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Resource Consumption and Emissions Induced by Logging Machinery in a Life Cycle Perspective

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Abstract

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Keywords: harvesters, forwarders, life cycle assessment, life cycle inventory, energy consumption

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Errata list

Page	Reads	Should read
Paper I		
p. 66, ref 11	Hultman, S-G. 1972. Forest machine oil spill: Its extent and causes, and a review of Sciences. Department of Operational literature on its effects. Swedish University of Agricultural Efficiency, Research Notes No 54, Stockholm. (In Swedish with English summary).	Hultman, S-G. 1972. Forest machine oil spill: Its extent and causes, and a review of literature on its effects. Department of Operational Efficiency. Swedish University of Agricultural Sciences, Research Notes No 54, Stockholm. (In Swedish with English summary).
Paper IV		
p. 7, Table 5	*Energy consumption ($MJtonkm^{-1}$) and emission factors ($gtonkm^{-1}$) for transport means*	*Energy consumption ($MJton^{-1}km^{-1}$) and emission factors ($gton^{-1}km^{-1}$) for transport means*

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Tuijalle

Φεύγω ψηλά για το βουνό
Κι ύστερα πέφτω στο γκρεμό
Και ταλαντεύομαι στα βάθη και στα ύψη

Και κουβαλάω μεσ' στη σιγή
Μιαν ανυπόταχτη κραυγή
Και κάποια ανείπωτη ελπίδα που 'χεις κρύψει

Γιατ' είμ' αέρας που περνά
Μέσα στης πόλης τα στενά
Και κάνει τα κλειστά παράθυρα να τρίζουν

Γιατ' είμ' αύρα εσπερινή
Πνοή καθάρια ζωντανή
Που κάνει τα γερμένα φύλλα να θροΐζουν

(Δημήτρης Παναγόπουλος)

Contents

Appendix

Papers I-IV

The present thesis is based on the following papers, which will be referred to by their Roman numerals.

I. Athanassiadis. D., G. Lidestav, and I. Wästerlund., 1999. Fuel, Hydraulic Oil and Lubricant Consumption in Swedish Mechanised Harvesting Opera tions, 1996. Journal of Forest Engineering 10:1.

II. Athanassiadis. D., G. Lidestav, and I. Wästerlund. Assessing Material Consumption Related to the Spare Part Utilisation by the Forestry Machinery. Journal of Forest Engineering. In press.

III. Athanassiadis. D. Energy Consumption and Exhaust Emissions in Mechanised Timber Harvesting Operations in Sweden. Science of the Total Environment. In press.

IV. Athanassiadis. D., G. Lidestav, and T. Nordfjell. Energy Use and Emissions due to the Manufacture of a Forwarder. Manuscript.

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Introduction

Mechanised harvesting operations and equipment

Forests are natural renewable resources that are used for wood production and recreation purposes, possess aesthetic values, provide habitat for the wildlife and reduce the amount of CO^2 in the atmosphere by fixing this substance in the biological growth process.

The forestry sector, i.e. forestry and forest industry, is of utmost importance to the Swedish society since it creates employment, provides raw materials and products for the country's needs and favours Sweden's export and trade balance. Every year about 60-70 million m^3 wood are harvested (Anon. 1999). Mechanisation of forest operations began with the introduction of the chainsaw in the 1950s which replaced the axe and the hand saw (Ager 1992). During the 1960s forest tractors (forwarders) replaced horses for off-road transportation of wood and some years later processing (delimbing, cross-cutting) of felled trees became mechanised. In late 70s the two-grip harvester was introduced, i.e. an one man operated off road machine capable of felling, delimbing and cross cutting trees. In 1983 the single-grip harvester was introduced and today with the forwarder it constitutes the dominating harvesting system i.e. cut-to-length harvesting system, in Sweden (Nordlund 1996). Together with mechanisation came an increase in the productivity, the costs were kept on a low level and the loggers work became safer and physically easier (Axelsson & Pontén 1990).

