Assessing Material Consumption Due to Spare Part Utilization by Harvesters and Forwarders

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ABSTRACT

The aim of this study was to i) develop and examine a methodology to handle spare part utilization data for work machinery for future inclusion into a life cycle assessment study and ii) assess the material consumption per 1000 m^{3}ub harvested and transported to the roadside due to spare part utilization by three types of forest machinery. Thirteen forwarders, 14 single-grip harvesters and 10 two-grip harvesters operating in northern Sweden were followed up by repair records that covered a period from half a year up to 3.5 years. The replaced machine components were sorted in seven material categories - steel and iron, aluminum, other metals (brass, copper), plastics, rubber, glass and batteries. Two scenarios with different assumptions on the consumption of saw chains, guide bars and tires were developed. According to the low scenario about 46 kg of material will be consumed for harvesting and transporting 1000 m^{3}ub to the roadside. The corresponding figure for the high scenario is 58 kg. The total component mass expected to be replaced during the operational lifetime (18000 E_{15} hours) of the machines was also calculated. According to the low scenario 38-45% of the mass of a machine will be changed during its operational lifetime. The corresponding figure for the high scenario is 50-56%.

Keywords: *Forestry machinery, spare-parts, maintenance, environmental impact.*

INTRODUCTION

The environmental functions of the forest ecosystem and the ecological properties of the wood based products are frequently discussed in the literature [6,13]. There is a need to assess the environmental impact of wood products and compare it to the impact caused by other competitive materials like steel. This need has created the necessity to trace - through a "cradle to grave" analysis - all the environmental inputs and outputs in the forestry sector. To achieve the above aim the forest sector could be divided into subsystems - forest production, wood harvesting, manufacturing of wood products, product use, waste management, transports. In the wood harvesting subsystem the contribution of machinery (use and maintenance) plays an important role.

Wood volume harvested annually in Sweden is estimated to be 55 Mm^{3}ub (solid wood under bark) [2]. The shortwood method where the stems are bucked to assortments at the stump dominates. According to calculations based on the official statistics [2] about ninety percent of the harvested wood volume is cut by harvesters and transported by forwarders (large scale forest operations). The harvester (single-grip or two-grip) fells and processes the trees and the forwarder transports the logs to the roadside. The production capacity of the system depends on machine type, stand density, ground conditions, operator skill [15], as well as machine availability and repair time.

During the operational lifetime of forest machinery consumables are needed like diesel, hydraulic oil, chainsaw oil, lubricants, and emissions are produced i.e. CO_2, NOx, HC, hydraulic- and chainsaw- oil spills. At the same time machine components (boom, feeding wheels, hydraulic motors, transmission shafts, hydraulic cylinders etc.) are changed once, or several times thereby contributing to the consumption of non-renewable resources. In earlier studies, in Sweden, mechanized harvesting operations have been dealt with from the aspect of fuel and oil consumption [3,4]. No previous research has been done to assess the material consumption associated with spare part utilization by forest machinery.

Life cycle assessment (LCA) has been used to describe and evaluate the overall environmental impact of the forestry sector as a whole [18] and some of its subsystems [17,23]. LCA is frequently used to provide an assessment of the environmental performance of a product, process or activity over its entire life cycle, including raw material extraction, production, use and end-of-life disposal [1]. In the automotive industry LCAs are employed to evaluate the environmental load of single components, complete products or designs [12,16,19]. No detailed LCA study for off-road heavy-duty machinery has been performed up to this date. However, a study concentrating on passenger cars and light trucks indicated that the maintenance of vehicles, together with the manufacture and the after use treatment of the vehicles, contributes significantly to the total environmental impact of road transportation [8].

An assessment of the quantity and nature of the spare parts needed to maintain the machinery during its work is very important when performing a comprehensive LCA

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study. Maintenance of the vehicles has not been included comprehensively in previous LCA studies on automobiles [12]. The reasons are probably the great variability in parts replaced, the difficulties to trace the amount of parts replaced and to identify the material composition of the spare parts.

The aim of this study was to i) develop and test a method to manage spare part utilization data for work machinery for future inclusion into an LCA study and ii) assess the material consumption per 1000 m^3ub harvested and transported to the roadside due to spare part utilization by the three most common types of forest machinery (forwarders, single-grip and two-grip harvesters).

MATERIALS AND METHODS

A component replacement follow-up that included 14 single-grip harvesters, 10 two-grip harvesters and 13 forwarders was obtained by a forest region in the north of Sweden. Average data for each machine type considered in the follow-up are illustrated in Table 1. The machinery were followed up for a period that varied from 690 E_{15} hours to 7252 E_{15} hours (Table 2).

