Life Cycle Assessment of Rapeseed and Mineral Oil Based Fluid Power Systems

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Summary

Life Cycle Assessment (LCA) is an environmental management tool that can be used to determine the environmental impact of a product or system over its entire life. In this thesis LCA has been used to determine the impact of the use of mineral and rapeseed oil when used in fluid power systems. This has been done using two case studies: forestry machinery and a road sweeper. The use of biodegradable fluid in mobile hydraulic systems has become more widespread in recent years due to increased awareness of the environmental impact of mineral oil spillage. This study was carried out to determine the whole life impact of using such oils in the machinery.

Data were collected from the machine manufacturers and the machine operators and detailed information about the use of the machines was obtained. Information about the oils and their performance and environmental impact was gained from environmental bodies and component producers.

The impact of the production of the oils differs depending on the environmental issue considered. Mineral oil has a greater impact than rapeseed oil on greenhouse gases while rapeseed oil has a greater impact on eutrophication. Overall it is not possible to say if one is better than the other. However, the oils do not have the same performance characteristics in the machinery and rapeseed oil requires more frequent replacement than mineral oil when used in mobile machinery. Therefore, when the use of the machinery is examined the impact from the rapeseed oil is higher in many cases than that of the mineral oil.

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1 Introduction

1.1 Introduction

In recent years, especially in the developed world, there has been a heightened awareness of environmental issues particularly in respect of the need to achieve sustainable development. This has had an impact on the design domain as it becomes recognised that the development of products and processes with a low environmental impact over their whole life-cycle is preferable to cleaning up during and after operation. In the case of fluid power systems, which is the focus of this thesis, the market is currently dominated by applications based on mineral oils as the working fluid. There is also a significant market for synthetic oils used where fire is a hazard. The recent funicular railway accident in Austria (November 2000) where the train caught fire in a tunnel killing over 160 people has made this a particularly topical issue as the German and Austrian media blamed the fire on the use of biodegradable hydraulic lubricants. Environmental issues along with safety considerations make it timely to examine the use of alternative fluids such as biodegradable fluids (or bio-oils) and water.

Many companies and organisations are trying to become more environmentally friendly. Mobile hydraulic systems can often work in "sensitive areas", such as forests and around rivers and lakes. Fluid power systems, although theoretically closed systems, often leak. Most of the time these leaks are slow and occur over many years. On some occasions the spills are larger, resulting in several litres of oil being spilled. Mineral oil is generally seen to have a negative effect on the environment if it is spilled. For this reason many companies have decided to use biodegradable oils in their systems.

There have been a number of studies carried out on the toxicity and biodegradability of many types of hydraulic oil. Much of this research is conducted during product development in order to comply with legislation. There has also been research undertaken on the use of some of these oils in hydraulic systems. This is at a relatively early stage and further research needs to be carried out as more biodegradable oils reach the market and as information is gained about the field performance of these fluids.

This chapter outlines the reason the study was undertaken, the objectives and the methods used in the study, why the case studies were chosen and the way in which the thesis has been organised.

1.2 Life Cycle Assessment (LCA)

It is now widely recognised that in order to evaluate the environmental consequences of a product or activity the impact resulting from each stage of its life cycle must be considered. This has led to the development of a range of analytical techniques that now come under the 'umbrella' of Life Cycle Assessment (LCA). Life Cycle Assessment is an environmental management tool which examines the environmental burden of a product or process over its entire life, from production, through use and on to disposal or recycling. Here the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole-life cycle from "cradle-to-grave" (Graedel & Allenby, 1995). LCA underpins the process of environmentally-sensitive design (or 'eco-design') that has focused very largely to date on products. In the case of fluid power systems based on oil hydraulics, a network of interconnected components needs to be evaluated within a circuit analysis framework.

The use of LCA eliminates the problems associated with transferring or ignoring environmental burdens when only one particular time aspect is examined. LCA requires all the energy inputs, raw materials inputs, emissions to air, soil and water, and waste to be examined at every stage of the life of the product or system. It is a simple, elegant idea, but it can become convoluted in practice.

The commonly accepted methodology for LCA was produced by the Society of Environmental Toxicology and Chemistry (SETAC) in the 1990's. This method has been adapted into an ISO series for LCA and these guidelines have been followed in this research. A full description of LCA is given in Chapter 2. So far LCA has been applied to many different applications, although not often to fluid power systems. Previous LCA's have been carried out on products as diverse as drink containers, nappies and lights.

1.3 Hydraulic Systems

Hydraulic systems are used to transfer power in a wide range of applications. They are common in mobile machines, for example tractors, reed cutters, sit-on-top mowers, forestry machinery, excavators and road sweepers. In hydrostatic systems energy is transferred by high pressure fluid, normally mineral oil, flowing at a relatively low speed. Many mobile fluid power systems work in sensitive environments and although theoretically they are closed systems there is always the potential for a oil spillage. In

Europe, 400 million litres of hydraulic oil is produced per annum, and only some 75% of this can be accounted for at any one time (Fluid Power Notes, University of Bath). Much of this oil is lost due to spillage, and it is because of this that the environmental impact of mobile machines running on biodegradable and mineral oil has been examined in this study.

Burrows (1996) recently traced the historical development of fluid power systems design and the environmental imperatives that have led to a re-evaluation of, for example, water hydraulics. The Scandinavian countries are leading the field in the application of environmentally-friendly fluids and Germany is also carrying out extensive research into this area. It is likely that these trends will be given added impetus by new European Union (EU) legislation and international standards, similar to, for example, ISO 14001. Several papers have been published at international conferences in Belgium, Finland and Germany giving preliminary results concerning the development of performance specifications and of the operational experience of companies using biodegradable fluids (see, for example, Tharp et al, 1998).

1.4 Research Objectives

The main objectives of the research described in this thesis are:

- To examine the life cycle of fluid power systems using alternative media: biodegradable oil and mineral oil.
- To examine the comparative impact of these systems over their life cycles using two case studies: forestry machines and road sweepers.
- To determine whether Life Cycle Assessment (LCA) is a useful and suitable tool for use within fluid power engineering.

The research carried out aimed to determine the whole life impact of hydraulic fluids and their use in the hydraulic systems in a realistic environment. This was done in order to determine the "true" environmental cost of these systems and to determine the differences, if any, resulting from running the systems on alternative fluids. In order to do this the following aspects were considered, for both case studies, with respect to their impact on the environment:

- production of the mineral and biodegradable oil

- manufacture of the hydraulic system of the machinery
- production of the machines
- use of the machinery including the fuel needed for operation
- use of the oil and associated maintenance of the hydraulic system
- disposal of the oil
- disposal of the machinery

1.5 Alternatives

Alternatives should be considered within any environmental research project. There are many alternatives to using mineral or rapeseed oil in hydraulic systems for mobile machines. One could use electrically driven systems or pneumatic systems. However, these also have their disadvantages including a low power to weight ratio. The main alternative would be to use different fluids in the hydraulic system. The rapeseed oil examined is one alternative to the conventional mineral oil. Other alternatives include synthetic oils which are also biodegradable and popular in industry. It would be very beneficial to examine these but due to a lack of accurate data it has been impossible to include these in the study. Data are available for the use of these fluids within systems, but there is no information available for the production of the oils. Efforts were made to obtain such data but oil companies were very reluctant to provide it. Another alternative fluid is water but this is not generally used in mobile systems in the UK due to freezing and evaporation problems and its ability to cause corrosion in the systems.

1.6 Data and Results

LCA is always dependent on the acquisition of a large amount of data which are usually extremely difficult to obtain. In spite of numerous requests to fluid and machine suppliers and manufacturers the data obtained for the study were inevitably incomplete. Care was taken to ensure that the data were sufficiently accurate to provide a reasonable estimation of the systems studied. As the quality and quantity of the data are crucial factors in the study a sensitivity analysis has been undertaken and is discussed in Chapter 8.