The introduction of heavy machines in the forests led to damage on the soil, roots and stems of the remaining trees creating a risk for future losses due to decreased growth rate and poor wood-quality (Isomäki & Kallio 1974, Fröding 1992). At the same time pressure from politicians, the public and environmental organisations increased the demand for environmental sound harvesting operations favouring sustainability and biological diversity. These were the driving forces that led to changes in forest machine technology and design such as decrease of the size of the machine, increased number of wheels, use of hydrostatic transmission and bogies, ergonomic improvement of driver cabin etc. Through these changes, damage to the remaining stand has been reduced and forest machines have become more efficient and versatile (Wästerlund 1994).

Another set of conditions that should be satisfied are related to the environmental performance of the machinery. Machinery should have low fuel consumption in relation to the production, a minimum of oil leakage and be suitable for use with environmental friendly oils and lubricants (Myhrman 1996, Boellehuus 1999). Furthermore, machine components should be able to withstand the difficult operation conditions that the forest environment poses due to cold weather, uneven terrain, tree size etc. In deciding which material to use for specific components energy consumption and emissions for the extraction and processing of the material, the possibility of repair, re-use or recycling of the component should be considered.

There is an increasing interest in ensuring buyers of wood products that the wood used to manufacture the products is derived from forestry operations managed on an environmentally sound and sustainable basis (Upton 1995, Berg 1996a). The wood harvested in forests should cause - through all stages of harvest, transport, processing and marketing to the finished product -the least possible environmental impact. The relative as well as the absolute contribution of these stages has to be assessed with the aim to improve the individual environmental performance of each stage. Among other tools for the assessment of environmental impacts of processes Life Cycle Assessment is found to be of considerable interest. Other tools that are used for analysing the environmental impact of systems are mainly limited to study impact on specific locations (Environmental Impact Assessment) and by specific business units or firms (Environmental Auditing) (Udo de Haes & Huppes 1994, Kirkpatrick 1996, Anon. 1997c).

Life Cycle Assessment (LCA)

LCA is an environmental decision support tool that provides the theoretical framework to analyse, quantify and evaluate the environmental impacts associated with product systems and activities, from the extraction of raw materials in the earth to end-of-life and waste disposal (Lindfors et al. 1995). It is used to compare alternative products that perform the same function or alternative life cycles for a given product and to indicate the relative importance of the different life cycle phases of a product (Andersson 1998). It is increasingly used by industries, governments and environmental groups to assist with decision making for environment-related strategies and materials selection (Baumann 1998).

The initial phase of an LCA includes the definition of the goals and scope of the study, and the collection and calculation of Life Cycle Inventory (LCI) data (Anon. 1997a, 1997b). The goal definition process determines the type of analysis needed, the intended uses of the study results and the manner in which the results are to be presented. The scope of the study describes the system to be studied and directs how much information is to be collected, in what categories and to what level of detail and quality. System boundaries are defined. This includes boundaries between the studied system and other studied systems, between the studied system and the environment as well as cut offs inside the studied system to exclude non-significant processes. When partitioning of energy flows and emissions is necessary then allocation procedures have to be selected (Anon. 1997b, Ekvall 1999b).

In the LCI stage material and energy flows of the studied system are recorded and associated with a functional unit. The way the inventory data are collected should be consistent with the study goals. Carrying out the LCI phase is time and money consuming and many times this is the only part of the methodology performed. The possibility to make the study more workable without losing the life cycle thinking that is behind the LCA methodology has been investigated by many researchers (Graedel et al. 1995, Curran 1996, Weitz et al. 1997, Graedel 1998, Weitz et al. 1999). Proposed procedures for reducing the cost and effort to conduct an LCI include exclusion of classes of materials if they comprise less than a certain percent of the mass of the product examined and use of qualitative or less accurate data in the place of not available data (Hunt et al. 1998). The LCI phase precedes the phases of Life Cycle Impact Assessment - which involve the classification, characterisation and evaluation of these data in relation to ecological impacts - and Interpretation (Anon. 1992, Anon. 1997c).

LCA/LCI studies on wood products and forest operations

A complete LCI study for wood products should include data from plant establishment to timber harvesting, terrain transport to the roadside and further to the industry, processing and manufacture of products, use of the products and waste management.

