form and skid size. Data was collected from HFM Kinleith forest estate in Tokoroa over the summer of 2018/19. Detailed video footage was recorded, providing times associated with work tasks and individual stems while STICKS harvest wood flow management specified stem details (piece size).

On average, the processor machine spent the most substantial portion of time, 59% processing stems into defined log grades. However, this varied between 43% and 67% for each crew. Only delays of less than ten minutes were recorded within this study; as such, a utilisation rate of 91% was calculated.

Productivity varied for 'competent' operators with a range of 34.8 m^3/hour to 79.1 m^3/hour between crews. This demonstrates that there can be a 50% difference in productivity for competent operators. There was also significant variation in productivity within each crew. ANOVA tests demonstrated that there were statistically significant differences in productivity between crews. As a result, it cannot be assumed that productivity is uniform amongst 'competent' operators working in Kinleith forests.

A positive trend between piece size and productivity was observed at all crews investigated within this study. This suggests that as piece size increases so too will processor productivity. For this study, the average piece size for each crew varied between 1.35 m^3 and 2.05 m^3. However, the relationship observed at each crew demonstrated that processor productivity varied up to 20% around the mean of 62.7 m^3/hour (assuming 1.5 m^3 piece size). This highlights that for 'competent' operators, there is still a level of variability in their abilities.

A categorical system was employed to analyse tree form; 0 (Good), 1 (Poor), and 2 (Bad). This study found that a stem in category 1 will take 56% longer and a stem in category 2 will take 84% longer to process than a stem in category 0. Productivity decreases with increasing tree form category demonstrating that poor quality stems adversely influence processor productivity. However, as the associated r-squared value was only 0.09, this highlighted that there is considerable variability in productivity for each tree form category.

Skid size was found to influence the average delay per stem; increased skid area resulted in reduced average delay per stem. A similar trend could be observed between skid size and productivity with larger skids having higher productivity values. However, this relationship was weak, with an r-squared value of only 0.32.

Results and conclusions made within this study will allow harvest managers to better understand factors that affect processor productivity. This knowledge can be applied to estimate fair contractor rates given the characteristics of the stand.

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9. Appendices

Crew:

<u>Questions</u>

1. How many years/hours experience do you have operating this machine?

2. Do you have any formal training for operation of this machine?

3. What are the characteristics of the stand?

4. What machines do you have operating at this skid?

5. How long have you been at this harvest area?

6. How many hours has the machine (excavator and processor) done?

Weather conditions:

Average piece size:

Number of crew members:

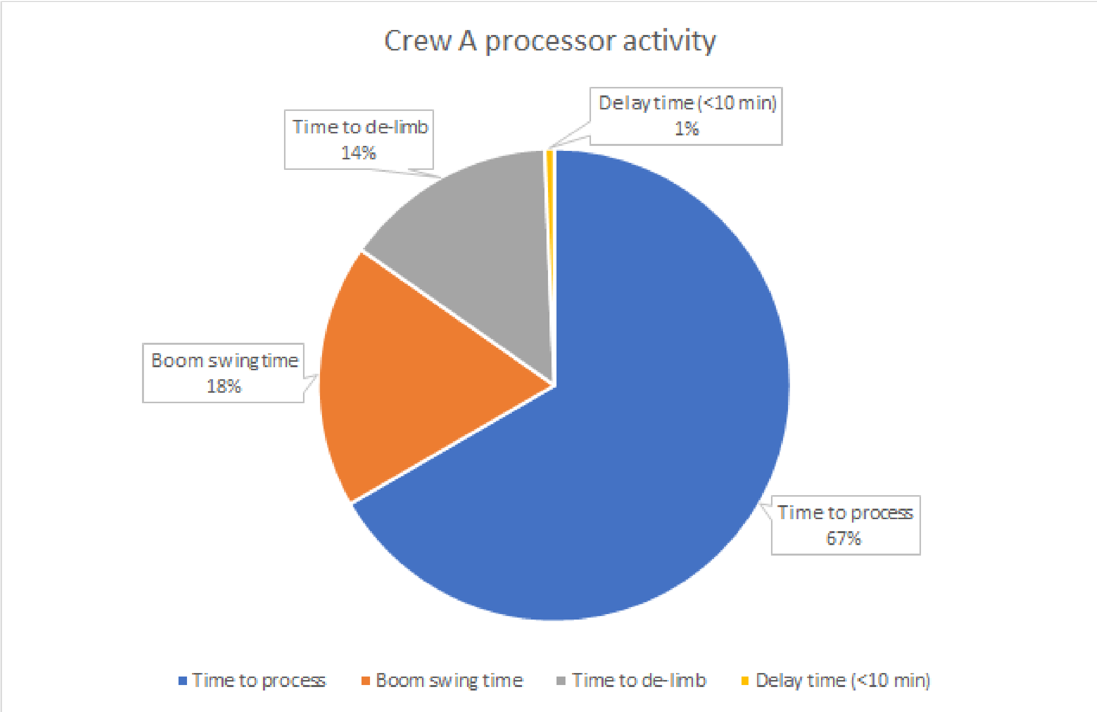
Any other influential factors/problems experienced while processing? I.e. can you think of any factors that may slow or delay the processor from performing its task?

