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RESEARCH ARTICLE

Predicting productivity of timber loading operations: a literature review

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Abstract

Loading is considered a bottleneck of the forest harvesting system as it acts as a connection between primary transport and secondary transport (from roadside/ landing to mills or central yards). Any delay during the loading component can cause delay in the primary wood extraction and/ or secondary transportation. This article reviewed the current knowledge on loading productivity studies. Based on the results, the main variables impacting the loading productivity include log size, log lengths, load volume per truck, number of logs (or pieces) per truck and number of safety straps. The productivity of loading operations ranged from 3.4 m3/PMH_0 in a manual loading to 168.9 m3/PMH_0 using mechanised loaders. The results of this review can assist the academic and industrial users for predicting, controlling and managing the productivity of loading operations.

Keywords

Harvesting, Productivity, Time, Loading, Log volume, Mechanised loader, Manual loader

Introduction

Forest harvesting as a system includes various components, such as felling/ processing, primary transport, loading, secondary transport, unloading and road construction (Conway, 1982). Loading is seen as a bottleneck of the forest harvesting system as it acts as a connection between primary transport (from stands to the roadside/ landing) and secondary transport (from roadside/ landing to the mills or central yards). Any delay in loading components can cause delay in the operations carried out by extraction machines and/ or trucks/ trailers (especially in hot-decking operations). In the case of cold decking (when timber is transported after finishing timber extraction phase), if the loading component is delayed it may result in larger volume of logs/ trees accumulated on the landings, which may reduce further the total efficiency of the harvesting system.

When harvesting small trees, a feller can fell the trees with a chainsaw and manually load them to the timber trucks; this is called a Bobtail system. In the case of loading large trees, the logs or tree lengths can be loaded by powerful mechanised loaders. The mechanised loaders (powered systems) may be big-stick loaders, self-loading timber trucks, pallets, grapple loaders, front-end loaders, loading cranes and booms (Conway, 1982). Russell and Mortimer (2005) reviewed small- scale harvesting systems and described two types of loaders, including wire-crane loaders and grapple loaders. Wire-crane loaders are powered by a winch that uses a high A-frame and stabiliser legs that can be used to load the timber trucks. Grapple loaders use hydraulic crane equipped with a grapple that can pick up single or a bunch of logs/trees to lift and load into the timber trucks.

Materials and methods

Productivity is defined as a relationship between some measures of output to some measures of input uses (Griliches, 1998 cited in Heinimann, 2021). Loading productivity is calculated by dividing volume per cycle (m^3) to the time per cycle (h) (http://www.fao.org/3/t0579e/t0579e07.htm)

Different factors such as stand conditions, machine type, work method and operator skills may impact on the work productivity of forest harvesting machines. Working time can be measured using the time study methods including using plot level, work shift level, work cycle or elemental level (Magagnotti et al. 2012). The results of time studies can be used by the forest harvesting planners to schedule the production, prepare the budget and compare different equipment and work methods (Murphy, 2005). This review article aimed to review the current knowledge on loading productivity studies to identify the main variables impacting the work productivity and provide productivity range of loading operations for the academic and industrial users.

The literature published in English language was found through online journal articles and technical reports by searching electronic databases including Google Scholar, Scopus and Web of Science. The following keywords were used for the electronic search: timber, loading, productivity, loader and time study. The review results were classified based on four main geographical areas (Asia/ Oceania, America and Europe).

Results: Loading productivity studies

Asia/ Oceania

A time study was conducted in East Indonesia by Kewilaa and Tehupeiory (2015) to evaluate the productivity of a log loader Caterpillar 966 F Type and WL 980 C in IUPHHK PD. The trees were manually processed with a chain saw into logs to be loaded by mechanical loaders into the timber trucks at the landing. The log volume (and its weight) was assumed to be the main factor influencing the loading productivity. The developed regression model showed that there was a linear relationship between productivity and log volume. The larger log volume resulted in higher productivity. In this case study (Kewilaa and Tehupeiory, 2015), 51 logs were measured with an average volume of 4.3 m^3. The average loading productivity for both loaders was 22.2 m^3 per productive machine hours (PMH_0). In the northern part of Iran, the mountainous broad- leafed natural forests are mainly harvested using a combination of chain saw for felling/ processing trees to short or long logs, skidders/ tractors to extract the logs to landing and front-end loader to load the logs into the timber trucks at the landings (Ghaffariyan, 2008; Ghaffariyan, Sobhani, 2008). A time study was conducted by Ghaffariyan et al. (2012a) to estimate loading productivity of a Volvo BM4500, model TD706 in an unevenly- aged Iranian forest where the main species was beech (*Fagus orientalis*). The average log volume was 2.78 m^3. The regression model was inverse type and the only factor influencing productivity was log volume. The study reported an average productivity of 41.9 m^3/PMH_0. Loading elements included selecting the log (19% of total work time), grappling (24%), loading (21%) and adjustment (13%). Major delays included operational (13%) and personal delays (4%).