In the forest products sector most LCA/LCI studies have been on paper products and packaging containers (Tillman et al. 1991, Ekvall 1992, Baumann et al. 1993, Grieg-Gran 1995, Rydberg 1995, Ryynänen & Nelson 1995). Many studies have concentrated on comparing the energy requirements and associated emissions for wood products with other possible substitute materials. Most common substitute materials were steel (Erlandsson et al. 1992, Buchanan 1993, Meil 1995), plastic (Richter 1996) and concrete (Buchanan 1993, Erlandsson et al. 1994, Engberg & Eriksson 1998). Products on which LCA/LCI studies have been contacted include utility poles (Erlandsson et al. 1992, Kuenniger & Richter 1995), flooring (Jönsson et al. 1995), roof construction (Erlandsson 1994a, Scharai-Rad et al. 1997), pallets (Menthiere 1997), laminated veneer lumber (Kairi 1999) etc. Most studies conclude that wood products require less energy to produce and less emissions are associated with their production.

Most LCA/LCI studies on wood products lack a common methodological structure and it is very difficult to combine or compare their findings in a consistent way. There are considerable differences between the studies on what environmental loads are addressed, what life cycle phases are taken into account, what is the functional unit. To overcome this obstacle, methodological recommendations have appeared on the collection, processing and reporting of the data as well as suggestions on system boundary setting, allocation procedures and data quality (Strömberg et al. 1997, Ekvall 1999a).

Considerably less studies are focusing on the actual forest operations (Loviken 1994, Berg 1996b, Hörnsten 1996, Karjalainen & Asikainen 1996, Berg 1997, Berg 1998, Sambo 1997, Aldentun 1999). Berg (1996b, 1997) compares motor-manual and mechanised methods in final fellings and thinnings concerning emission levels from combustion of fossil fuels. He reports that emission levels are higher during mechanised methods. He also states that shelterwood cutting shows higher CO_2 and NOx emission level compared to clear cutting because of more machine entries and lower machine productivity. Loviken (1994) compares three different methods of forest regeneration, natural regeneration, sowing and planting. He concludes that sowing shows the lowest emission levels while plant production and transportation are the main emission source for the planting method and large number of machine entries is the main emission source for the natural regeneration method since seed trees are left and cut at a later occasion (Loviken 1994). Aldentun (1999) and Hörnsten (1996) report data on energy and emission data from seedling production at forest seedling nurseries. Karjalainen & Asikainen (1996) and Sambo (1997) give an estimation of fuel consumption in forest operations in Finland and Canada.

Most studies report that the combustion of fossil fuels by the machinery contributes the most to the environmental impact of different forest operations. Figures on the consumption of other oils (hydraulic oil, chainsaw oil) or some indication of in which degree spare part replacement and manufacture of the machine could affect the total energy balance of the operations are not given. This is in line with the common practice in LCA/LCI of other products and processes where production of capital goods (machinery and buildings) is left outside the system boundaries because it is believed that it has an insignificant effect (less than 5%) compared with the direct impact of the other life cycle stages. However it has been shown by Weidema et al. (1995), cited in Mattsson (1999), that the manufacture of agricultural machinery may account for 10-15% of the total energy use for agricultural crop production.

Aim of the thesis

The aim of this thesis was to examine resource consumption and emissions induced by harvesters and forwarders throughout their life cycle and identify those parts of the life cycle that contribute the most to the total environmental load. For this purpose a life cycle inventory focusing on energy consumption and associated emissions to air was compiled. The inventory was based on four studies on resource consumption, energy input and amount of emissions from different life cycle phases of harvesters and forwarders.