A total of 210, 501 and 460 repair occasions for forwarders, single-grip harvesters and two-grip harvesters, respectively, were recorded. Every repair occasion involved one or more component changes. A total of 1321 different machine component categories were included in the study. The component mass and material composition were obtained by following a five step procedure. The degree of uncertainty that characterizes the acquired data increases the deeper one proceeds in the procedure:

- Three machine manufacturers were contacted and asked to give the mass and material composition of each component in the follow-up that belonged to one of their models. Components that belonged to these manufacturers represented the 95% of the total amount of components in the follow up. One machine manufacturer refused to leave any information, another one provided only the mass of the components while the third one provided both the weights and the material composition of the components. Therefore it was possible to calculate the mass of 60% of the total components and to identify the material composition of 14% of these (9% of the total components).

- Sixty five percent of the total amount of components had the same functions as the 9% whose mass and material composition were known and were assigned the same material composition.

- Twelve percent of the total amount of components was identified by contacting the manufacturer of the component or a manufacturer of a component similar with the component in question.

Table 2. Machinery type related to the total follow up time.

Follow-up (E_{15} hours)	Forwarders	Single-grip harvesters	Two-grip harvesters
690-1000	5	2	-
1001-2000	1	4	-
2001-3000	1	3	3
3001-4000	3	-	1
4001-5000	-	1	3
5001-6000	2	2	1
6001-7000	1	-	2
7001-7252	-	2	-

Table 1. Data for the machinery included in the study (in parenthesis the standard deviation).

	Forwarders	Single-grip harvesters	Two-grip harvesters
Mean machine age*	12 814 (7 676)	8 723 (4 860)	15 018 (2 002)
Mean E_{15} hours	2 712 (2 032)	3 205 (2 350)	4 211 (1 390)
Mean m^3ub harvested or transported	39 701 (29 313)	41 017 (33 476)	67 091 (28 081)
Productivity m^3ub/E_{15} hours	15.8 (4.02)	12.96 (4.40)	15.6 (3.14)
Assumed machine lifetime (E_{15} hours)	18 000	18 000	18 000
Mean machine mass (kg)**	14 500	12 500	18 120

*In E_{15} hours at the end of the follow-up period
**Derived from machine brochures

- Five percent of the components was identified by a machine service team located in Umeå.

- A further 7% of the components was identified on the basis of the professional judgment of a fellow researcher.

Seven broad material categories were distinguished: Steel and iron, aluminum, other metals (brass, copper), plastics, rubber, glass and batteries. The level of aggregation in the material categories reflects the level of detail of the delivered data. Two percent of the components were left unidentified.

Consumption of parts that are not included in the spare parts follow-up (tires, saw chains, guide bars, filters) was calculated by information made available from manufacturers and the literature. Consumption of hydraulic hoses and wiring is not included in the study. A high and a low consumption scenarios were constructed for comparison purposes. The high consumption scenario included the consumption of 10 alloy steel saw chains and 3 alloy steel guide bars by each harvester for every 1000 m^3ub produced [10]. According to the same scenario forwarders change a total of twelve tires, each, during their operational lifetime. For the low consumption scenario the amount of saw chains and guide bars consumed was decreased to 4 and 1, respectively, while the amount of tires consumed was decreased to six. It was further assumed that in both scenarios 1 oil filter is needed to be replaced for each one of the harvesters and forwarders for every 1000 m^3ub harvested and forwarded to the roadside. Additionally it was assumed that all three forest machine types have an average operational lifetime of 18000 E_{15} hours. This agrees well with the financial lifetime of harvesters and forwarders in Sweden reported by Strömgren [20].

As functional unit - the unit to which all the material consumption is related to - 1000 m^3ub (solid wood under bark) harvested and transported to the roadside was selected. This unit was found to be the most appropriate to express the amount of work performed by the machinery.

Total amount of wood expected to be harvested or transported under the operational lifetime of a machine was calculated as the product of the assumed lifetime and the productivity of the machine under the follow up period.

The total mass of the components in each material category expected to be replaced under the operational lifetime of the machinery is computed as the product of the total amount of wood the machine will harvest or forward to the roadside and the mass of every component consumed per m^3ub.

The coefficient of determination (R^2) in the linear regression procedure of SPSS [14] was used to test the correlation between the mass of the components replaced for every 1000 m^3ub harvested or transported to the roadside (excluding filters, saw chains, saw bars, and tires) and the age of the machinery (expressed in E_{15} hours at the end of the follow-up period).

Some terms used are defined as follows:

Machine component category. A group of components that share the same component number.

Gross effective time (E_{15} hours): Machine production time that includes delays shorter than 15 minutes.

