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RESEARCH ARTICLE

Work productivity assessment of small forwarders in forest operations: An international review

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Abstract

There are two types of forwarders available in the practice including conventional forestry forwarders and farm tractors equipped with a trailer/grapple loader that operate as a forwarder. Forwarders loading capacity can vary depending on the machine size. This paper aims to review the work productivity of small size forwarders (payload<10 tonnes and engine power<120 HP) to create an overview of their performance for small scale operations within the small-scale forestry/plantations management or agroforestry systems. According to the review, small forwarders were mainly used for harvesting small trees over gentle slopes. Main machine types include light tractor-trailer and purpose-built forwarders. The reported productivity by international scholars ranged from 3.4 to 19.2 m^3/PMH_0. Main variables impacting the productivity of small forwarders included forwarding distance, load volume, piece volume, number of logs per turn, season, operator skills and harvesting intensity. This report has summarised recommendations from literatures on the proper application of small forwarders to improve harvesting efficiency, which can be of use to the forest industrial and academic users for practical and research purposes.

Keywords

Forest harvesting, Small forwarder, Productivity, Time study, Load volume

Introduction

Sustainable forest management as a dynamic and evolving concept aims to maintain and enhance the economic, social and environmental value of all types of forests, for the benefit of present and future generations (UN, 2008). In this context "sustainability" means harvesting wood resources in a way which produces materials with low operation cost, high product quality, low environmental impact, and high social benefits for the community. Timber harvesting is a key part of a sustainable forest/plantation management. Timber harvesting deals with several activities from stump to the mill gate such as forest road planning, road maintenance, tree felling/processing, timber extraction, loading, transportation and unloading (Conway, 1982). Timber extraction is one of the most difficult jobs within the timber supply chain as forest terrains are often rough or steep and timber sizes are large. Industrial revolution introduced the farm tractors to the farms. Consequently, most of the forest growing and contracting companies around the world started using tractors into the forest operations (Johansson, 1996). One of the early studies was reported by Boe (1963) that referred to the application of a D-8 tracked bulldozer to skid the large logs from old-growth redwood forests (*Sequoia sempervirens*) located in California (USA). Over time, forest engineers and logging planners realized that skidders and tractors can only skid a limited mass of timber per each turn in a short cycle time. Skidding logs/trees on the ground also led to heavy soil and site disturbance (Ghaffariyan, 2020). Considering the above-mentioned limitations with skidders/tractors, a new machine called forwarder was invented and introduced to the forest industry in the early 1960s in Sweden (https://magnetawanlibrary.ca). The forwarder that was (often) equipped with a grapple to load timbers (logs or trees) onto a bunk to forward the timbers to a roadside/landing. A forwarder usually works in combination with harvesters within a cut-to-length operation. Forwarding helps increase the load mass per turn (e.g. up to 20 tonnes in the case of a large forwarder). Unlike with skidding, the forwarded logs/trees have no contact with the soil on their way to the landing. There are two types of forwarders available in the practice including conventional forestry forwarders (Kellogg and Bettinger, 1994; Nurminen et al. 2006; Ghaffariyan et al. 2007, 2012, 2015) and farm tractors equipped with a trailer/grapple loader that operates as a forwarder (Stańczykiewicz et al. 2016). The loading capacity of a forwarder can vary from 5 to 25 tonnes (t). These machines can extract up to 25 m^3 per each working cycle (https://magnetawanlibrary.ca). Several scholars have extensively studied the performance of medium and large size forwarders worldwide in North America, Europe, Asia and Oceania (Kellogg and Bettinger, 1994; Hossain and Olsen, 1998; Hanell et al. 2000; Spinelli et al. 2002; Turner and Han, 2003; Nurminen et al. 2006; Rottensteiner et al. 2008; Berg et al. 2018; Ghaffariyan et al. 2019; Gagliardi et al. 2020;). However, there are fewer published scientific reports on work studies of small forwarders. Thus, this paper aimed to review the work productivity of small size forwarders (payload<10 tonnes and engine power<120 HP (90 kW)) to create an overview of their performance for small scale operations within the small-scale forestry/plantations management or agroforestry systems. The other objective of this research was to identify the main variable impacting the work productivity and main reasons for delays during the small forwarder operations. The final study objective was to summarise the international knowledge on how to improve the work productivity of small forwarders.