Materials and methods

Description of the system

The cut to length harvesting system is applied both in thinning and final cutting operations. The trees are felled, delimbed, and cross-cut by the harvester (single-grip or two-grip). The logs are hauled to the roadside by the forwarder. Harvesters and forwarders have been developed especially for harvesting and terrain transport. Both machines are built upon the same base machine concept with the main elements being frame steering, hydrostatic-mechanical transmission and bogies in one or both axles. They are equipped with a boom that carries a grapple (forwarders), a harvester head (single-grip harvesters) or a felling unit (two-grip harvesters). The mass of the machines varies from 10 to 20 tons while the financial lifetime of harvesters and forwarders in Sweden is 18 000 E_{15} hours (Strömgren 1999). In Paper I it was calculated that the expected amount of wood harvested under the operational lifetime of a single-grip and a two-grip harvester is 230 000 and 280 000 m^3ub, respectively Furthermore, the expected amount of wood transported to the roadside by a forwarder reaches 280 000 m^3ub. For a more detailed description of the machines the reader is referred to Malmberg (1989), Harstela (1996) and Timperi (1997). Forest machinery are assembled from components manufactured by numerous suppliers in many different countries. When operating in the forest the machines use fuel, hydraulic oil and lubricants. At the same time due to demanding working conditions a large amount of components has to be replaced for the performance of the system to remain in high level.

A principal flowchart of the life cycle of a forest machine is provided in Figure 1. In Figure 2 the segment "Use of the machine" is presented more analytically. Papers I, II, III concentrated on the work of the machine in the forest examining fuel, lubricant, and spare part consumption during the operational lifetime of the machinery (Figure 2), while Paper IV concentrated on machine manufacturing (Figure 1). Energy and material flows and emissions to air were estimated and normalised to the functional unit. The functional unit of the studies was 1000 m^3ub harvested and transported to the roadside.

In Paper I machine consumption of fuel, hydraulic-, engine-, transmission-, chainsaw oil and greases and spillage of hydraulic- and chainsaw oil were examined. Detergent and cooling agent usage was considered to be of minor importance and therefore not included in the study.

In Papers II and IV spare part consumption and material composition of the machines were examined. Hydraulic hoses and wiring were disregarded in paper II due to lack of data but included in Paper IV as access to better data was attained. Eight material categories were identified. Those were: steel, aluminium, copper, brass, lead, plastics, rubber and glass. Other materials such as magnesium were not taken into account in the analysis due to their low ratio in the machine. In Paper IV literature and primary data was collected on energy consumption and associated emissions to air for the production of primary and/or secondary materials and the manufacture of the machine. Component renovation and reuse, incineration and landfilling of used machine components were considered of minor importance in this context and therefore not included in the study.

In Paper III literature data was collected on energy consumption and associated emissions to air for extraction, production, use and waste management of the fuel, hydraulic- and chainsaw oil.

Partitioning of energy input and emissions between co-products was utilised in some activities included in the system studied. For example, in Paper III the environmental burden from the extraction and processing of fuels and lubricating base oils was allocated proportionally to the main product and the co-products according to mass (mineral oils) or feedstock energy (rapeseed oil) of the products. In the case of machinery assemblage (Paper IV), all energy input and emissions were allocated to the machinery although there might have been other products manufactured there (e.g. loaders, frame etc.). In the steel production case (Paper IV) allocation was avoided by expanding the studied system. In many cases (e.g. aluminum, polypropylene, polybutadiene etc.) it was not feasible to identify which allocation procedures were used.

The compilation of an LCI is a data intensive process. The type of quantitative data chosen in each study depended on the question posed in the actual study, the availability of the data and the correctness of the data. Primary data (e.g. fuel and lubricating oil consumption by the contractors and forest companies in I, spare part consumption by a forest company in II, energy consumption for the assembling of the forwarder in IV) was combined with general data from the literature (e.g. energy and emissions for the extraction and processing of the fuels in III, emission factors of energy carriers in IV) and trade organisations (e.g. steel, aluminium and copper production in IV). Subjective data was also used (e.g. transport distances and transport mean in IV). Primary and secondary data was compared with other published data on the similar processes to ensure that the selected data was accurate and consistent with the aims of the studies.

The studies

In Paper I, data was collected on fuel and lubricating oil consumption by contractor and forest company owned harvesters and forwarders in practical harvesting operations in Sweden. Data was collected by means of a mail questionnaire sent to a random sample of 300 contractors and the five largest forest companies. The main results of the study are presented in Table 1. Hydraulic oil spillage for both harvesters and forwarders was 20 l/1000 m^3ub. For felling and cross-cutting trees a further 35 l/1000 m^3ub of chainsaw oil was spilled.

