Analyzing and Estimating Delays in Harvester Operations

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ABSTRACT

Time and motion studies have been and still are frequently used to describe, understand, and improve forest operations. Delays are recognized as being one of the major factors that limit productivity in most operations and are, therefore, an integral part of most time studies. But, delay events are erratic in both occurrence and magnitude and are, therefore, difficult to precisely quantify within the relatively short observation period of a typical time and motion study. Thus, delay information from individual studies have limited transferability. This paper analyzes the delay component of 34 harvester time study data sets that were recorded between 1998 and 2006. All of the studies were designed and carried out with the same principal investigator. The data sets were all based on harvesters either harvesting and or processing. Three delays categories were used: mechanical, operator, and other. Delays averaged 28.9 percent of the total scheduled time for all 34 studies, comprising of 7.1 percent mechanical, 4.7 percent operator, and 17.1 percent other delays. Delay averages were compared within category descriptions assigned to each data set for statistical significance. Example results include: total delays were higher for operations working on hot decks versus cold decks and operations working in mixed stands had more than twice the overall delays compared to operations in plantations. Considering only mechanical delays, machines that both felled and processed, compared to just processing, had higher mechanical delays. Interestingly, dedicated harvesting machines versus harvesting heads mounted on an excavator base had on average higher operator delays.

Keywords: *time study, logging, harvester, machine delays, forestry*

Introduction

Time and motion studies have been and still are frequently used to describe, understand, and improve forest operations. Research on the productivity of forest operations is obtained by measuring the time consumed and the quantity produced and then carrying out a statistical evaluation to relate the two quantities (Steinlin 1955). Performance studies can be comparative or correlation studies (Samset 1990). The aim of correlation studies is to find the relationship between the performance of the machine and the various influencing factors, such as tree size, extraction distance, terrain slope, etc. (Appelroth 1985, LeDoux and Huyler 2000). Correlation studies should only be carried out on machines and methods which are generally used in practical forest operations (Bergstrand 1991).

For most forest operations productivity studies, the data collection procedure consists of a set of detailed time and motion studies conducted at the cycle level. In general, detailed time studies are more discriminating than shift-level studies and can detect smaller differences between treatments (Olsen et al. 1998). Cycle times are defined and split into time elements considered to be typical of the functional process analyzed. This is done with the intent of isolating those parts of a routine that are dependent on one or more external factors (e.g., tree size, percent of leaning trees, slope, travel distance) in order to enhance the accuracy of the productivity models. The criteria followed for such subdivisions should focus on:

1. isolating significant cycle elements;
2. reflecting as much as possible on other similar existing protocols (Berti et al. 1989, Landau 1998) and,
3. avoiding unnecessary detail.

There have been various attempts to standardize time study procedures, including those by the Nordic Council of Forestry, IUFRO (Bjorheden et al. 1995), and the European Union (CTBA 1997). For example, differentiating between scheduled machine hours (SMH) from the work only productive machine hours (PMH) and defining mechanical availability (MA%) are all common concepts. A comprehensive set of definitions for forest operations terms, including common time study terminology, was published by the U.S. Forest Service (Stokes et al. 1989). Most of their time study definitions were in turn taken from two American Pulpwood Association technical publications (APA 1972, 1981). These time study terminology definitions help in defining each term and in many cases suggest appropriate categorization of time elements

Differing definitions still occur to reflect local work condition or simply reflecting methodologies used by previous studies with which one intends to compare results. Although most proposed protocols agree in principle and are relatively clear and simple, problems exist in their application in the field.

Conway (1982) noted the importance of delays in all phases of production. A major problem exists in the reliable recording and evaluation of machine delays. Even basic definitions have

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not been interpreted consistently. Early definitions focused on two types of delays: productive and non-productive (McGraw and Hallett 1970). Many recently published productivity studies seem to prefer using mechanical, operational, and personal delays categorization (Visser and Stampfer 2003). Each definition set seems to have strengths and weaknesses. For example, categorizing regular maintenance and unexpected breakdowns into productive and unproductive, respectively, is easily understood. In the second set, however, there seems to be no common ground on deciding if regular maintenance is mechanical or an operational delay. Conversely, moving equipment is commonly interpreted as being operational, but it is not clear if it should be considered productive or non-productive. Regardless of the number of delay categories used in a time and motion study, there is always a need to add a generic other category to accumulate time events that are either not recognized by the person carrying out the time study – or genuinely does not fit a category.