Materials and Methods

Work productivity for small forwarders

The typical work cycle of small forwarders includes travelling empty to the sites, loading the timber, travelling loaded to the landing and unloading (Kellogg and Bettinger, 1994). The work productivity is calculated using time study method where forwarding time (including productive and delay times) and work output (volume of forwarded wood) are measured (Griliches, 1998 cited in Heinimann, 2021; Magagnotti et al. 2012). Different factors can impact the productivity of a forwarder such as forwarding distance, piece size, load volume, operator skill, slope of skid trail, harvesting intensity etc. which are taken into account during time studies (Kellogg and Bettinger, 1994; Spinelli et al. 2002; Gagliardi et al. 2020). Productivity studies can help improve work performance, enhance work design (Heinimann, 2021), schedule the production, prepare a harvesting budget and compare different equipment and working systems (Murphy, 2005; Magagnotti et al. 2012).

To find the required literatures (in English language) for this review the following keywords were used; productivity, time studies, timber harvesting, forwarding, mini forwarder and small forwarder. The electronic search engines such as Google Scholar, Scopus and Web of Science, Research Gate and Academia were used. The review results were classified based on their region/country with a brief description of the work method and productivity outputs. Important concluding remarks made by international scholars were all summarised in the conclusion section of this review article to provide an overview of the most important conclusions for the readers.

Results

America

Canada

A case study was conducted by Meek (2001) in a thinning operation of a softwood plantation (species not reported) in New Brunswick in Canada. The terrain was flat and DBH ranged from 10 to 14 cm (average volume was 0.1 m^3). Average skidding distance was 150 m. Trees were felled and processed by a harvester-processor. Then a purpose-built forwarder (Figure 1) was used to extract the short logs. The forwarder was made using a Versatile 276 tractor attached with a Hardy 1700 boom and a Patu trailer (capacity of 5 tonnes). The study yielded a productivity of 8.2 m^3 per productive machine hours (m^3/PMH_0) (Table 1).

Figure 1. A purpose-built forwarder tested in Canada (Meek, 200)

Asia

Australia

According to McCormack et al. (2000) in small scale forestry, farmers and small-scale forest/plantation owners are included in the management that requires adaptation of both farming and forestry techniques to match with the requirements. As farm forestry has started increasing in Australia the farmers equip their tractors with suitable trailers to extract the timber. A farmer planted pine seedlings (*Pinus radiata*), which can be grown up to 40 years where farmers conduct first, second, third thinning and final cuts during the management period to mainly produce pulpwood in Victoria. Plantation size was about 20 ha and terrains were flat. Trees were felled and processed to short logs. Logs were first skidded by a large farm tractor then were loaded into a forwarder which was a combination of Fiat 6066 4WD farm tractor and trailer with the capacity of 6 tonnes. The trailer was equipped with a grapple and crane to load and unload. The productivity of this machine was not reported.

Japan

In Japan, small forwarders are used in the thinning or final cuts. Suzuki et al. (2017) studied an IWAFUJI U-3C forwarder (engine power not reported, capacity of 3 tonnes) in the Kochi region which was used to extract the short logs produced by a manual feller using chainsaw. The stand was composed of Japanese Cedar with the age of 40 years. The slope was gentle and maximum extraction distance was 300 m (average of 150 m) that resulted in an average productivity of 3.5 m^3/PMH_0. A small tracked-based forwarder (Figure 2) was applied to extract the logs in steep terrains within thinning and final cut operations in Tochigi area (Japan) (Aruga et al. 2017). The main species were Japanese Cedar and Japanese Cypress. The slope varied from 1% to 58%. Piece volume – from 0.3 m^3 to 1.0 m^3. The forwarding distance varied from 139 to 590 m. Trees were felled manually by chain saw then bunched using a grapple loader. Then a processor machine processed the trees into short logs to be extracted by the tracked-based forwarder to the roadside. The average forwarding productivity in thinning operations was 5.7 m^3/PMH_0 (note that the author of this review assumed a productive working time of 6 hours per day to obtain this value from this case study). Study results indicated that shorter skidding distances and larger thinning areas contributed to larger work productivity (Aruga et al. 2013). The forwarder in clear cut achieved higher productivity (6.5 m^3/PMH_0) than the one in thinning operations (5.7 m^3/PMH_0).

