Life Cycle Assessment of Lawnmowers

- Two Mowers' Case Studies

Master's Thesis in Environmental Measurements and Assessments

XING LAN

YU LIU

Department of Energy and Environment
Division of Environmental System Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2010
Report No. 2010:11

MASTER'S THESIS (2010:11)

Life Cycle Assessment of Lawnmowers

Master's Thesis in the Master Programme of Environmental Measurements and Assessments

XING LAN
YU LIU

Department of Energy and Environment
Division of Environmental System Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2010

Life Cycle Assessment of Lawnmowers
-Two Mowers’ Case Studies

Master’s Thesis in the Environmental Measurements and Assessments

XING LAN
YU LIU

© XING LAN & YU LIU, 2010

ISSN 1404-8167
Master’s Thesis 2010:11
Department of Energy and Environment
Division of *Environmental System Analysis*
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Preface

This Master thesis has been conducted in collaboration with Husqvarna AB and Center for environmental assessment and material systems (CPM) in Gothenburg, Sweden. During the period between September 2009 and April 2010, the project was performed in the division of Environmental Systems Analysis (ESA) at Chalmers University of Technology, with a pause during 2009's Christmas.

The work has been supervised and guided by Emma Rex in CPM and Professor Anne-Marie Tillman in ESA has been responsible for the examination process. We would like to take this opportunity to show our deepest appreciation for the help they have given us throughout this project. Although the processes were not so easy, we did enjoy the meetings and discussions with Emma, and nice weather as well.

The participating personnel in Husqvarna AB and Husqvarna UK should be also acknowledged. Without their help, data collection would not be possible. Besides, people in ESA gave us really valuable suggestions and sometimes they were really inspiring. We would say thanks to all, including the coffer machine.

Last but certainly not least, we both would like to thank each other, our loving family and friends for their support.

Göteborg, May 2010
Xing Lan
Yu Liu

Life Cycle Assessment of Lawnmowers
-Two Mowers' Case Studies
Master's Thesis in the Environmental Measurements and Assessments
XING LAN
YU LIU
Department of Energy and Environment
Division of *Environmental System Analysis*
Chalmers University of Technology

Abstract

Husqvarna AB, as a leading outdoor power company, has chosen two typical lawnmowers to analyse their environmental impacts from lawnmower branch. These two, one is the traditional walk-behind lawnmower LC48VE and the other one is named Automower 220AC. The distinct characteristic between these two is that the former one is petrol-driven while the latter is electricity-driven. Besides, the traditional one needs people's control while the other can be programmed and work without external manpower. Due to the highly different working patterns and market consideration, the results for two cases will not be compared. The main reason for putting them together is for further product development and internal life cycle thinking auxiliary. Life cycle assessment was used to evaluate the environmental impacts of these two chosen products from production, use and maintenance and end-of-life phases.

Data collection was the most time consuming part of the whole procedures and database in SimaPro were widely used but some processing data were still missing. The result shows that production phase which is also covering raw material extraction and use phase together contribute dominant environmental impacts. The characterisation and weighting methods as EPS2000 and Eco-indicator 99 were applied and shown difference in final results because of the different emphasis of each method. Sensitivity analysis showed that increasing the share of recycled metals could make better environmental performances of both mowers while electricity productions in different countries have obvious impacts on Automower's impacts.

In terms of product development, the most common way of using life cycle perspectives is through life cycle thinking (LCT) in design chain, in this case, which could mean increase of the ratio of recycled materials and improvement of products' durability.

Table of Contents

1. Introduction

1.1 Background

Husqvarna AB is the world's largest outdoor power products production company, the major products including lawn mowers, chainsaws, garden tractors, trimmers and blowers. It is one of the leaders in construction and stone industries in the world. It is also the leader of consumer European irrigation equipments. The products are distributed and sold in more than 100 countries (Husqvarna AB, 2009).

Husqvarna is actively engaged in being part of the environmental solutions by its products and processes' development. Since environmental awareness is increasingly important in the manufacturing industry and also for consumers.

The company has expressed their environmental concerns in several aspects. For example, they have already issued Eco-Smart ^{TM} technology on several products which were assessed as aspects of materials, fuel consumption, fuel type, lubricant, emissions, vibrations, packaging, recyclability and noise and Eco-Smart approach has been applied on current 10 products by far. For example X-TORQ is one of these solutions which have less fuel consumption and low emissions.

As the commitment of its environmental responsibility, the company considers starting up systematic LCA work in the organization. Experimental assessment had been made on chainsaws ten years ago. Besides the company also wants to keep on its leader position, since the industrial competitions are making efforts on the improvement of environmental performance of products and the legislation. Marketing also needs the focus about the environmental performance of products and could be supported by the LCA.

1.2 LCA in general

Life cycle assessment, the abbreviation of which is LCA, is defined as the "compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle" in ISO14040. The life cycle includes the extraction of resources, processing of materials and product parts, manufacturing of products, use of products and the waste management with all the transports involved in the system, therefore, well known as "cradle to grave" (Baumann & Tillman, 2004).

In Figure 1 the boxes illustrate the procedural steps and the black arrows shows the order while the white for the possible iterations. The first step is to identify the objective and determine the work plan of LCA study. After flowchart designing, data collection, multifunctional processes allocation and final calculation, the main result is an inventory about the "quantified inputs and outputs in terms of per functional unit". And the life cycle impact assessment (LCIA) refers to define a list of impact categories and select "models for relating the environmental interventions to suitable category indicators for these impact categories". Then the modeling results are calculated in the characterisation step which is a compulsory step in ISO14040 while the followings including weighting are optional processing ways for inventory, and "there is no best available method". (Guinée, 2002). In this case weighting is used to get a dimensional index to give a direct view of the product's environmental performance while the aggregation will sacrifice the details and competence of environmental information. Finally, in interpretation phase all the choices, assumptions and analytical results will be evaluated "in terms of soundness and robustness" and then drawn the "overall conclusion", while the interactions between each steps make the LCA procedures as a whole.

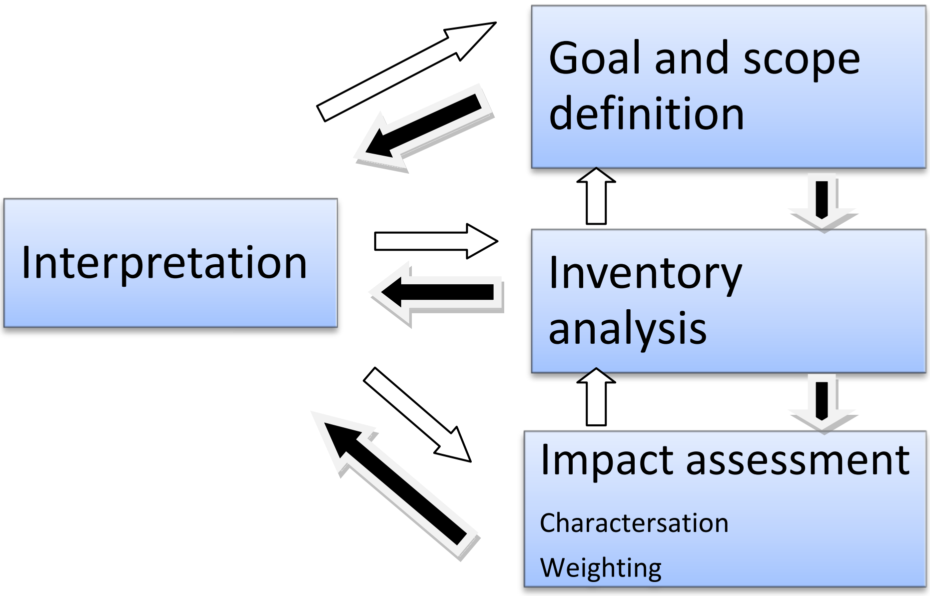

Figure 1 The LCA procedures (Baumann & Tillman, 2004).

Figure 2 gives illustration on how to aggregate inventory input (resources, energy, etc.) and output (emissions, etc.) data into defined impact categories and further to one single index.

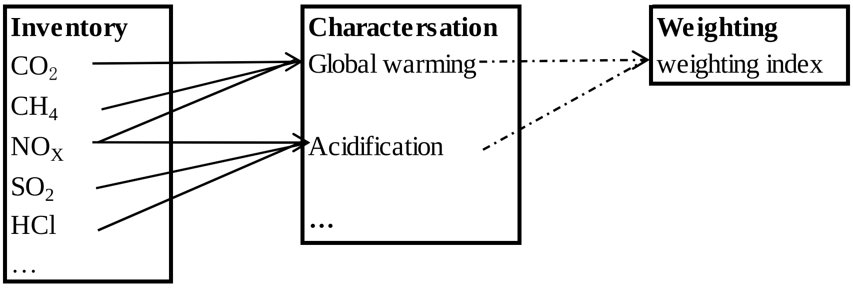

Figure 2 The life cycle impact assessment illustration (Baumann & Tillman, 2004).

For companies, the fundamental characteristic of LCA as analytical tool is to provide information for decision making, to identify the improvement possibilities, and to communicate for marketing reasons.

2. Goal and scope definition

2.1 Goal

The goal of this LCA study was to evaluate the environmental performances of two chosen products: lawn mowers running on petrol and automowers using electricity power, and to give recommendations for making LCA studies in Husqvarna, including discussion about its applicability in the company.

Two tasks have been done in this report:

- Investigation of the environmental impacts of these two products;
- Suggestions of improvement in internal LCA implementation and application.

The main intended audiences of the report are personnel in Husqvarna including the product designers and the decision makers. In the long run, LCA studies can also be used for communication with consumers and research and development (R&D) phase to improve environmental performance of products.

Since this company is at the beginner level on LCA study, its environmental manager firstly wants to have a report about the environmental impacts of products and bring more focus on environmental management at company level as well as consideration at product development phase. Therefore, it’s not comparison work which is called as “change-oriented LCA” but an accounting task based on the purpose of the commissioner.

2.2 Scope

2.2.1 Options

Two products have been selected according to the consideration of Husqvarna. And pictures of these two products are shown in Figure 3.

- Lawnmower LC 48VE with petrol engine which is assembled in Höör, Sweden
- Automower 220 AC which is assembled in Newton Aycliffe, UK.

Figure 3 Pictures of lawnmower LC48VE and Automower 220 AC.

2.2.2 Initial flowchart

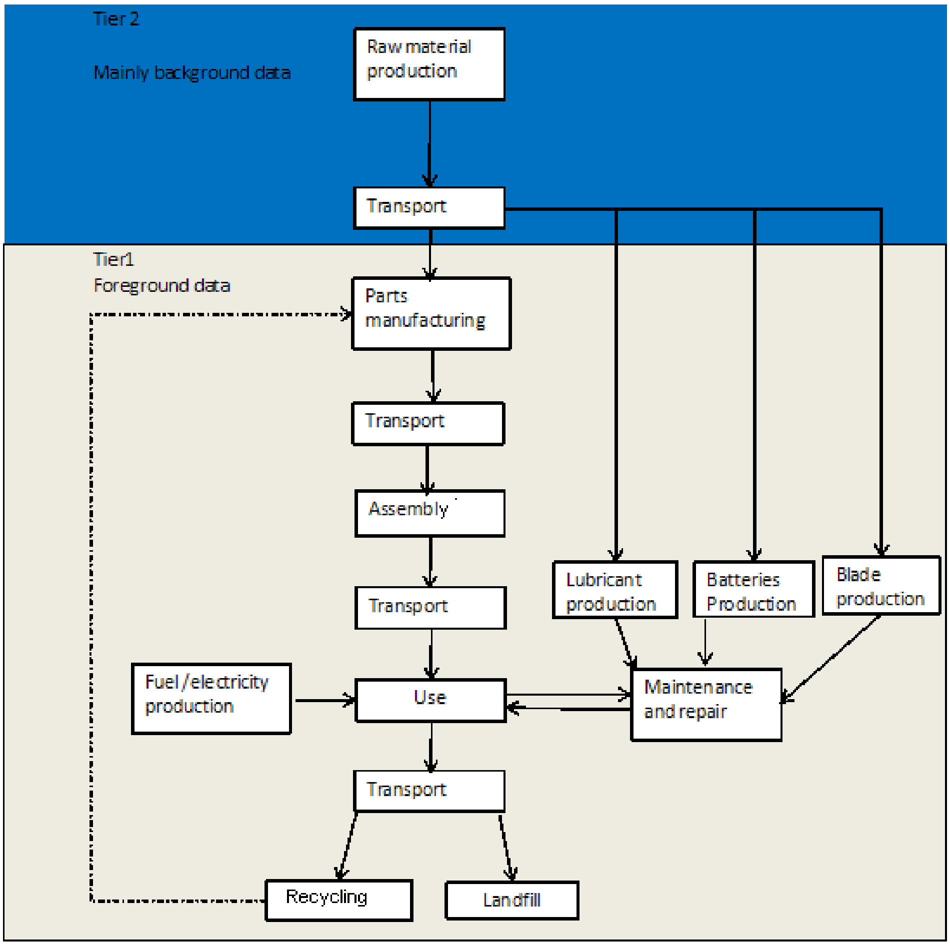

Figure 4 Rough flow chart of the products.

2.2.3 Functional unit

The functional unit is used to link the input and output during the quantum of the products' environmental performance. In this case, mowing 1000 m^2 lawn (Swedish lawn in south of Sweden) for 10 years was defined as functional unit. The important concerns are energy usage and environmental impact. And in the following context, the f.u. is the abbreviation for functional unit.

2.2.4 Impact assessment

Characterisation

Impact categories were used in the characterisation phase and the data from the inventory are aggregated into a number of impact categories. To quantify the environmental impact in each category, equivalency factor which has been defined after cause-effect chain modeling is used. (Baumann & Tillman, 2004). For example, as many emissions could contribute to acidification and the acidification potential (AP) of 1 kg SO_2 can be set as baseline, while others like 1kg NO_X and 1kg HCl has the same AP as 0.7kg and 0.88kg SO_2, respectively. Thus, the result of acidification category should be the sum of the quantity of SO_2 equivalents, SO_2 inclusive. In later characterisation sections, the abbreviated unit- “kg eqv/f.u” means kg specific equivalent per functional unit in each category.

In ISO standard, the equivalency factors were named as category indicators and in this case the impact categories are selected according to the SETAC-WTA2 list (SETAC-Europe, 1996):

- Depletion of abiotic resources
- Global warming
- Ozone depletion potential
- Human toxicity
- Ecotoxicity
- Photochemical ozone creation potential (POCP)
- Acidification
- Eutrophication

In this case, the data for land use category are not collected directly but from the background data in the database.

Microsofte Office EXCEL has been used as the data store and basis for calculations. Foreground data have been collected from Husqvarna, suppliers and waste management company, while the background dataset available are from professional software, LCA database, and previous LCA studies.

Weighting

CML, Eco-indicator 99, EDIP and EPS2000 are some of the most popular LCIA methods today. In this case, EPS2000 and Eco-indicator 99 were chosen for the weighting.

EPS2000, developed by CPM (center for environmental assessment of product and material system) was chosen because the EPS system is aimed to be a tool for a company’s internal product development process. It may be used externally and for other purposes, like for environmental declarations, for purchasing decisions, for education or for environmental accounting, but in those cases, the knowledge of the EPS system and its features and limitations is crucial (CPM, 2010). EPS is based on willingness-to-pay to avoid environmental damages (Baumann & Tillman, 2004) and impact is expressed in a monetary value called “ELU” (Environmental load units).

Eco-indictor 99 is also a widely used method and the purpose of using two methods is to let the company to see the different result with different analysis ways. Eco-indicator 99 is based on distance-to-target principle.

2.2.5 System boundaries

The whole life cycle of lawnmowers, namely from raw material extraction to waste management, was covered. The LCA studies included accounting environmental performances, “hot-spot” analysis, and sensitivity analyses.

Transports from the central warehouses to retailers, from retailers to consumers and from consumers to waste treatment plants were not included. The recycling data have been discussed in the study. Environmental impacts from the capital goods manufacturing, such as machines used in the manufacturing of the vehicles, were not considered, nor were impacts from activities of employees.

Geographical and time boundary

The Automower 220 AC is assembled in Newton Aycliffe, UK while Lawnmower LC 48VE is in Höör, Sweden. However, most parts of the product are purchased globally and the products would be retailed by Husqvarna’s wholesale network. Therefore the geographical boundary was defined as global. But the use site point is set to be in south Sweden. And for transport, the NTM data have been selected to evaluate the environmental impacts (NTM, 2009).

According to the company, regarding the use phase of the product, the life span of Automower 220 AC is 10 years (Gustvasson, 2009) and for LC 48 VE is 250 hours (Edman, 2009). Since the site is south Sweden where the grass growth period is from May to September, 5 months per year and working time per month is 5 hours, the life span of LC 48 VE in this case is also 10 year. Therefore the time boundary is 10 years covering the use phase.

Data collection and quality

Data collection is one of the most time consuming activities in LCA (Baumann & Tillman, 2004). There is no one universal principle for it yet. However, some planning suggestions were followed:

For most of raw materials production phase, general data were used. For processing phase, data were as far as possible obtained from Husqvarna and first tier suppliers by personal communication and internal documents, some general data were used as well. Regarding end-of-life treatment, data were collected from Renova AB (Renova AB, 2010).

Result interpretation

Sensitivity analysis aims to find the theoretical sensitivity for indicators which could identify the specific potential of improvement. In dominance analysis phase, “hot-spot” will be found to investigate what parts of the life cycle take the dominant environmental impacts.

Normalization and weighting both are optional in LCA; however in this case weighting was chosen because the final single index will help the decision maker to have a complementary view of the environmental performance of products as integrated “result”.

3. Case of lawnmower LC48VE

3.1 Inventory analysis

The life cycle of the lawnmower LC48VE was divided into these phases:

- Production: components production and assembly in Höör
- Transport involved in purchase and wholesale
- Use and maintenance
- End-of-life (EOL)

Detail descriptions for these phases are in the following Flowchart part.