Table 1. *Average calculated consumption (l/1000 m^3ub) at harvesting and forwarding based on the questionnaire answers (N)*

	Forwarders			Single-grip harvesters			Two-grip harvesters		
	Consum	Std. Error	N	Consum	Std. Error	N	Consum	Std. Error	N
Diesel oil	935	36	81	1167	54	89	1010	65	21
Hydraulic oil	17	2	74	34.6	3	71	32	4	19
Engine oil	8	0.6	62	8.5	0.8	61	6	0.5	19
Transmission oil	6	0.7	55	3.5	0.5	54	5	1	19
Greases*	1.5	0.2	35	1.8	0.3	37	1	0.2	9
Chainsaw oil				35	5	63	21	2.5	20

* kg/1 000 m^3ub

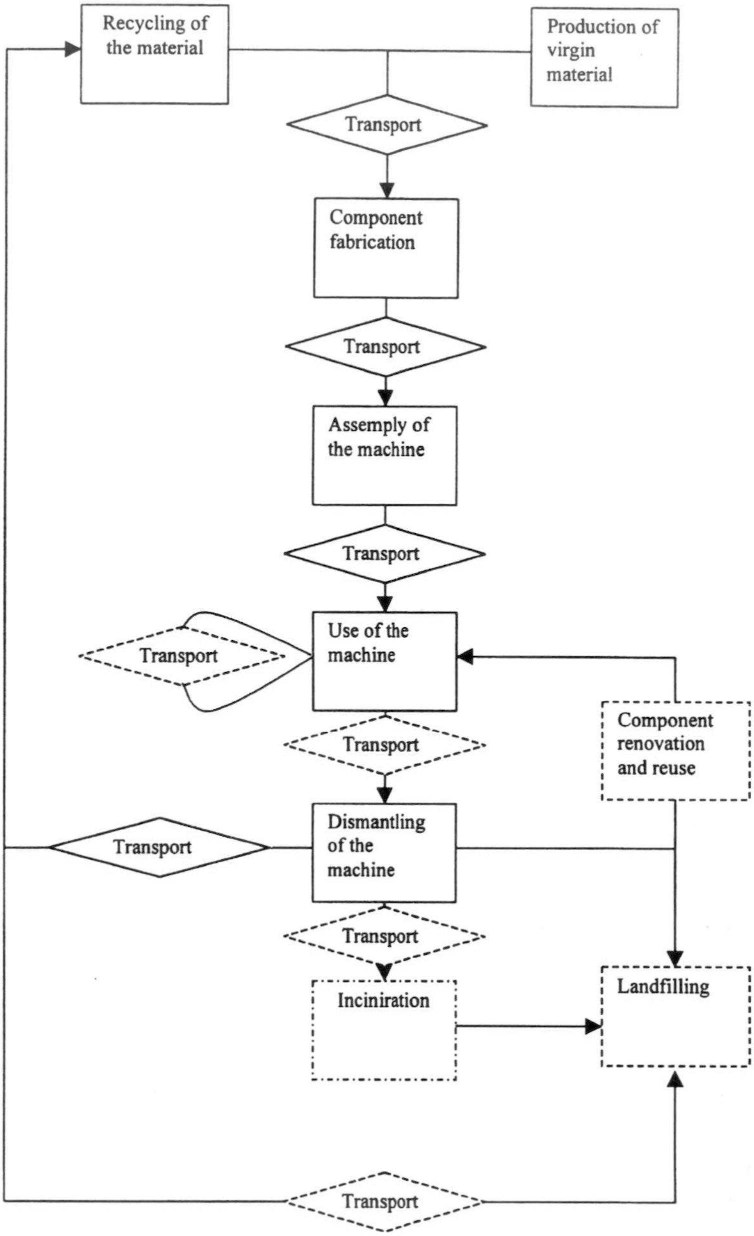

Fig. 1. Principal flow chart of the life cycle of a forest machine. Activities in dash-lined boxes are not included in the study.