1.7 System Boundaries

An LCA can be traced back through many stages of a product and every component will have its own individual LCA. However, in practice, to carry out individual LCA's on each component would mean that the study would never be complete. It would also be so complex that its significance would be lost in the amount of detailed data generated. Therefore system boundaries have to be identified. In general, in this study, the boundaries have been drawn around the direct inputs but not the indirect inputs. For example, in the production of the rapeseed oil the amount of diesel fuel used (and the impact to produce this) in ploughing the field for the rapeseed has been considered, but the production of the plough has not been included. Flow diagrams of what has been included are shown in Chapters 6 and 7.

1.8 Functional Unit

It is important to specify what the functional unit is in a study. In the present case the overall functional unit is the use of the machinery over its lifetime. However, this is broken down in some of the chapters to the production of 1kg of oil or to the production of the machines. This is to enable a comparison to be made at different stages in the life cycle of the systems.

1.9 Thesis Structure

The thesis is divided into nine chapters. Chapters 2 - 5 provide the methods and introductory material required in the case studies. The results and analysis are discussed in Chapters 6 - 9. This is shown diagrammatically in Figure 1.1.

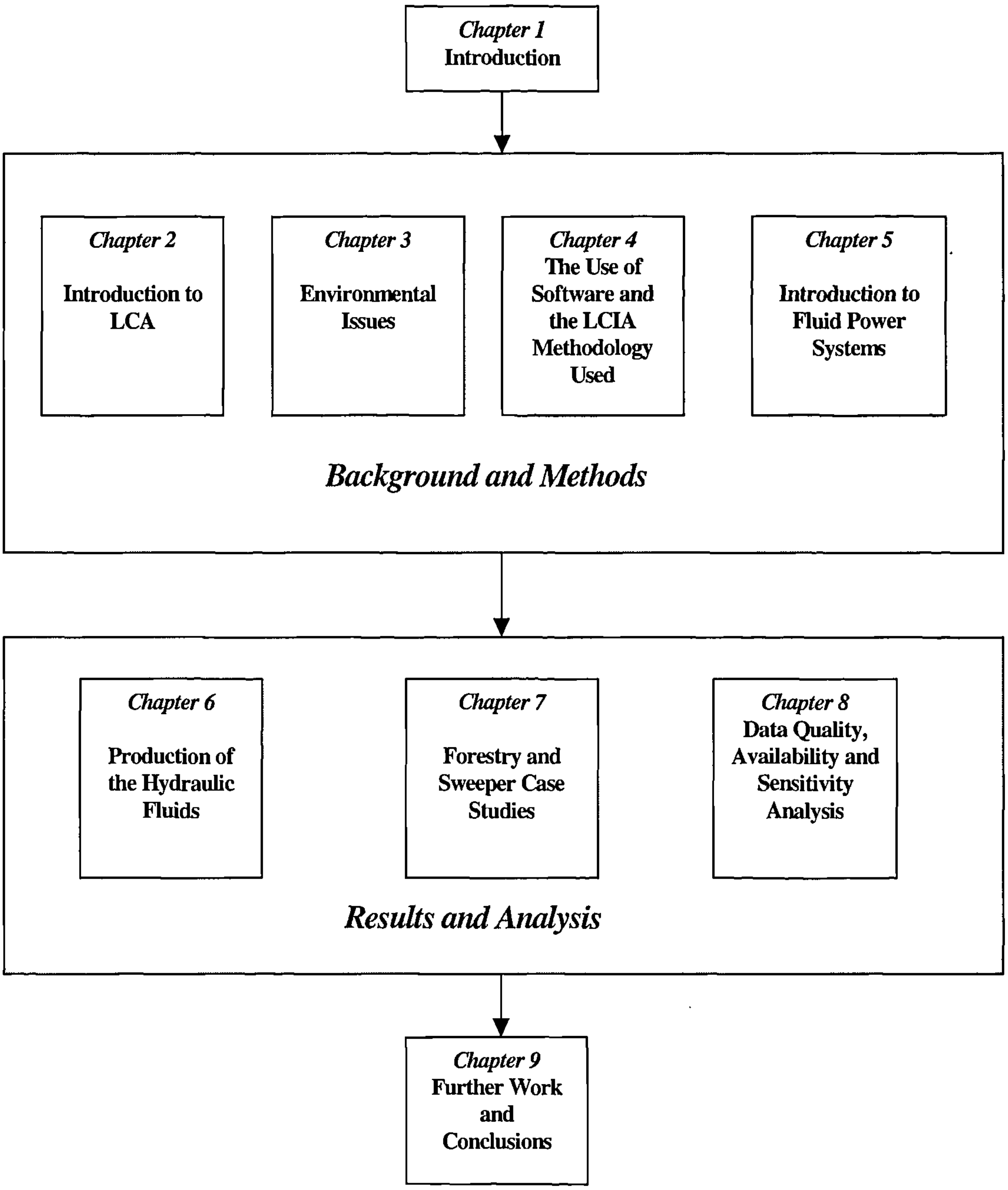

Figure 1.1 Schematic Representation of the Thesis Layout

2 An Introduction to Life Cycle Assessment

2.1 Introduction

LCA is an environmental management tool that assesses the environmental impact of a product or system over its entire life, from the "cradle to the grave". There are a number of definitions of LCA, perhaps the most commonly quoted is from the Society of Environmental Toxicology and Chemistry (SETAC, 1993):

"Life-Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of a product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance, recycling, and final disposal."

LCA is a data-hungry tool. Many believe that no-one has yet managed to produce a "complete LCA" and that the completion of an LCA will not be reported for many years, if ever. This is because of a lack of data availability, limited manpower in most companies carrying out an LCA and a general lack of expertise in the latter stages of LCA. This is coupled with a lack of across the board environmental knowledge by most individuals. Although the number of LCA's being carried out is increasing world wide, a definitive methodology for all the stages in an LCA has not yet been determined and it is recognised by research councils and foresight panels as an area which requires further research.

The use of commercially available software eases the compilation of an LCA (or a baseline LCA) but this may lead to inaccuracies. The use of software can yield results which potentially are not understood by the researcher or practitioner and therefore are of little value. This is because the software may incorporate databases which have been compiled from data with differing levels of accuracy and the software may utilise data that are not relevant to the study being undertaken.

As LCA encompasses many environmental issues ranging from, for example, human health effects to global warming, it is important that the issues studied are understood by the person carrying out the work. One person's expertise is bounded and consequently it is recommended by the author that where possible a full LCA should be carried out by a team of people.

2.2 *Introduction to LCA*

LCA may be used in conjunction with other environmental management tools such as Environmental Impact Assessment and Environmental Risk Assessment. However, unlike these tools, LCA considers impacts and effects over the entire life cycle of a product or system. As such it is the only environmental management tool that avoids positive ratings for measurements which result from shifting the environmental consequences of a product or activity. A shift of environmental impacts can occur in a study that only examines one aspect of a product. For example, changing the type of plastic used in a product may reduce the environmental impact of the manufacture of the product, but the disposal of the product may have a greater environmental burden. LCA negates this because everything within the life cycle must be considered within the study. An LCA will assess the energy input, materials input, emissions to air and water, and solid waste over the entire life cycle.

One of the main benefits of LCA is that it can be utilised in the design process. Environmental issues are considered along with the traditional factors of cost effectiveness and technology. This differs from the more traditional design approach that selects the most efficient, cost effective materials and processes and subsequently tries to reduce their environmental impact. An increasing awareness of environmental issues will impact on design methodology of products. This should lead to engineering design being inherently more environmentally friendly.