Plantations of Australian pine and eucalypt are mostly harvested using whole-tree and cut-to-length methods (Lambert, 2006). Within the whole- tree method, feller-bunchers are used to fell the trees then the grapple skidders extract the whole trees to the roadside to be processed by a processor into short or long logs (Ghaffariyan, 2019). Then front-end grapple loaders are used to load the logs to the trailers at the roadsides. For the cut-to-length method, the harvester-processors fell and process trees into short logs at the stump. Then forwarders could extract the logs to the roadside. Forwarders or front-end grapple loaders can be then used to load the logs into trailers. A case study was conducted using the whole- tree harvesting method in an 11-year-old plantation of *Eucalyptus globules* (blue gum) at Clear Hills in Western Australia. The average tree volume was 0.2 m^3. According to the results of the time study, the average productivity of a Cat 320C excavator-based grapple loader was 86.2 m^3/PMH_0 (Figure 1). The work delay (mainly operational type due to waiting for the timber trucks) was 8.1% of the total working time (Ghaffariyan et al. 2012b).

Another case study was conducted in Southern Tasmania within pine plantations (*Pinus radiata*). The tree size averaged 2.6 m^3 and the mean log volume was 0.7 m^3. The harvesting system consisted of a tracked feller-buncher, processor, forwarder and loader. The loader model was Komatsu PC300 with a Randalls grab, which was used to load the short logs on the mini B-double truck. The average productivity of the

Figure 1. A front-end loader working in eucalypt plantations (Western Australia, photo by Rick Mitchell)

Figure 2. Manual loading in Turkey (Guelci and Erdas, 2018)

loader was 100.8 m^3/PMH_0. Based on the results of Ghaffariyan et al. (2012c), 2.9% of the total time was spent for waiting for the timber trucks to move during loading, while 97.1% of the total time represented the actual loading time).

Europe

Akay et al. (2004) have reported that there are various types of loading from manual to highly mechanised ones. One of the powerful types is the hydraulic front-end loader that can handle short and long logs. According to Akay et al. (2004), the number of pieces per each truck is a significant variable impacting the loading time (used by Schneider (1978) as an independent variable). The study area in Kahramanmaras (Turkey) was covered by cedar, pine and fir with average tree volume of 0.7 m^3 and average slope of 31%. A Cat 322-B loader was applied to load the logs into the timber trucks where logs were produced at the landing using bucking the long logs skidded to the landing with a tracked-skidder. The average productivity in this case study was 45.3 m^3/PMH_0. Another Turkish loading productivity study was conducted by Guelci and Erdas (2018) in stands of Brutian pine (*Pinus brutia* T.) with average ground slope of 33% and average log volume of 0.14 m^3 to 0.29 m^3. The study included two loading methods: manual loading (Figure 2) and electric loading (Figure 3).

Figure 3. Loading with an electric winch loader in Turkey (Guelci and Erdas, 2018)

Using an electric power winch increased the productivity by 25%. The average productivity was recorded at 3.40 m^3/PMH_0 for the manual loading, while the productivity reached up to 4.25 m^3/PMH_0 for the electric power loader. The higher productivity of the electric power loader was due to the higher load capacity. Load volume per each truck was the significant variable impacting the productivity based on a linear regression analysis. Glueci et al. 2018 studied the productivity of Cat 428-E front-end loader in the Osmanniye area of Turkey. The mean volume per load was 0.45 m^3 which resulted in an average productivity of 2.40 m^3/PMH_0 (detailed information was not provided in the source of Glueci et al. 2018). Akay et al. 2020 studied the Liebherr L 514 Stereo front-end loader in Turkey. The study area was flat and covered by eastern spruce (*Picea orientalis*) and eastern beech (*Fagus orientalis*) located near Ordu in Turkey. The processed short logs were previously extracted to the roadside (landings) and were then loaded to the timber trucks. Two people worked in loading, including a loader operator and a worker guiding the operator to stack the logs on the truck. The average log size was 0.38 m^3. An average productivity of 34.3 m^3/PMH_0 was reported. Akay et al. (2020) found that the log volume and diameter were significant variables impacting the productivity, as demonstrated by the linear type regression model in their study. Work elements such as moving to the truck (31% of the total time) and moving to the log pile (31%) consumed the largest share of loading time. The working delays (including mechanical and personal ones) were recorded to account for 25% of the total work time.