Appendix 1*: Questionnaire used to gain information from crew members about their experience operating the processor machine and stand characteristics.*

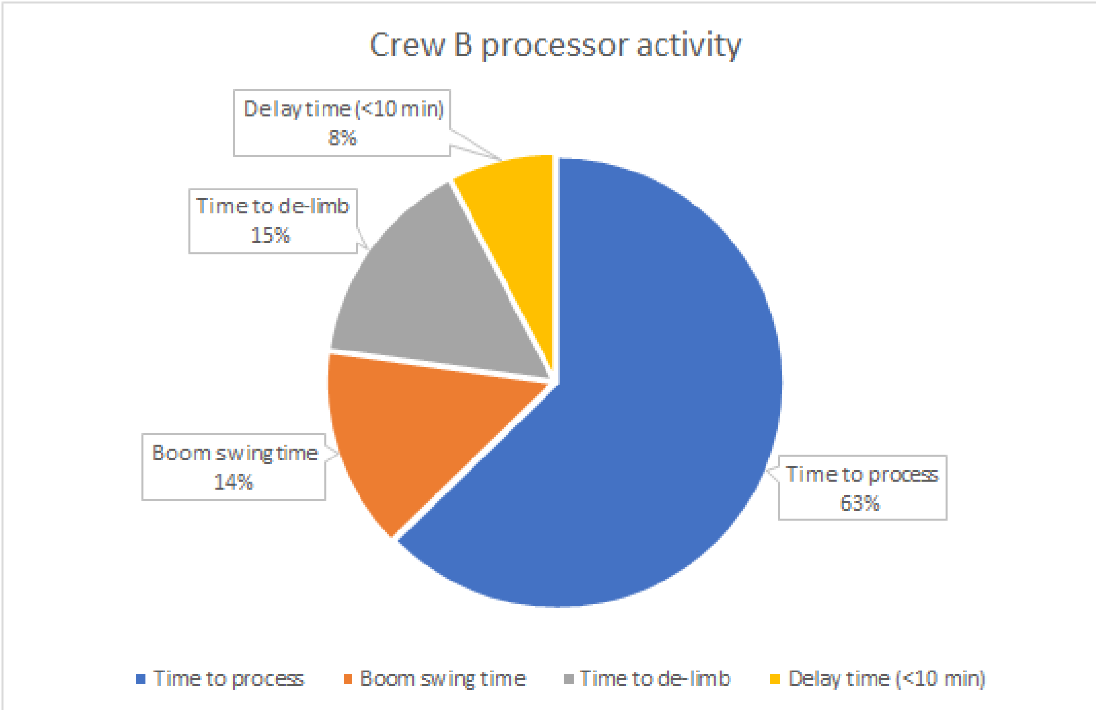
Appendix 2: *Illustration of a stem that falls within tree form category 0 with no deformations observed.*

Appendix 3: *Illustration of a stem that falls within tree form category 1 as some large branches are present on the stem.*