Figure 2. Small track-based forwarder tested in Japan (Aruga et al. 2017)

Iran

Small farm tractors are used to extract timber on gentle slopes from the Iranian mountainous forests located near the Caspian Sea (Gilanipoor et al. 2012). The loaded farm tractors in Iran can travel over a maximum slope of 15% during uphill forwarding. A study was reported by Mousavi and Naghdi (2014) in a clear-cutting a mixed stand of Alder (*Alnus glutinosa*), Caucasian walnut (*Petrocarya fraxinifolia*), Chestnut-leaved Oak (*Quercus castaneifolia*), Persian ironwood (*Parrotia persica*). Slope ranged from 0 to 5%. Average tree volume was 0.6 m^3. Felling and processing was carried out using a chain saw operator. Then a worker loaded the short logs manually into a trailer attached to the 8502 four wheels drive tractor (engine power of 75 HP). The forwarding distance averaged at 167 m. The study yielded an average forwarding productivity of 3.6 m^3/PMH_0 which was 2.3 times higher than the skidding productivity in the study area. Collecting and loading the logs took the longest time among the elements making up 40.2% of the total work time. The unloaded travel was the shortest element, consuming 3.5% of the time. Other work elements included travelling loaded and unloading. The time spent for work delays accounted for 3.8% of the total work time. Load volume and number of logs per turn significantly impacted the productivity based on the regression model developed by Mousavi and Naghdi (2014).

Europe

Czech Republic

The Czech Republic is a country that applies forwarders in the harvesting of 72% of all its forest area (Dvoˇrák et al. 2021). A study was conducted in two sites mainly covered by coniferous species (species were not reported). Trees were felled and processed by a harvester-processor; then the logs were collected and extracted by three forwarders. One of the forwarders was Novotný LVS 5 with the engine power of 55 kW and bunk capacity of 5 t. The tree volume and forwarding distance averaged at 0.11 m^3 and 389 m respectively. The terrain was mainly flat. The average productivity was reported to range from 3.5 to 5.8 m^3/PMH_0 (Table 1) (Dvoˇrák et al. 2021). The forwarding cost did not differ significantly from larger forwarders such as John Deere 1010 (engine power of 82 kW) and John Deere 1010E (engine power of 115.5 kW).

Ireland
Mini-forwarders are equipped with roll-over protection systems (ROPS). The productivity of these machines can be competitive with conventional large forwarders especially in small and non-uniform thinning practices. One of the small tractors is Vimek Minimaster101 with the engine power of 16 HP that is equipped with a tailer to extract the timber in British forests (Russell and Mortimer, 2005).

Italy
An Italian mini-forwarder was tested in thinning operations by Spinelli and Magagnotti (2010). The machine was Entracon Loglander LL85 with the engine power of 67 HP (50 kW) and loading capacity of 4.5 t. The plantation was based on a flat ex-farmland consisting of three hardwood species including walnut (*Juglans regia L.*), southern alder (*Alnus cordata Loisel.*) and ash (*Fraxinus ornus L.*) with an average DBH of 11.7 cm. The second study site consisted of Austrian pine (*Pinus nigra J.F. Arnold*) with an average ground slope of 15% and DBH of 14.8 cm. In both study sites trees were felled by a chainsaw operator and processed into short logs which were manually stacked into small piles. The mini-forwarder achieved an average productivity of 3.1 to 3.8 m^3/PMH_0 for both sites when the forwarding distance averaged at 400 m. In this case study the load size and forwarding distance did not change much, thus the speed of the mini-forwarder was mostly influenced by the slope of the ground. In the steeper site, the operator drove 20-40% slower than the flat site which reduced the work productivity. Longer forwarding distances resulted in lower machine productivity due to an increase in travelling time (including travelling loaded and empty). Spinelli and Magagnotti (2010) added that their reported productivity for the Entracon Loglander LL85 mini-forwarder was higher than the productivity of a mini-forwarder ranging from 1 to 2.5 m^3/SMH reported in Japan by Shishiuchi (1993) that had smaller engine power and load capacity operating on shorter forwarding distances.

