HARVESTING TECHNICAL NOTE

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Effect of Piece Size on Felling Machine Productivity

Summary
Understanding how stand and terrain parameters affect productivity is important for determining the optimum use of harvesting equipment. Most studies of mechanised harvesters conclude that tree size, or piece size, is the dominant predictor that affects overall productivity. A common concept, known as the "piece-size law", is that with increasing piece size, productivity increases at a decreasing rate. What is not well understood is the upper limit to this piece size law. A series of studies of mechanised felling in clearfell radiata pine was carried out, in which stands with relatively large trees were chosen. As the tree size increased, the machine started to struggle, resulting in a decrease in productivity. Productivity tended to decrease gradually, not drop off suddenly beyond the optimum. Contractors should be aware of both the optimum piece size and machine limitations of their equipment. Forestry companies that include piece size in either productivity or costing predictions need to ensure it is correctly modelled.

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INTRODUCTION

In forestry, harvesting machine productivity is influenced by stand and terrain variables. Understanding these effects through productivity studies is important for determining the optimum use of harvesting equipment being used in different conditions. The regression models derived from such studies can be used for many purposes, including wood-flow planning, predicting machine or system productivity (Spinelli *et al.*, 2002), and costing models (McDonagh *et al.*, 2004). However, at a more fundamental level they allow us to understand the behaviour of harvesting machines and/or systems under varying stand and terrain conditions.

Mechanised felling is used where possible in New Zealand as it increases productivity and cost effectiveness, and can also reduce the occurrence of stem breakage and increase personal safety (McConchie and Evanson, 1995). A large number of variables can affect mechanised harvesting machine productivity. We can attempt to group them as stand and terrain variables. Typical stand variables include piece (tree) size (Evanson and McConchie, 1996; Visser and Stampfer, 2003), stocking density and/or thinning intensity (Eliasson, 1999), type of cut and total volume (Suadicani and Fjeld, 2001). Typical terrain variables include slope, extraction distance, trafficability, and terrain roughness.

Figure 1: Excavator-based harvester operating in large piece size Radiata pine.

For specific studies, variables such as tree form (Evanson and McConchie, 1996), branch size (Glöde, 1999), pruned status, selection criteria of trees to harvest (Eliasson and Lageson, 1999) and/or degree of windthrow can also significantly influence productivity. Mechanised harvesting productivity can also be affected by the operator, with human performance resulting in a 20-50% variation in machine productivity (Bergstrand, 1987; Murphy and Vanderberg, 2007).

Machine productivity determined in short-term time studies is typically also higher than found in follow-up longer-term studies (Sirén and Aaltio,

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2003). While productivity relationships can often be established quickly with key parameters, understanding delays and or machine interaction effects can be problematic in time studies (Spinelli and Visser, 2008).

Most felling studies conclude that piece size is the dominant variable that influences overall mechanised felling productivity. A common concept, known as the "piece-size law", is that productivity increases at a decreasing rate with increasing piece size. This is shown as the 'increasing' phase in Figure 2, whereby the other two phases are the optimum (or 'sweet-spot') and a predicted decreasing phase beyond the optimum.

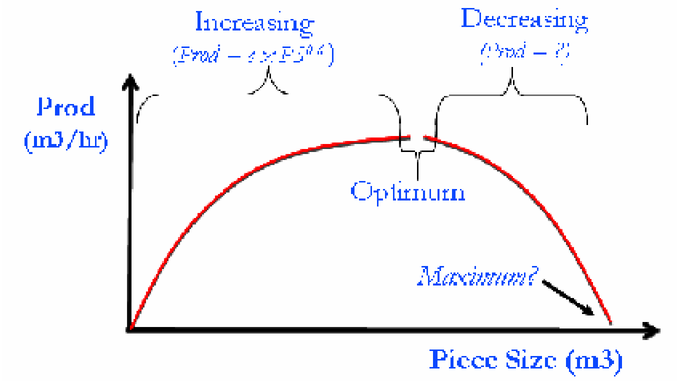

Figure 2: Graph showing the basic relationship between piece size and productivity.

Forestry machines typically work in this 'increasing' phase. The reason is that stands are never uniform and a machine will be required to fell and process a range of tree sizes. While larger machines may be less efficient at felling smaller trees, it can be dangerous to fell larger trees with smaller machines. Machines are therefore typically over-sized for the average conditions they encounter.

For prediction equations a power function can best be used to describe this 'increasing' phase. Many studies indicate that a power factor of approximately 0.6 provides the best productivity-to-piece size (PS) relationship. That is:

$$\text{Productivity } (m^3/hr) = a \times PS^{0.6}$$

In a time study we just need to establish co-efficient 'a' and we gain a very good understanding of the piece size/productivity relationship for a given machine under given conditions.