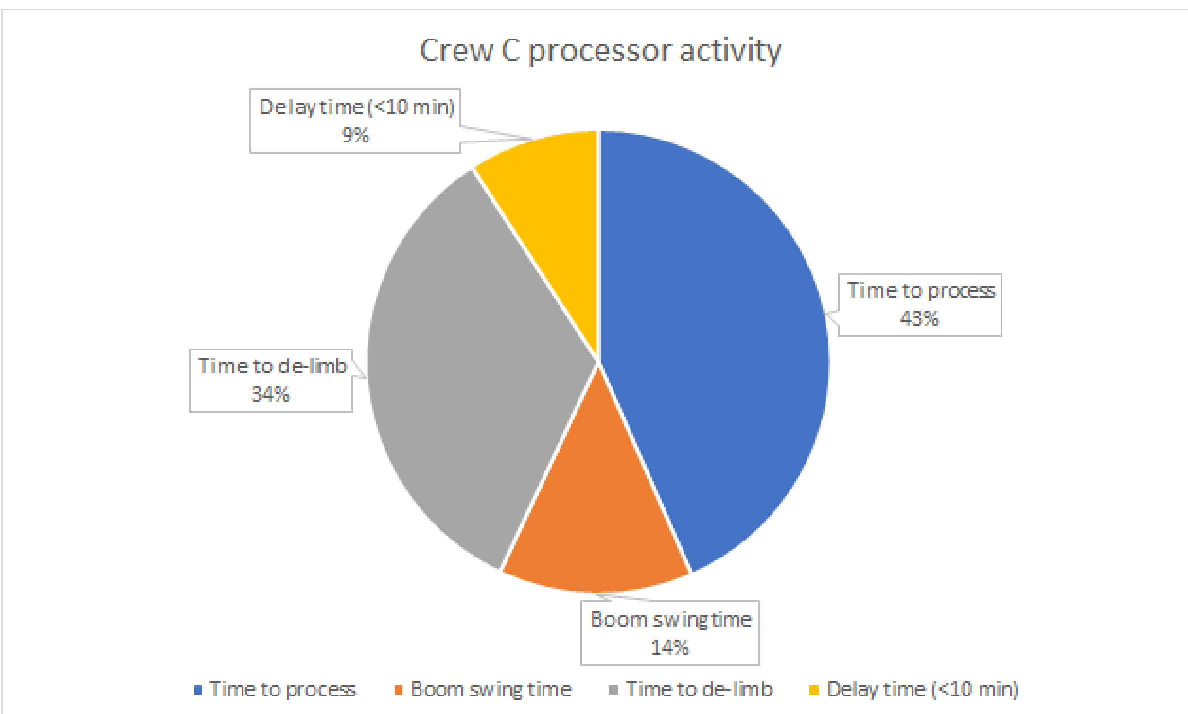
***Appendix 4**: Illustration of a stem that falls within tree form category 2 due to the multiple leaders observed at the quarter of the stem.*



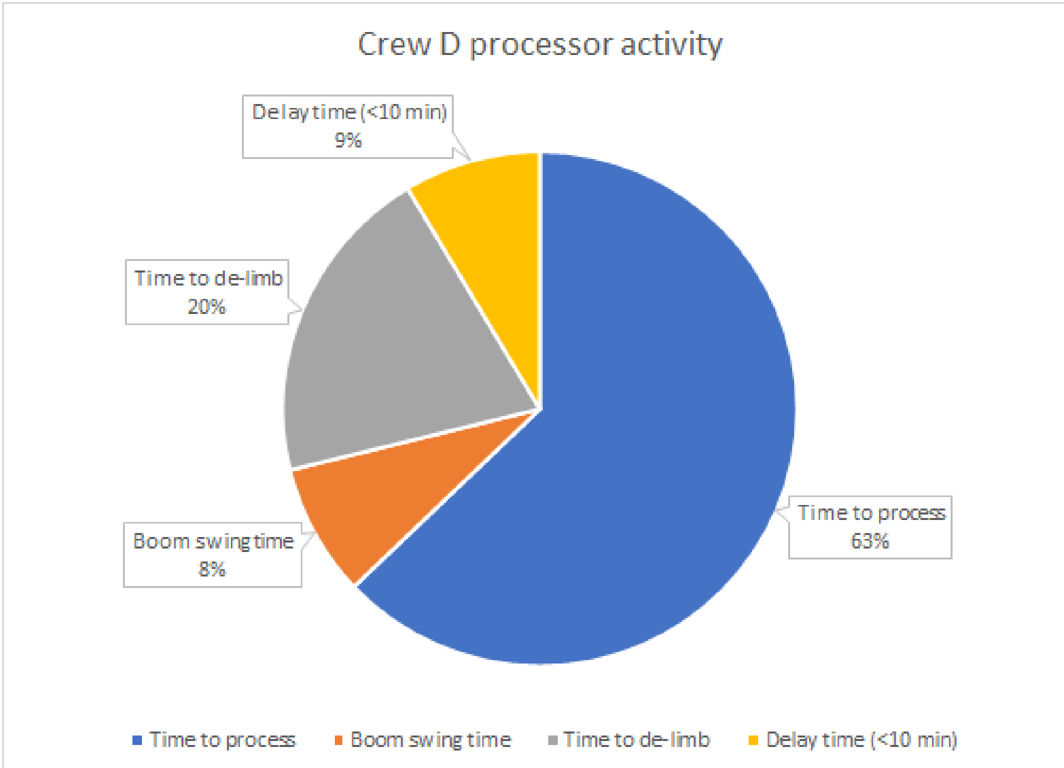
***Appendix 5**: Percentage time spent by processor performing work tasks at crew A.*