Other differences occur in the differing data interpretation methodologies. One clear example is that most central European countries prefer including delays up to 15 minutes into the work only time, denoting this with PMH_{15}. This means their published delays are only those greater than 15 minutes. There is no published data that suggests appropriate conversion factors to allow corroboration of either the PMH_{15} into PMH or the delay time itself.

In the field there is the inherent difficulty of obtaining representative samples of a typically erratic phenomenon from relatively short observation periods. This makes it difficult to translate into practice the results obtained from models able to predict work only productivity, otherwise very accurate and potentially useful. Stampfer and Steinmueller (2001) noted that for efficient generation of productivity models for harvesters it is simpler to only capture the data for the work time components and then use a delay model based on the literature. But, no such delay models exist except for individual values from specific time studies.

Little scientific work has addressed the development of reliable delay factors, and the translation of net production data obtained from scientific time studies into scheduled time performance is obtained by applying empirical reduction coefficients or using the results of studies coming from a long distance in space and time (Brinker et al. 1989). The application and/or extrapolation of empirical study results for the purpose of determining appropriate harvesting rates also requires an accurate understanding of delays. The utilization rate, which is defined as (SMH – delays)/SMH, determines the allocation of fixed and running costs (Miyata and Steinhilb 1980).

During an extensive research program to help promote mechanization of Italian operations, the National Council for Research (CNR) of Italy conducted a large number of time studies on a range of mechanized equipment. This included 34 complete harvester times studies recorded between 1998 and 2006. Such a large data set provides an opportunity to analyze in detail the delays associated with harvester operations.

The goal of this study was to produce and analyze delay factors that can be applied to the estimated net work time productivity. This would allow translating the theoretical estimates of many studies into a more workable pool of knowledge, ready for application in the field. Example applications include being able to estimate the actual time consumption and/or operating costs under operational conditions, as faced by commercial operators.

Materials and Methods

Thirty-four complete times studies, recorded on harvesters between 1998 and 2006, were used for the analyses of delays. All of the time studies were set up and carried out by the same principle investigator and with the same methods. All of the time elements and related time-motion data were recorded with Husky Hunter® hand-held field computers running Siwork3® time study software (Husky Computers Ltd. 1991, Kofman 1995).

All of the time studies used three clearly defined delay types:

1. mechanical delays (breakdowns, saw-chain derail, saw-chain replacement),
2. operator delays (rest, break, physiological, smoke, phone call), and
3. other delays (including waiting, interference, reconnaissance, refuel, preparation).

Delays caused by the study itself, including giving instructions and measuring logs, have all been excluded. Delays for the main meal (if the operator took any) and relocation to and from site are also not included in the data sets. All other delays are included.

Each data set allows itself to be categorized depending on what the harvester was doing and where it was doing it. As the research group is based in Italy, 26 of the data sets were from Italy with three from the United States, two from Portugal, and one each from Austria, Canada, and Spain. Although there were the same number of softwood stands as short rotation plantation stands, only four softwood stands were short rotation plantations; that is, they are clearly different categories. In Europe there are also many hardwood short rotation plantations, mostly poplar and eucalyptus, with a rotation of 7 to 14 years. Twelve of the studies were on dedicated harvester machines (i.e., machines designed from the ground-up as a forest harvesting machine). The remainder of the machines were excavator bases with either a harvesting or processing head attached to its boom. Another classification differentiation was made according to the task of the harvesting machine during the time study. On 21 sites the machine both felled and processed (cut-to-length type operations) the trees, whereas on the remaining 13 sites the machine only processed the stems (typically at roadside or at the landing). In addition, it was recognized that hot-deck operations, where the trees are being brought onto the landing as the machine is processing, are likely to be more susceptible to delays than cold deck operations. It was also noted that the highest operator delays were all from processing operations under a cable yarder, and they too were categorized for further analyses.