2.2.1 History

Despite a general consensus that Life Cycle Assessment originated approximately 25 years ago there is a lack of agreement in explaining the current extensive interest in LCA. Claims for the place of origin range from the UK during the energy crisis in the 1970's (Boustead, 1996) to, very specifically, the Midwest Research Institute in the US (Klöpffer, 1997). However, general consensus seems to be that LCA is a product of greater environmental awareness and arose from concern over the increased use of packaging and the depletion of natural resources, in particular fossil fuels.

2.2.2 Methodology

Since the original development of LCA there has been continual refinement of the methodology to ensure more widespread coherency in its application. This was achieved to some extent by SETAC (Society of Environmental Toxicology and Chemistry) who, in a series of workshops in the early 1990's, established the guidelines now commonly used by LCA practitioners. These guidelines have been further refined by LCANET (Life Cycle Assessment Network) which is a concerted action group, based at the University of Leiden, set up under the auspices of the European Commission's Environment and Climate Programme to establish a European Network for Strategic Life Cycle Assessment Research and Development. These guidelines have formed a framework for the ISO 14040 series standards. However, the ISO standards do not present a rigorous methodology so each individual practitioner still has scope for flexibility when performing an LCA. This flexibility can lead to disagreements, thus there is a need for further refinement.

2.2.2.1 SETAC Methodology

SETAC defined a framework for LCA which was based upon four main stages. These are:

- **Goal Scoping and Definition**

  Used to define the system boundaries, purpose and functional unit of a study

- **Inventory**

  Data gathered and stored in a spreadsheet format

- **Impact Assessment**

  The impact is assessed through three sub-divisions:

  - Classification

    Which aggregates data into separate categories e.g. resource depletion, ozone gases and greenhouse gasses

- Characterisation

  This quantifies the relative contributions each make to environmental problems, e.g. global warming potential, acid rain.

- Valuation

  This assigns relative values or weights to impacts in order to facilitate comparisons – this is a subjective process

- **Improvement Assessment**

  Incorporates the results into applications for product design, ecolabeling, policy formation etc.

The initial stages, goal scoping and definition and inventory have been well documented within the literature and the methodology for these is fairly well established. Any difficulties within these stages now tend to relate to the need for more fine tuning of the methodology and to the availability of data rather than any fundamental issues. The methodology for Impact Assessment has been hotly contested within recent years but there has been very little work on the Improvement Assessment stage. Work on the latter should accelerate after there has been some consensus upon the Impact Assessment stage.

There have been some recent discussions about, and adaptations of, the SETAC methodology, including the incorporation of LCA into ISO Standards. These changes will be addressed and discussed here under the initial headings proposed by SETAC.

2.2.2.1.1 Goal Scoping and Definition

The goal scoping and definition stage of LCA is arguably the most important but it is often overlooked or rushed. It forms the planning key to a study and is the point at which initial goals and boundary definitions should be set. At this step it is beneficial to create a flow diagram incorporating all of the possible impacts and effects from the study. These should then be investigated at a preliminary level in order to establish the significance of each. Depending on the findings of this initial examination the boundaries for the final study can be defined. However, it is important to note that the goals and definitions set out at the initial stages should not be rigid and should be reassessed and fine-tuned throughout the study as more information is obtained.

2.2.2.1.2 Inventory

The Inventory stage of the study is often the most time consuming part of the study as large amounts of detailed data are required at this stage. During this stage it is important to think ahead to the Impact Assessment stage for which the methodology is less established. During this study consideration was given to the Impact Assessment method when accumulating the raw data.

2.2.2.1.3 Impact Assessment

According to ISO 14042 Life Cycle Impact Assessment (LCIA) "examines a system's life cycle inventory results to better identify their possible environmental relevance and significance" and can be used to:

- Identify and to assist prioritisation of system improvement opportunities;
- Characterise or benchmark a system and its operations over time;
- Make relative material and energy based comparisons among systems, although the comparisons may be difficult and remain inconclusive;
- Indicate categories where other techniques may provide complementary environmental data and information useful to decision-makers.

Obviously these all depend on the areas of classification chosen and form a very important part of the study. Many LCA's to date have completed the Inventory section but have not progressed onto the Impact Assessment stage. This is possibly due to the lack of finalised methodology and to the subjectivity of the stage. However, the list of emissions and raw material inputs produced in the inventory can be meaningless without the Impact Assessment stage and so it is worth persevering with the full study. Since the creation of the SETAC stages it has been suggested by LCANET that the Impact Assessment Stage be modified to encompass:

- Definition
- Classification
- Characterisation
- Analysis of Significance
- Valuation

This is a change from the original SETAC proposals although the only additions are the definition stage and the analysis of significance stage. The definition stage formalises the initial stages of the impact assessment in which reasons should be given for the choice of classifications. Analysis of significance is also an important addition as it is a type of sensitivity analysis whereby the significance of individual contributions to the LCIA can be determined.

2.2.2.1.4 Improvement Assessment

Obviously the study would not be complete if there were not some mechanism for providing positive feedback of the study into the product or the design. An Improvement Assessment allows this to be done in a formal manner whilst also allowing for a discussion of the scientific integrity of a study. LCANET has also suggested that the Improvement Assessment be renamed as Interpretation. This has been accepted into the ISO Standards and so the stages within LCA according to ISO are Goal Scoping and Definition, Inventory Analysis, Impact Assessment and Interpretation Assessment. To some extent this weakens LCA because there should always be a scientific discussion within LCA. Moving away from a specific stage which would clearly identify areas for improvement and highlight implications for design, to a stage only containing interpretation, could weaken LCA in the eyes of designers.

2.2.2.2 ISO 14040 Series

These draft ISO standards are relatively new and therefore many people still use the SETAC methodology in their studies. ISO 14042 creates a framework for the Impact Assessment stage. There has not been much discussion about the changes in methodology in the literature so the following section outlines the similarities and differences between the two methods in order to create some clarity about the two methods. Table 2-1 shows the main stages within the two methods.

A combination of the original SETAC framework and the LCANET framework has been adopted in ISO 14042. It states that impact assessment should be split into different sections for a number of reasons. Firstly it enables everything to be handled more manageably in small sections so there is a distinct procedure which can be followed and reviewed. Secondly, and more controversially, because "all elements are not required for every application". Some studies do not proceed beyond the inventory stage whilst others proceed to the classification and characterisation stages (characterisation is called Relative Contribution to Impact Categories in the ISO standards). However, it is important to note that these do not constitute complete Life Cycle Assessments and it may be beneficial to determine a separate name for such studies such as Partial Life Cycle Assessments.

ISO 14042 Stages	SETAC and LCANET Equivalent Stages
Selection and Definition of Impact Categories	*Definition and Classification*
Assignment of LCI Results	*Classification and Characterisation*
Category Modelling	*Characterisation*
Relative Contribution to Impact Categories	*Characterisation*
Weighting Across Impact Categories	*Valuation*
Other Techniques	*Could Include Analysis of Significance*

Table 2-1 Comparison between SETAC and ISO Stages

Many of the changes between SETAC and ISO are simply alterations in name but some exhibit slight delineation modification. Interpretation of the meaning can also be different for some. Selection and Definition of Impact Categories falls into both the LCANET Definition stage and the SETAC/LCANET Classification stage, Assignment of LCI (life cycle inventory) results straddles the Classification and Characterisation stages, Category Modelling and Relative Contribution to Impact Categories also fall into the Characterisation stage whereas Weighting Across Impact Categories falls into the Valuation Stage. Other techniques could include a significance or uncertainty study although this is not required within the report unless used for comparative assertions disclosed to the public. These categories will be examined in full individually under the new ISO 14042 headings:

2.2.2.2.1 Selection and Definition of Impact Categories

This section is a welcome addition from the International Standards as it requires that some reason or guidance is given for the selection of impact categories within a study. This will ensure that the selection of categories is consistent with the goal and scope of the study and it will help to maintain transparency. The ISO document states that the categories selected should be scientifically sound and internationally agreed upon. Categories listed within ISO 14042 are:

- Global climate change
- Acidification
- Eutrophication
- Photochemical smog
- Human toxicity
- Resources

This list ignores potentially significant issues such as waste, ozone depleting gases and the opportunity to add more specific areas of study. Although it is desirable to have a mechanism for determining the scientific credibility of areas chosen to be studied within an LCA it is important not to allow the areas to become too narrow by imposing constraints which may be overly rigorous.