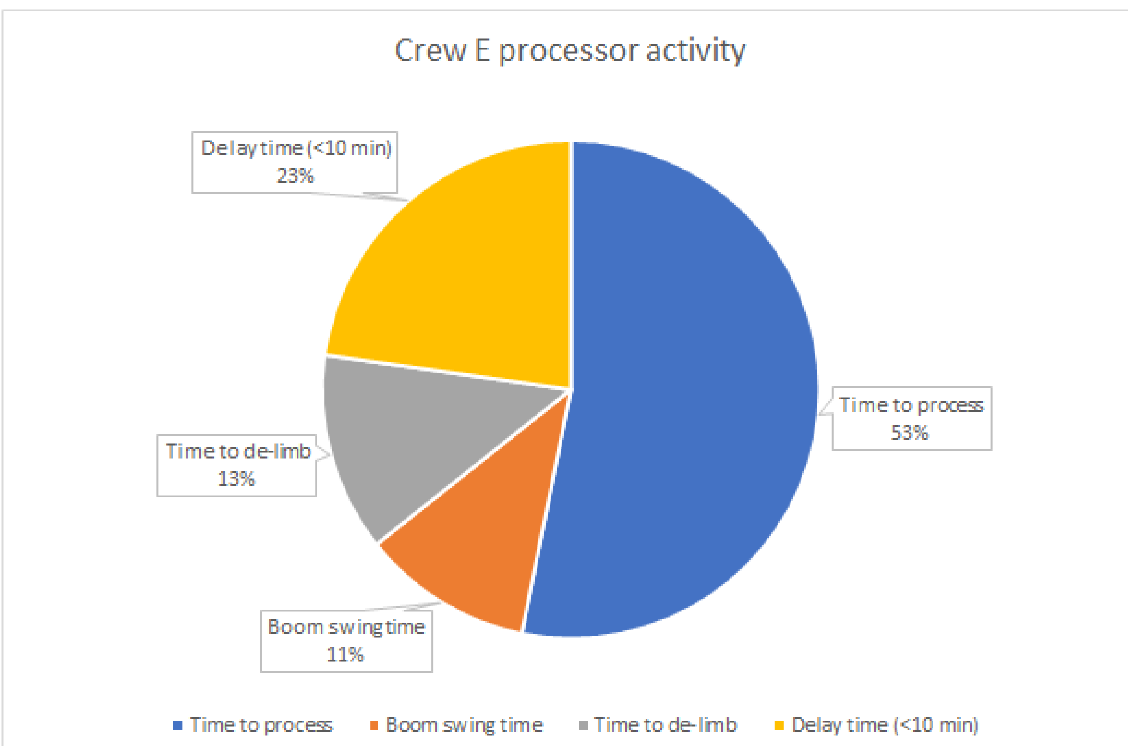
Appendix 6*: Percentage time spent by processor performing work tasks at crew B.*