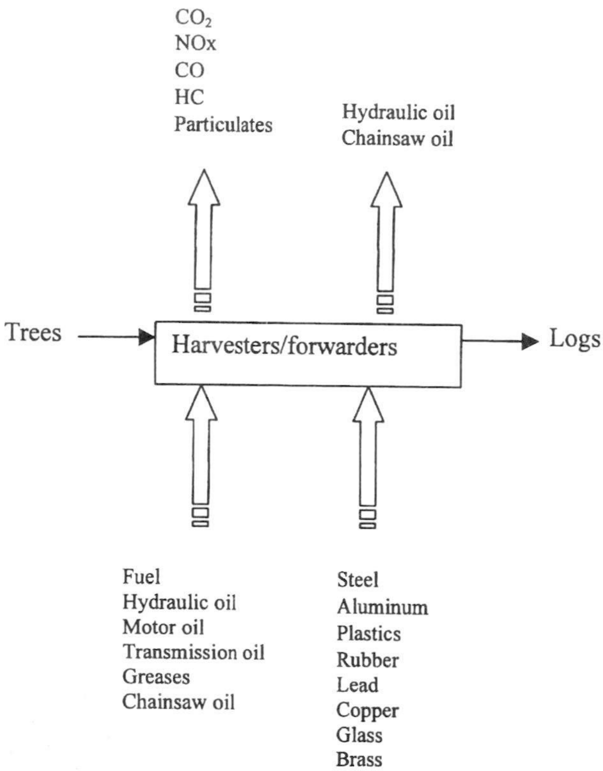

Fig. 2. Input and output flows during the machinery's work in the forest.

In Paper II, data was collected on resource utilisation due to spare part consumption by harvesters and forwarders. A component replacement follow-up obtained by a forest region in the north of Sweden was used. The follow-up included 14 single-grip harvesters, 10 two-grip harvesters and 13 forwarders. In this study two scenarios with different assumptions on the consumption of saw chains and guide bars by harvesters and tires by forwarders were developed. The high consumption scenario assumed a consumption of 10 saw chains and 3 guide bars by each harvester for every 1000 m^3ub produced and a consumption of twelve tires during the operational lifetime of a forwarder. 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. These scenarios represent realistic consumption figures published in the literature or experienced in the field. The main results of the study are presented in Table 2.

Table 2. *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.*

Material	Low scenario			High scenario		
	Forwarders	Single-grip harvesters	Two-grip harvesters	Forwarders	Single-grip harvesters	Two-grip harvesters
Steel	5033	4641	6226	5042	6508	8471
Aluminium	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

In Paper III, data on fuel, hydraulic- and chainsaw oil consumption (Paper I) was combined with literature data on emissions during the whole life cycle of the fuel and the oils. Three fuel types (rapeseed methyl ester, environmental class 1 and environmental class 3 diesel fuels) and two types of lubricating base oil (mineral- and vegetable-based) were examined. The main results of the study are presented in Table 3.

Table 3. *Exhaust emissions for harvest and transport 1000 m^3ub with three different fuel types (fuel combustion, the production phase of the fuels, the chainsaw and the hydraulic oil, and the reprocessing of the used oil are included)*

	Fuel type	CO_2 (ton)	*Rapeseed base oil* CO (kg)	HC (kg)	NOx (kg)	PM (kg)	CO_2 (ton)	*Mineral base oil* CO (kg)	HC (kg)	NOx (kg)	PM (kg)
	EC3	3.67	17.01	3.67	32.2	2.66	3.66	16.99	3.7	32.12	2.66
Forwarders	EC1	3.79	15.02	3.2	31.8	2.33	3.78	15	3.23	31.71	2.33
	RME	4.54	12.96	1.38	45.6	2.32	4.55	12.97	1.59	45.73	2.34
	EC3	4.43	20.44	4.45	38.8	3.2	4.4	20.37	4.56	38.59	3.2
Harvesters	EC1	4.58	18.06	3.88	38.3	2.81	4.54	17.99	3.99	38.11	2.81
	RME	5.47	15.59	1.7	54.9	2.79	5.44	15.52	1.81	54.68	2.79
	EC3	*8.1*	*37.45*	*8.11*	*70.9*	*5.86*	*8.06*	*37.37*	*8.26*	*70.7*	*5.86*
Total	**EC1**	*8.37*	*33.08*	*7.07*	*70.1*	*5.14*	*8.33*	*32.99*	*7.22*	*69.82*	*5.14*
	RME	*10*	*28.55*	*3.08*	*100*	*5.11*	*9.96*	*28.46*	*3.22*	*100.2*	*5.1*