RESULTS

Material consumption (kg/1000 m^3ub) for the three types of machinery is presented in Tables 3-5. Forty five and twenty three percent of the steel consumption by the harvesters at the "high" and "low" scenario, respectively, is due to the consumption of saw chains and guide bars. Almost all rubber consumed by the forwarders was due to the tire consumption. In Table 6 an estimation of the material consumption (kg) by forest machinery in the form of spare parts during their operational lifetime (18 000 E_{15}) is given. Steel and iron dominate material consumption as they account for 92% of the total mass of the harvester replaced components and 66% of the forwarder components according to the high scenario. It can be calculated that in the "low" scenario 45% of the mass of the forwarder will be replaced during its operational lifetime while the corresponding figures for the single- and two-grip harvesters is 41% and 38%, respectively. In the "high" scenario 52% of the mass of the forwarder will be replaced during its operational lifetime while the corresponding figures for the single- and two-grip harvesters is 56% and 50%, respectively. It is calculated that the expected amount of wood harvested under the operational lifetime of a single-grip harvester and a two-grip harvester is 233400 and 280700 m^3ub, respectively, while the expected amount of wood transported to the roadside by a forwarder reaches 284300 m^3ub. No statistical significant correlation was found between the total mass of the exchanged components and the age of the machinery. The R^2 was 0.486 for forwarders and 0.018 and 0.008 for the single- and two-grip harvesters, respectively.

Table 3. Material consumption (kg/1000 m^{3}ub) by the forwarders due to spare part replacement according to a high and low consumption scenario.

Material	Follow-up	Tires (low)	Tires (high)	Filters	Total (low)	Total (high)
Steel/iron	15	0.035	0.068	2.64	17.675	17.708
Aluminum	0.15				0.15	0.15
Plastics	0.07	0.07	0.14	0.66	0.8	0.87
Rubber	0.07	3.5	7		3.57	7.07
Other metals	0.07				0.07	0.07
Glass	0.28				0.28	0.28
Batteries	0.41				0.41	0.41
Sum	16.05				22.955	26.558

Table 4. Material consumption (kg/1000 m^{3}ub) by the single-grip harvesters due to spare part replacement according to a high and low consumption scenario.

Material	Follow-up	Saw chain (low)	Saw chain (high)	Guide	Guide bars (low)	Filters bars (high)	Total (low)	Total (high)
Steel/iron	12.7	2	5	2.5	7.5	2.64	19.84	27.84
Aluminum	0.12						0.12	0.12
Plastics	0.11					0.66	0.77	0.77
Rubber	0.61						0.61	0.61
Other metals	0.03						0.03	0.03
Glass	0.09						0.09	0.09
Batteries	0.52						0.52	0.52
Sum	14.18						21.98	29.98

Table 5. Material consumption (kg/1000 m^{3}ub) by the two-grip harvesters due to spare part replacement according to a high and low consumption scenario.

Material	Follow-up	Saw chain	Saw chain (low)	Guide (high)	Guide bars (low)	Filters bars (high)	Total (low)	Total (high)
Steel/iron	15	2	5	2.5	7.5	2.64	22.14	30.14
Aluminum	0.36						0.36	0.36
Plastics	0.07					0.66	0.73	0.73
Rubber	0.65						0.65	0.65
Other metals	0.05						0.05	0.05
Glass	0.09						0.09	0.09
Batteries	0.72						0.72	0.72
Sum	16.94						24.74	32.74

Table 6. Estimation over the material consumption (kg) of forest machinery in form of spare parts over their operational lifetime (18 000 E_{15}) according to a low and a high consumption scenario.

	Low scenario			High scenario		
Material	Forwarders	Single-grip harvesters	Two-grip harvesters	Forwarders	Single-grip harvesters	Two-grip harvesters
Steel	5033	4641	6226	5042	6508	8471
Aluminum	42	28	101	42	28	101
Plastics	228	181	206	248	181	206
Rubber	1015	141	182	2010	141	182
Other metals	21	7	13	21	7	13
Glass	79	21	25	79	21	25
Batteries	116	122	201	116	122	201
Total	6534	5141	6954	7558	7008	9199

DISCUSSION

To assess the material consumed due to spare part utilization by the forest machinery all repair and maintenance activities that take place in the forest, on the road or in a service station and lead to machine part substitutions must be recorded and specified. The follow-up data used in the present study were obtained from a forest region located in the north of Sweden where a reliable component maintenance record of all company-owned harvesting machinery was held.

A five step methodology was developed to process the available spare part follow-up and identify the material content of individual components. For 85% of the total amount of components there was a good access to high quality current data from the manufacturing companies. The identification of 13% of the components is accompanied with low to medium uncertainty since secondary sources were used. Two percent of the reported components were left unidentified and removed from the data set. The components were unfamiliar to the machine manufacturers and data on these were not available.