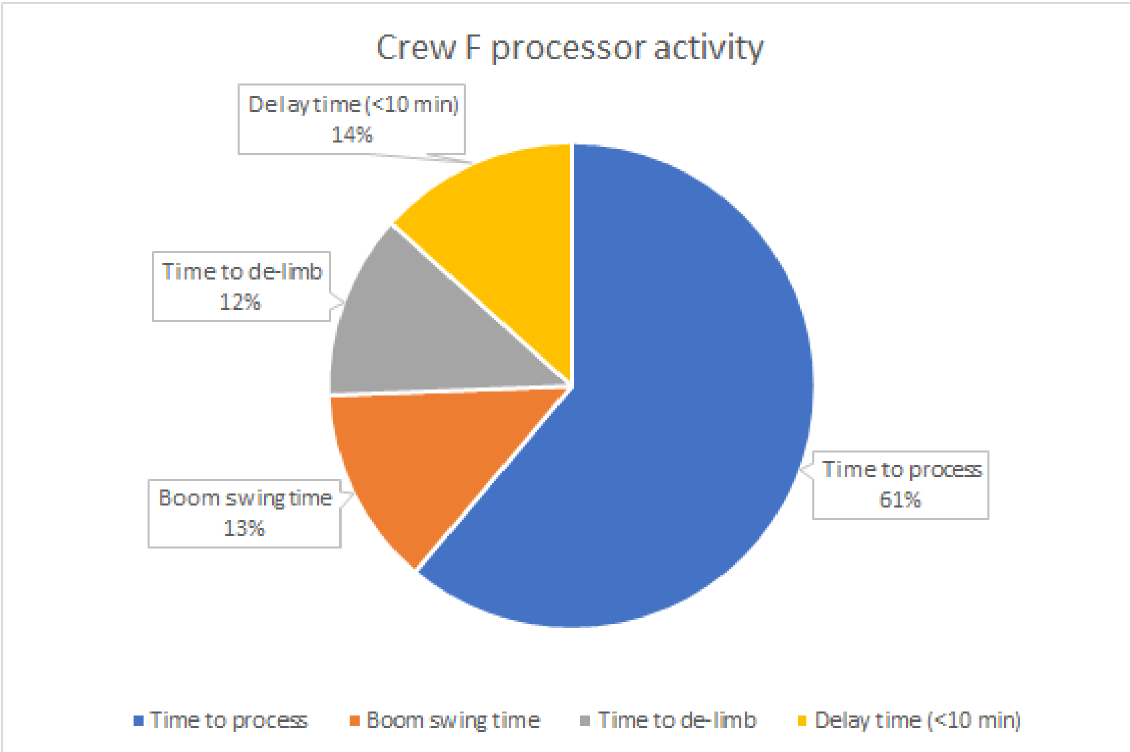
Appendix 7*: Percentage time spent by processor performing work tasks at crew C.*



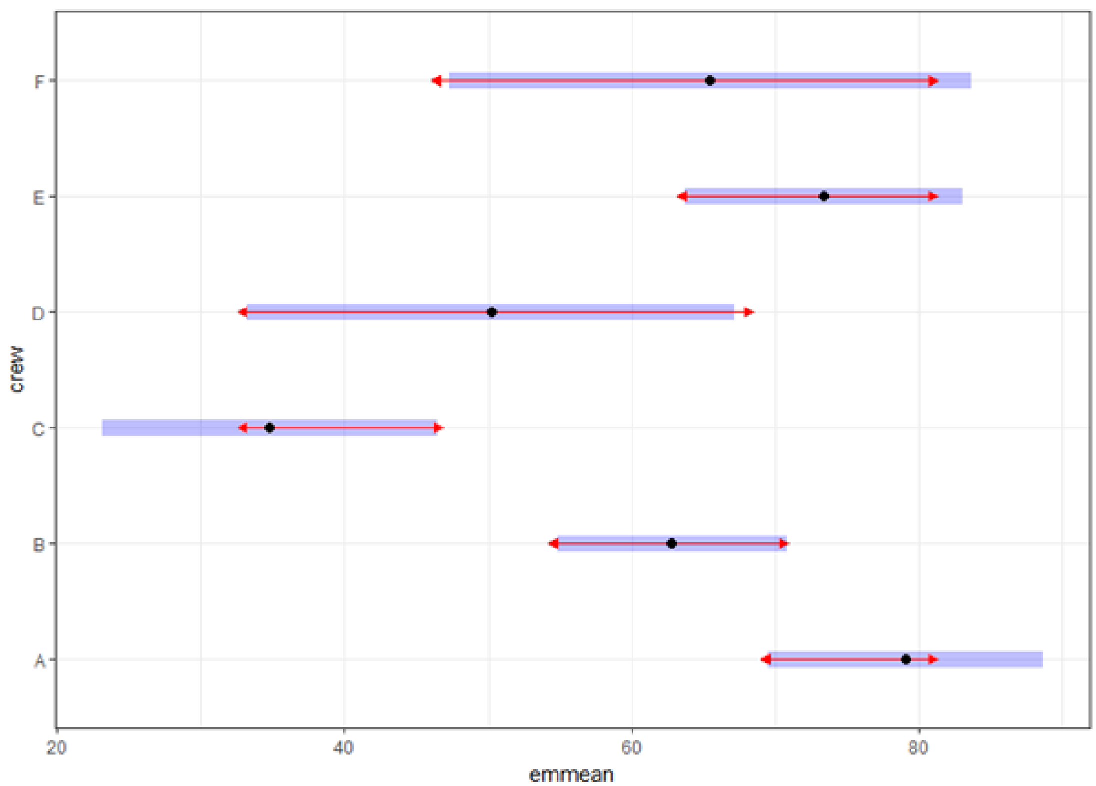
Appendix 8*: Percentage time spent by processor performing work tasks at crew D.*