3.1.1 Flowchart

Figure 5 shows the simplified flowchart of lawnmower LC48VE. The production phase includes the processes that happened before all the components and materials arriving at Höör, as well as the steel components manufacturing processes in Höör. Raw material extraction, transport and other processing procedures were included. The production process would be divided into several modules according to Husqvarna’s internal Alpha modular system and each module includes several components. The grey box represents processes occurring in Höör, where the main steel components were produced and assembly happened, and the powdering process was included in the assembly part.

Transport phase covers the processes in both components purchase and products wholesale, but excluded transports happened in retail processes. Besides, the transport happened in raw material extraction, purchased by suppliers can be only approached in data base, which were defined as background transport and were accounted to each module’s environmental impacts in this case. And the process in dotted box indicates the processe which has been omitted.

Use and maintenance statics data were from Husqvarna, while end-of-life data were base on telephone interview with Kurtl Lindman in Renova, a Swedish waste treatment company and assumptions.

3.1.2 General data

Raw material

For LC48VE, Husqvarna purchased many components while only manufactured main steel parts and assembled both in Höör. The data collection processes mainly focused on the direct supplied components’ raw material origins, processing impacts and transport from suppliers to Husqvarna and from Husqvarna to different central warehouse. In this case, average data, not the site-specific of raw material production were adopted. Thus the technological differences existed in different sites were omitted due to the data completeness limitation.

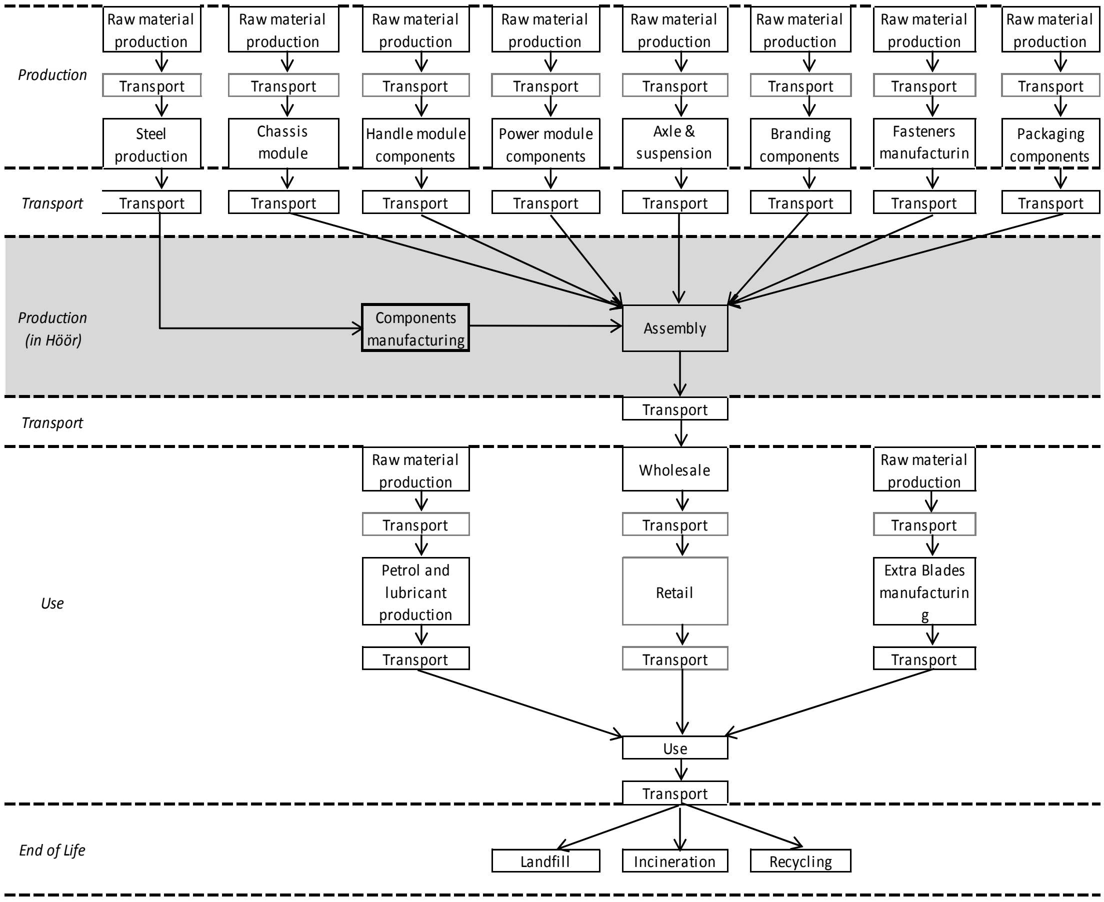

Figure 5 Flowchart of lawnmower LC48V (processes in dotted boxes excluded)

Raw material production processes in this case were divided into 2 categories; one is labeled with lower case letter “r” as r1 and the other with capitalized letter “R” as R1, R2 and so on. Take steel alloy production R1 for example:

Steel alloy: Husqvarna bought different kinds of steel alloy components or as raw material, and most are steel alloy sheet. The steel alloy A517b with zinc electroplated in SimaPro 7.1 database was selects as reprehensive for all kinds of steel alloy being used since the dominant steel alloys from SSAB are with the most similar chemical compositions, seen in Table 1 and Table 2, while steel wire and stainless steel were exceptions and would be discusses later separately.

Table 1 Chemical compositions of steel sheet Dogal Form 36.

Steel grade	C max	Si Max	Mn max	P max	S max	Cr max	Altot max
Dogal Form 36 (%)	0.004	0.030	0.20	0.020	0.015	0.050	0.020

(SSAB,Swedish Steel, 2008)

Table 2 Chemical compositions of steel sheet A517b.

Material content in 1kg A517b		
Steel	0.9797	kg
Manganese	0.01	kg
Silicon	0.003	kg
Molybdenum	0.002	kg
Chromium	0.005	kg
Vanadium	0.0003	kg
Titanium	0.0001	kg

Table 2 is from SimaPro database, but only the compositions of steel A517b were given based on average statics data from all suppliers in Western Europe for 1995-1999 with transport data not included. This simplified list could not be used directly in inventory. Thus, in this case, the way adopted was to trace back each kind of material or substance to find detailed input and output of each material and substance. The impact of A517b was assumed the sum of the environmental impacts to produce these materials and substances. Data were still Western Europe average data between 1995 and 1999 covering ore extraction, processing and transport processes.

The flowchart of steel alloy production R1 was assumed as Figure 6 according to its compositions and processing step, electroplating labeled with zinc electroplating (P3). The lower case letter “r” processes generally include each material or substances’ extraction, processing and what was called background transport as before.

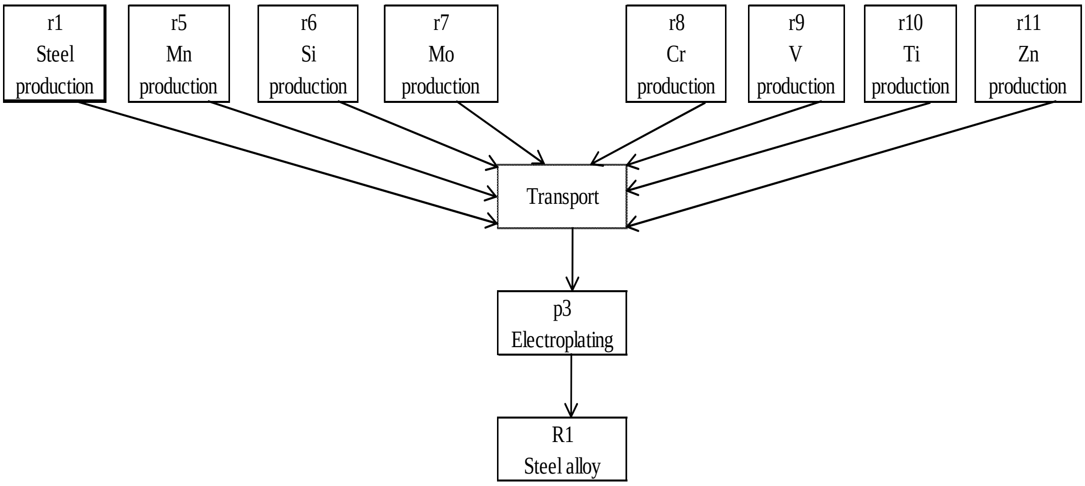

Figure 6 Flowchart of R1 steel alloy production.

Steel wire: Beside steel alloy sheet, steel wire components were also used in LC48VE and the data from Gabi 4 Education were used as world average. For steel wire production R2, steel billet production were the major material need to trace back and the processing included ore extraction, transport, heating and rolling and drawing.

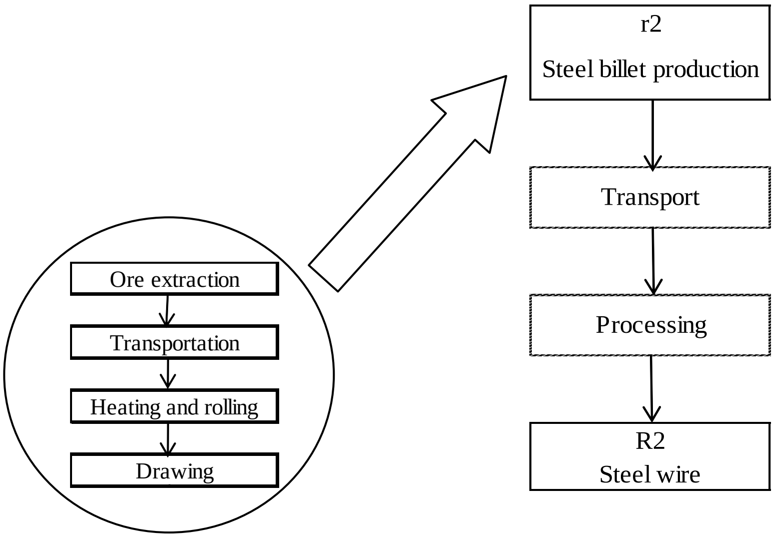

Figure 7 Flowchart of R2 steel wire production.

Stainless steel: The same method was used for stainless steel production R16 as steel alloy R1, while with different chemical compositions approached from SimaPro database. Transport and processing data were omitted due to lack of data.

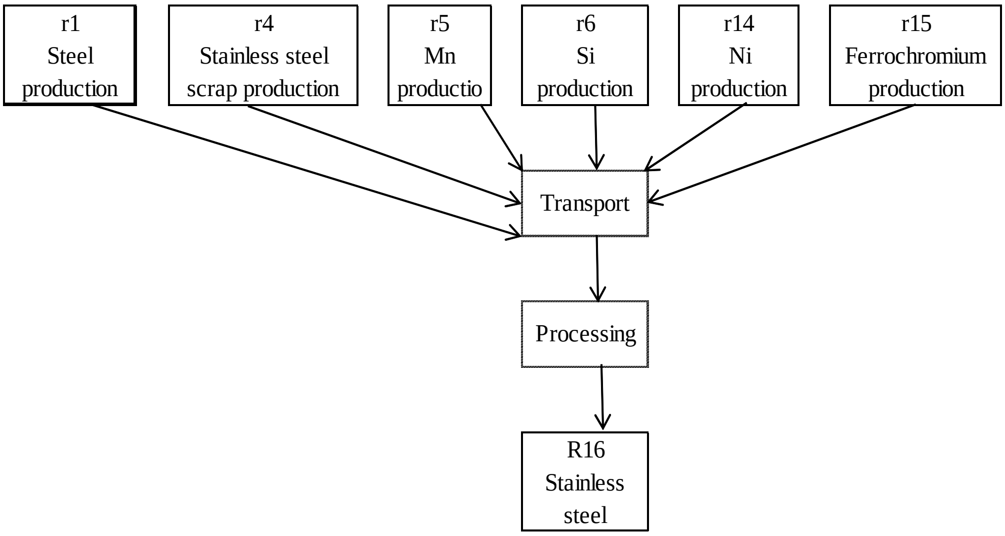

Figure 8 Flowchart of R16 stainless steel production.

Aluminum alloy: The material analysis report for lawnmowers in Husqvarna (Husqvarna, 2009)shows that there exist two kinds of Al alloy, ADC12 and EN46000. ADC12 is the material no. from Japanese Industrial Standards (JIS) system and as equivalent of EN AC-46100 in European Standard system. Its EN denomination is G-$AlSi_{12}Cu$ (Misumi Europe), while EN46000 is G-$AlSi_9Cu_3$ (Fe)(Ericsson). The chosen average LCA data for these two different alloys were G-$Al_{12}Cu$ and G-Al_8Cu_3 from SimaPro database, respectively, while data in Table 3 and

Table 4 are based on average data from all suppliers in Western Europe for 1990-1994, and transport data are not included. Meanwhile, the material and substances traced back data covered ore extraction, processing and transport processes.

Table 3 Chemical compositions of Al ADC12.

Material content in 1 kg Al ADC12	
Aluminum ingots	0.706 kg
Aluminum recycled	0.15 kg
Silicon	0.12 kg
Copper	0.01 kg
Steel	0.008 kg
Manganese	0.003 kg
Magnesium	0.003 kg

Table 4 Chemical compositions of Al EN46000.

Material content in 1 kg Al ADC12	
Aluminum ingots	0.714 kg
Aluminum recycled	0.15 kg
Silicon	0.08 kg
Copper	0.03 kg
Zinc	0.012 kg
Steel	0.008 kg
Manganese	0.004 kg
Magnesium	0.002 kg

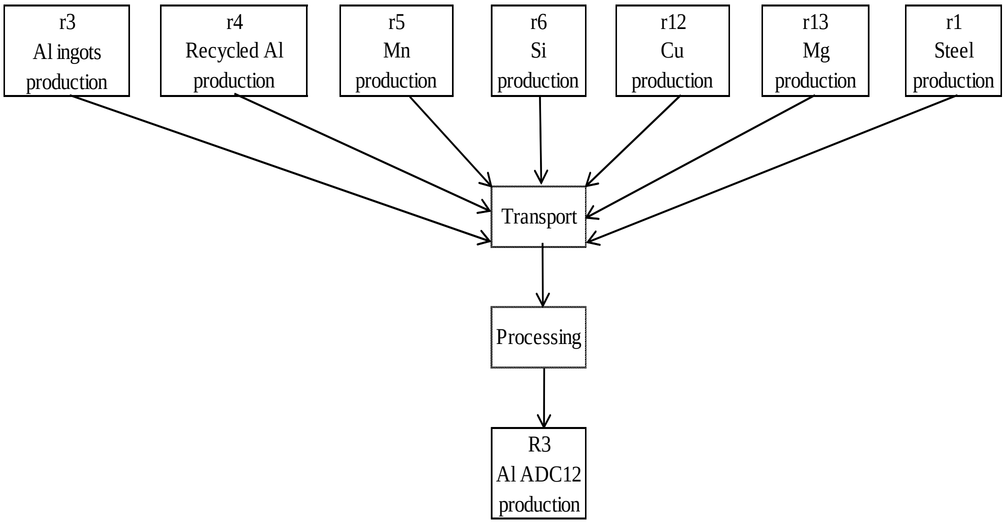

Figure 9 Flowchart of R3-Al ADC12 production.

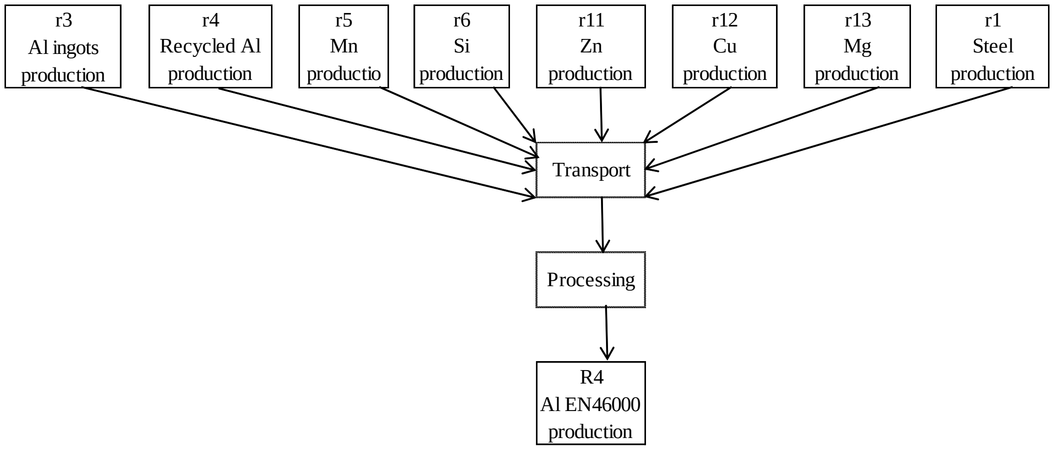

Figure 10 Flowchart of R4-Al EN46000 production.

Plastic: R5-Polypropylene (PP) granulate, R6-Acrylonitrile butadiene styrene (ABS) granulate R7-Polyvinyl chloride (PVC) granulate R8-Polyamide 6 (PA6) granulate and R9-PA6 30GF. All of these data were obtained from SimaPro 7.1, and inventory data of R4-R9 production are based on average Western Europe data for 1995 to 1999, transport data are not included.

Others: R10-Rubber, R11-Zinc, R12-Copper, R13-Crude iron steel, R1-sulfuric acid and R15-Lead.

Electricity production

Electricity production in different countries and regions are based on different energy sources. In this study electricity consumption was considered in Sweden. Swedish sources is considered as nuclear (46.5%), oil (2.06%) and hydro electricity (51.44%)(Baumann & Tillman, 2004)

3.1.3 Production

Chassis module

The lawnmower chassis module consists of several materials, mainly steel and plastic while the detailed weights of each component were listed in Table 5, and Figure 11 shows the specific flowchart for chassis module. The processes in the grey box, in terms of what happened in Höör, were included in assembly part and the same for all the following modules.