Poland
Manual felling is a common practice in Polish forest operation as 80% of the operations is carried out by manual felling. Grzywinski et al. (2018) studied the impact of seasons on harvesting work productivity. Early thinning of young alder stands (*Alnus glutinosa Gaertn.*) was performed by chain saw operators who felled and processed the trees. After felling and processing, the logs were manually loaded into a farm tractor (Zetor 7045 (with engine power of 65 HP), equipped with a trailer. Mean DBH was 15 cm. Forwarding distance averaged at 545 m. The statistical analysis confirmed that the forwarding productivity in winter (3.8 m^3/PMH_0) was significantly lower than in summer (5.7 m^3/PMH_0) due to the longer time required to perform similar tasks (Grzywinski et al. 2018).

Another similar case study tested a farm tractor attached with a trailer in thinning Scots pine stands (*Pinus sylvestris*) (Leszczynski et al. 2021). The stands were 25 years old, and were felled and processed by a small harvester-processor. Then MTZ Belarus 952.2 farm tractor (engine power of 90 HP) equipped with FAO FAR 842 Logging Trailer with 3264 Crane (loading capacity of 8 t) was used to extract timber to the roadside. The tree volume averaged at 0.08 m^3 and the average forwarding distance was 500 m under flat terrains. The average productivity of the forwarding was 4.1 m^3/PMH_{15} (note PMH_0 was not reported). The forwarding distance was the main variable, impacting the productivity of forwarding, based on a linear regression model developed by Leszczynski et al. (2021).

Spain

Eucalypt plantations are one of the forest resources in Spain, Southern Europe. Forwarders have been in use to harvest these types of plantations (Spinelli et al. 2004). Two types of small capacity forwarders were tested by Spinelli et al. (2004) in clearcut operations of an even-aged *Eucalyptus globulus* plantation in Northern Spain. The slope averaged at 23%. The average DBH was 12 cm. The average tree mass was 122 fresh kg (assuming conversion factor of 1:1 this is equal with 0.1 m^3). The purpose built forwarder in use was Deutz 913 (6× 6 wheel drive), with the engine capacity of 119 HP (89 Kw) and loading capacity of 8.5 t. The other forwarder was a farm tractor-trailer type (4 × 4 wheel drive) with a Sisu Diesel 20 engine (power of 109 HP (81 kW)). The purpose-built forwarder yielded an average productivity of 17.6 m^3/PMH_0 (mean forwarding distance of 693 m), while the tractor-trailer one produced an average productivity of 19.2 m^3/PMH_0 (mean forwarding distance of 174 m). The shorter forwarding distance resulted in higher productivity gained by the tractor-trailer forwarder. Loading and travelling loaded took the longest time during the operations of small forwarders. The other work elements included: travelling empty, manoeuvre, move, unload and others. Delays consumed less than 15.3% and 9% of the total work time for the tractor-trailer and purpose-built forwarder respectively. According to a regression analysis, the productivity of the purpose-built forwarder was significantly impacted by forwarding distance, load weight per turn (payload) and piece volume, while the tractor-trailer's productivity depended on forwarding distance and load weight per turn.

Figure 3. Purpose-built forwarder tested in Spain (Spienlli et al. 2004)

Sweden

The farm tractors have been used in Swedish timber harvesting especially for early thinning and clear cutting of small size trees. Johansson (1996) tested a Ford 276 Versatile frame farm tractor that was equipped with a small felling head at the front, a crane to load/unload and a trailer at the back. The machine was first used to fell and process the trees to short logs. The engine power was 116 HP. The stands were a mix of pine and spruce (species not mentioned in the report by Johansson (1996)), and were thinned for first time. The soil was frozen, covered by 10-40 cm of snow, and tree volume averaged at 0.14 m^3. Product types in this study included sawlogs and pulpwood. In the case of the sawlog, the average driving distance during loading travelling loaded distance, and travelling empty, the distance was 313 m, 253 m and 352 m respectively. The average load volume per turn was 9.2 m^3 (average log length of 4.60 m). Sawlog forwarding productivity averaged at 11.2 m^3/PMH_0. In the pulpwood recovery site the average driving distance during loading, travelling loaded distance and travelling empty, the distance was 303 m, 288 m and 370 m respectively. The average load size was 8.5 m^3 (average log length of 4.25 m) which resulted in average work productivity of 9.4 m^3/PMH_0 (Johansson, 1996). The longer forwarding distance and smaller piece volume resulted in lower work productivity in pulpwood production.