Appendix 9*: Percentage time spent by processor performing work tasks at crew E.*



Appendix 10: *Percentage time spent by processor performing work tasks at crew E.*



Appendix 11: *Emmeans test to illustrate statistically significant differences in mean productivities between crews.*

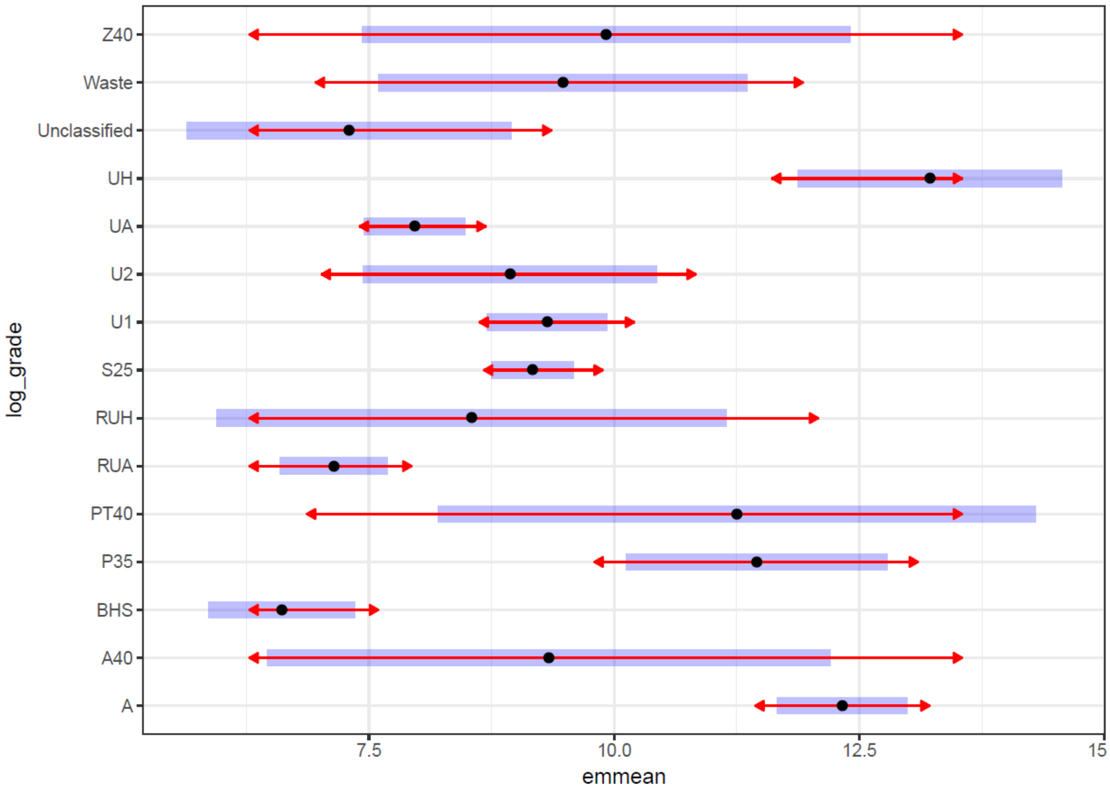
```
> # Multiple comparisons
> grades_emms <- emmeans(m1, "log_grade")
> pairs(grades_emms)
 contrast               estimate    SE   df t.ratio p.value
 A - A40                  2.9921 1.503 1642   1.991  0.8037
 A - BHS                  5.7164 0.509 1642  11.227  <.0001
 A - P35                  0.8731 0.757 1642   1.153  0.9982
 A - PT40                 1.0754 1.589 1642   0.677  1.0000
 A - RUA                  5.1843 0.438 1642  11.833  <.0001
 A - RUH                  3.7800 1.367 1642   2.766  0.2668
 A - S25                  3.1596 0.400 1642   7.902  <.0001
 A - U1                   3.0073 0.460 1642   6.537  <.0001
 A - U2                   3.3861 0.836 1642   4.050  0.0048
 A - UA                   4.3608 0.427 1642  10.212  <.0001
 A - UH                  -0.8941 0.765 1642  -1.169  0.9979
 A - Unclassified         5.0291 0.910 1642   5.524  <.0001
 A - Waste                2.8493 1.016 1642   2.803  0.2458
 A - Z40                  2.4088 1.312 1642   1.836  0.8835
 A40 - BHS                2.7243 1.513 1642   1.801  0.8980
 A40 - P35               -2.1190 1.613 1642  -1.313  0.9932
 A40 - PT40              -1.9167 2.134 1642  -0.898  0.9999
 A40 - RUA                2.1922 1.491 1642   1.471  0.9801
 A40 - RUH                0.7879 1.974 1642   0.399  1.0000
 A40 - S25                0.1675 1.480 1642   0.113  1.0000
 A40 - U1                 0.0152 1.497 1642   0.010  1.0000
 A40 - U2                 0.3939 1.652 1642   0.238  1.0000
 A40 - UA                 1.3687 1.487 1642   0.920  0.9999
 A40 - UH                -3.8862 1.617 1642  -2.403  0.5125
 A40 - Unclassified       2.0370 1.691 1642   1.205  0.9972
 A40 - Waste             -0.1429 1.750 1642  -0.082  1.0000
 A40 - Z40               -0.5833 1.937 1642  -0.301  1.0000
 BHS - P35               -4.8434 0.777 1642  -6.230  <.0001
 BHS - PT40              -4.6410 1.599 1642  -2.902  0.1961
 BHS - RUA               -0.5321 0.472 1642  -1.127  0.9986
 BHS - RUH               -1.9364 1.378 1642  -1.405  0.9869