Table 5 Material compositions of chassis module per functional unit.

Materials	Weight(kg)
Steel alloy	13.182
Steel wire	0.628
Aluminum	0.291
Plastic-PP	4.17
Plastic-ABS	0.545
Plastic-PVC	0.159

Chassis, the main part of this module was made from steel EN 10327 or DX54D Z100 (Dogal Form 36 with zinc coating thickness 7um at per side) and manufactured in Höör. In sheet production phase, 1% loss was assumed mainly due to cold forming and electroplating zinc processes.

For the rest steel wire components: grass bag frame, axle rear discharge and spring, while processes include iron mining, steel billets making and heating and rolling for wires, 5% loss was assumed for the components processing.

Plastic components PP, PVC and ABS were made from each specific granulate with injection mould processes P1which was assumed to be the same for all the plastic components. While the losses of granulate production were excluded, the loss during the injection processes were assumed as 3%. This loss rate was based on the interview with (Foster, 2010) in Husqvarna UK, which produced most of the plastic components for their products.

Then for Aluminum components, from Huqavarna internal material report (Husqvarna, 2009), the Al used in chassis module is EN46000. The major process P2 being considered in this case is alloy forging. 1% loss was assumed as happened in forging process and the alloy production loss was not taken into consideration.

And the loss ratio settings were the same for all the modules as followed in production phase.

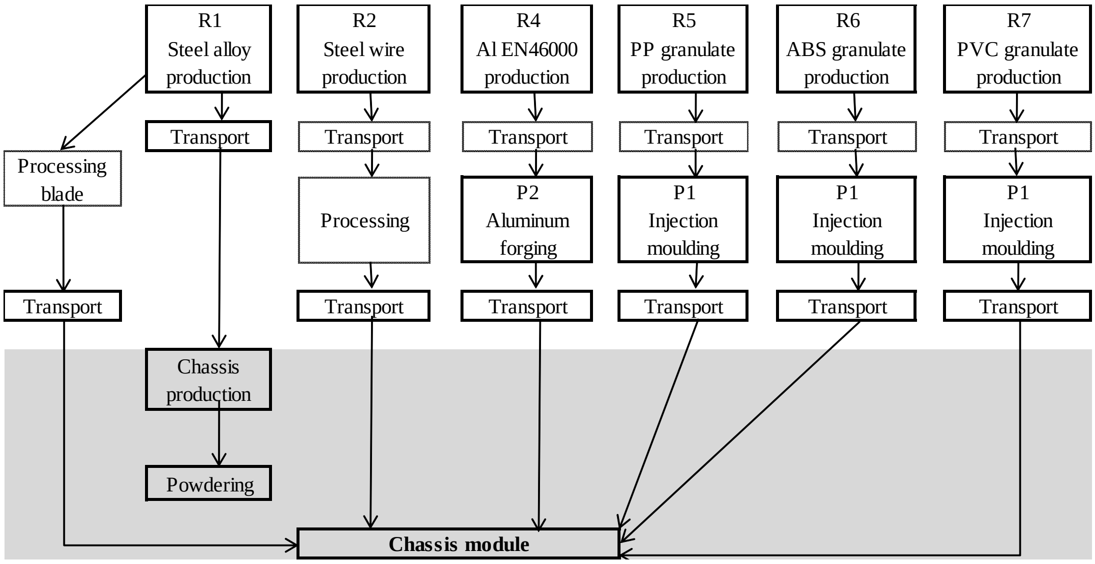

Figure 11 Specific flowchart of chassis module.

Handle module

The lawnmower handle module also consists of mainly steel alloy, steel wire, aluminum and plastics while the detailed weights of each material are listed in Table 6, and Figure 12 shows the specific flowchart for handle module. P2 represents the aluminum forging process and is about the energy used to transform materials as both ADC12 and EN46000. And the data is also average data and from a project named IDEMAT2001 from Delft University of Technology. And the data been used for the plastics processing was still P1 injection mould.

Table 6 Material compositions of handle module per functional unit.

Materials	**Weight(kg)**
Steel alloy	4.957
Steel wire	0.594
Aluminum	0.279
Plastic-PP	0.055
Plastic-PA+PA30GF	0.11
Rubber	0.04

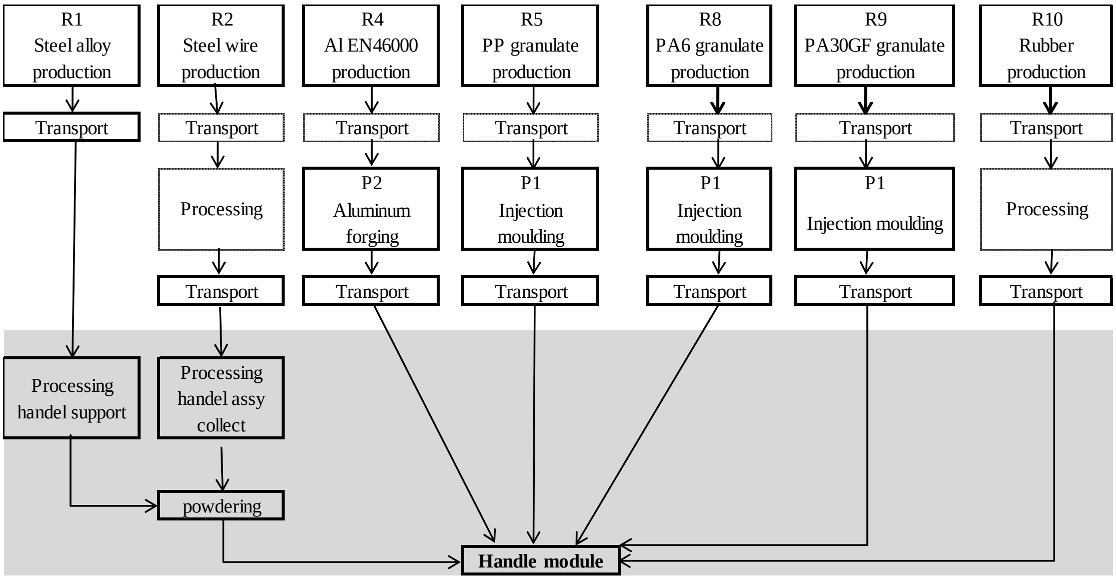

Figure 12 Specific flowchart of handle module.

Axle and suspension module

Plastics components were still processed from granulate and the mould injection (P1) and Al EN46000 were forged from other substances and materials as P2 showed. The impacts here for steel alloy components and steel wire components basically were assumed from raw material production impacts due to lack of processing data and major transport data from raw material suppliers. Figure 13 shows the specific flowchart for axle and suspension module.

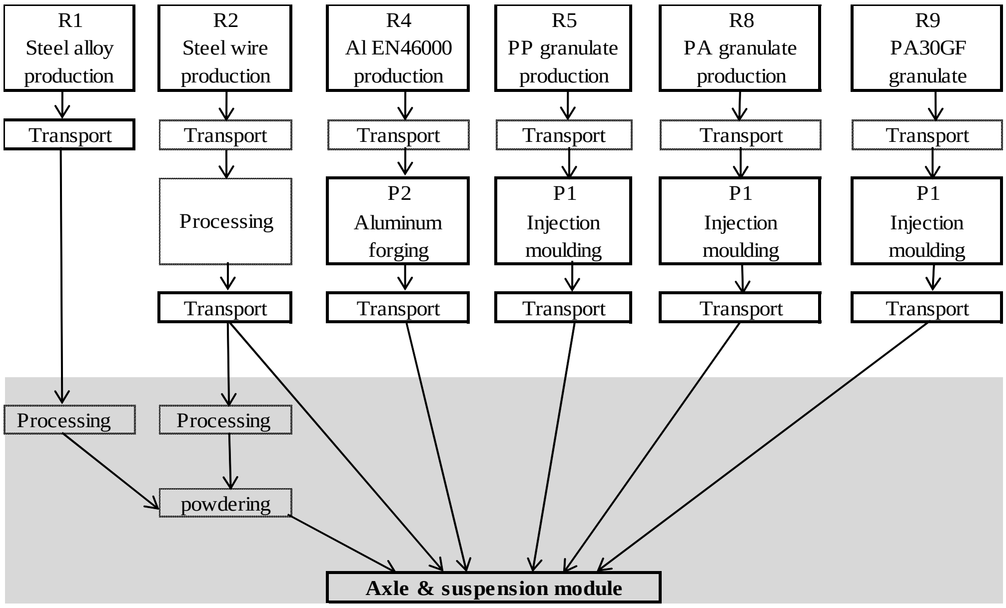

Figure 13 Specific flowchart of axle and suspension module.

Power module

The major parts of power module are engine, gearbox and starter battery. All the data available from suppliers are only the chemical composition of these components, which could be seen in Table 7 and

Table 8. The battery is lead-acid battery, and manufacturing data is based on one battery life cycle study (Rantik, 1999).

Table 7 Material compositions of engine per functional unit.

Material	Weight(kg)
Aluminum-ADC12	5.453
Steel	2.1411
Iron	1.6412
Plastic	1.1902
Copper	0.1138
Zinc	0.0096
Rubber	0.0362
Miscellaneous	0.2944

Table 8 Material compositions of battery per functional unit.

Material	Weight(kg)
Grease	0.035
H_2SO_4	0.15
Other	0.1255
Pb	0.55
PbO_2	0.2

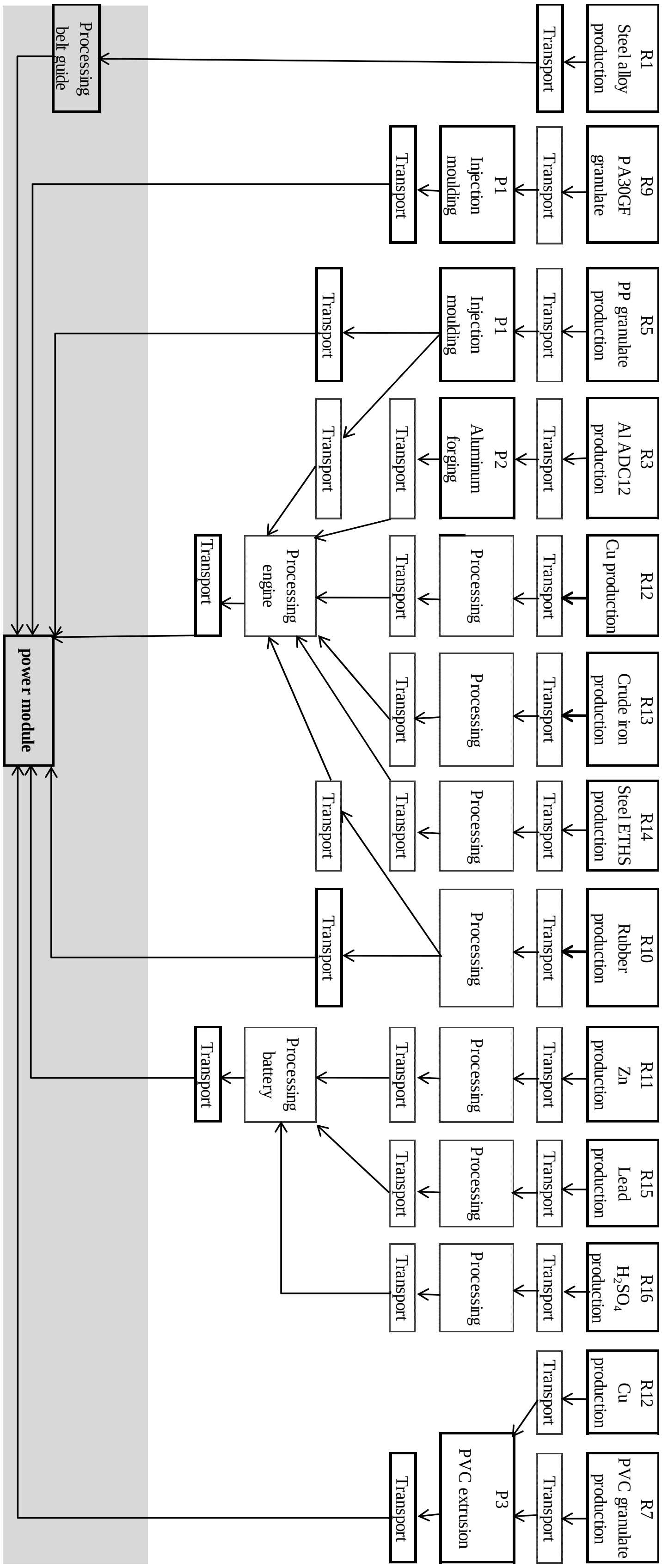

Figure 14 Specific flowchart of power module.

Branding module

In this module, 3 groups can be divided: plastic components, stainless steel skid plate and the wheel. Processing of rubber and steel was omitted since the weights are too small compared with the total weight of the lawnmower.

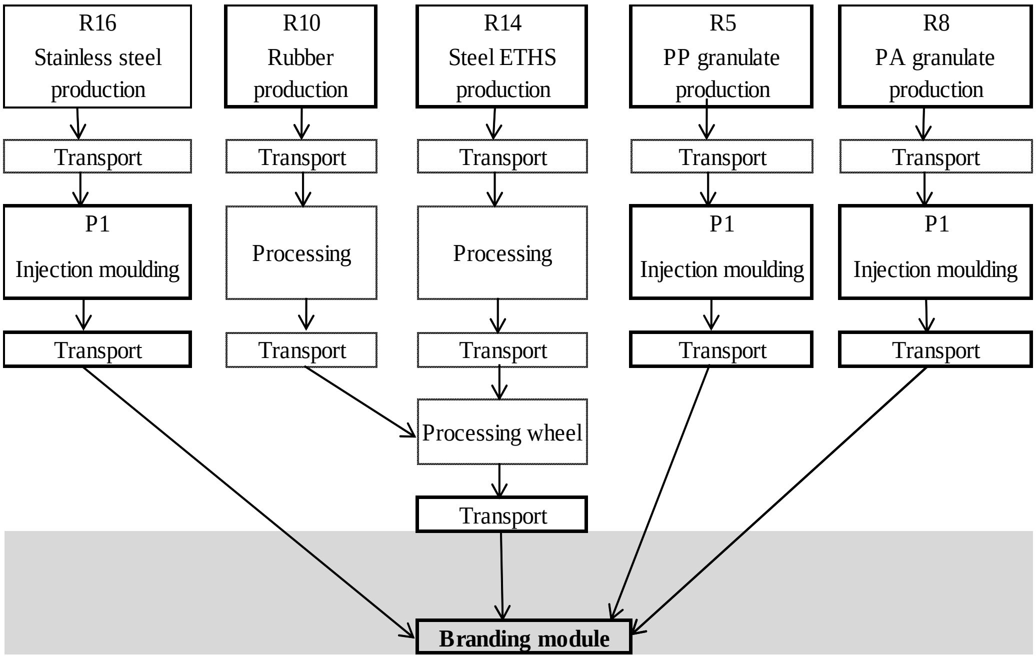

Figure 15 Specific flowchart of branding module.

Fasteners

In this study the steel wire is assumed been used for fasteners and as Figure 7 shown the steel wire production processes included ore extraction, general transport, heating and rolling and drawing processes. Due to the supplier didn't reply the survey, the transport and specific fasteners processing are unknown. Compared with the steel wire production the processing of fasteners can be omitted.

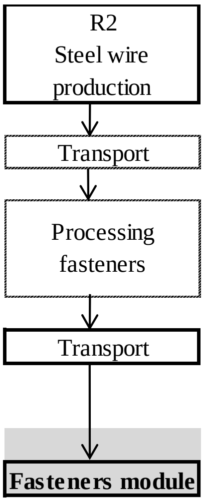

Figure 16 Specific flowchart of fasteners processing.

Packaging

Table 9 Material compositions of packaging module per functional unit.

Parts name	Material composition	Weight(kg)
Carton	Corrugated cardboard	5.50
Manual	Virgin material paper	0.20

Production of wood containing uncoated paper (94% dry matter) mainly from thermo mechanically produced wood pulp with some bleached sulphate cellulose in one factory in Switzerland .This kind of paper is mainly used in printing industry.

Assembly

As the assembly work is finished in Höör, it was accompanied with the main steel components processed as well as the powdering process. The capital goods and human resources were not taken into considerations.

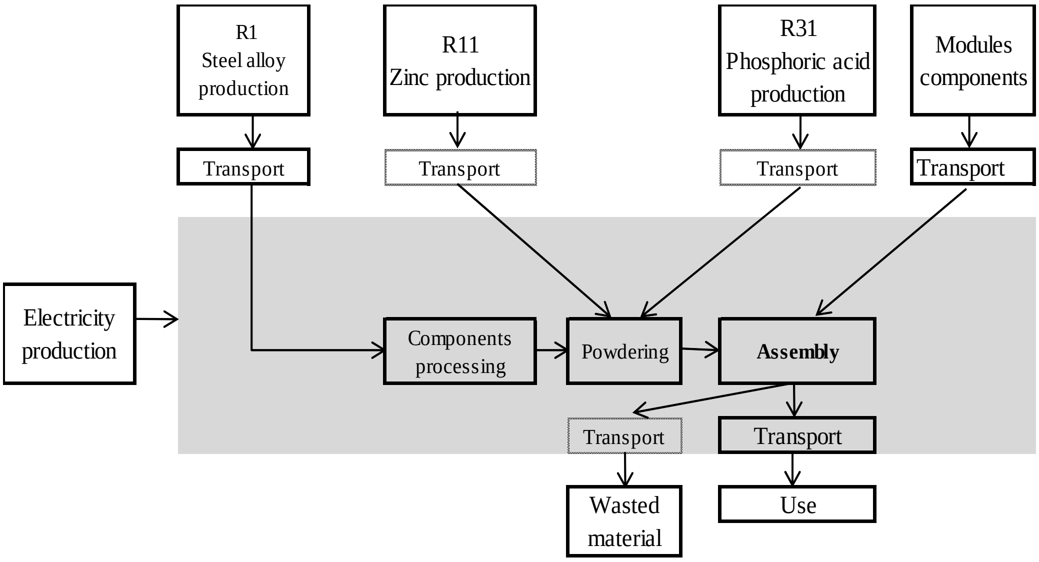

Figure 17 Specific flowchart of assembly.