Because of the mono-directional nature of this function, when used for productivity prediction the 'optimum' productivity is always at the maximum piece size. The raw data of some published studies shows a tendency to decrease at the upper limit. This simply means that the increase in time is greater than the increase in piece size. This can be problematic if such an equation is being used by a company to predict productivity, or is used to negotiate a logging rate. Common sense suggests that there must be an optimum or 'sweet-spot' followed by a decline. For contractors, knowing this sweet-spot will improve the opportunity to correctly match the machine to the harvest area.

To improve our understanding of the piece size-to-productivity relationship, especially in the optimum and decreasing phases, this study focused on mechanised harvesters working in harvest areas with large trees.

STUDY METHODS

Four mechanised felling, or felling and processing, operations were studied to investigate the effect of piece size on productivity:

1. Waratah 624 harvester in Lowmount Forest – rolling terrain with silty, sandy soils
2. Waratah 622 harvester in Bottle Lake Forest – flat terrain with sandy soils
3. Satco 630 feller-director in Tarawera Forest – flat terrain with volcanic ash soils.
4. Satco 630 feller-director in Ashley Forest – rolling to steep terrain

All study areas were radiata pine clearfell operations. The base machine for each feller-director/harvester head was a 25-30 tonne excavator. A classic time and motion study was conducted at each site. The work tasks used for the study are shown in Table 1.

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Table 1: Work task definitions for the mechanised harvester study

Work task	Description
Fell	Felling and bringing the tree to the ground
Delimb	Delimbing the whole tree
Bunch	Pre-bunching stems for extraction
Move	Repositioning between trees or rows
Clear	Moving slash and/or tops for either moving or felling
Delay	All operational and mechanical delays

In a suitable part of each harvest area, working ahead of the harvester, the diameter at breast height (DBH) of each tree was measured and recorded, and the trees were either flagged with tape or painted (Figure 3). The felling and delimbing work tasks were combined for the Waratah harvester heads, as operators typically commenced delimbing before the tree hit the ground.

Figure 3: Waratah 622 with pine clearfell in Bottle Lake Forest. Note that all trees are marked with unique colour-bands prior to felling.

Post-felling, approximately 20 trees were scaled by measuring diameter at 5-metre intervals along the stem, as well as a top length and diameter. A simple tapered cylindrical volume equation was used to establish the volume of each segment, and summed to arrive at a close approximation of the volume of the tree. A regression was then used to correlate DBH to tree volume.

Productivity information (m^3/PMH) was calculated based on the time it took the head to fell and process different piece sizes. Note that the productivity information shown in this study is for productive machine hours (PMH) only, and includes only the felling and delimbing phase. Combining all four studies, approximately 40% of the time was felling and delimbing, the remaining 60% bunching, clearing, moving or in a delay.

RESULTS and DISCUSSION

In the two Waratah studies we succeeded in collecting enough data 'beyond the optimum' to clearly show the declining productivity phase. For example, the Waratah 624 (felling and delimbing) data are shown in Figure 4.

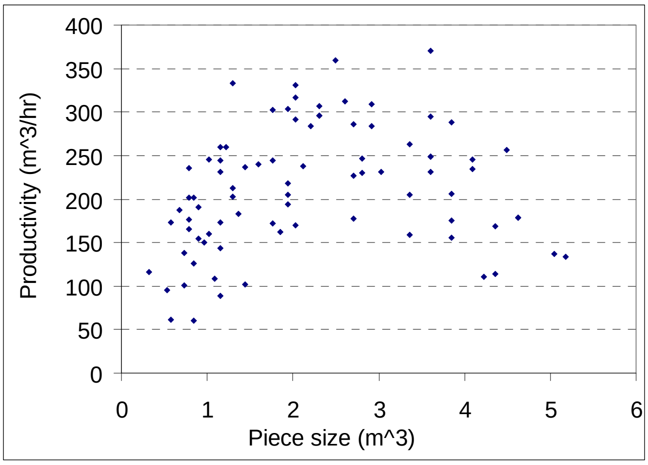

Figure 4: Felling and delimbing productivity vs. piece size for Waratah 624 harvester in Lowmount Forest.

The trees sampled in this study ranged in piece size from 0.3 up to 5.2 m^3. The optimum (sweet-spot) for the Waratah 624 was 2.8 m^3. Figure 4 also indicates that as the piece size approached 6 m^3 (approx. 80 cm) the productivity approached zero, and this matched closely with the manufacturer's published maximum head opening (76 cm).