The collected data showed high variation in spare part utilization for different machines. Sources of variability may be technical differences among machines, operator skill, type of harvest, and worksite conditions. Since every material category in the study was multiplied by the production capacity a slight inaccuracy in that would have an impact on the results. A bias may have been introduced in the study by the assumptions on the tire, filter, saw chain and guide bar consumption level while the lack of data on hydraulic hose and wiring consumption induces an underestimate of the total mass of the replaced components. It proved to be difficult to further increase the level of disaggregation of the material categories. Thus, the environmental profiles of the materials inside the categories can differ a lot (steel and cast iron, recycled and virgin aluminum). An increase in the level of detail of the material categories would allow a more detailed analysis of the environmental profile of a forest machine and should be pursued in consequent studies.

Consumption of hydraulic hoses and wiring is not included in the study since reliable data were not available. Inclusion of wiring would chiefly increase the amount of the other metals group due to cables' content in copper. Inclusion of consumed hydraulic hoses would increase rubber and steel/iron consumption mainly by the harvesters due to the fact that hose disruption occasions are more frequent to this type of machinery [3]. In an evaluation study on productivity, availability, repair needs, length measuring accuracy and delimbing quality on five different models of multifunction machines it was observed that hydraulic hoses were one of the most frequently broken items accounting for 13% and 23% of all repair occurrences under 1483 and 3583 productive machine hours on two models of single-grip harvesters [15]. By a rough estimation, based on the assumption that 13% of all repair occurrences was due to a broken hydraulic hose of one meter in length and 1.2 kg in mass, the amount of rubber consumed by the single-grip harvesters in this study would increase with 0.15 kg/1000 m^3ub or 20%. Further research should be done to assess the amount of hydraulic hoses replaced following hose disruption.

Wear of the chain and the guide bar can increase with inceased frequency of stones in the forest floor, the regeneration, the stretch of the chain and the driver's carefulness [10]. Richardson [15] reports that 29 % and 16% of the repairs or replacements that occurred on two single-grip harvester models were on saw chains while 9% were on guide bars. Saw chain, guide bar and tire replacement was not always reported in the spare part replacement register that the present study is based on. Therefore a "low" and a "high" scenario were set up based on experience from operators to examine the sensitivity of the results. It was found that the results were highly sensitive to the assumptions made. A comparison between the "low" and the "high" scenarios revealed a difference of 14% for the forwarders and about 25% for the harvesters in the consumed material.

To assess the environmental impact that is associated with repair and maintenance activities the material of the machine components must be identified. Different materials need different amounts of energy to be produced and have different energy requirements when treated and shaped to fabricate a piece of machinery. Börjesson [5] assumed that agricultural and forestry tractors are composed by 45% steel, 45% iron and 10% rubber and calculated that energy consumed for spare parts is 30% of the tractor's total embodied, fabrication and repair parts energy. Doering [7] calculated that replacement parts and materials over the reliable life of an agricultural tractor account for more than 25% of the tractor's total embodied, fabrication and repair parts energy. Knechtle [11] used a percentage of the total mass of the machinery to estimate the spare part needs of a single-grip harvester and a forwarder. He assumed that 30% of the total mass of the machine will be changed during the machine's operational lifetime. In the present study seven broad material categories were distinguished and spare part replacement was recorded in detail. This information will allow a better estimation of the resources consumed and emissions generated due to part replacement in the course of the machine's manufacture, use and disposal.

The functional unit of a life cycle assessment study should be clearly defined and measurable and based on the specific main function of the system under study [1]. Gaines et al. [9] use the per-mile energy use and emissions to compare a conventional truck against trucks of different technology. Ericksson et al. [8]in a LCA study of the Swedish road transport sector relate the environmental impact of different transport classes to the kilometers covered. In Knechte [11] and in the present study the functional unit used is an expression of the amount of work produced by the machinery.

No statistical significant correlation was found between the mass of the components (excluding filters, saw chains, saw bars, and tires) replaced for every 1000 m^3ub harvested or transported to the roadside and the age of the machinery. Sundberg [21] assumes that the cost for maintenance and repairs increases with the age of the machine and the same was expected for the total mass of the components replaced. For shortwood harvesters Williams [22] reports that, over the years, the hourly cost of maintenance and repair could be accurately estimated with a fixed cost while for some other groups of machinery it was found to increase over time.

CONCLUSIONS

The inclusion of this data in a life cycle assessment study of forest machines is of great importance since it will provide a better picture of the use of resources, emissions and wastes related to the mechanised harvesting operations. Based on the vehicles in this study the high variation in spare part utilization indicates that a large number of machines is required in order to make a reliable estimation of the material consumption due to spare part replacement. Close co-operation with forest machine manufacturers and access to detailed component follow up records from forest machine owners is essential if meaningful deductions are to be made.

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