Energy, as electricity, has been already allocated in Höör: 4.32 kWh for each piece of product which covers steel processing, powdering and assembly (Johan, 2010). Electricity use is the Swedish average data from the IEA statistics (Baumann & Tillman, 2004).

The powder in use is named phosphate zinc and for each unit 0.13kg was used (Edman, 2009). The specific powder production data have not been found, then the reaction between Zn and phosphate acid is assumed as:

$Zn+H_3PO_4 \rightarrow H_2+ Zn_3(PO_4)_2$

In this case, zinc production (R11) represented world average data and background transport covering delivery to Rotterdam with technology in 2000. R31 phosphoric acid production was on German total aggregated system inventory covering production from calcium phosphate and sulfuric acid. No land use and capital equipments were accounted.

3.1.4 Transport

Transport phase calculations were based on communication with Monica Arvidsson and Carl Risholm in Husqvarna AB. Only first tier suppliers were taken into considerations in this phase and the basic assumptions for procurement were that transport in Europe were with truck while outside of Europe were with ship (Risholm, 2009). While for wholesale, external logistic companies were used to distribute the mowers from the factory in Höör to different locations in Europe in 2009 and trucks of 13.6 loading meter were assumed to use (Arvidsson, 2009). All the goods are transported by truck with semi-trailer (13.6 loading meter included in this category), long distance transport based on the assumption that 70% load capacity is used which included empty return transports (NTM, 2002).

The aggregated data of input and output of transport phase are given in Table 10. The data include the fuel consumption and major emissions from the vehicles, and also energy requirements and emissions from production and distribution of the fuel. This fuel gives Euro 3 emission which is significantly lower than standard fuel, and components or products with oversea transport are transported by medium sized ship (NTM, 2002). The environment impact of construction of vehicles, roads, or other infrastructure is not included. The data is based on fuel of environmental class 1 (more than 90% of the fuel sold in Sweden is of this type).

Table 10 Inventory of the transport per functional unit.

	Wholesale	**Suppliers**	**Total**	**Unit**
INPUT				
Diesel	0.884	1.376	2.260	l/f.u.
OUTPUT				
Energy	31.654	49.257	80.911	MJ/f.u.
CO_2	2286.120	360.196	2646.316	g/f.u.
NO_X	14.508	70.955	85.463	g/f.u.
HC	2.066	3.033	5.099	g/f.u.
Particulate matter	0.251	2.509	2.760	g/f.u.
CO	2.022	3.856	5.878	g/f.u.
SO_2	0.572	43.498	44.070	g/f.u.

3.1.5 Use and maintenance

Use phase description

In the goal and scope definition phase, the functional unit and the system boundaries have been decided, which are maintenance of 1000 m^2 lawn in Sweden during 10 years. And the maximum working hours for LC48VE is 250 hours (Ahlund, 2009), while the grass growth period in Sweden is 5 months, the working hours for LC48VE per week is：

$$\mathrm{t} = \frac{(250h/10year)/(12months/year)}{4weeks/month} = 1.25h/months$$

Besides, the cutting length for LC48VE is 48cm, which means the velocity is:

$$\mu\text{=}(\frac{1000m2}{0.48m}/1.25h) = 1.67km/h$$

And which would not exceed the engine’s maximum velocity 5.4 km/h.

Emissions and fuel consumption

When fuel consumption calculated, the data was based on the scenario that the engine worked under half of maximum load with intermediate 3060 revolution per minute (Edman, 2009) . And the emission data was from environmental approval of Brigg & Statton Corporations.

Table 11 Input and output of LC48VE’use during the whole life cycle per functional unit.

INPUT		**Unit**
Petrol	219.75	l
Engine oil	4.2	l
Blade	2	pieces
OUTPUT		
CO_2	173.08	kg
HC	3.07	kg
NO_X	0.77	kg

The basic maintenance for LC48VE includes the lubricant usage and blade replacement (Johan, 2010), and during the 250 hours life time, one LC48VE needs 4.2l engine oil as well as 2 pieces of extra blades. Figure 18 illustrates the use phase of LC48VE. P25 petrol production is about the unleaded petrol in Europe stock (ETH-ESU, 1996). P26 lubricant production is found in CPM database which was one study on rapeseed oil for use as hydraulic oil in forest machines in Sweden (Marby, 1999). P27 HDPE bottles production includes blow mounding process, production of PE resin, transport of the resin to the converter, the conversion process itself and packaging of the finished product for onward dispatch (Plastics Europe, 2005).

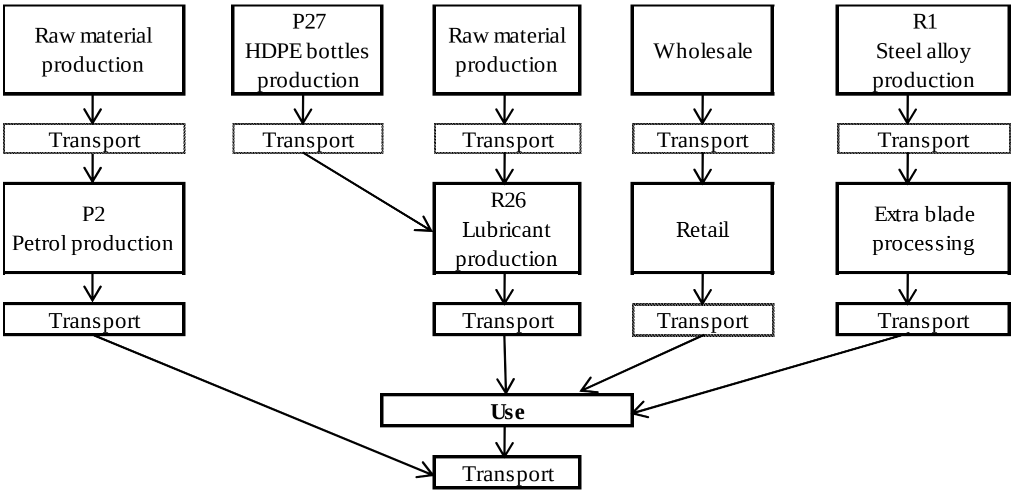

Figure 18 Flowchart of use phase.

3.1.6 End-of-life

There is no data availiable for how waste companies treat the old lawnmowers. So based on literature research and telephone interview with Lindman in Renova, the local waste treatment company. Figure 19 shows the flowchart for end-of-life phase and scenario is as following:

For plastics, all the plastics can be assumed to be inceneranated (Lindman, 2010). All the metal would went through scrappers being separated as well as the metal in batteries, and they can be recycled (Lindman, 2010). Since in one previous end-of-life study about vehicles the recycling rate is calculated as 97%, the same rate is used in this situation. In this case the metals considered as recyclable included Al, steel and lead in the mower. Recycling of lead-acid batteries is done by the blust-furnace process. Inventory data bout the incineration and recycling processes were taken as European average level.

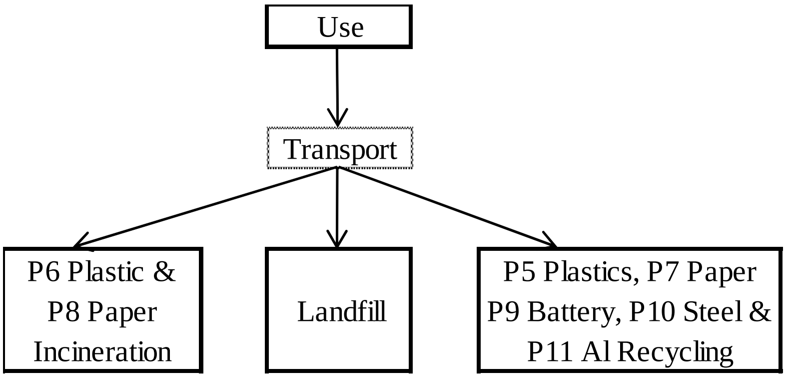

Figure 19 Flowchart of end-of-life phase.

3.2 Impact assessment

3.2.1 Characterisation

Table 12 shows the total result covering production, transport, use and maintenance and end of life phases. Potential contributions to environment in the chosen categories are shown in Figure 20. Generally the production and use phase together always have dominant impacts on the environment compared with the others. The negative value for photochemical ozone creation potential (POCP) mainly comes from the use phase. The reason for this is because of the NO_X emission from the lawnmowers, since NO has obvious positive performance in this impact. That means NO will decrease the potential of photochemical ozone creation. As can be seen, transport part also shows negative value in POCP column due to NO emissions from fuel consumption.

Table 12 Life cycle impacts of lawnmower LC48VE per functional unit.

Category	Unit	Weight
Depletion of abiotic resources	kg Sb_{eqv}	5.07
Acidification	kg $SO_{2\ eqv}$	2.49
Global warming	kg $CO_{2\ eqv}$	321
Eutrophication	kg $PO_4^{3-}{}_{eqv}$	0.884
POCP	kg ethylene $_{eqv}$	0.0291
Human toxicity	kg 1,4-DCB $_{eqv}$	1280
Ecotoxicity	kg 1,4-DCB $_{eqv}$	19.2
Ozone depletion potential	kg CFC-11 $_{eqv}$	0.000913

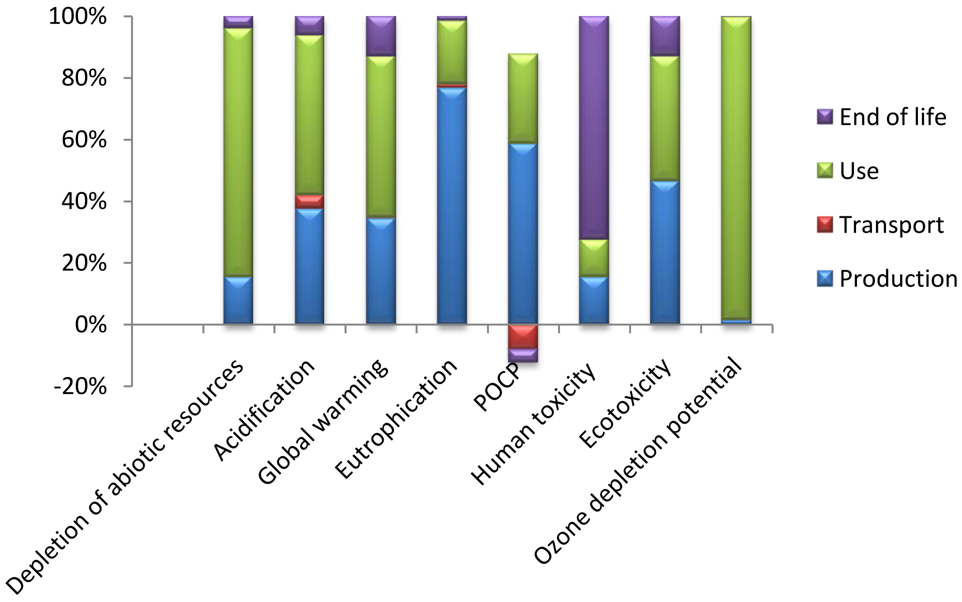

Figure 20 Characterisation results from the whole life cycle of Lawnmower LC48VE.

If traced back in the production phase, the main contributors of the environment impacts could be found as power module and chassis module.

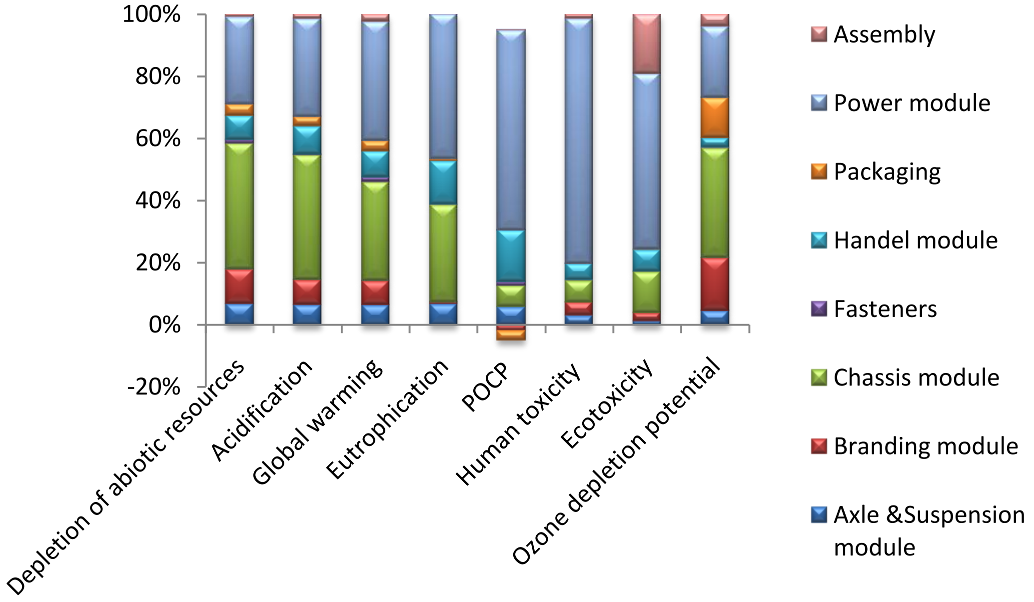

Figure 21 Characterisation results from the production phase of Lawnmower LC48VE.

3.2.2 Weighting

The results of two weighting methods are shown in Table 13, and one thing needs to be noted is that Eco-indicator 99 and EPS2000 are based on different principles and weighting factors. Thus the values of the results can not be compared in absolute number. But EPS2000 and Eco-indicator 99 both represented the same as the characterisation result illustrated: use and production take dominant impacts. Graphic illustrations can be seen in Figure 22.

Table 13 Results according to different weighting methods.

	Total	**Production**	**Transport**	**Use**	**End-of-life**	**Unit**
EPS 2000	297.7	139.9	1.5	145.3	11	ELU
Eco-indicator 99	37.6	7.5	0.3	28.2	1.6	

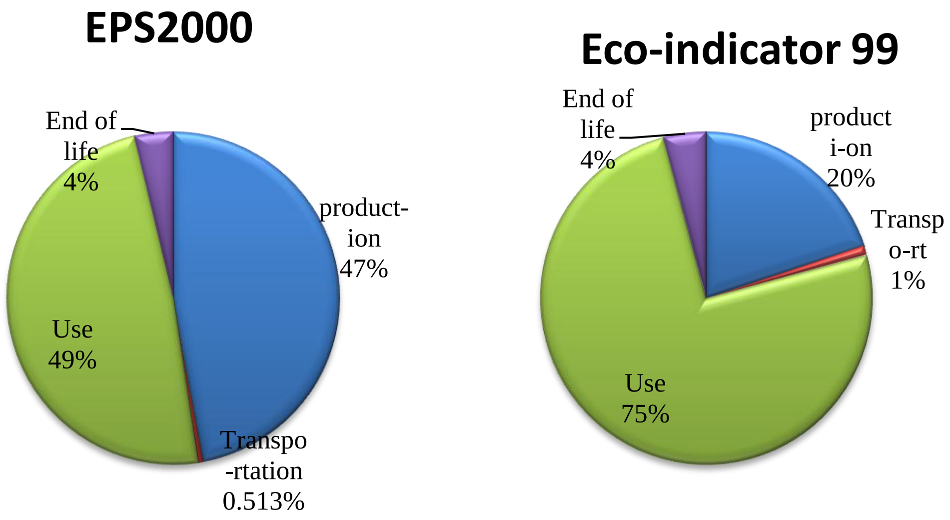

Figure 22 Weighting results of LC48VE's life cycle impacts according to EPS2000 and Eco-indictor 99.

The chassis and power module together take the overwhelming majority of total environmental impacts, while Figure 23 illustrates the contribution of each source in production phase and use phase. The power module in production phase contributes 43% of total impacts in this phase, followed by chassis module as almost 40%. And in use phase, due to continuous petrol consumption the crude oil needed majorly for petrol consumption took more than 60% of total and followed by CO_2 emissions, 15%. One thing needs to be mentioned is that noise can be taken into calculation in EPS2000 and the noise factor for each vehicle is 0.00253 (ELU/ kilometres). In this case, only the noise generated during use phase. For LC48VE in 10 years life time span, the velocity as calculated in use phase is 1.67km/h, so the environment impacts can be evaluated as:

$$\text{Noise} = \frac{1.67km}{h} \times 250h \times 2.53 \times 10^{-3}km = 1.056$$

And the impact of the noise as can be seen in Figure 23 is insignificant.

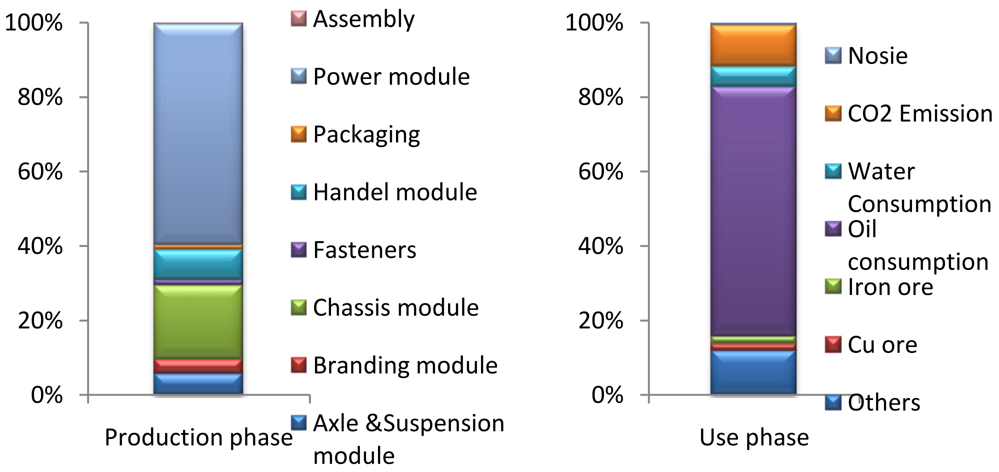

Figure 23 Weighting results of production phase and use phase according to EPS2000.