Many LCA's rely on Impact Assessment methodologies which are incorporated into software packages. Many of these follow the guidelines set out by SETAC and the later ones follow the guidelines set out within ISO 14042. However, some of the software packages state that that they are "not intended for use in environmental marketing, for environmental labelling or for proving in public that product A is better than product B" (Goedkoop, et al., 1995). The software goes through all the stages of Impact Assessment and can result in a weighted assessment with a single number generated for comparison. This single number approach is very limited in use and therefore it is questionable why it is included in a study.

2.2.2.2.2 Assignment of Life Cycle Inventory Results

This is the equivalent of the SETAC classification stage. Here inventory results are assigned to impact categories. Results that contribute to one category only can be easily assigned. For those that contribute to more than one, a mechanism for allocation must be established. Environmental processes are not always straight forward and the type of impact caused by the specific result should be identified. According to ISO 14042 these types of impacts are called "interventions with multiple impacts" and include parallel impacts, serial impacts, indirect impacts and combined impacts. Results within the inventory with these types of impacts should be clearly identified. For some cases the results should be divided between the two categories – the amount allocated to each must reflect the relative impact and should be clearly identified and discussed. In cases where a secondary impact is indirect the result should be allocated to the first category in order to avoid double counting.

In LCA the assignment of values to the characterisation and normalisation pertains to actual emissions and not to potential impacts. Therefore, all the values attributed to, for example, greenhouse gases are estimations of the possible impact, not the actual impact. The manner in which the characterisation is carried out – by attributing different values to different emissions is in itself very simplified. Each emission will have differing effects depending on the conditions of release and on combinations of emissions and the nature of the receiving environment. The actual impact arising from the release may be different from the one predicted as possible by LCA. However, to date this methodology appears to be the best for attributing potential impacts.

2.2.2.2.3 Category Modelling

This is the equivalent of the SETAC characterisation stage and provides a basis for the aggregation of data within a category. The method by which this is carried out must be clear and transparent and ISO 14042 recommends that the approach employed should be internationally accepted and if not it should be clearly stated why the methodology has been chosen. The scientific or subjective basses for making the choice should also be clearly identified.

2.2.2.2.4 Relative Contribution to Impact Categories

According to ISO 14042 this is often referred to as normalisation. Within LCA literature the term commonly compares the classified and characterised data with known values for the same emissions in order to determine their individual significance. For example, the emissions for greenhouse gases for a study would often be compared with the greenhouse emissions produced by a country, or the average emission produced by a country or region per person. It is a forerunner to the procedure of valuation.

This category within ISO 14042 also aims to determine the relative contribution of the results from a study, but the mechanisms to be used in order to achieve this are far from clear.

2.2.2.2.5 *Weighting Across Impact Categories*

This is the equivalent of SETAC's valuation stage. This is the procedure in LCA whereby the results are assigned a value to enable comparisons to be made. The allocation of such values or weightings are usually based on "value choices" and rarely on rigorous scientific knowledge. This part of the impact assessment is subjective and it is important therefore that all the methods used to assign weightings are clearly documented and identified. If weighting is to be used then different weighting techniques should be used within a study in order to compare the various results.

2.2.2.2.6 *Other Techniques*

"Other techniques" used within the LCA are outlined within ISO 14042 as dominance analysis, uncertainty analysis, sensitivity analysis and the inclusion of other environmental data. *Dominance analysis* identifies the areas within a study which have the greatest influence over the final results. These areas should be re-investigated in order to ascertain the quality of the data. Uncertainty analysis based on statistical analysis identifies the level of accuracy of the LCA result. *Sensitivity analysis* quantifies how variations in data or methods will change a result. *Other environmental data* can be used as additional information within the study. It is recognised within ISO 14042 that not all of these methods will necessarily be applicable to all studies.

2.3 Methodology Discussion

Life Cycle Impact Assessment is not a complete assessment of all possible environmental impacts associated with a product as the inventory data boundaries do not encompass all the possible system activities, nor do they include all the inputs or outputs. Nor does an LCIA include all the possible environmental categories; these are selected by various means and are often determined by the software in use.

The categories selected in classification must include all those thought to be important in the valuation stages. LCANET believe that it is unnecessary to include categories which will have no impact after the weighting system (Finnveden & Lindfors, 1997). However, it is not always easy to determine which impacts will be significant and it is also important to realise that the valuation may change through time as new environmental issues are raised.

The benefit of LCA is dependant upon the knowledge that it is not a tool through which individual environmental impacts will be identified. It is a tool through which the areas of impact identified at the classification stage can be ascertained and compared for different stages of the system or product. LCA can therefore act as an initial environmental management tool, the results of which may lead on to the use of other environmental management tools such as Environmental Risk Assessment, Environmental Impact Assessment and Environmental Auditing. The way in which Life Cycle Impact Assessment and other Environmental Management tools should and can interact needs to be fully examined. LCA cannot incorporate local impacts and therefore should be used in conjunction with tools such as EIA when local impacts are important to the study.

2.4 Previous LCA's

The increasing popularity of LCA is reflected by the studies reported in the literature. These range from LCA's of floor coverings (Potting & Blok, 1995), recycling (Craighill & Powell, 1996), chemical production processes (Bretz & Frankhauser, 1997), diesel and biodiesel (Sheehan et al., 1996) and stainless steel (Caspersen, 1996) to solid waste (Finnveden et al., 1995) and lamps (Pfeifer, 1996). Pfeiffer's review of an LCA highlights some of the benefits of LCA as a comparative mechanism showing that mercury life cycle emissions of filament and fluorescent lamps are similar despite mercury being contained within fluorescent lamps only. This equal emission is due to the greater energy consumption of the filament lamp.

LCA can be used to determine the amount of time a system, for example a power plant, must be used in order to outweigh any negative impacts encountered during its production. Tahara et al, (1997) have used LCA to determine the CO_2 payback time for different types of power plants. The amount of CO_2 produced during production was compared with the amount of CO_2 produced during use. This allows the amount of time a plant must run for it to be "CO_2 efficient" to be established.

A slight twist of the methodology can also mean that the indirect receiving environment is considered. As well as the traditional classification procedure the software PEMS also offers the option to determine the amount of air, water, soil, etc. needed to absorb the emissions produced from a certain process or system (Kneil et al, 1996). This means that once the emissions inventory has been established it is relatively easy to determine whether the receiving environment can cope with the system, this enables a more

"Environmental Impact Assessment approach". It does however depend on specific knowledge of the geographical location of the emissions and does not comply with LCA guidelines. However, this twist of the methodology is useful and, depending on the quality of the data, can help ascertain whether a product or system will have a significant impact on the local environment.

LCA can be used in order to translate sustainability demands into product and process improvements (Tukker et al, 1997). As the current desire and European initiatives for increasing sustainability increase within both countries and companies, this application may become one of the most important for LCA. The standard methodology is used to achieve this but the results can be related to sustainability indicators as set by the government and European Union. Producers can identify areas in which improvements can be made in order to achieve greater sustainability. A further tool for use in this area which is linked to LCA is SFA (Substance Flow Analysis) which is suitable for performing more detailed analysis of market developments on a regional scale (Tukker et al, 1997). SFA is generally limited to one substance; all flows of the substance throughout the economy and/or the environment are determined for a specific year or a geographical area. SFA is a good tool for substances such as CFC's, plastics, etc. where it is beneficial to understand all the processes and flows for the individual substance within a product rather than for the product itself.