The studies totaled 692 hours of observation (87 scheduled workdays) and ranged from 4 hours up to 59 hours (average 19.7 hours) for the individual studies. Utilization (defined as PMH divided by SMH) ranged from 49 to 90 percent, with an average of 71.1 percent. Conversely, delays averaged 28.9 percent of the total scheduled time for the studies, comprised of 7.1 percent mechanical, 4.7 percent operator, and 17.1 percent other delays.

In most published reports, delays are reported as a percent of the total scheduled time. Assuming just three delay categories, SMH can be calculated by Equation [**1**].

$$\mathrm{SMH} = \mathrm{PMH} + \mathrm{H}_{\mathrm{mech}} + \mathrm{H}_{\mathrm{op}} + \mathrm{H}_{\mathrm{oth}} \qquad [\mathbf{1}]$$

where:

SMH = scheduled machine hours,

PMH = productive machine hours,

$\mathrm{H}_{\mathrm{mech}}$ = hours of mechanical delay,

H_{op} = hours of operator delay, and

$\mathrm{H}_{\mathrm{oth}}$ = hours of other delay.

Normally delays are presented as a percentage of SMH. Mechanical delays (MechD), for example, can be expressed by Equation [**2**]:

$$\mathrm{MechD} = \frac{\mathrm{H}_{\mathrm{Mech}}}{\mathrm{SMH}} \qquad [\mathbf{2}]$$

where:

MechD = mechanical delay (%)

Expressed in terms of utilization (%), we can derive Equation [**3**] that separates the three delay percentages. The last line rearranges the Equation to isolate mechanical delay.

$$\mathrm{Util}(\%) = \frac{\mathrm{PMH}}{\mathrm{SMH}} = \frac{\mathrm{SMH} - \mathrm{SMH}\left(\frac{\mathrm{MechD}+\mathrm{OpD}+\mathrm{OthD}}{100}\right)}{\mathrm{SMH}} \qquad [\mathbf{3}]$$

$$\frac{\mathrm{PMH}}{\mathrm{SMH}} = 1 - \frac{(\mathrm{MechD}+\mathrm{OpD}+\mathrm{OthD})}{100}$$

So

$$\mathrm{MechD} = 100 - 100 \times \frac{\mathrm{PMH}}{\mathrm{SMH}} - \mathrm{OpD} - \mathrm{OthD}$$

where:

OpD = operator delays (%) and

OthD = other delays (%).

Equation [**3**] shows that mechanical delays becomes a function that is also dependent on operator and other delays. This assumes a level of dependence between the delay types. We tested for correlation among all three delay types and none was found. This indicates that an operation that has, for example, above average mechanical delays is no more likely to have either above or below average operator or other delays. Therefore, it makes more sense to report delays as an increase over the work-related time elements (net productive time), as such a value is then transferable to other operations. To ensure a distinction, we will refer to a delay factor (still in %), which is to be added to the productive machine time.

To illustrate the need for this distinction, consider the following example. For a 20-hour time study (i.e., SMH = 20) on a skidder, there was a 10-hour other delay because there were no trees on the ground to skid, and there was a 2-hour mechanical delay, with 8 hours of work time recorded (i.e., PMH = 8). Normally we would report this operation as having 10 percent mechanical delay. If we wish to transfer this delay information to other operations, it would be more useful to state that for 8 hours of productive work, we had 2 hours of mechanical delay (i.e., a mechanical delay factor of 25 percent which is to be added on to the work time to account for the breakdowns). Reporting the information in this manner means the mechanical delay is now independent of the 'other delay' occurrence.

In equation form the total delay factor is just the summation of the three individual delay factors (Eq. [**4**]) and the conversion of PMH into SMH is given in Equation [**5**].

$$\mathrm{DF}_{\mathrm{tot}} = \mathrm{DF}_{\mathrm{mech}} + \mathrm{DF}_{\mathrm{op}} + \mathrm{DF}_{\mathrm{oth}} \qquad [\mathbf{4}]$$

$$\mathrm{PMH} \times \left(\frac{\mathrm{DF}_{\mathrm{mech}} + \mathrm{DF}_{\mathrm{op}} + \mathrm{DF}_{\mathrm{oth}}}{100}\right) = \mathrm{SMH} \qquad [\mathbf{5}]$$

where:

$\mathrm{DF}_{\mathrm{tot}}$ = total delay factor (%),

$\mathrm{DF}_{\mathrm{mech}}$ = mechanical delay factor (%),

$\mathrm{DF}_{\mathrm{op}}$ = operator delay factor (%), and

$\mathrm{DF}_{\mathrm{oth}}$ = other delay factor (%).