Digging into the impacts sources of power module and chassis module in production phase, copper consumption and iron ore consumption were the major contributors respectively. Due to the weighting factor differences (for copper ore is 208ELU/kg and for bauxite is 0.449 ELU/kg) the copper with smaller weight than Al have bigger impacts although. For the chassis production large amount of steel have been used, and that could explain why iron ore consumption contributed more than 40% of chassis module's total impact with iron consumption's weighting factor 1.23 ELU/kg. EPS2000 emphasized the depletion of resources and the other is that huge gaps between the weighting factors could explain had larger percentage of chassis module's impacts and also 5.45 kg Aluminum-ADC12 had much smaller influence than 0.114kg copper, and even 1.64kg iron.

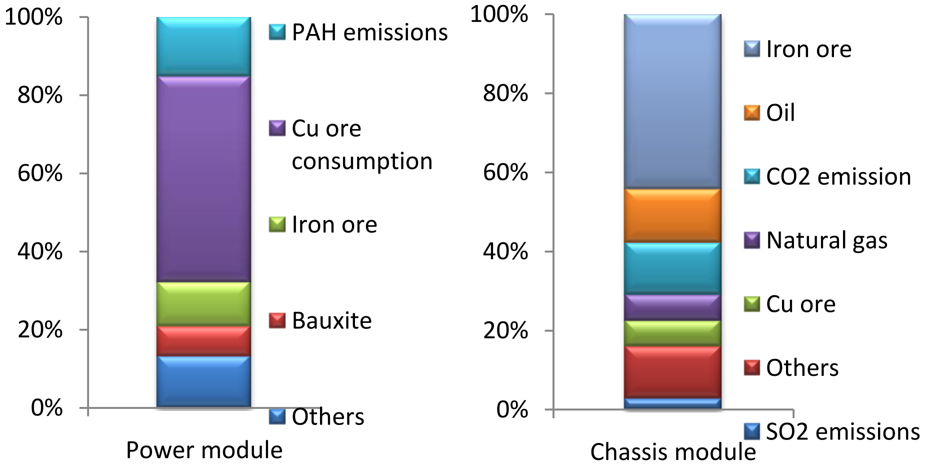

Figure 24 Impacts sources for power module and chassis module according to EPS2000.

Huge differences existed in the relation of different phases when different weighting methods were used. As EPS2000 and Eco-indicator 99 being used, similar trends the results showed as Figure 24 and Figure 25. That chassis and power module together are dominant in production phase as oil consumption in the same situation to use phase.

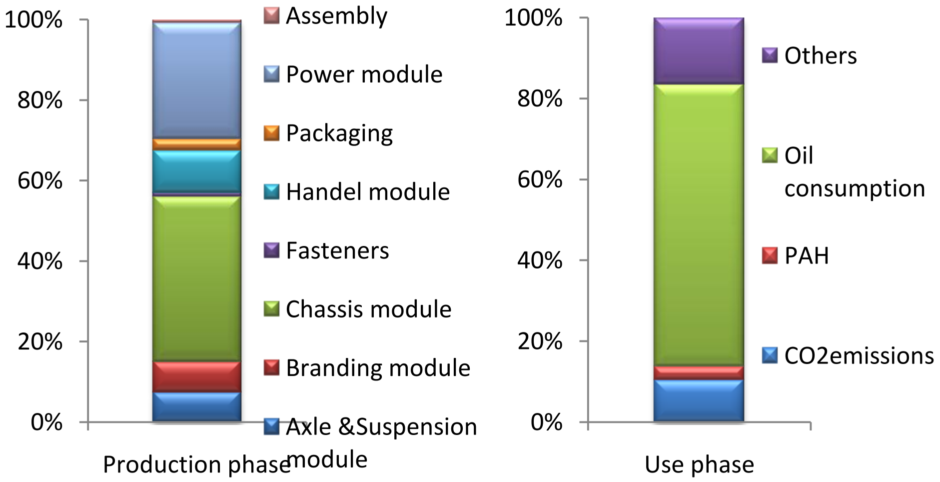

Figure 25 Weighting results of production phase and use phase according to Eco-indicator 99.

3.3 Sensitivity analysis

Sensitivity analysis can be used to identify the sensitivity of critical data. Because metals show to have a large impact of the result, and the recycling rate was uncertain, recycling has being considered in sensitivity analysis.

Figure 26 shows the characterisation results from variations of recycling rate, metals have been recycled in end-of-life phase are steel alloy, aluminum, crude iron and copper, the percentages indicate that how many percentage of the recycled metals go back to system, and 0 is the base case which shown in Figure 10. It is obviously that increasing the share of recycled metals makes better environmental performances of Lawnmower LC48VE. POCP and acidification categories are the most influenced factor by variation of recycling rate.

The weighting results from variations of recycling rate are presented in Figure 27 and Figure 28, ELU value decreased 35% if all the recycled metals go back to the system compared to the base case, however only 17% impact is decreased according to Eco-indicator 99.

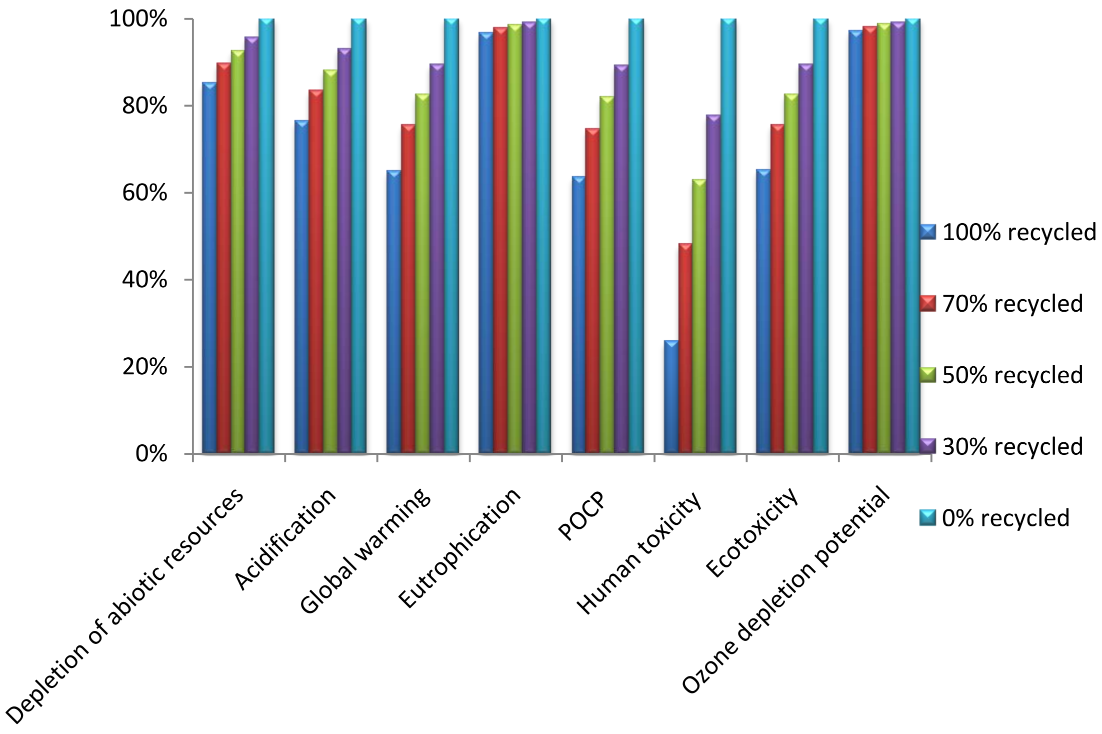

Figure 26 Characterisation results variations with different recycling rate.

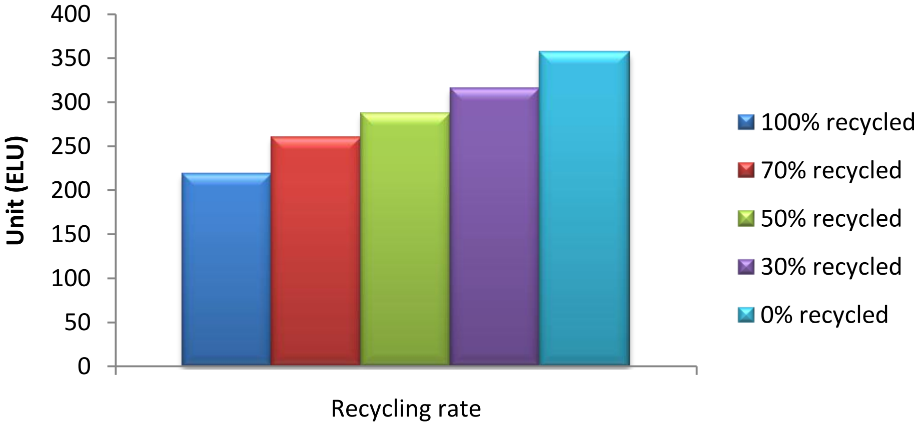

Figure 27 Weighting results variations with different recycling rate according to EPS2000.

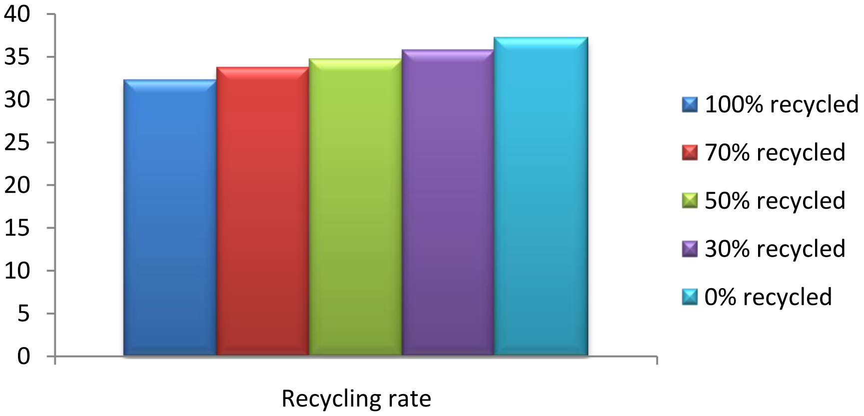

Figure 28 Weighting results variations with different recycling rate according to Eco-indicator 99.

3.4 Discussion

In use phase, impacts of Lawnmower LC48VE vary due to user habits and results are based on average using time in this study. Recycling of batteries is not included, if all the batteries are recycled, there would be a better environmental performance of Lawnmower LC48VE.

One limitation of this case study is that data cannot be found in most production processes. Material losses were only calculated in plastic parts injection, losses during transport and other processes were not considered.

3.5 Conclusion

- Production phase and use phase together contribute dominant impacts after characerisition impacts of each environment categories, especially major impacts in Human toxicity.

- Weighting methods as EPS2000 and Eco-indicator 99 being applied show difference in final result which is because different emphasis of each method, while in EPS2000, production contributed the major impact 47% and use phase for 49% of final and for Eco-indicator 99 use phase took 75% in total.

- In production phase, the major impacts contribution was from chassis module and power module due to the large metal demand in these two modules. In use phase, no matter which weighting method used, oil consumption contributes dominant impacts, both more than 60% of total.

- Increasing the share of recycled metals could make better environmental performances of Lawnmower LC48VE.

- The assembly in Höör only contributes a very small part of the environmental impact.

4. Case of Automower 220AC

4.1 Inventory analysis

The inventory analysis of Automower 220 AC consists of an analysis of following phases in the lifecycle:

- Production (including raw materials, components and assembly)
- Transport
- Use
- End-of-life

Data were collected and results are presented for each of these phases. These phases are described in the following subsection.

4.1.1 Flowchart

Figure 29 shows the simplified flowchart of Automower 220 AC.

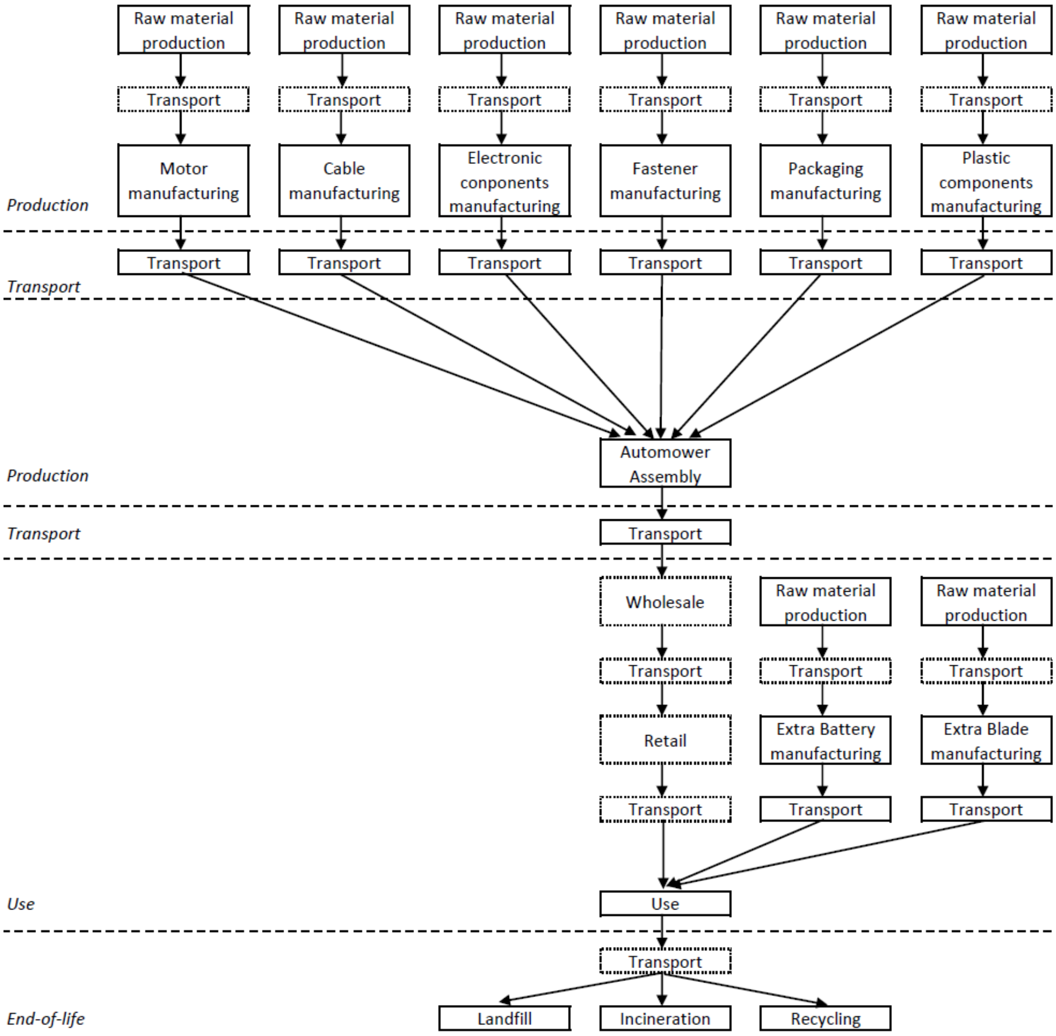

Figure 29 Simplified flowchart of Automower 220AC (dotted boxes was not considered in this study since lack of data).

An initial flowchart has been constructed, depicting all the different data needed to succeed in making of this LCA. The activities with dotted line are not considered in this study since lack of data, and not considered having a major impact on the result based on the scope of the study.

The production phase includes the processes that happened before all the components and materials arriving at Newton Aycliffe, UK, as well as the plastic components manufacturing processes in Newton Aycliffe. Raw material extraction, transport and other processing procedures were included. The production process would be divided into several modules and each module includes several components. Transport phase covers the processes in both components purchase and products wholesale, but excluded transports happened in retail processes. Besides, the transport happened in raw material extraction, purchased by suppliers can be only approached in data base, were defined as background transport and were accounted to each module's environmental impacts in this case. Use and maintenance statics data were from Husqvarna, while end-of-life data were based on assumptions and telephone interview from Renova AB, which is a Swedish waste treatment company.

4.1.2 General data

Raw material

For Automower 220AC, Husqvarna purchased many components while only manufactured main plastic parts and assembled them in Newton Aycliffe, UK. The data collection processes mainly focused on the direct supplied components' raw material origins, processing impacts and transport form suppliers to Husqvarna and from Husqvarna to different central warehouse. In this case, average data of raw material production were adopted.

Acrylonitrile-Butadiene-Styrene (ABS) mainly used as covers of Automower and inventory data of ABS granulate production (R17) is from SimaPro database. Data based on average data from all suppliers in Western Europe for 1995-1999, and transport data are not included. The inventory data for acrylonitrile-styrene-arcylate (ASA) production (R16) is assumed to be the same as R17 since lack of data for ASA.

Data of Polyamide 66 (PA 66) production R18 were obtained from SimaPro database, PA66 GF30. PA 66 is the product of polyamide 30% glass fibre production. Inventory data of PA66 production are based on average Western Europe data for 1995 to 1999, transport data are not included and no applicable allocations.