In Paper IV, data on spare part replacement (Paper II) and material composition of a forwarder was combined. Data on energy input and amount of emissions was collected on the activities connected with the production of the vehicle; raw material acquisition and intermediate processing, fabrication of individual components, assembly of the vehicle, and associated transports. For the purpose of this thesis it is assumed that energy input and amount of emissions for the production of a single-grip harvester is the same as for the forwarder. Therefore all values in Table 9 in Paper IV are presented here doubled to account for the production of the harvester (Table 4).

Table 4. *Primary energy (MJ) consumed and emissions (g) emitted per unit of production (1000 m^3ub) for the manufacture of forest machines*

	Premanufacture	Component manufacture	Assembly	Transport	Total
Energy (MJ)	3346	1286	474	184	5290
Emissions (g)					
CO_2	247738	23866	8400	14116	294120
CO	1380	38	36.2	13.64	1467
NOx	406	68	15.2	126.2	615
Particles	108	3	0.6	1.96	114
SOx	460	24	11.6	0.44	496
N_2O	-*	0.8	0.66	-	1.5
HC	-	5.4	2.78	7.04	15
CH_4	-	0.6	0.64	-	1.2

*no data available

Results and discussion

It has been suggested that there exists a dominant phase in a vehicle's life cycle as it concerns energy input and discharges to the environment, namely the use phase (Eriksson et al. 1996, Gaines et al. 1998, Landfield & Karra 2000). The results of the present studies support these findings. It was found that when Swedish environmental class 1 diesel fuel (EC1) is used then 82% of the total energy input during the life cycle of the machinery can be associated to machine operation (Table 5). The second more contributing phase is the fuel production phase. Extraction and processing of rapeseed methyl ester (RME) exhibits greater values of energy consumption and emissions compared with the extraction and processing of EC1 (Table 5). It should be noted however, that there was a difference in the choice of the system boundaries for the two fuels and direct comparisons are not advisable (Ragnarsson 1994). It was also found that, when EC1 is used, the manufacture of the machinery and the spare parts contributes with 6% to the total energy consumption and 0.2-4% to the total emissions for every 1000 m^3ub harvested and transported to the roadside (Table 5).

Table 5. *Energy input and associated emissions to air per unit of production (1000 m^3ub) for the different life cycle phases of the machinery*

	Fuel Combustion			Fuel extraction and processing			Lubricant base oil extraction and processing		Manufacturing
	EC3	EC1	RME	EC3	EC1	RME	RBO	MBO	
Energy (GJ)	73	73	73	4	9	36	0.9	0.7	5.3
Emissions									
CO_2 (kg)	7790	7790	7740	250	510	2200	70	30	294
CO (g)	37300	32424	25777	30	525	2646	130	40	1468
HC (g)	3370	3372	647	4660	3623	2352	70	220	15
NOx (g)	69300	66494	85756	1180	3106	14258	500	220	615
PM (g)	5830	4370	4344	739	739	735	30	30	114

The environmental impact of the manufacture of the machinery depends on the assumptions made on the total amount of wood harvested and transported during the operational lifetime of the vehicles. If the amount decreases then the relative contribution of energy input and associated emissions to air from the manufacture phase will increase. The same will occur as a result of emission control techniques on the engines used on the machinery.

In the presented studies the functional unit used is an expression of the amount of work produced by the machinery. It is the function of the forest machines (cut and transport 1000 m^3ub to the roadside) that it was the focus of the studies. Hence, resource, material and emission flow in each process and stage was calculated always in relation to the functional unit. The use of the above unit is recommended by Strömberg et al. (1997) and it permits the integration of the findings of these studies with other studies that use the same or similar functional units (Anon. 1996, Berg 1998). For example energy consumption during stand establishment and timber transportation (Berg 1998) could be simply added up to the energy consumption of the system described here.