These delay factor representations are used throughout the analyses and results.

To complete the statistical analyses, two-tailed t-tests were used to test for differences between categories in the delay data. We should note that these data sets were not collected with the intention of doing a delay comparison; there is no study design to balance operational, stand, or terrain types. These results should, therefore, be considered indicative not definitive and are analyzed for indications of trends.

Delay Length Distribution

As an additional part of the study, all of the individual delay events were used to determine what a typical distribution for delays might be. In particular this is to address the issue of published productivity models where delays less than 15 minutes are included in the work time (mainly the central European countries) with those that report all delays. The question, therefore, arises, what percent of delays are less than 15 minutes so that a correction factor can be applied for productivity comparison?

For 29 of the 34 data sets, the original data collected was still readily accessible in a form whereby the individual cycles could be compiled. All cycles with a delay in them were aggregated for evaluation. In total, this amounted to 2,151 individual delay events representing a total of 144 hours of delays.

Results and Discussion

All of the delay data was separated according to the categories. **Table 1** presents the total delay factor (%) as categorized by the studies. In addition to whether or not the categories were statistically significantly different ($p < 0.05$), **Table 1** shows the number of cases and the average delay for each category along with the standard error of the mean for the data set.

Three combinations were statistically significantly different at the 5 percent level for the total delay factor. Harvesters working in natural stands averaged a higher total delay than those working in short rotation plantations (49.7% vs. 20.8%). Hot deck operations (62.6%) and those working at a cable yarder landing (71.1%) had very high total delays factors: once again, this result confirms the difficulty of achieving good unit balance in complex operations.

Table 2 breaks down the total delay factor into the individual delay factors for the three delay categories. For mechanical delay factor, natural stands yielded statistically significant higher delay factors values than plantations. In addition, operations in softwoods also have a higher mechanical delay than operations in hardwoods: this might be related to the higher incidence of natural stands in the softwood category. Although not specifically designed for forest operations, excavator-base units do not seem to be more vulnerable to mechanical damage than purpose-built machines; in fact the average mechanical delay factor is less for excavator machines.

For the operator delay factor column in **Table 2**, the only category that was statistically significantly different was the dedicated machine as compared with the excavator-base. This might be related to the fact that over half of the operations conducted with dedicated machines took place in natural stands and on relatively steep terrain, placing a high stress on the operator, hence the need for more frequent and longer rest breaks. Not statistically significant, but possibly a trend, harvesters working in softwood, natural stands, and felling all had higher operator delay factors at about the 10 percent significance level, which may corroborate the above-mentioned inference.

All of the categories, with the exception of hardwood/softwood showed significant differences in other delays. Working on a cable yarding landing or on a hot deck, felling, working with an excavator base machine, as well as working in mixed stands all had clearly higher percentage of other delays, although the specific cause of delay could be different among these categories. The higher incidence of other delays associated with excavator-base units, for example, could be related to the fact that all of the machines working under a yarder were excavator-base units. This may also explain the higher occurrence of these delays in Italy, where all of the yarder operations in the study come from. As to mixed stands and felling, higher delays may depend on the more frequent need for reconnaissance and work planning.

Overall it should be noted that the other delay factor is large, both in absolute terms as well as relative to the other two categories. If an operational delay category had been used it would have captured most of this data (preparation, waiting, interference, etc.).