The declining phase can be clearly seen, and may be attributed to a number of factors. While technically the Waratah cutting capacity was much greater than the optimum shown, operator experience indicated that the bar was likely to

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pinch, or jam, with larger diameter trees. The operator therefore used a front-cut, moved the head around the base of the tree, and then completed the back-cut for the larger trees. Extra time was also required for delimbing the larger-branched trees, as well as manipulating the heavy stems.

The shape of the data set from the study of the smaller Waratah 622 in Bottle Lake Forest was similar. The trees sampled ranged in piece size from 0.3 to 3.8 m^3. The Waratah 622 sweet-spot was 2.2 m^3, with the maximum of 4.0 m^3. The initial part of the increasing phase of the productivity curve was almost identical for the two different Waratah head sizes. This demonstrates that smaller harvesters can operate at approximately the same productivity as larger machines. When considering the higher operating costs of larger harvester heads, then smaller harvester heads are more cost effective in smaller piece size (Jirousek *et al.*, 2007).

It would be unreasonable to attempt to fit a mono-directional function to the Waratah data sets. A series of different functions was fitted to the data (Visser *et al.*, 2009), whereby it was established that the following function best describes the productivity to piece size relationship beyond the optimum:

$$Prod = a \times PS \times e^{b \times PS^c}$$

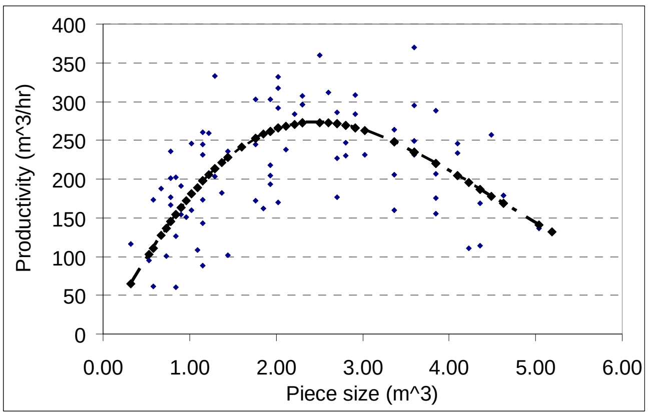

Figure 5. Graph showing the Waratah 624 productivity data, as well as the quadratic and two exponential regression approximations.

Using the statistical software R to run an iterative optimising algorithm, the iteration yielded a= 203.2, b=0.136 and c=1.655. Figure 5 shows the 3–coefficient exponential function.

The results of the Satco felling study in Tarawera Forest (piece size range 1.0 to 5.3 m^3) are typical of many productivity studies, in that the sweet spot is not obvious (Figure 6). However, the results of this study can be used to illustrate the benefit of the improved regression equation.

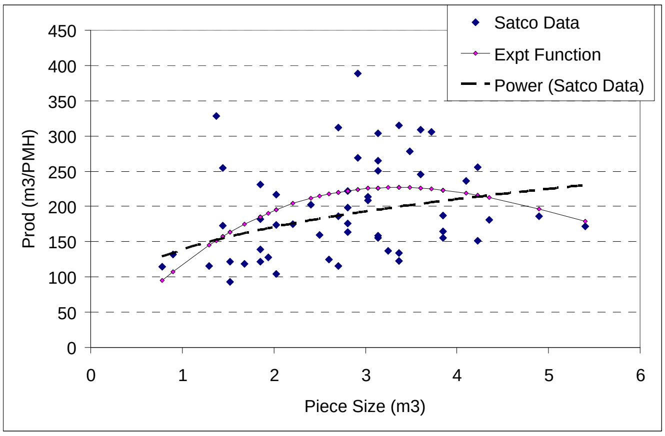

Figure 6: Productivity of the Satco (felling only) in Tarawera Forest.

Fitting a basic power function to the Satco data yields:

$$Prod = 138 \times PS^{0.30} \qquad (r^2 = 0.13)$$

This equation indicates that only 13% of the productivity relationship is explained by piece size. By using the more complex productivity function, the regression identified the optimum piece size of 3.4 m^3, and established the following relationship:

$$Prod = 130 \times PS \times e^{0.1 \times PS^{1.55}} \qquad (r^2 = 0.42)$$

CONCLUSION

Time studies are a great tool in forest engineering to understand the effects that many stand and terrain variables can have on machine and harvest system productivity. While many

variables exhibit a mono-directional relationship with productivity, this study has shown that piece size does not. Logically, there should be an optimum piece size ("sweet-spot") where productivity is maximised. For future studies used by a company to predict productivity, or to negotiate logging rates, consideration should be given to using a more complex function when relating piece size to productivity.

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