 BHS - S25               -2.5569 0.437 1642  -5.854  <.0001
 BHS - U1                -2.7092 0.492 1642  -5.501  <.0001
 BHS - U2                -2.3304 0.854 1642  -2.728  0.2887
 BHS - UA                -1.3556 0.462 1642  -2.936  0.1811
 BHS - UH                -6.6105 0.785 1642  -8.425  <.0001
 BHS - Unclassified      -0.6873 0.927 1642  -0.741  1.0000
 BHS - Waste             -2.8672 1.031 1642  -2.780  0.2587
 BHS - Z40               -3.3076 1.324 1642  -2.498  0.4421
 P35 - PT40               0.2024 1.694 1642   0.119  1.0000
 P35 - RUA                4.3113 0.733 1642   5.882  <.0001
 P35 - RUH                2.9069 1.488 1642   1.954  0.8249
 P35 - S25                2.2865 0.711 1642   3.217  0.0858
 P35 - U1                 2.1342 0.746 1642   2.860  0.2164
 P35 - U2                 2.5130 1.022 1642   2.459  0.4707
 P35 - UA                 3.4877 0.726 1642   4.802  0.0002
 P35 - UH                -1.7671 0.964 1642  -1.832  0.8848
```

```
P35 - Unclassified      4.1561 1.084 1642  3.836  0.0110
P35 - Waste             1.9762 1.174 1642  1.683  0.9382
P35 - Z40               1.5357 1.438 1642  1.068  0.9992
PT40 - RUA              4.1089 1.578 1642  2.604  0.3676
PT40 - RUH              2.7045 2.041 1642  1.325  0.9926
PT40 - S25              2.0841 1.568 1642  1.329  0.9923
PT40 - U1               1.9318 1.584 1642  1.220  0.9968
PT40 - U2               2.3106 1.731 1642  1.335  0.9920
PT40 - UA               3.2853 1.575 1642  2.086  0.7442
PT40 - UH              -1.9695 1.698 1642 -1.160  0.9981
PT40 - Unclassified     3.9537 1.768 1642  2.236  0.6385
PT40 - Waste            1.7738 1.825 1642  0.972  0.9997
PT40 - Z40              1.3333 2.005 1642  0.665  1.0000
RUA - RUH              -1.4043 1.353 1642 -1.038  0.9994
RUA - S25              -2.0247 0.351 1642 -5.761  <.0001
RUA - U1               -2.1771 0.419 1642 -5.201  <.0001
RUA - U2               -1.7983 0.814 1642 -2.209  0.6581
RUA - UA               -0.8235 0.382 1642 -2.155  0.6968
RUA - UH               -6.0784 0.741 1642 -8.208  <.0001
RUA - Unclassified     -0.1552 0.890 1642 -0.174  1.0000
RUA - Waste            -2.3351 0.998 1642 -2.339  0.5611
RUA - Z40              -2.7755 1.298 1642 -2.138  0.7092
RUH - S25              -0.6204 1.342 1642 -0.462  1.0000