Table 1. ~ *Categories that allow the studies to be compared, breakdown of number of studies within the category, average total delay factor, and standard error of the delay factor.*[a]

Categories	n	Average total delay factor	Standard error
		- - - - - - - (%)	- - - - - - -
Italy	26	40.3	4.6
Other country	8	28.9	5.2
Hardwoods	20	34.0	4.6
Softwoods	14	43.7	6.8
Natural stands	20	**49.7**	4.7
Short rotation plantations	14	**20.8**	1.8
Dedicated machine	12	32.9	4.0
Excavator base	22	40.2	5.4
Felling and processing	21	33.7	3.4
Processing	13	44.0	8.2
Hot deck	7	**62.6**	10.5
Cold deck	27	**31.2**	2.9
Cable yarder landing	5	**71.1**	13.0
Other	29	**31.9**	2.7

[a] Numbers in **bold** are statistically significantly different at the $p < 0.05$ level.

Table 2. ~ *Average mechanical, operator, and other delay factors (%) by study category.*[a,b]

Categories	n	Average DF_{Mech}	Average DF_{Op}	Average DF_{Oth}
		- - - - - - - - - - -	(%)	- - - - - - - - - - -
Italy	26	8.6 (1.3)	6.0 (0.9)	**25.7** (4.4)
Other country	8	12.7 (3.4)	8.4 (1.8)	**7.8** (1.9)
Hardwoods	20	**6.4** (0.8)	5.4 (1.0)	22.1 (4.6)
Softwoods	14	**14.6** (2.7)	7.5 (1.3)	21.6 (6.5)
Natural stands	20	**12.3** (1.9)	7.6 (1.1)	**29.8** (5.3)
Short rotation plantations	14	**5.6** (1.0)	5.1 (1.2)	**10.1** (2.2)
Dedicated machine	12	12.0 (2.8)	**9.1** (1.3)	**11.7** (2.5)
Excavator base	22	8.2 (1.3)	**5.2** (1.0)	**26.9** (5.1)
Felling and processing	21	**11.5** (1.9)	7.6 (1.2)	**14.6** (2.4)
Processing	13	**6.5** (1.0)	4.9 (0.9)	**32.7** (7.9)
Hot deck	7	7.5 (1.3)	4.9 (1.3)	**50.2** (10.5)
Cold deck	27	10.1 (1.6)	7.0 (1.0)	**14.1** (2.0)
Cable yarder landing	5	6.9 (1.2)	5.1 (1.5)	**59.2** (12.7)
Other	29	10.0 (1.5)	6.8 (0.9)	**15.0** (2.0)

[a] Standard error in parentheses.
[b] Numbers in **bold** are statistically significantly different at the $p <$ 0.05 level.

Length of Delay

Analyzing the 2,151 individually recorded delay lengths from the 26 studies, **Figure 1** shows the frequency of the delays broken down by delay type and duration of the individual events. We can clearly see that in a continuous time study, most of the delay events are less than 15 minutes in duration (94%).

It is not the number of occurrences, however, but the total delay time that has more relevance to the results of a time study. **Figure 2** shows the accumulated time for each type and time category (i.e., the sum of time for all delay events of that given type and within that time category). Sixty-one percent of all of the delay time was recorded for delays that were less than 15 minutes in duration.

This would suggest that time studies that report productive time as including delays less than 15 minutes would represent the data very differently compared to time studies of delay-free net productive time. We can make the point by using the average of these 34 harvester time studies, where delay-free productive time represents 72 percent of total scheduled work time (i.e., delays are 28% of the total). If productive work time is assumed to include all delay events less than 15 minutes in duration, utilization increases from 72 to 89 percent, whereas delays decrease from 28 to 11 percent.

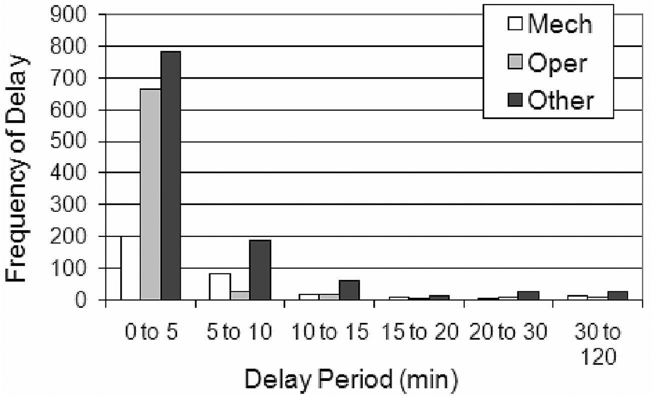

Figure 1. ~ *Frequency of the total number of delays, by delay type, that occurred during the 26 harvester studies for which the elemental time study data was still available, grouped by delay periods (n = 2,151).*