Raw materials R19 to R24 are:
R19-propylene (PP),
R20-polymethyl methacrylate (PMMA),
R21-poly-formaldehyde (POM),
R22-ethylene-propylene-diene monomer (EPDM),
R23-Polyamide 6 (PA6),
and R24-polythene (PE).

Data of R19–R24 were obtained from SimaPro database, and inventory data of R19 to R24 production are based on average Western Europe data for 1995 to 1999, transport data are not included.

Inventory data of R27 steel production is from SimaPro database, “steel ETH”. Data based on average Western Europe data for 1990-1994, transport from mine to factory is not included. Aluminum production (R28) data from SimaPro database, Aluminum ingot were used. Data based on average data from all suppliers in Western Europe for 1990-1994, transport data are not included.

LCI data for R29 copper production is based on world average data for 1993, (Simonson, Andersson, & Rosell, 2001). It is assumed as a mix product of 80% virgin and 20% recycled copper. Data include transport from mine to factory gate.

Electricity production

Electricity production in different countries and regions are based on different energy sources. In this study electricity consumption was considered in Sweden and United Kingdom. Energy sources of English electricity production mainly consist of hard coal (35.5%), nuclear (28.08%) and fuel gas (36.42%), and Swedish sources are considered as nuclear (46.5%), oil (2.06%) and hydro electricity (51.44%)(Baumann & Tillman, 2004).

4.1.3 Production

The Automower consists of motor module, cable module, electronic module, fastener module, packaging module and plastic components module. Data were collected and results are presented for each module in this section.

Plastic components module

The plastic components of Automower are mainly produced by Husqvarna, rest parts are purchased from different suppliers. Total weight of plastic components per functional unit is 8.45 kg and contains several materials (Automower BOM, 2009). Detailed flow chart of plastic components is shown in Figure 30.

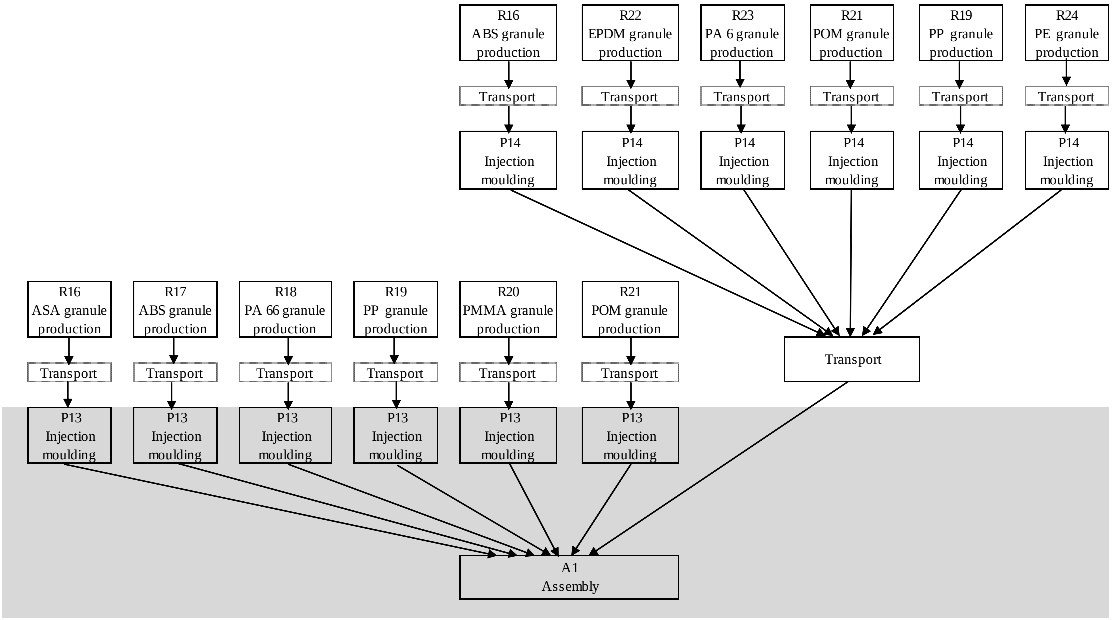

Figure 30 Flowchart of plastic components module. Processes occurring in Husqvarna factory are marked with grey shade.

Resources use and environmental impacts of raw material production R16-R24 were calculated by using general raw material inventory data (Section 4.1.2 Raw material). After aggregated same material, the material composition and their weights are given in Table 14.

Table 14 Material and weight for plastic components (Automower BOM, 2009) .

Material	**Weight (kg/f.u.)**
ABS	2.682
ASA	3.252
EPDM	0.137
PA 6	0.029
PA66	0.417
PE	0.002
PMMA	0.155
POM	0.08
PP	1.696

Raw materials of components which are made by Husqvarna UK are produced and transported to Husqvarna, then moulded by injection machines. P13 is injection moulding in Husqvarna and electricity use for P13 is 6.924 kWh per functional unit (Coates, 2010). Geographical region of Electricity production was defined as UK and emissions and resources use during electricity production were calculated by using average British electricity production (International Energy Agency, 2000).

Production data for PP components which are not made by Husqvarna was obtained from SimaPro database, PP injection. All the production data for P14 were assumed to be the same as for PP injection.

Raw materials losses caused by warming up and cleaning machine were assumed as 3% (Foster, 2010). Transports (with dot line) and weight losses during plastic granule production were not concerned since lack of data. Assembly A1 and transport with solid line will be discussed in section 4.1.3 and section 4.1.4 respectively.

Electronic module

Electronic components include batteries, printed circuit boards (PCBs) and other small electronic parts. Battery is used for provide energy for Automower. Automower used a pack of 15 cells which also includes tags, solder and other packaging material, the total weight for one cell is 49.68 g (GP Battery, 2009), the battery is delivered to Husqvarna UK from GP Battery Company, Hong Kong, raw materials and their weights in R25 are shown in Table 15, the data for producing raw materials in R25 were obtained from a previous LCA study about batteries of electric vehicles (Jose, Maria; Garcia, Acevedo, 1996). Energy consumption during battery production P15 is 0.2kWh/PCS (Leon, 2009); emissions and resources use during electricity production were calculated by using average British electricity production (International Energy Agency, 2000), emission data for P15 were not available from suppliers and thus not included in this study.

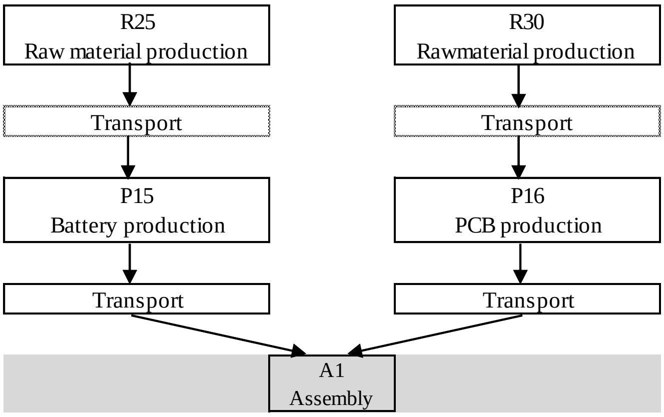

Figure 31 Flowchart of electronic module.

Table 15 Material content in one cell of NiMH battery (GP Battery, 2009).

Material content in NiMH battery	
Nickel	34.22%
Iron	26.55%
Nickel hydroxide	22.06%
Water	7.75%
Polypropylene	4.53%
potassium hydroxide	3.10%
Other Compound	1.79%

PCB is a very complicated electronic unit, and inventory data for PCB were assumed to be the same as for Printed board (SimaPro database), both raw material production R25 and PCB processing P16 are included in this data set, data based on modern technology during 1995-1999 in Western Europe. Total weight of PCB per functional unit is 0.636kg.

Fastener module

Figure 32 shows three main parts of fastener module, screws, blades and Al plate. Environmental impacts from raw material production R27 and R28 were calculated by using general material production inventory (Section 4.1.2 Raw material).

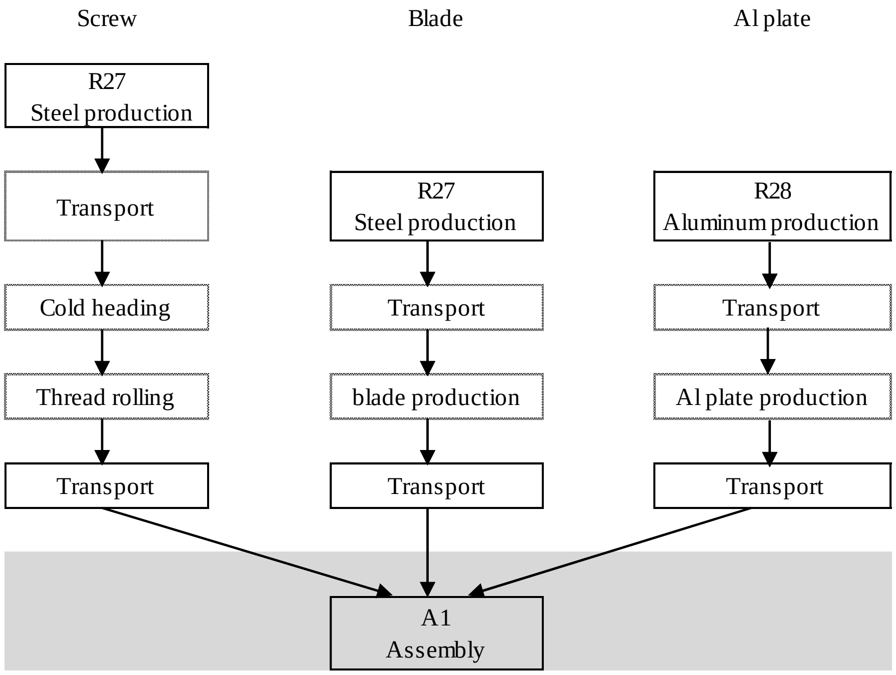

Figure 32 Flowchart of fastener module.

Activities with dot line were not counted in the inventory of fasteners module due to lack of data, but is not assumed to be major impact on the result since fastens only take a small weight percent of the whole product. Transport and assembly process Al are discussed in subsection "Assembly".

Motor module

An Automower includes 3 motor parts, which were made by different suppliers and delivered to Husqvarna. Figure 33 shows the flowchart of Motor module, resources use and emissions from raw material production R16, R26, R27, R28 and R29 were calculated by using general material production inventory (Section 4.1.2 Raw material). Due to lack of processing data, inventory of Motor module were calculated by material composition only. Material composition of these components is shown in Table 16.

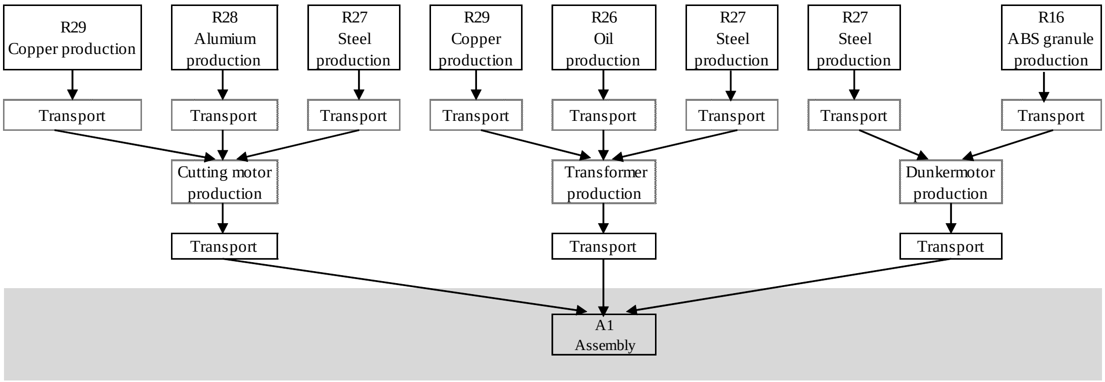

Figure 33 Flowchart of Motor module.

Table 16 Material composition of Motor module (Foster, 2010).

Parts name	**Material composition**	**Weight (kg/f.u.)**
Motor Cutting System	10.5%Cu+17.9%Al + 71.6% steel	0.400
Euro Transformer	32%Cu + 22% Oil + 46% steel	1.470
Dunkermotor Drive Assy	80% steel +20% ABS	2.000

Packaging

Carton is produced from 100% new fibers (Saica Packaging, 2009). Inventory data of carton is from SimaPro database, new carton, based on average technology during 1990-1994 in Western Europe, system boundaries were defined as from forest to carton. The weights of packaging materials are given in Table 17.

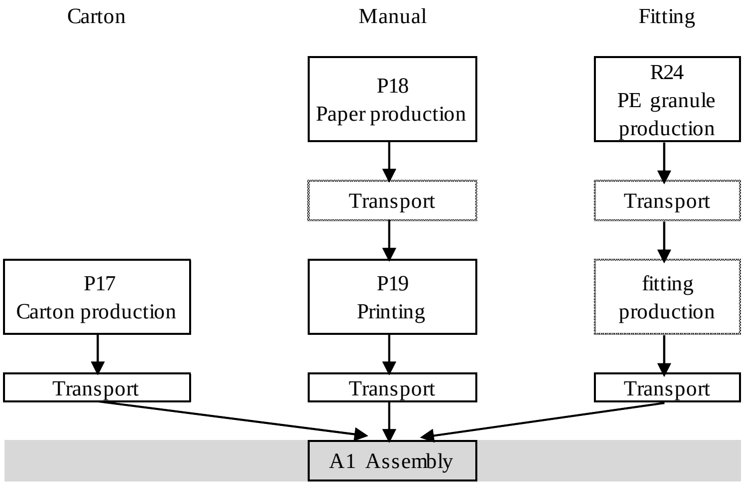

Figure 34 Flowchart of Packaging module.

Fitting is made from PE, and the PE production R9 has been defined in section 4.1.2. However processing data of fitting are not available since lack of data.

Table 17 Weights of packaging materials per functional unit (Gilmore, 2009).

Material	Weight(kg)
Carton	1.542
Paper	0.234
PE(fitting)	2.018

Paper of manual was defined as uncoated paper, production of this paper (94% dry matter) mainly from mechanical wood pulp with some bleached sulphate cellulose and latex coating in a factory in Switzerland for 1994, paper are delivered to printing plant to get print and then transported to Husqvarna UK, the inventory data of P18 paper production and P19 printing process were obtained from SimaPro database (Pre Consultants BV, 2008).

Cable Module

Cable Modules consists of cables, wires and looms. They are assumed have the same material composition and production process. Figure 35 shows the life cycle of cable module.

Total weight of cable is 3.467kg per functional unit, and 67.5% copper and 23.5% PE was defined as cable constitutes (Margaret, 2001). LCI data for R29 (Copper production) and R24 (PE granule production) have been state in section 4.1.3. Processes with dot line were not count into the cable inventory data since they are not available, transport with solid line is discussed in section 4.1.4. Data for P24 was obtained from CPM database, "Copper extrusion and drawing to profiles", which was based on average German industry data of 1995.

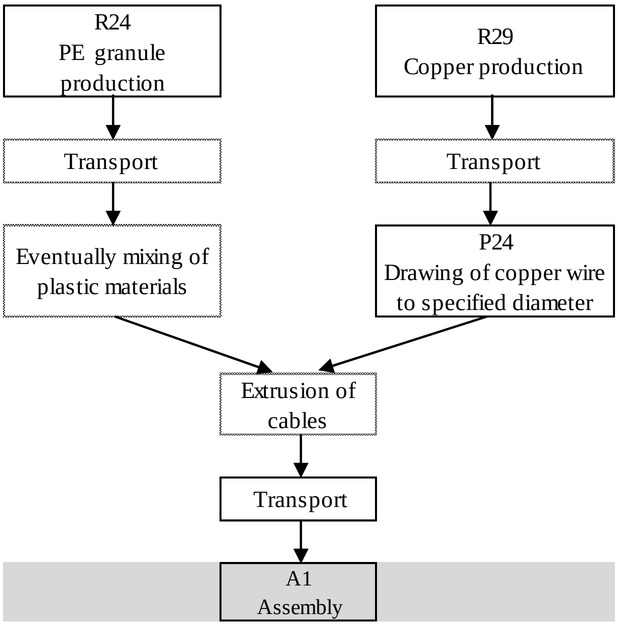

Figure 35 Flowchart of Cable module.

Assembly

Automower is assembled (A1) in Husqvarna UK, all the parts are transported along the assembly line, and then assembled manually. One electricity meter record total electricity for 14 assembly lines in the assembly factory. Electricity consumption for one Automower is

2.61kWh, which energy consumption was allocated by pieces. Geographical region of electricity production was defined as in UK, while emissions and resources use during electricity production were calculated by using average British electricity production data (International Energy Agency, 2000).

4.1.4 Transport

Only transports from first tier parts suppliers to Husqvarna Aycliffe factory and transports from Aycliffe to wholesales were calculated in this part. All the goods are transported by truck with semi-trailer, long distance transport, Euro 3 standard, and based on the assumption that 70% load capacity is used (NTM, 2002). Products for Mexico and Canada are transported by medium sized ship (NTM, 2002). The aggregation data of means of transport and their loads are given in Table 18.

Table 18 Means of transport and load.

Direction	**Truck**	**Ship**	**Unit (/f.u.)**
Suppliers to Husqvarna	23.0455		Tonne*km
Husqvarna to Wholesales	35.4347	140.3968	Tonne*km

4.1.5 Use

Three packs of batteries (one pack per 2.5 years) and 81 blades (9 blades per year) are needed to be replaced during a life time of 10 years (Gustvasson, 2009) has been assumed. It is assumed that to mow 1000m^2 lawns, Automower is used as 12 hours (6 charges) per day, 3days per week, namely 396 charges per year (Gustvasson, 2009). Energy efficiency for charging was calculated as 52% (Jose, Garcia, & Schluter, 1996), electricity use for charging is 1069.2 kWh per functional unit. Geographical region of electricity production was defined as in Sweden while emissions and resources use during electricity production were calculated by using average Swedish electricity production data (International Energy Agency, 2000).