2.5 Data Availability

A common format for data and a basic data resource that could be used by all LCA practitioners and researchers would be beneficial within LCA. This has been called BID (Background Inventory Data) by Schaltegger (1996). Data availability of this sort then would mean that time taken to carry out an LCA would be reduced and the quality of LCA would improve as data would be constantly updated, augmented and peer-reviewed.

Data are often very hard to obtain for an LCA study and it can be very time consuming to gather enough for a credible study. Often it is impossible to obtain enough information to generate a comprehensive inventory for all the areas identified in the goal scoping and definition stage of a study. It is important not to ignore these areas. An explanation about the lack of available data and an estimation is far better than ignoring the effects altogether. Few studies to date mention the difficulty of obtaining data or of the reliability of the data.

LCA case studies, such as those discussed earlier, have helped to improve LCA methodology and have also helped to establish individual databases which if amalgamated could be used within further studies. Easy access to data used in these studies could decrease the inordinate amount of time spent gathering data from companies and governments. This would increase time devoted to performing LCA's and refining the methodology. In practice SPOLD has not yet managed to create a database which is widely available to the public although it has established a database format which allows the easy transfer of data from one database to another. This format has been adopted to some extent by the LCA software companies. It is not used ubiquitously, but its creation has raised an awareness of the need for more compatible databases. To date the largest databases are probably contained within the LCA software and are sometimes available only to those who purchase the software.

2.6 Links with Economics

There has been much connection in the literature between LCA and environmental economic tools such as Cost Benefit Analysis (CBA). This may be partially due to the management tool Life Cycle Costing which seeks the middle ground between LCA and CBA by looking at the costs of a product or system over its entire life cycle. Obviously it is beneficial to determine the monetary cost as well as the environmental cost as any potential design change may be rendered non-viable if cost is ignored. For this reason it is important to consider cost from the beginning of the design process. This can be incorporated into LCA and need not be considered separately as part of an economic study. The connection between LCA and economics may also be partially due to early environmentalists' envy of the economists' government-funded data. It was initially thought that some of these data could be interpreted to give indications of environmental performance (Bousted, 1996). Unfortunately this does not work. Economic data are often too broad to allow specific processes to be isolated and economic values change in a way that environmental ones do not. Both LCA and CBA are based on a balance of gains and losses, advantages and disadvantages. CBA is determined by the comparison of net gains against net losses and to a certain extent LCA is too. However, the tools are very different in terms of the results they can offer. CBA often tries to ascertain costs to the environment with the utilisation of tools such as Willingness to Pay (WTP) and Willingness to Accept (WTA) – these are subjective tools and although they are widely accepted they have been criticised (Turner et al., 1994). Although the Impact Assessment stage of LCA is generally considered subjective, the database should be based on rigorously tested data. It is therefore thought that both tools are important for different remits.

2.7 Other Environmental Tools

LCA should not be considered in isolation of other environmental management tools. Although it can be used as a stand-alone tool it does complement other environmental management tools such as Environmental Impact Assessment (EIA) and Environmental Risk Assessment (ERA). LCA does not consider environmental impacts but life cycle impacts. If a study is to embrace the environmental impacts of a system or process within the scope of the LCA then a tool such as EIA must be used. Indeed, LCA is very poor at identifying actual environmental impacts as it considers impacts towards categorised issues rather than to a specific receiving environment. This is very different from a tool such as EIA.

2.8 System Boundaries

Determination of system boundaries is a very important part of LCA. In order to be able to compare and contrast LCA's it is important to know what has been taken into consideration. Although it would be ideal to be able to gather data for all the stages in the life cycle of a product or system this is often not possible. Consider the case where biodegradable oil is to be used in a hydraulic system: there are many factors to be considered, for example the growth of the seeds, the harvest and production of the oil, transportation of the seed and the oil, use of the oil within the machinery, changes made to the machinery as a result of the oil, impact of spills of the oil on the receiving environment, and the disposal of the oil. All these factors need to be considered in detail as well as other impacts like the production, use and disposal of seals which need to be replaced as a result of the differing oil use. To study the impacts of each one of these areas leads to a cascade of factors. For example, the growth of the rapeseed could necessitate the study of the pesticides used on the crops, the effects this will have on the ecology of the area, the impact on plants and animals in rivers in which there is run off, the energy needed to harvest the seeds, the land used to store the seeds, the potential health effects from contact with the seeds, the potential effects of monocultures in areas in which the crop is grown, etc. The information required could quickly become so large that it is impossible to manage, therefore it is imperative that the system boundaries are defined at the start of a study. As well as determining the information required this also ensures that the system studied is not examined in isolation from its context. For the example of hydraulic oil, this means that the use of the oil will not be examined without regard to the effects other parts of the machinery will have. For example the effects associated with using a diesel engine in the machine may far outweigh any effects from the use of hydraulic fluids.

2.9 Sensitivity Analysis

One of the potential problems with LCA is that some data may be more significant than others but it is difficult to determine which data are significant. For this reason it is important to undertake a sensitivity analysis to determine the effects that a slight change on any of the individual data may have on the final results. Many software packages allow this to be performed within the LCA programme, or it is possible to analysis the data statistically .

Sensitivity analysis is also very important where there are some data whose quality is unknown. Where analysis shows that the end results are very dependant on such data these should be closely examined. Steps should be taken to verify the quality of the data or to find reliable alternatives.

2.10 Ethics

There have been calls for a code of ethical conduct within LCA (Denison, 1993) due to the lack of consistent data, precise methodologies and increased subjectivity. One of the greatest complaints about LCA is that the results often favour those who fund the project: whether fact or perception, this complaint must be addressed. This would require rigorous peer reviewing as suggested by both Denison in his paper on Ethical Conduct and within the SETAC methodology. A peer review process at various points throughout the LCA can ensure that the study is progressing ethically and in sufficient detail. To be adequate, peer reviews must be able to access the raw inventory data. Obviously, if there were a general LCA database this would make the process easier. The research described in this thesis has been discussed internally at the University of Bath at regular Engineering Design Centre Steering Committee meetings and it has also been presented at conferences and seminars worldwide. Some of the papers presented at these seminars and conferences are shown in Appendix 1.

Many LCA's are carried out in order to compare one product with another. In many cases the comparison is between two products which are either slightly different or those which perform the same function. The question of what reasonable alternatives should be considered has been raised (Denison 1993). For example, within LCA, should a study on disposable nappies compare one brand with another or should these brands also be compared with reusable nappies? In the absence of any guidelines a comparison may be chosen out of self-interest and which may potentially obscure the full context in which the product should be evaluated. If all alternatives are not to be studied then they should at least be prominently mentioned.

The functional unit of the product in the study should also be clearly identified. For example, if the comparison is between vacuum cleaners, although all will be used to vacuum the floor, some may also be used to suck dust off shelves and hence reduce the use of dusters. The way in which the functional unit has been determined should also be established. Results originating from manufactures guidelines may well differ from those gained by a survey of users.

2.11 Limitations of Life Cycle Assessment

The main and obvious limitations of LCA are the problems with data gathering and the time the study takes. There are also limitations with parts of the methodology – specifically the impact assessment stages. Once this has been refined, consistency and coherence within LCA's should improve.

The way in which the LCA methodology is still very subjective in some parts is also a limitation. Reputable science relies on reproducibility and as such the aim of all LCA practitioners should be to produce a transparent study which can be followed from start to finish with all the data, methodologies and assumptions clearly outlined.