RUH - U1               -0.7727 1.361 1642 -0.568  1.0000
RUH - U2               -0.3939 1.529 1642 -0.258  1.0000
RUH - UA                0.5808 1.350 1642  0.430  1.0000
RUH - UH               -4.6741 1.492 1642 -3.134  0.1085
RUH - Unclassified      1.2492 1.571 1642  0.795  1.0000
RUH - Waste            -0.9307 1.635 1642 -0.569  1.0000
RUH - Z40              -1.3712 1.834 1642 -0.748  1.0000
S25 - U1               -0.1523 0.378 1642 -0.403  1.0000
S25 - U2                0.2265 0.794 1642  0.285  1.0000
S25 - UA                1.2012 0.337 1642  3.559  0.0294
S25 - UH               -4.0536 0.719 1642 -5.641  <.0001
S25 - Unclassified      1.8696 0.872 1642  2.144  0.7048
S25 - Waste            -0.3103 0.982 1642 -0.316  1.0000
S25 - Z40              -0.7508 1.286 1642 -0.584  1.0000
U1 - U2                 0.3788 0.826 1642  0.459  1.0000
U1 - UA                 1.3535 0.407 1642  3.326  0.0622
U1 - UH                -3.9013 0.754 1642 -5.176  <.0001
U1 - Unclassified       2.0219 0.901 1642  2.244  0.6328
U1 - Waste             -0.1580 1.008 1642 -0.157  1.0000
U1 - Z40               -0.5985 1.306 1642 -0.458  1.0000
U2 - UA                 0.9747 0.808 1642  1.206  0.9971
U2 - UH                -4.2801 1.027 1642 -4.167  0.0030
U2 - Unclassified       1.6431 1.140 1642  1.441  0.9834
U2 - Waste             -0.5368 1.226 1642 -0.438  1.0000
U2 - Z40               -0.9773 1.481 1642 -0.660  1.0000
UA - UH                -5.2548 0.734 1642 -7.159  <.0001
UA - Unclassified       0.6684 0.885 1642  0.755  1.0000
UA - Waste             -1.5115 0.993 1642 -1.521  0.9731
UA - Z40               -1.9520 1.295 1642 -1.508  0.9752
UH - Unclassified       5.9232 1.089 1642  5.441  <.0001
```

```
 UH - Waste                3.7433 1.179 1642  3.176  0.0965
 UH - Z40                  3.3028 1.442 1642  2.291  0.5975
 Unclassified - Waste     -2.1799 1.278 1642 -1.706  0.9316
 Unclassified - Z40       -2.6204 1.524 1642 -1.719  0.9272
 Waste - Z40              -0.4405 1.590 1642 -0.277  1.0000

P value adjustment: tukey method for comparing a family of 15 estimates
```

Appendix 12*: ANOVA regression performed in RStudio to find statistically significant differences in the time to process log grades.*



Appendix 13: *Emmeans test to compare the statistical significance of time to cut log grades*.