America

In 1978, a study was conducted by the United States Department of Agriculture in Intermountain Region, Idaho (USA). The study included four types of loaders: cable loaders with tongs, cable loader with grapple, self-propelled hydraulic loaders and truck mounted hydraulic loaders. The delay-free working time per each cycle was significantly impacted by the number of pieces per each truck based on a linear model (Schneider, 1978). Cass et al. (2009) conducted short time studies for a period of two to four days on five loader operators in Georgia and South Carolina (the machine model was not reported). The operations included the first thinning and clear-cuts. The harvesting system included feller-buncher, skidder, knuckleboom loader with a pull-trough delimber and a hydraulic ground saw. Log diameter ranged from 7.5 cm to 20 cm. The log length ranged from 3.8 m to 8.8 m. Loading productivity did not vary for different product, but it varied for different drivers from 69.4 ton/PMH_0 to 135 ton/PMH_0 (note the values in m^3 had not been reported). The operators who performed delimbing and topping functions during loading took longer time and that resulted in a lower productivity. A case study was conducted by Soman (2019) in central Maine at a site consisting of mixed hardwood and softwood, including eastern hemlock (*Tsuga canadensis* (L.) Carr.) and yellow birch (*Betula alleghaniensis Britt*.) and other species. The slope angle was usually lower than 9%. Partial harvest and clear-cut methods were applied in the region. Trees were felled by feller-bunchers then extracted to the roadside by the grapple skidders to be processed at the landing. Loading with a Serco 300 grapple loader included elements such as swing empty, grapple, cutting, swing loaded and sorting. Sorting with loader was significantly impacted by the number of logs per turn. The average productivity was 168.9 m^3/PMH_0 for both study treatments (partial harvest and clear-cut) as the log piles were combined to facilitate sorting similar market products. The log volume was not reported in this case study. Soman (2019) carried out another study in Maine to compare the tree length with the whole- tree harvesting method. The slope was gentle, less than 15%. The stands were mixed and included various species, mainly balsam fir (*Abies balsamea (L.) Mill.*), red maple (*Acer rubrum L.*), red spruce (*Picea rubens Sarg.*), black spruce (*Picea mariana Mill.*), eastern white pine (*Pinus strobus L.*), quaking (*Populus tremuloides Michx.*) and big-tooth aspen (*Populus grandidentata Michx.*). Harvesting machines included a feller-buncher, grapple skidder, processor, loader and a truck. The loader type was Sterco 300 and loaded the pulpwoods and sawlogs. Work cycles included swing empty, grappling, swing loaded, loading into the timber trucks. For some cycles there was a bucking element to cut the logs to market dimensions after the swing was loaded. Stem density varied from 1071 to 1149 trees per ha and total basal area ranged from 24.0 m^2/ha to 27.2 m^2/ha. Loading productivity averaged at 95 m^3/PMH_0, which was the same for both study treatments (Soman, 2019). Another study by Harril and Hun (2020) investigated the cost and productivity of integrated biomass harvesting in private forestlands in northern California. The stands consisted of tanoak, madrone (*Arbutus menziesii)* and young growth Douglas-fir *(Pseudotsuga menziesii)*. The slope varied from 0 to 45%, while DBH ranged from 23.8 cm to 28.5 cm in the study units. The average tree volume was 0.66 m^3. A mechanised system was applied to clear-cut the area using a combination of a feller-buncher, two Komatsu PC300 loaders (to swing/shovel the bunches of whole trees to the roadside), loaders to load the bunches onto two timber trucks to deliver the woods to a centralised processing site. The average productivity of loading whole trees was 138.4 m^3/PMH_0 (note this value was transformed using a tree weight of 0.35 Bone Dry Tonnes (BDT) as cited in Harril and Hun (2020)). The slope, number of grapples per turn, loaded swing degrees, number of compaction and the travel distance were significant variables in the regression model (as linear type) to predict the delay-free loading time per cycle (Harril and Hunt, 2020). A Cat 322C loader was studied by Han and Han (2020) in northern California, USA. The stand was a mixed conifer forest, including white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), incense-cedar (*Calocedrus decurrens*) and sugar pine (*Pinus lambertiana*). Cable yarding was applied using the whole tree and tree length methods to reduce fuel in thinning operations. The study area was steep as ground slope varied from 37% to 68%. The tree size was small and averaged at 0.03 m^3. Trees were felled with a chain saw then yarded to the roadside using a cable yarder. A processor was used at the roadside to process whole trees then a Cat 322C loader was applied to load the whole trees into timber trucks from a cold deck. The study results showed that there was no significant difference between average loading times between the two harvesting methods. The number of logs per turn was the only significant variable impacting the loading time based on a linear type regression. The loading productivity for the tree length method averaged at 59.4 m^3/PMH_0, while the whole- tree method yielded an average productivity of 60.5 m^3/PMH_0 (Han and Han, 2020).