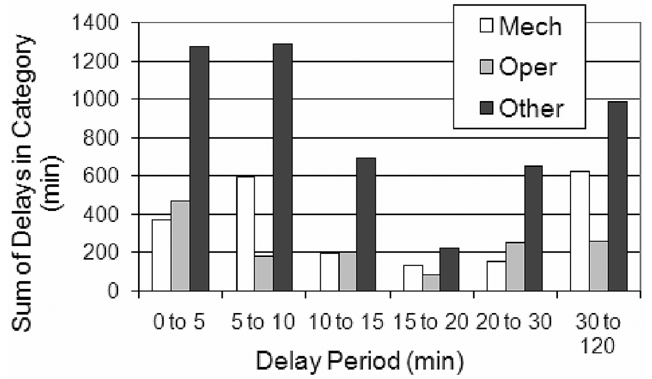

Figure 2. ~ *Sum of all delay times, by delay type, that occurred during the 26 harvester studies for which the elemental time study data was still available, grouped by delay period (n = 2,151; sum of all delay time was 8,936 min.).*

Impact of Length of Study on Average Utilization

Another interesting hypothesis to test is the notion that as we study an operation for a longer period of time we are more likely to capture more significant delay events. Perhaps stated more realistically, researchers are less likely to commence or continue a study if there are significant delays at the beginning or near the end of a study. Using the study data to review this hypothesis, we can chart utilization versus length of study (**Fig. 3**). Although a statistically significant ($p = 0.003$) decline in utilization for increased study length is evident, this simple model only explains 27 percent of the variation ($r^2 = 0.27$). If one removes the data points associated with cable yarding operations (the longest studies with the lowest utilization), then both the significance and the amount of variation explained by the model decreases. Hence, the association of a low utilization and a long study duration may be coincidental, not causal.

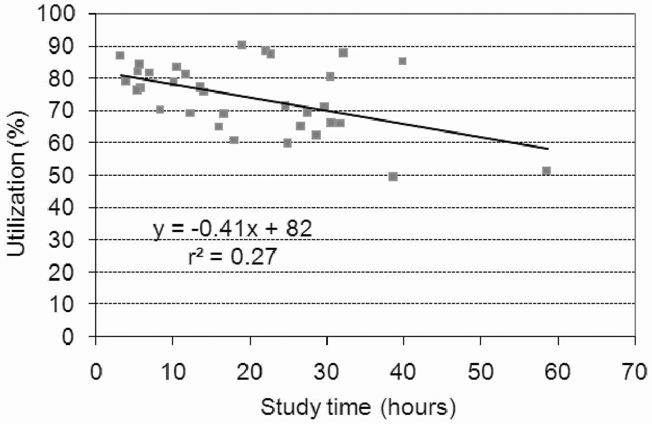

Figure 3. ~ *Utilization (%) vs. duration of time study (hours) for all 34 harvester studies.*

Conclusions

Time studies are an integral part of forest operations research. Their results are increasingly used for management decisions such as aiding in setting productivity targets, assessing payment schedules, optimizing systems, and selecting among alternative machine choices. Published time and motion studies have shown that while it is possible to accurately capture and analyze work time related aspects of an operation, it is difficult to accurately assess delay information. Our analyses of 34 harvester time study data sets indicated that delays vary significantly, not only by machine type, but by stand and terrain variables. The availability of reliable delay factors makes it possible to generate ad-hoc data by relatively short time study sessions, potentially reducing the cost of harvesting optimization work. On most operations, net process time can be modeled quite well with a reasonably limited number of data points: if delay data can be excluded and a delay factor added to the net productive time, then the duration of individual time study sessions can be dramatically reduced and so can the cost of the investigation. In addition, researchers who use time studies must understand the possible inaccuracies as well as the nuances that even a standardized time study protocol may have. Results of different studies should only be compared with much caution.

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