4.1.6 End-of-life

When mowers are out of use, they are sent to recycle company nearby, metals and papers are recycled and plastic parts are incinerated, others were assumed to go to land fill(Renova AB, 2010).

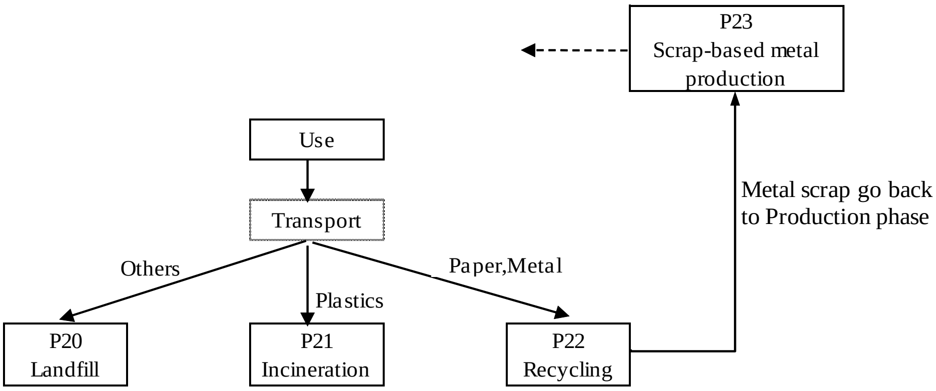

Figure 36 Flowchart of end-of-life.

Inventory data of recycling metals are based on previous LCA study of vehicles and only 97% (Boss, 2005) weight of metals could be obtained after recycled since there would be some losses when recycling. Environmental impacts were allocated by weight. Products of recycling metals are 5.4kg steel, 2.77kg copper and 0.16kg Aluminum. Data of incineration P21 was obtained from SimaPro database, plastics to municipal waste incinerator. Plastics were defined as long life plastic. Inventory data of P21 include the environmental impacts of transport to the Municipal Waste Incinerator (on average 10 km), treatment of flue gas, and further waste treatment of slags and ashes. Data were based on average Europe situation of 1995. Emissions of landfill P20 were not traced. For recycling, data was calculated by using the data of a previous LCA report (Boss, 2005), which included the inventory data for metal recycling. P23 is the scrap based metal production; data for this activity was obtained from CPM database (CPM, 2010).

4.2 Impact assessment

In this section the impact assessment of Automower 220AC is presented, the calculation based on a comprehensive coverage of production, transport, use phase and end-of-life, as well as electricity generation. The recycled metals were considered as not go back to the system, but the emissions and inputs needed in recycling were take account into the impact assessment. Impacts of production phase was further analyzed and discussed in order to get a deep understanding and facilitate product development of Automower.

4.2.1 Characterisation

Table 19 list the total life cycle impacts according to defined characterisation of Automower. Generally, production and use phase always have larger environmental impacts compare to the others. As shown in Figure 37, in the categories global warming, acidification, eutrophication, ecotoxicity, POCP (photochemical ozone creation potential) and ozone depletion, production phase account for more than 60% of the total impact. Use phase takes 80% of total impact in resource depletion category due to crude oil consumption in electricity production, which is used for battery charging.

Table 19 Life cycle impacts of Automower per functional unit.

Category	Unit	Weight
Global warming	kg $CO_{2\ eqv}$/f.u.	273
Acidification	kg $SO_{2\ eqv}$/f.u.	9.54
Eutrophication	kg $PO_4^{3-}{}_{eqv}$/f.u.	0.137
Resource depletion	kg reservebase$^{-1/}$f.u.	0.450
Human toxicity	kg 1,4-DCB $_{eqv}$/f.u.	52.1
Ecotoxicity	kg 1,4-DCB $_{eqv}$/f.u.	6.65
POPC	kg ethylene $_{eqv}$/f.u.	0.367
Ozone depletion	kg CFC-11 $_{eqv}$/f.u.	5.83E-06

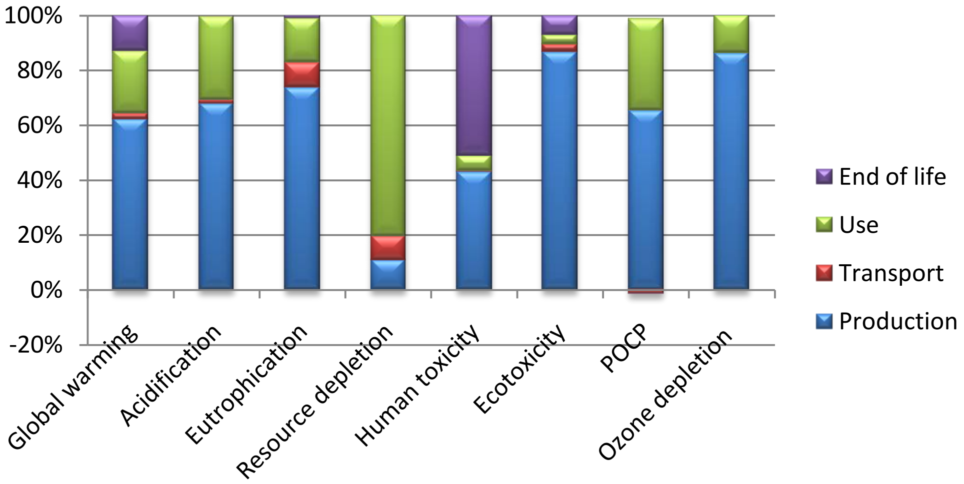

Figure 37 Contribution to the characterisation results from the entire life cycle of Automower.

The results of further analyzed from production perspective are shown in Figure 38. Electronic module contributes approximately half to all impact categories except resource depletion and ozone depletion. This is mainly caused by toxic and chemical substances which have large consumption in PCB and battery production. Plastic components module shares approximately 40% impacts in resource depletion and ozone depletion category. That’s due to the crude oil consumption in plastic production. Cable module gives 40% acidification and POCP impacts; the reason for this is because of the sulfur dioxide emissions in copper ore extraction. Packaging, fastener and motor module take relative lower impacts in production phase.

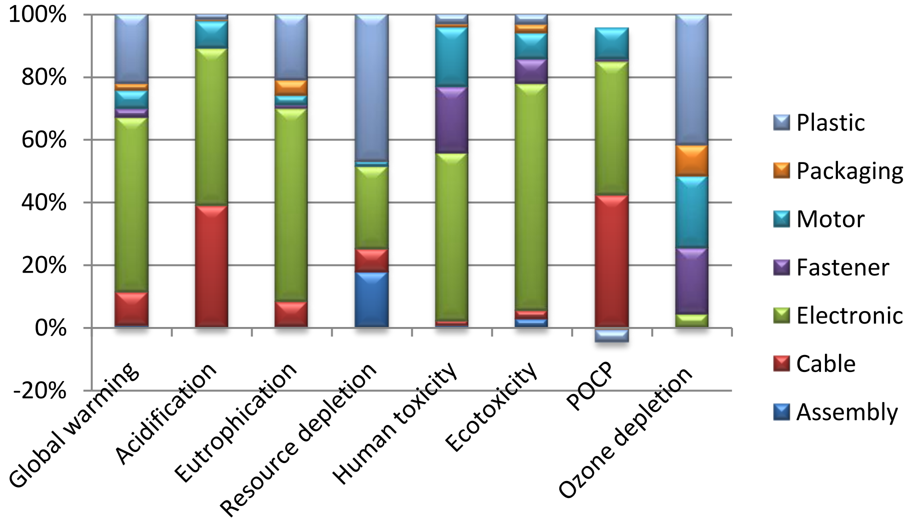

Figure 38 Contribution to the characterisation results from the production phase of Automower.

From a life cycle perspective, most influencing substances and phases for each category are summarized in Table 20.

Table 20 Most influencing substances and phases for each category.

Category	Substances	Phases
Global warming	CO_2	Electronic module production (PCB production)
Acidification	SO_2	Cable module production Electronic module production Use
Eutrophication	NO_x	Electronic module production
Resource depletion	Crude oil	Use
Human toxicity	Cadmium	End of life
Ecotoxicity	Nickel	Electronic module production
POCP	SO_2	Cable module production Electronic module production Use
Ozone depletion	Halon 1301	All the production

4.2.2 Weighting

Table 21 shows the results of two different weighting methods, these two methods were described in section 3.1.1. Both of the two methods were dominated by the production phase which is further analyzed in Figure 39. Transport, use and end of life phases take slight impact in the life cycle of Automower.

Table 21 Results according to different weighting methods.

	Total	**Production**	**Transport**	**Use**	**End-of-life**	**Unit**
EPS 2000	624.55	594.41	1.10	23.99	5.04	ELU
Eco-indicator99	14.25	9.60	0.19	3.26	1.19	

Results of different module productions according to EPS and Eco-indicator vary considerably. For example, cable module occupied 68% impact of production phase according to EPS weighting, but only 19% in Eco-indicator weighting, the reason for this is EPS weights copper ore consumption much higher than Eco-indicator weights, and cable production shares more than 80% in the total copper consumption. Use of resource is considered as an important factor in EPS weighting method. Electronic module contributes 7% impact of production phase by using EPS weighting, however it is the dominate contributor according to Eco-indicator weighting. This is due to coal consumption and CO_2 emissions from electronic components production.

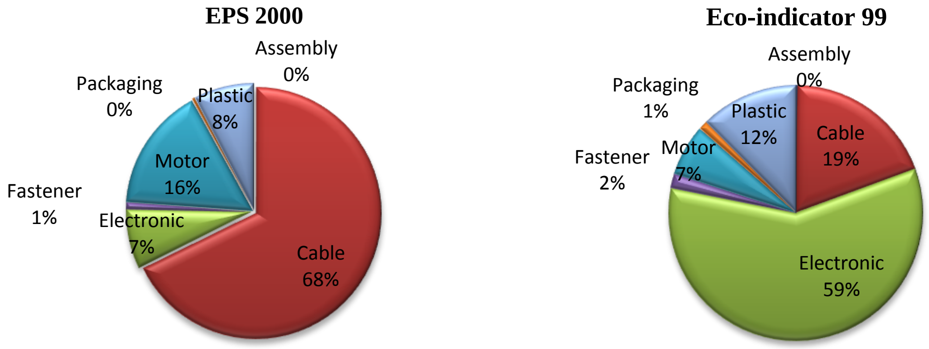

Figure 39 Weighting of production phase according to EPS 2000 and Eco-indicator 99.

4.3 Sensitivity analysis

Some parameters will be varied in different conditions. One thing that might have a large impact is where the automower is used. Figure 40 shows the characterisation results for Automower which is used in UK. Compared to Figure 37, if the use place is changed to UK, the proportion of impact in use phase has a large increase in global warming, acidification, resource depletion as well as eutrophication categories, and become dominated in the whole life cycle.

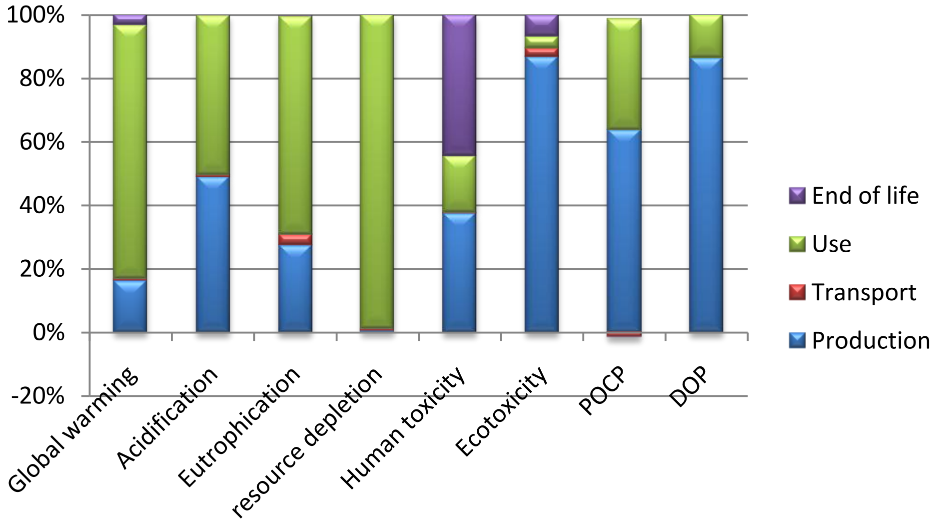

Figure 40 Contribution to the characterisation results for Automower using in UK.

Results of different use places according to EPS and Eco-indicator weighting method are shown in Figure 41 and Figure 42 respectively. ELU value of Automower used in Sweden is 624 and 153ELU will be added if it is using in UK. Eco-indicator results change from 14.25 to 34.75 when Automower uses in UK instead of uses in Sweden. In general, to use an Automower in UK has larger environmental impacts than use in Sweden. The main reason for this is electricity production in UK and in Sweden based on different energy sources. Energy sources in UK are mainly based on hard coal, natural gas and nuclear, while Swedish electricity production are based on nuclear energy and hydro energy.

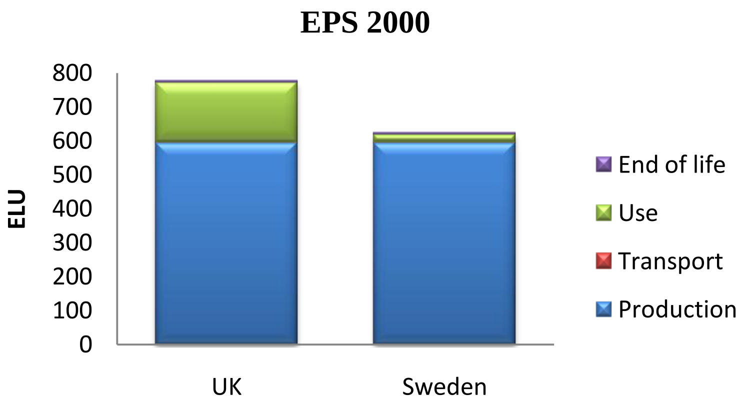

Figure 41 Comparison of weighting results according to EPS 2000, use phase in UK and Sweden.

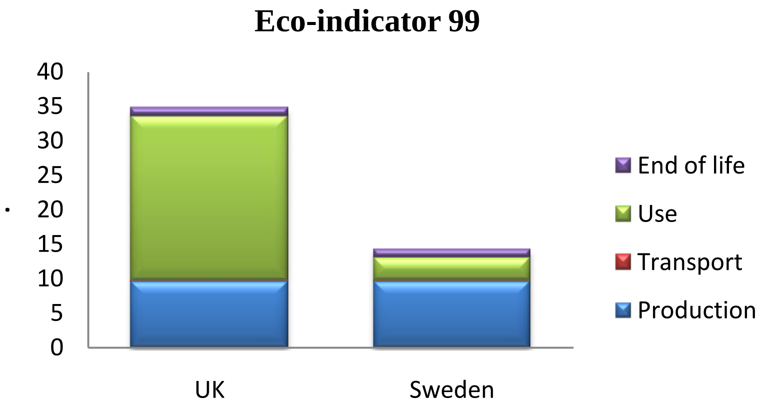

Figure 42 Comparison of weighting results according to Eco-indicator 99, use phase in UK and Sweden.

Figure 43 shows the characterisation results from variations of recycling rate, metals have been recycled in end-of-life phase are steel, aluminum and copper, the percentages indicate how many percentage of the recycled metals go back to system, and 0 is the base case which shown in Figure 37. It is obvious that increasing the share of recycled metals makes better environmental performances of Automower. POCP and acidification categories are the most influenced factor by variation of recycling rate.

The weighting results from variations of recycling rate are presented in Figure 44 and Figure 45. ELU value decreased 78% if all the recycled metals go back to the system compare to the base case, however only 17% impact decreases according to Eco-indicator 99.

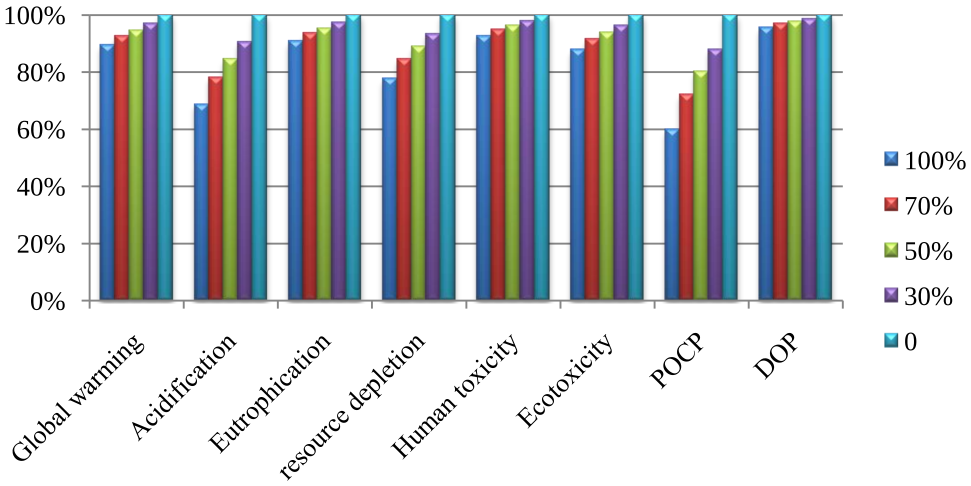

Figure 43 Characterisation results from variations of recycling rate.