Grapple loaders are also used in Brazilian forest operations. A case study was carried out by Arcego et al. (2019) in pine stands (*Pinus taeda*) in Otacilio Costa, Brazil. Trees were felled with a feller-buncher then skidded to the roadside with a grapple skidder to be processed to logs using a mechanical processor. Then a tracked based Komatsu PC200 (Figure 4) was used to load the short logs into the B-double timber trucks with the gross weight of 57 t. Log length varied from 2.4 m to 7.0 m. The log

Figure 4. Komatsu PC200 loader working in Brazil (Arcego et al. 2019)

bundles were equipped with four to eight safety straps. The results showed that average loading productivity for 2.4 m logs (using six straps) was 105.8 ton/PMH$_0$. For 3.4 m logs with using four or eight straps the productivity increased to 151.2 ton/PMH$_0$. The highest productivity at 177 ton/ PMH$_0$ was achieved by loading 7.0 m logs using four straps (note the values in m^3 were not reported). The mean productivity for all study treatments was 144.7 ton/PMH$_0$ (Arcego et al. 2019).

Table 1. Summary of loading productivity studies

Continent	Country	Piece volume (m^3)	Independent variables	Machine model	Productivity (m^3/PMH$_0$)	Reference
Asia	Indonesia	4.3	Log volume	Caterpillar 966 F Type and WL 980 C in IUPHHK PD	22.2	Kewilaa and Tehupeiory (2015)
	Iran	2.78	Log volume	Volvo BM4500	41.9	Ghaffariyan et al. 2012a
Oceania	Australia	0.2	n/a	Cat 320C	86.2	Ghaffariyan et al. 2012b
		0.7	n/a	Komatsu PC300	100.8	Ghaffariyan et al. 2012c
Europe	Turkey	0.7	Number of pieces per truck	Cat 322-B	45.3	Akay et al. (2004)
		0.14	Load volume	Manual	3.40	Guelci and Erdas (2018)
		0.29	Load volume	Electric winch loader	4.25	
		0.38	Log volume	Liebherr L 514 Stereo	34.3	Akay et al. (2020)
America	USA	N/A	Number of logs	Sterco 300	95-168.9	Soman (2019)
		0.66	Slope, number of grapples per turn, loaded swing degrees, number of compaction and travel distance	Komatsu P300	138.4	Harril and Hun (2020)
		0.03	Number of logs	Cat 322C	59.4-60.5	Han and Han (2020)
	Brazil	N/A	Log length and number of straps per bundle	Komatsu PC200	144.7 (t/PMH$_0$)	Arcego et al. 2019

Conclusions

Log volume is one of the important factors impacting the loading productivity. Larger log volumes can result in higher productivity due to increase work efficiency in handling larger pieces (Ghaffariyan et al. 2012; Arcego et al. 2019). Thus, the size of logs can be an important consideration when choosing suitable size/ type of the loader (and the size of the timber trucks) in order to eliminate any potential deficiency in loading (and haulage) operations. Also, all logs need to be carefully processed to match with loader (and truck) specifications. When landings are well planned/ maintained and when the timber loads are well stacked at the landings, the loaders may operate more effectively. Ghaffariyan et al. 2012c suggested applying a better machine management to reduce the downtimes of loaders when waiting for the timber trucks. Loading should be in harmony with the other components of the harvesting system (e.g. felling, extraction, etc.) in order to ensure achieving an effective production for the whole supply chain (Akay et al., 2020). Han and Han (2020) mentioned that the loading productivity for logs produced using two harvesting methods (including whole tree and tree lengths) were not significantly different but the number of logs per turn was a key variable impacting loading time per cycle. If the number of safety straps per each bundle of logs is reduced it can increase the efficiency of the loading operation (Arcego, 2019). Regarding manual loading, Guelci and Erdas (2018) and Akay et al. (2020) mentioned that this type of loading in Turkish forestry may face some challenges, such as lack of labour in the regions, and might not be productive due to long time requirement to load a unit volume of load compared with the mechanised loaders.

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