Early thinning can produce small size timber that can be used for bioenergy production. Wang (1999) indicated that one of the common Swedish mini forwarders was Vimek 606D which could fit with the small size tree harvesting operations. This machine had a low power of 20 HP and loading capacity of 0.3 t. The advantages of this small machine included its simple design, high work productivity and low fuel consumption rates, compared to other similar machines (Wang, 1999). Over time, more powerful types of Vimek forwarders were introduced in Swedish forestry. Lazdins et al. (2016) tested a small-scale harvesting system consisting of a Vimek harvester-processor and forwarder. The study was conducted in two spruce stands (*Picea sp*.). Trees were felled and processed into short logs by the harvester-processor then extracted to the roadside by a forwarder. The harvested tree volume ranged from 0.04 to 0.06 m^3. The average forwarding distance was not noted in this study report. The terrain was flat. Vimek 610 had an engine power of 60 HP and loading capacity of 5 t which was more powerful than earlier models e.g., Vimek 606D. The average work productivity was 10.5 m^3/PMH_0 (note that this value was calculated by the author of this review article, based on the percentages of travelling time reported by Lazdins et al. (2016) as they only reported loading and unloading productivity). The work elements of this time study included travelling empty, travelling loaded, reaching to logs for loading, locating the head while loading, unloading and arranging while unloading. Travelling empty and travelling loaded took the longest time among the work elements, accounting for 24.3% of the total cycle time.

South Africa

A small-scale harvester-processor/forwarder technology has been tested by Ackerman et al. (2022) to recover from a low volume and lowquality *Pinus patula* plantation located in the Highveld region of Mpumalanga during the winter season. The machine model was Malwa 560C that had a combination of harvester-processor and forwarder. The engine power was 74 HP with the loading capacity of 5.5 t. The stand age was 10 years and the tree volume averaged at 0.2 m^3. The terrain was flat. Trees to be removed, as part of the thinning regime, were marked prior to harvesting. Trees were felled and processed to short logs (pulpwood and sawlogs) by the harvester-processor. Then the logs were loaded to the bunk of the forwarder and extracted to the roadside. The forwarding cycle included travelling empty, loading, travelling loaded and unloading. During the time study, the average forwarding distance and load size were 219 m and 2.8 m^3 respectively. This study yielded a mean forwarding productivity of 5.0 m^3/PMH_0. According to the multiple regression model developed by Ackerman et al. (2022) the forwarding distance and load volume had significant impact on the productivity of forwarder. The larger load volume and shorter skidding distances resulted in lower forwarding productivity. Table 1 provides a summary of selected time study results on mini-forwarders around the world.

Table 1. Summary of productivity studies on farm tractors equipped with trailer

Continent/ country	**Operation**	**Machine type**	**Power (HP)**	**Payload (t)**	**Forwarding distance (m)**	**Slope (%)**	**Piece Volume (m^3)**	**Average productivity (m^3/PMH_0)**	**Reference**
America/ Canada	Thinning	Versatile 276 (farm tractor)	116	5	150	0	0.1	8.2	Meek (2001)
Asia/ Japan	Thinning	IWAFUJI U-3C	n/a	3	150	0	n/a	3.5	Suzuki et al. (2017)
Iran	Clear-cut	8502 4WD (farm tractor)	75	5	167	2.5	0.6	3.6	Mousavi and Naghdi (2014)
Europe/ Czech Republic	Thinning	Novotný LVS 5	74	5	389	0	0.11	3.5-5.8	Dvoˇrák et al. 2021
Italy	Thinning	Entracon Loglander LL85	67	4.5	400	0-15	0.06-0.08	3.1-3.8	Spinelli and Magagnotti (2010)
Poland	Thinning	Zetor 7045	65	n/a	545	0	n/a	3.8-5.7	Grzywinski et al. (2018)
	Thinning	MTZ Belarus 952.2 (farm tractor)	90	8	500	0	0.08	4.1	Leszczynski et al. 2021
Spain	Clear-cut	Deutz 913 Sisu Diesel 20 (farm tractor)	119 109	8.5 8	693 174	11 9	0.1 0.1	17.6 19.2	Spinelli et al. (2004)
Sweden	Thinning	Vimek 610	60	5	n/a	0	0.05	10.5	Lazdins et al. (2016)
	Thinning	Ford 276 Versatile (farm tractor)	116 116	5 5	306 320	0 0	0.44 0.27	11.2 9.4	Johansson (1996)
Africa/ South Africa	Thinning	Malwa 560C (combined harvester-forwarder)	74	5.5	219	0	0.2	5.0	Ackerman et al. (2022)