The fact that local impacts are not taken into consideration within an LCA is a significant issue and should be realised before an LCA is undertaken. However, there is potential to incorporate studies such as EIA and ERA into a LCA by means of comparison. Alternatively a separate category entitled "local impacts" could be incorporated into the classifications. This has more associated dangers and the areas covered by such a classification would have to be clearly defined within the study. It would also have to be pointed out that this classification was not a life cycle impact and therefore could not be evaluated and compared in the same manner as the other classifications. In general, if possible, it appears beneficial not to try to incorporate local impacts into life cycle classifications for impact assessment. It is better to generate a separate study, for example an EIA, which can be analysed in conjunction with the LCA.

Stirling (1997) appraised the problems encountered in attempting to characterise environmental effects as "externalities" in the energy industry. He examined twenty different dimensions of environmental appraisal and discussed their effectiveness and the way in which they have been incorporated into environmental management. Although his work was based upon the energy industry it can equally be related to more general environmental management issues. His work highlights complex problems such as the inclusion of intergenerational equality, reversibility of impacts, fairness of exposure, quantifiability of issues and impacts and weighting between human and non human impacts. Stirling highlighted many interesting points which could in future be introduced into LCA.[1]

2.12 Concluding Remarks

LCA is a beneficial environmental management tool. Its use has become more widespread in recent years. LCA methodology is becoming tighter, although there is still scope for improvement. The concept of LCA is very simple and elegant and it represents true holistic thinking. However, it can quickly become convoluted and complex in practice. Data acquisition is a significant problem in LCA, although as more studies are undertaken this should become less of an issue.

The "whole-life" thinking associated with LCA ensures that environmental burdens are not merely shifted from one stage of the life cycle to another. It will also help designers "design for the environment" as they will become increasingly required to do. The concept of LCA is good, although steps need to be taken to make it more accessible and easily used without reducing its scientific integrity.

[1] Stirling's work has been expanded by Sandy Smith (University of Bath), Professor Hammond (University of Bath) and the author. This has taken the form of a "pro forma" which can be used as a checklist to determine whether or not certain issues have been included in an LCA.

3 Environmental Issues

3.1 Introduction

This chapter describes the environmental issues considered within the study and outlines some of the impacts associated with the use of the fluid power systems that are not included in the study. The LCA study considers the impacts of two systems (forestry machinery and road sweepers) on greenhouse gases, ozone depleting gases, acidification, eutrophication, summer smog, winter smog, heavy metals, carcinogens, respiratory disorders, radiation, ecotoxic substances, land use and raw materials. Other impacts associated with the use of these systems are local impacts which are especially important because the impact on the local environment has led to the use of biodegradable fluids. However, LCA is not a tool that can assess the local impacts of a product or system. There have been several studies undertaken to assess these impacts, using environmental management tools which are far better suited to the assessment of local impacts. An outline of these effects is given here. Table 3-1 to Table 3-6 show the main impacts associated with the case studies.

3.2 Environmental Issues

The reasons for studying particular environmental issues in an LCA over other issues ought to be transparent because the choice can change the outcome. The environmental issues chosen should be selected because of their relevance and not because they may mask certain impacts.

It would have been beneficial to include the impact on land use. An examination of the sustainability of the use of mineral oil would also have enhanced the study. Both these impacts are important when examining the life cycle impact of these case studies, but all the impacts cannot be examined in an LCA; that is a key deficiency. In these case studies these issues were examined when EcoIndicator 99 was used and not when EcoIndicator 95 was used. EcoIndicator 99 was used only in the sensitivity analysis whereas EcoIndicator 95 was used throughout the study. The incorporation of land use in LCA is new and is not by any means complete. The use of results from this could lead to inaccurate studies. Also, it is impossible to determine the global reserves of oil because extraction techniques improve all the time, therefore it is difficult to ascertain the sustainability of the use of oil.

The issues chosen within this research were guided by what was available in the software. These issues, and the data underlying the methods for determining the impacts were examined. These issues provide a good general overview of the issues involved.

3.2.1 Regional and Global Environmental Issues

This section outlines the effects considered in EcoIndicator 95 (EI95) and EcoIndicator 99 (EI99) which are the impact assessment methods used in the case studies. The indicators are described more fully in Chapter 4: EI95 was used throughout the whole study, but EI99 is used only within the sensitivity analysis.

3.2.1.1 The Greenhouse Effect

The greenhouse effect is a natural phenomenon which has operated for billions of years, long before the Earth was inhabited by Man. Without the greenhouse effect this planet would not be suitable for life as we know it and would have an average temperature of about $-17^{O}C$ compared to the current average of approximately $+15^{O}C$. Most of the Sun's energy, mainly in the form of short-wave radiation, passes through the atmosphere and warms the Earth's surface. Heat energy in the form of long-wave radiation, is radiated back into the atmosphere. Some of this heat escapes out into space, but most of it is absorbed or held by CO_2, water vapour and other 'greenhouse' gases. By absorbing the heat these gases become warmer, and heat is reflected into the atmosphere in different directions. Therefore, although the term "greenhouse effect" is commonly used in the media and in quasi-science as a "problem" it is not really the greenhouse effect that is being discussed, it is the "enhanced greenhouse effect", or "global warming". The greenhouse effect is a fact that was first described in 1896, but the enhanced greenhouse effect, or global warming, is still scientifically uncertain (see, for example, Emsley (Ed), 1996) although it is often treated as a fact.

Global temperatures are rising, but the cause of this rise has not yet been established. Many claim that temperatures are rising due the increased amount of greenhouse gases in the atmosphere associated with the burning of fossil fuel. This may be true, but the earth is also currently in an "interglacial" period. The earth has had many ice ages in the past, when temperatures have been much colder than they are today. However, during interglacials, temperatures also rise higher than present with fluctuations based around 100,000 and 10,000 year cycles (Imbrie & Imbrie, 1979). It is possible that the reason for these fluctuations is the differing distance between the Earth and the Sun. There are also shorter cycles within these larger cycles which may be accounted for by sun-spot activity.

The current "popular" idea is that the warming of our atmosphere is due to the impact of Man. This may be true, although it may also be true that the warming we are seeing is an entirely natural phenomenon. The intricacies of our atmosphere and climate are complex, chaotic and difficult to understand, and until a better understanding is reached it is advisable to restrict emissions into the atmosphere. For this reason the contribution to greenhouse gases has been considered in this study.

3.2.1.2 Ozone Depletion

The ozone layer is part of the stratosphere, lying from 19 - 48 km above the Earth's surface. In this region some of the potentially harmful Ultra Violet (UV) radiation from the Sun (wavelengths between 240 and 320nm) is absorbed. As a result of the action of sunlight on oxygen, ozone is formed, a process that has been occurring for many millions of years. Naturally occurring nitrogen has kept ozone levels fairly constant but a depletion in the amount of ozone in this layer was first recorded by scientists from the British Antarctic Survey in the mid-1980's. It was discovered that gases containing chlorine, e.g. CFC's, rise in the atmosphere and are broken down by sunlight. The chlorine then reacts with and destroys the ozone molecules. Other man-made chemicals also effect the ozone layer; for example nitrous oxides from fertilisers, HCFC's and bromide halocarbons. Depletion of the ozone layer results in more UV radiation reaching the Earth's surface; it is predicted that this will cause an increase in cancers and cataracts, damage to some crops, accelerated plankton growth, an increase in carbon dioxide, and will affect the marine food web. There is now a global effort to reduce and eliminate the chemicals that affect the ozone layer.

3.2.1.3 Acidification

Acid rain was first recognised in the mid-1800's in industrialised Europe. It is rain that has a pH of less than 5.65 (the pH which is produced by carbonic acid in equilibrium with atmospheric CO_2). The degree of acidity seems to be increasing, especially in some parts of the world because of the increase in sulphur and nitrous oxides emitted from fossil fuel combustion. Two further factors contribute to an increase in the severity of the problem. The first is the change from coal to natural gas: coal burning produces a lot of sulphate, but it is partially neutralised by the high calcium content of the relatively unfiltered smoke emissions; natural gas burning produces less sulphate, but it is not neutralised. The second factor causing acidification is the increase in height of smoke stacks. These were increased in height to relieve local problems which have now become regional ones.