The emission factors presented in III are aimed for use in LCA studies that deal with whole mechanised forest operations. Since the amount of emissions from a diesel engine are highly depended on engine speed and load (Löfgren et al. 1999) it would be recommendable to conduct studies that record fuel consumption for every operational moment (driving, loading, unloading, idling etc). This has already been done for agricultural tractors (Hansson & Mattsson 1999).

In all Papers in this thesis, data is presented in a transparent way to allow for sensitivity analysis of different scenarios and can be adapted to future data inputs or assumptions, as required. Enlargement of the system to include operations prior or after the harvesting of the trees or operations that complete the overall picture given is also feasible. For example according to my calculations based on official statistics (Anon. 1999) energy consumption from moving the machinery between logging sites accounts for almost 1% of the total energy consumed during logging operations. The calculations were based on an average harvesting object of 5 ha, an average removal of 200 m^3ub in clear cuttings and 70 m^3ub in thinnings and 30 km distance between sites.

The emissions of interest to this thesis were basically emissions to the atmosphere associated with energy production (Paper III, IV). In addition to these discharges data was collected on hydraulic and chainsaw oil emissions to soil (Paper I). Main attention was drawn on carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), particulate matter (PM) and sulphur dioxide (SO_2). These discharges are contributing to the greenhouse effect (CO_2), in the formation of ground-level ozone (NOx, HC) and acidification (NOx, SO_2). PM is associated with health impacts related to breathing while exposure to CO can cause dizziness, headaches, and fatigue.

The thesis presented here is one of the first studies to apply a life cycle perspective to a timber harvesting system and on work machinery. The use of LCA methodology has assisted in the setting of appropriate environmental objectives and the identification of areas where the greatest reduction in environmental burden can be achieved. The findings of this thesis were influenced by uncertainties in the data, by assumptions and methodological choices such as system boundaries and allocation procedures. Through the use of different scenarios and sensitivity analyses an attempt was made to investigate the influence of certain data choices on the findings of the separate papers.

To identify options for improvement in the forest machine life cycle it was necessary to secure company specific data for a number of processes mainly on the machine manufacturing (Paper IV) and work in the forest (Papers, I,II,III). For this reason it was strived to attain close co-operation with forest machine manufacturers and forest companies. Such a co-operation offered accessibility to valuable product and facility specific data.

Conclusions

The studies described in this thesis used the Life Cycle Assessment framework to compile an inventory of energy and material inputs and emissions to air associated with the harvesting of trees, debarking and cross-cutting the logs and transporting the logs to the roadside. The findings provide valuable information that can serve as a building block towards the goal of determining the environmental impact of wood products.

On the basis of the papers included in the study some concluding remarks can be made:

• Energy consumption and emissions for the manufacture of the machinery, measured per 1000 m^3ub, should always be considered when the environmental load of harvesting systems is examined.

• An average of 80% of energy use and emissions to air during the life cycle of forest machinery is due to the operation phase. Decrease of fuel consumption at this phase (through the use of alternative fuels, the use of more efficient and less polluting engines and energy efficient hydraulic systems) will definetely improve the environmental profile of the machinery and the harvesting operations.

• Spare parts is an important material flow over the operational life cycle of the machinery and should be included in LCA studies. Forty to sixty percent of the mass of the machine will be replaced as spare parts and need to be considered in addition to the original mass of the machine.

• The environmental performance of forest machinery should be considered in forest certification schemes. In this context the use of biodegradable alternatives instead of mineral chainsaw and hydraulic oil is very important. Those oils show a higher degree of biodegradability and lower aquatic toxicity than the corresponding mineral oils and their release to the forest soil does not affect the environment as much and as long time. Conservation of non-renewable (mineral oils) and use of renewable resources (vegetable oils) is at a high level of importance in the LCA framework.

• Forest machinery should be studied more closely and all environmental aspects of the mechanised harvesting operations should be put together in order to get a complete picture of the environmental performance of harvesting systems and methods. This will give us the opportunity to compare different harvesting systems (e.g. tree-length, full tree, cut-to-length, chipping in the forest) with different degrees of mechanisation according to fuel consumption, component reliability, material composition of the machinery involved, discharges to the environment during machinery lifetime and impact to the forest environment during operation.

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