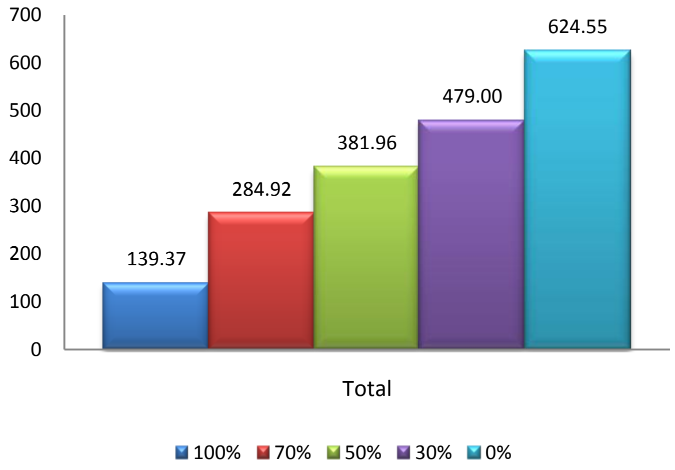

Figure 44 Weighting results variations with different recycling rate according to EPS2000.

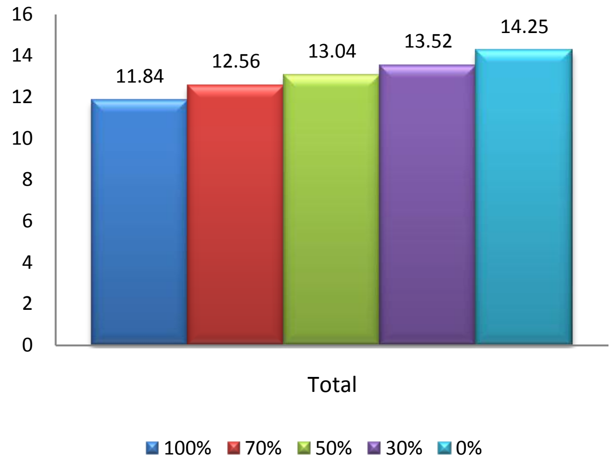

Figure 45 Weighting results variations with different recycling rate according to Eco-indicator 99.

4.4 Discussion

Specific uncertainties of this Automower case study are discussed in this section. Uncertainties and limitations for the whole study are discussed in Section 5.

In reality, environmental impacts in use phase of Automower are various due to different user habits and the size of mowing area. Charging frequency and total electric power consumption lead to variation of environmental performance. In this study, calculations are based on average using time.

Another important parameter could be the energy sources for electricity production. The use of fossil fuel based electricity is obvious has heavier environmental load than the electricity which produced based on clean energy sources. That is to say, using Automower in other countries could give different environmental impacts.

Recycling of batteries was not included, if all the batteries are recycled and the materials are reused, there could be a better environmental performance of Automower.

One limitation of this case study is that data cannot be found for most production processes. Material losses were only calculated in plastic parts injection. Spoilage, losses during transport and other production losses were not considered.

4.5 Conclusion

- Production phase including raw material extraction contributes 60% impacts of each environment category, exclude resource depletion and human toxicity.
- Cable (Cu) production occupied more than half EPS indices.
- Electronic module production dominant environmental impacts according to Eco-indicator 99.
- Using Automower in Sweden has better environmental performance than using in UK due to different sources of electricity production.
- Assembly in Husqvarna’s factory only takes a minor part of total impacts.
- Increasing the share of recycled metals could make considerably better environmental performances of Automower.

5. Discussion

Uncertainties and limitations, as well as their effects are discussed in this section.

In this study, the functional unit was defined as mowing Swedish lawn for 10 years as the same as lifetime assumed. However, in reality the lifetime of lawnmowers (both traditional mowers and automowers) varies very much which will affect the final result. For instance, if the real lifetime is longer than 10 years, which is very probably in automower case, the environmental impacts for producing per piece of mower will differ from per functional unit. And extended lifetime will decrease environmental impacts in production phase compared to former one which could lead to a better environmental performance of the products.

Users always mow lawns on their own ways; variations between users' habits leading to different amount of energy consumptions, namely the frequency of petrol filling or battery charging are undertrained. Besides, aesthetic matters and fertilization use for the lawn maintenance have not been taken into account.

Treatment of old mowers depends on waste management companies and their locations, in Sweden, all the metals and papers of an old mower are recycled while all the plastic parts are incinerated, and these could be changed in diffident locations. The recycling rate depending on techniques and scales of the recycling companies, generally, larger companies could have new techniques which leading to a relevant higher recycling rate. Recycling rate also depends on the recyclability of materials and how the product is designed (the recyclability). As analyzed in section4.3, different recycling rate could vary the results rather much.

The noise of lawnmower was analyzed by using a method for auto cars; the suitability of this could be discussed. For the working environment, the Automower obviously has lower noise than other lawnmowers; however, the noise of Automower was not account into the impacts, comparison in this category is not feasible.

Raw material production data from database is called general data; these data usually based the average technology in relative large area (e.g. Western Europe). The use of these data is hard to apply in material selection and green purchasing, if the company wants to focus on these aspects, more site-specific data are needed.

Most processing data for components missing is one of the significant limitations in this study, for example, the processing data for engine production was missing, as well as the chemicals used for battery production. Material losses and spoilage during processing and transport were normally not accounted for.

Apart from some data missing, the timeliness of these data is still partly sensitive as some "green" technologies have been improved and others were already mature then. Some of the uncertainty based on technology can be referred in different industrial annual report. Although this would be time consuming and the usual way is to compromise the system boundary.

Allocations existed in resource consumptions, emissions and energy consumptions were allocated by weight in this study, and therefore components made from the same material with heavier weight took relative larger impacts than the lighter ones. Sometimes, the environment impacts can be also allocated by pieces, normally in energy consumptions.

Transport data mentioned in this study only include first tier suppliers, namely the transport from first tier suppliers to factories and the transport from factories to wholesales. Transport data in production phase are considered as background data, most of which are included in production inventory data. However, compared to production and use, transport phase, this is only a minor part. Due to the limitations of weighting methods, not all the inventory parameters were taken account into impact category.

6. LCA application

6.1 Methodology application

ISO (the International Organization for Standardization) has contributed the 9000 series of standards for integration of products quality(Guinée, 2002). And recently the 14000 series has been more and more focused, and in which, 14001 on Environmental Management has been already implemented in Huqvarna. Furthermore, the 14040 series are related with LCA. Compared to 14001 with attention at organizational level, the ISO LCA standards also cover the technical aspects of an LCA projects(Guinée, 2002).

ISO 14040 (2006): About the principles and framework for life cycle assessment (LCA), technique detail is not included in this standard, nor does it specify methodologies for the individual phases of the LCA (ISO, 2006).

- ISO 14041 (1998): A standard on goal and scope definition and inventory analysis (Guinée, 2002).

- ISO14042 (2000): A standard on life cycle impact assessment (Guinée, 2002).

- ISO14043 (2000): A standard on life cycle interpretation (Guinée, 2002).

- ISO14044 (2006): About requirements and guidelines for life cycle assessment (ISO, 2006).

- ISO/CD 14045 (under development) : About Principles, requirements and guidelines of Eco-efficiency assessment of product systems (ISO, 2010).

- ISO/TR 14047 (2003): Technical report “provides examples to illustrate current practice in carrying out a life cycle impact assessment in accordance with ISO 14042.” They highlight the key issues when implementing the life cycle impact assessment (ISO, 2003).

- ISO/TS 14048 (2002): Technical specification provides “the requirements and a structure for a data documentation format” in consideration of transparency, precision and flexibility of inventory data, “thus permitting consistent documentation of data, reporting of data collection, data calculation and data quality, by specifying and structuring relevant information” (ISO, 2002). This can be applied to design “questionnaire forms and information systems” (ISO, 2002)..

- ISO/TR 14049 (2000): Technical report provides “examples of application of ISO 14041 to goal and scope definition and inventory analysis” (ISO, 2000).

Besides, another application of LCA is to communicate, covering the business to business (B2B) and business to consumer (B2C), which also can be called as “green procurement” and “green marketing”. “To ensure comparability” Type III environmental declaration programmes and Type III environmental declarations have been applied with more highly standardised LCA methodology (Baumann & Tillman, 2004).

- ISO 14025 (2006): About principles and specific procedures for developing Type III environmental declarations (ISO, 2006).

6.2 Data collection strategy

It's a long lasting discussion about how to improve the effectiveness of data collection, and there needs compromise in system boundary and accuracy of data. Following experiences and suggestion were based on the Husqvanar's cases studies.

Raw materials

Raw materials data are difficult to obtain from suppliers, therefore different types of databases are recommended for company internal study including industrial life cycle inventory (LCI) reports from specialized associations (Plastic - Plastic Europe, Steel - World Steel and Aluminum - European Aluminum Association) and research institute or software – SimaPro, Gabi and Ecoinvent).

Processing

In this case, processing mainly means the activities which transform raw materials to components. On-site investigation is direct but may not be as useful as expected since the level of details requirements. The suppliers' sustainability reports could be helpful as suppliers' average data for electricity consumption, main resources depletion and focused emissions as CO_2, NO_X and SO_2. Questionnaire way is operable but low efficient.

Transport

Energy consumptions and emission factors were from the network for transport and environment (NTM, 2009) and distances was obtained based on electronic maps.

Use

In this case testing data about the engine working were from supplier while the petrol and lubricant consumption were from internal study. Although feedbacks from consumers are ideal, for instance, use pattern covering the frequency of use.

End-of-life

General data for waste treatment could be found from local waste management companies but for lawnmowers there still lack of specific data. Information on what is actually happening with old lawnmowers would be better choice compared to average data.

Data management

More specific material data of assembly parts are needed and internal data management needs improvement, e.g. periodic update and review of an internal database. Inquiring material and processing information from suppliers when purchasing is a more efficient way to obtain data systematically.

6.3 Recommendation

Figure 46 shows the level of detail when applying life cycle perspective in companies. The general Life Cycle Thinking is the idea of always considering the impacts from the product's whole life cycle. The most detailed perspective is performing an LCA study where the detailed data is generated into an estimation of the environmental impact. The life cycle perspectives when analyzing, evaluating and improving an organization or a specific product, prevents problem shifting that can occur when focusing on a division or level in an organization or one phase of the products life cycle. The most common way of using life cycle perspectives is through life cycle thinking, LCT. Considerations are made on a very general and qualitative level (Frankle & Rubik, 2000). However more specific approaches to incorporate life cycle perspectives are available.

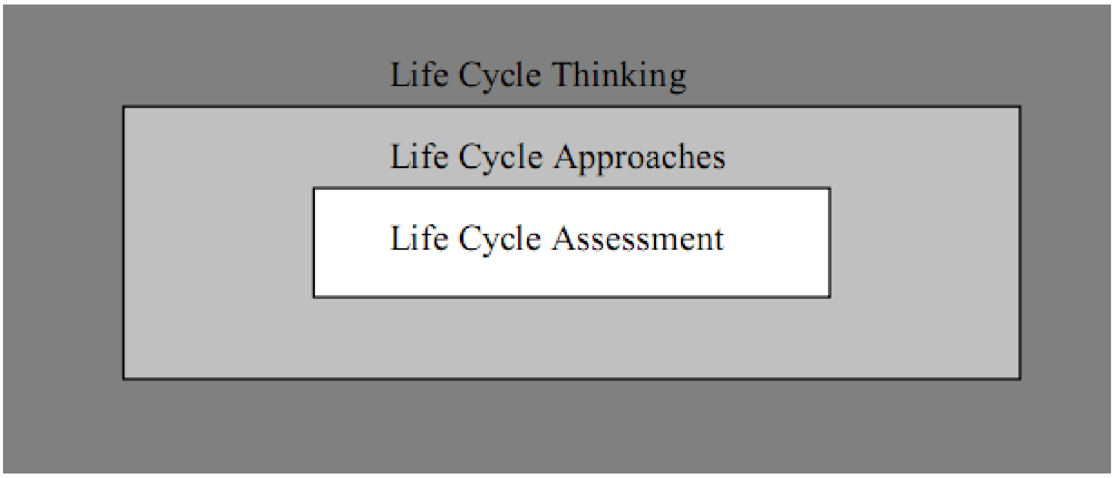

Figure 46 Levels of life cycle perspective(Frankle & Rubik, 2000).

A full LCA for a product is comprehensive and detailed; using professional LCA software is a good choice to facilitate data management. However, it's not recommended Husqvarna do LCA for all the products since it's time and labor consuming, therefore, doing LCA of typical products and using life cycle thinking during product design (e.g. increasing recyclability of the product) are more recommended.

7. Conclusions

This report presented LCA studies of the two products Lawnmower LC 48 VE and Automower 220AC. For both cases, production phase and use phase contributed dominant impacts of all impact categories exclude human toxicity, EPS2000 showed production phases including raw material as the most critical and Eco-indicator 99 illustrated use phases are more important for the two cases.

Assembly in Husqvarna factories and transports had little impact in most cases. Different emphasis in the two weighting methods caused this result and comparison will help decision maker have multi-view of different phase’s impacts in life cycle.

For both mowers recycling rate of metal can influence different categories to different extends in characterisation part, and since EPS2000 emphasized the resources depletion, better environmental performance can be achieved if more recycled metals are used in product system. What’s more, according to the discussion, to improve the durability of mowers will have positive impacts of the products’ environmental performance.

For company, improvement of internal database management is needed, and doing LCA of typical products and using life cycle thinking during product design are recommended.

Reference

About Husqvarna. (2009, 09). Retrieved 04 12, 2010, from http://corporate.husqvarna.com/index.php?p=about&afw_lang=en.

Baumann, H., & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA* (Vol. Studentlitterarur). Lund, Sweden: Studentlitteratur.

Boss, A. (2005). *Life Cycle Assessment of a Gas-Electric Hybrid Waste Collection Vehicle.* Göteborg, Sweden.

BUWAL 250. Life cycle inventory for packagings. Berne, Switzerland: Swiss Agency for the Environment, Forest and Landscape (SAEFL); 1998.

CPM. (2010). *Impact assessment methods*. Retrieved 02 20, 2010, from CPM: http://www.cpm.chalmers.se/CPMDatabase/StartIA.asp

CPM. (2008). *SPINE LCI dataset: Copper extrusion and drawing to profiles*. Retrieved 01 21, 2010, from CPM: http://www.cpm.chalmers.se/CPMDatabase/Scripts/sheet.asp?ActId=Designer1997-12-08834

CPM. (2010). *SPINE LCI dataset: Scrap-based steel production*. Retrieved 04 14, 2010, from CPM: http://www.cpm.chalmers.se/CPMDatabase/Scripts/sheet.asp?ActId=CPMCTHXXX1998-04-08837

Ericsson. (n.d.). *Material data.* Retrieved 12 2, 2009, from Materials list: http://materialsdata.ericsson.net/materials_list.htm

Frankle, & Rubik. (2000). Life cycle assesment in industry and business: Adoption patterns, applications and implications. *The International Journal of Life Cycle Assessment* , 133.

GP Battery. (2009). *Supplier BOS 220SCH for customer.*

Guinée, J. B. (2002). Handbook on Life Cycle Assessment. Kluwer Academic Publisheds.

Husqvarna. (2009). *Material Analysis Report 966975401.*

International Energy Agency. (2000). *Electricity production based on different energy sources,during 1998.*

IDEMAT 2001, Database, Faculty of Industrial Design Engineering of Delft University of Technology, The Netherlands (2001).

ISO (International Orgnaztion for Standarzation), http://www.iso.org.

Johan, N. (2010, 1 21). Questions about LC48VE. (X. Lan, Interviewer) Husqvarna.

Jose, M., Garcia, A., & Schluter, F. (1996). *Life-Cycle Assessment for Batteries of Electric Vehicles.* Goteborg.

Jose, Maria; Garcia, Acevedo. (1996). *Life-cycle Assessment for batteries for electric vehicles.*

Marby, A. (1999). Livscykelanalys . *KTH Ingenjörsskolan* .

Misumi Europe. (n.d.). *Technical data*. Retrieved 11 22, 2009, from www.misumi-europe.com/www/pdf/eng/.../2863_2864.pdf

NTM. (2002). Retrieved 2002, from www.ntm.se

NTM. (2009). Retrieved November 22, 2009, from NTM: http://www.ntm.a.se/english/eng-index.asp

Pre Consultants BV. (2008). SimaPro 7.1. Software and database manual. Amersfoort ,The Netherland.

Rantik, M. (1999). *Life Cycle Assessment of Five Batteries for Electric Vehicles under different charing regimes.* CTH.

Renova AB. (2010, January).

Saica Packaging. (2009).

SETAC-Europe. (1996). Towards a methodology for life cycle impact assessment. *Reprot from the SETAC-Europe working group on impact assessment.*

Simonson, M., Andersson, P., & Rosell, L. (2001). *Fire-LCA model:Cable case study.* Sweden.

SSAB,Swedish Steel. (2008). *Dogal 200 and Dogal Form Mild Steels for Drawing.* DOGAL.

SimaPro 7. Software and database manual. Amersfoort, The Netherlands: Pre Consultants BV;

ETH-ESU 96. Ökoinventare von Energiesystemen. ESU Group, (both unit and system processes), ETH Technical University of Zürich, 1996.

Personal communication

Bengt Ahlund. Husqvarna AB (2009, October).

Carl Risholm. Purchasing and Supply manager. Husqvarna AB (2009, October).

Coates, P. Project Engineer,Reserch and Development. Husqvarna AB (2010, January 26).

Jonas, Edman. Project Manager Petrol Wheeled dep. Husqvarna AB (2009, September 07).

Foster, P. Buyer, Materials Management. (2010, January 26).

Gilmore, D. (2009, December 03).

Gustvasson, C. Product Development Manager, Robotic Mowers. (2009, September 07).

Johan, Nilsson. Husqvarna Manufacturing Sweden AB. (2010, January 21).

Lindman, K. Recycling of lawnmowe. Renova. (2010, January 31).

Monica, F. Purchase Department, Husqvarna Manufacturing Sweden AB. (2009, September, 17).

Monica Arvidsson Business Administrator, Husqvarna AB. (2009, November, 23)