The effects of acid rain are not consistent and they are especially serious in areas underlain by highly siliceous bedrock (for example, Scandinavia, parts of Canada and Scotland). The ecological effects of acid rain are still under debate. In conjunction with changes in land-use the effects can be quite dramatic - such as the "tinsel syndrome" seen in trees in Scotland and Scandinavia, caused by increased acid in the air. The syndrome causes leaves on coniferous trees to fall off leaving the tree looking like an old Christmas tree, hence the name. As a result of the increased number of leaves dropping (the leaves are quite acidic) and the acid rain, soil and water acidity have increased in some areas. Natural aluminium contained in the soil becomes more mobile in acidic conditions and this mobility increases the level of aluminium in nearby waterways. This can result in "fish kill" in lakes and, to a lesser extent, rivers. In the UK, many of the (commercial) trees are grown in Scotland where the underlying geology and geomorphology is often acidic, with a granitic or peaty base. These areas are even more prone to an increase in acidity than less sensitive areas.

3.2.1.4 Eutrophication

Natural eutrophication is the process by which bodies of water produce nutrients and thus over a period of thousands of years are able to sustain life. Humans have greatly accelerated this process around the globe. The resulting anthropogenic eutrophication is caused by excess nutrients in a water body. The excess nutrients can occur in a number of ways; runoff from fields, lawns and golf courses being one of the major causes. Treated or partially treated sewage is another major cause. As a result of the excess of nutrients (phosphates in particular) algal blooms can form. The growth of these blooms is very fast and can lead to oxygen depletion in the water which in turn can cause "fish kill".

3.2.1.5 Summer Smog

Summer smog is caused by a mixture of pollutants from road vehicles, fuels used to heat and light buildings, and vapours from petrol and some industries. The action of sunlight on these pollutants produces ozone, which is a pollutant at ground level. One hundred years ago the ozone concentration averaged over the whole year was approximately 10ppb (parts per billion). At present it is 25ppb. At 30ppb and above crop damage can occur (PRé, 1997). Summer smog is more common on hot, sunny days and occurs mainly in built-up areas where the pollutants are emitted. Ozone at ground levels can affect human health.

3.2.1.6 Winter Smog

Winter smog is caused by pollutants from road vehicles and fuels used to provide energy to buildings. It is formed when these pollutants build up at ground level due to a layer of cold air (temperature inversion) trapping the pollutants. Winter smog generally occurs in built-up areas on cold, calm days, often after a clear night and it is frequently associated with an early-morning frost or a mist close to the ground. The main pollutants involved with winter smog are Sulphur Dioxide (SO_2), Suspended Particle Matter (SPM), Nitrous Oxides (NO_x), organic substances and Carbon Monoxide (CO). SPM and dust particles often also contain heavy metals (see below). Winter smog is especially harmful to those with respiratory disorders.

3.2.1.7 Heavy Metals

Since the start of the Industrial Revolution the production of heavy metals such as lead, copper and zinc has increased tenfold with an associated increase in the emissions. The use of heavy metals is not a new phenomenon; the Romans added lead to wine to improve the taste, lead arsenate was used to control insects, and mercury was used to alleviate toothache. The lead concentrate in ice layers in Greenland exhibits a steady rise in level consistent with the mining renaissance in Europe. In the mid-1990's the levels found were one hundred times the natural level (World Resources Institute, 1998 - 1999).

In recent times exposure to heavy metals has been linked to development retardation, cancers, kidney damage, autoimmunity (which can lead to diseases of the joints, circulatory and central nervous system), and even death. Despite these links, exposure to heavy metals continues. Once heavy metals are emitted they can reside in the environment for hundreds of years. Obviously, different heavy metals will have different effects on human health and the environment. Individual human exposure to heavy metals will differ depending on location. Lead levels in children's blood has reduced in the past 30 years in the West (SimaPro database manual), but there is still a need to reduce the emissions of heavy metals.

3.2.1.8 Carcinogenic Substances

Most people's lives have been touched by cancer, either directly or indirectly. Many scientists involved in the field believe that a significant number of cancers may be associated with the environment in which humans work and live. Substances eaten, drunk and smoked, natural and medical radiation, workplace and home exposure, drugs, aspects of sexual behaviour and substances in the air, water and soil can all be associated with cancers. Exact environmental factors cannot be associated with specific cancers, but in many cases some understanding about general carcinogens exists. Many lists of known carcinogens have been produced and it is advisable to reduce the production of these where possible.

3.2.1.9 Waste

In any process or system there will be some form of waste. Whether this is recycled, reused, incinerated, composted or landfilled depends largely on the region or country in which the waste is produced. The solid waste produced is considered in the characterisation of the data, but not in the normalised stage. Normalisation of the waste is not included in EI95 due to lack of data concerning the waste processes in all the European countries.

3.2.1.10 Respiratory Effects

Several substances can lead to detrimental respiratory effects in humans. Particulate Matter with a diameter less than 10 micrometres and 2.5 micrometres (PM_{10} and $PM_{2.5}$) nitrate, sulphate, Sulphur Trioxide (SO_3), ozone (O_3), Carbon Monoxide (CO), ammonia (NH_3), Volatile Organic Carbons (VOC's), Sulphur Oxides (SO_x) and probably Nitrogen Oxides (NO_x) all have an effect on the respiratory health of mankind. Respiratory diseases include asthma and other breathing disorders. Reported cases of these are increasing and although some of these are due to more people reporting their problems it is likely that the prevelelance of these conditions is growing. It is possible that this is due to a rise in particulates resulting from car use and other pollution.

3.2.1.11 Ionising Radiation

Exposure to ionising radiation is a common fear amongst many. Exposure is thought to increase the risk of cancer. However, its effect is not something that has often been considered in LCA. Radiation is released naturally in many areas due to geology, it is also released in the nuclear fuel cycle, in phosphate rock extraction, in coal-power plants and in coal and gas extraction. These are considered in the EI99. The potential impact of large exposure due to leaks is not considered.

3.2.1.12 Ecotoxic Substances

These substances, for example cadmium compounds, selenium compounds, copper and zinc compounds, can affect the ecosystem in a number of ways, both temporarily and permanently. They can affect biodiversity, aesthetic and cultural values, ecological functions and resources. The effect of toxicity on the ecosystem is measured in EI99 by the Potentially Affected Fraction (PAF) of species. This expresses the effect on water- and soil-dwelling creatures such as fish, crustaceans, algae, worms, nematodes and plant species.

3.2.1.13 Land Use

The impact of land use on ecosystems is very important. Biodiversity is easily affected, and the impact of monocultures can be severe. The impact of land use is complex: land use change tends to be gradual and it is difficult to determine what is a natural land use and what is not. Most areas in Europe have been affected by man for many thousands of years, the impact of further changes is often difficult to gauge within an LCA. However, it is possible to determine the effect on the number of species living in an area or the nutrient and chemical levels.

3.2.1.14 Raw Materials

Most processes rely on the use of large quantities of raw materials. The extraction and refinement can have quite an impact. Continued use of such materials is not sustainable, therefore they must be considered within an LCA. Extraction of raw materials, for example oil, can mean that resources left in the ground are either not of sufficient quality or not in a suitable position to be extracted with current technology. Therefore, the quality as well as the quantity of the remaining resources has to be considered.