Table 2 presents the descriptive statistics of main parameters such as machine power, payload, forwarding distance, slope, piece volume, and work productivity of international case studies mentioned in Table 4. Within the reviewed time studies on small forwarders, the reported productivity by international scholars ranged from 3.4 to 19.2 m^3/PMH_0. Engine power did not exceed more than 199 HP while the lowest engine power was 30 HP for small forwarders. The engine power and load capacity consequently influenced the payload which ranged from 3 to 8.5 t with an average of 5.6 t that is much less than conventional forwarders. The maximum forwarding distance within the data base of this review was less than 700 m while the average value was 334 m. This is an important consideration to be used by logging planners to select suitable and optimal spacing among the forest road segments. An important observation is that the tested small forwarders were all limited to slopes less than 11%. The average slope of 2.3% indicates that internationally these types of machines are applied in flat to moderate slopes. The range of piece volume and its average value (0.2 m^3) indicates that small forwarders are mostly used for small tree size harvesting operations mostly in early thinning or in clear cutting of stands with small tree size.

Table 2. Descriptive statistics for the time study data

	Minimum	Maximum	Mean
Engine power (HP)	60	119	90.1
Payload (t)	3.0	8.5	5.6
Forwarding distance (m)	150	693	334.4
Slope (%)	0	11	2.3
Piece volume (m^3)	0.05	0.6	0.2
Productivity (m^3/PMH_0)	3.4	19.2	8.1

Conclusions

Meek (2001) suggested maintaining a high utilisation rate for the small-scale harvesting machines to achieve a cost-effective operation. Appropriate planning should include night shifts; applying proper maintenance regimes and allocating suitable stands for harvesting could be potential alternatives. According to Aruga et al. (2017) forwarders can work more efficiently in clear cuts, rather than in thinning operations which could be due to the larger harvesting intensity and piece volume. Dvǒrák et al. (2021) pointed that the application of small forwarders can sometimes result in similar range of forwarding costs per unit, thus the application of larger machines does not necessarily reduce the costs. In this sense proper planning should be made to achieve higher machine utilisation and productivity to reduce the costs.

Spinelli et al. (2004) suggested using a light tractor-trailer type for shorter forwarding distances and as a complement to the current timber extraction. For longer forwarding distances (<1 km) the purpose-built forwarder would be a more suitable option from economic perspective. According to Ackerman et al. (2022), the forwarding distance and load volume are the two most significant variables impacting the forwarder productivity.

Regarding the mini-forwarder's performance in steep terrains, Spinelli and Magagnotti (2010) mentioned that although these machines have high manoeuvrability due to their narrow width and good ground clearance, the operators should only drive them straight along the grade because of low machine stability.

Spinelli and Magagnotti (2010) concluded that mini-forwarders can carry smaller loads than farm tractor-based forwarders and their loading and unloading efficiency is also lower due to weaker grapple loader. Mini-forwarders should be limited to an extraction distance of 1 km and a proper and optimal forest road network can be helpful for the application of mini-forwarders. The Swedish experience indicated that a suitable work pattern is to combine mini-forwarders with harvester-processors in thinning operations so that they can follow the path of the harvesters to pick up the stacked short logs (Lazdins et al. 2016). An early Swedish study confirmed that forwarding sawlogs could result in higher machine productivity, compared to pulpwood recovery, due to the larger piece size in the case of sawlog production (Johansson, 1996). The other general conclusion was that the application of small farm tractors equipped with trailers is a low-cost option with good work productivity and proper ergonomic performance.

The season has a significant impact on the productivity of mini forwarders that needs to be considered in harvesting planning. Thick snow and cold temperatures during winter can reduce the machine's productivity (Grzywinski et al. 2018). Future research could test new mini-forwarders in more diverse forest types (small scale native and plantation forests), terrain conditions (including various slopes and soil conditions), and product types (sawlog, pulpwood, biomass and integrated biomass production). This will create a more comprehensive overview of the machine's performance to be useful for decision making purposes.

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