3.2.2 Local Environmental Issues

LCA, as a tool, focuses on regional and global effects. This is a limitation of LCA and the incorporation of local impacts into an LCA has often been discussed in LCA meetings. However, LCA is not the only available environmental management tool available and there is a suite of environmental management tools, all of which have benefits and disadvantages. LCA examines the overall impact of a process or system. The use of an environmental impact assessment (EIA) in conjunction with an LCA ought to be considered when site-specific issues have been identified.

In the context of this research, local issues associated with the potential impact of spilling hydraulic oils have also been identified. The risk of these spills and the impacts associated with them can be examined through tools such as EIA and risk assessment.

3.2.2.1 Spills of Mineral Oils

Oil spillage from machines is not regular, nor is the rate of oil spilled from a machine constant. The potential for hydraulic oil spillage is the reason most machine users state for using biodegradable oil instead of mineral oil. In Europe, 400 million litres of hydraulic oil are produced per annum, and only some 75% of this can be accounted for at any one time. This oil spillage is potentially of major concern given that a small quantity of oil in a waterway can have a major effect on the local ecology from which it may take many years to recover.

The effect a spill of mineral oil has on the environment is the reason why many companies have adopted the use of biodegradable oils. Many criteria affect the impact of a spill of oil, including the amount of oil spilled, the sensitivity of the receiving environment and the toxicity of the oil (the additive package used). A litre of oil in a river can have devastating effects. Mineral oil spilled on soil can result in contaminated land which has to be remediated. This can be extremely costly and can also have lasting effects on the ecosystem. The best course of action after any spill is to clear the area of the oil as soon as possible. This can be done with booms in water areas, and by removing the soil when it is spilled on the ground. Oil from a hydraulic system, if spilled when in use, is likely to be at a very high temperature.

3.2.2.2 Spills of Biodegradable Oils

It is important to remember that a spill of biodegradable oil will also have an environmental effect. If the oil is hot and under pressure it is likely that all plants it hits will die or will be damaged. However, if biodegradable oil is spilled the soil will recover sooner than if the spill were of mineral oil. A spill of biodegradable oil in water will rapidly biodegrade. If it is a large spill it will cause rapid deoxygenation of the water, resulting in loss of life. However, biodegradable oils will generally be less toxic than mineral oils and hence the environment will recover faster than if the spill was a mineral oil.

The Environment Agency ensures that oil they use has been tested against the Organisation for Economic Co-operation and Development (OECD) standards:

OECD 201	Algae
OECD 202	Daphnia
OECD 203	Fish (acute)
OECD 204	Fish (chronic)
OECD 209	Bacteria
OECD 301B	Biodegradation
OECD 305D	Bioaccumulation
OECD 401	Acute oral toxicity

3.3 Ethics of Oil Companies

One aspect of the whole life impact of oil that has not been considered is the ethical aspect. Human rights and ethics are important issues, and especially so in the oil industry. These issues are however so complex that it is almost impossible to quantify them objectively. Mineral oil is often extracted in developing countries where environmental and ethical laws are not as well established as they are in European countries. The highly publicised problems in Nigeria between Shell and the Ogoni people is just one example. Here the Ogoni protested against Shell as they claimed that their oil production had not only destroyed the local environment as a result of leaks from oil transporting pipes, but that the economy of the region had been destroyed as there was no longer any economic viability in the region for local farmers and producers. It has not been possible to include the impact of this type of issue on mineral oil production, but it is important that it is not completely forgotten.

3.4 Concluding Remarks

LCA assesses the contribution a process or a system makes to designated environmental issues. It does not, as such, examine the "damage" done to the local environment. This is because such damage, for many environmental issues, can only be calculated on a local scale. True global environmental effects can be considered completely by LCA, but other issues are only examined as a contribution to total emissions and the damage done to local areas may differ significantly. This is one reason why LCA ought to be used in conjunction with other components of the "environmental management tool box".

This chapter has outlined the environmental issues considered in this study and has also indicated the potential impact of some of the environmental issues associated with the case studies which are not considered within the study.

Life Stage	Impact Considered?	Impacts not considered
Rapeseed Production		
Production of pesticides	Yes	
Use of pesticides	Yes, but no local impacts	Surface water and ground water pollution
Production of fertilisers	Yes	Local impacts of emissions.
Use of fertilisers	Yes, but no local impacts	Surface and ground water pollution
Use of water	No	Local impacts towards aquifers, increase in water demand, e.g. in East Anglia.
Production of farm machinery	No	Cf. production of e.g. forestry machinery
Use of farm machinery	Diesel emissions only	Poaching of soil
Transport of rapeseed	Emissions only	No local impacts or social impacts
Effect of growth on local ecology	No	Monocultures
Effect of growth on local health issues	No	Asthma?
Impact of refining	Emissions and energy	Local impact
Impact of the refinery site	No	Any impacts associated with the site - need a full EIA
Impact of the transport of oil	Emissions	Use of roads Localised emissions
Impact of the packaging	No	Production Use Disposal

Table 3-1 Main Impacts Associated with the Rapeseed Production

Life Stage	Impact Considered?	Impacts not considered
Mineral Oil Production		
Seismic research	No	Impact on whales and dolphins
Production/disposal of rigs	No	Emissions, energy, local impacts
Drilling	Yes	No local impact considered, only energy use, emissions, etc. No effects of large spills, e.g. Nigeria
Distillation	Yes	No local impact considered, only energy use, emissions etc
Impact of the refinery	No	Full EIA needed, likely to be emissions to water, atmosphere, visual impact, noise, odour, social issues
Transportation of the oil	Emissions	Social and local impacts. No effects of large spills e.g. Alaska, Pembrokeshire

Table 3-2 Main Impacts Associated with the Mineral Oil Production

Life Stage	**Impact Considered?**	**Impacts not considered**
Use of Rapeseed in the Machinery		
Length of life of oil	Yes	
Spills	Only amount of oil normally lost due to spills	Localised impacts
Large spill on soil	No	Time taken for soil/flora/ fauna to recover from heat/oil
Large spill near water	No	BOD; fish kill; amount recovered; disposal of recovered oil; disposal of bunding
Large spill on/near road	No	Oil recovery; whether oil gets into drainage systems; disposal of recovered oil; disposal of bunding
Small spill on soil	No	Effect on flora and fauna. Recovery time
Small spill near water	No	Effect on flora and fauna. Recovery time
Small spill on/near road	No	Effect on flora and fauna. Recovery time
Length of life of hydraulic system components	Yes	

Table 3-3 Main Impacts Associated with the Use of Rapeseed in the Machinery

Life Stage	Impact Considered?	Impacts not considered
Use of Mineral oil in the Machinery		
Length of life of oil	Yes	
Spills	Only amount of oil normally lost due to spills	Local impacts
Large spill on soil	No	remediation costs and effects
Large spill near water	No	Time for recovery, disposal of bunds and recovered oil. Fish kill.
Large spill on/near road	No	Oil recovery, whether oil gets into drainage systems, disposal of recovered oil, disposal of bunding
Small spill on soil	No	Recovery time, effects on flora and fauna
Small spill near water	No	Recovery time, can still have large effect on aquatic life
Small spill on/near road	No	Whether it gets into drainage system.
Length of life of hydraulic system components	Yes	

Table 3-4 Main Impacts Associated with the use of Mineral Oil in the Machinery

Life Stage	Impact Considered?	Impacts not considered
Disposal of Machinery etc. using rapeseed oil		
Disposal of oil	Yes	
Disposal of booms if used in a spill	No	Special waste?
Disposal of hydraulic components	No	Dependant on disposal method

Table 3-5 Main Impacts Associated with the Disposal of the Machinery using Rapeseed Oil

Life Stage	Impact Considered?	Impacts not considered
Disposal of Machinery etc. using mineral oil		
Disposal of oil	Yes	
Disposal of booms if used in a spill	No	Special waste?
Disposal of hydraulic components	No	Dependant on disposal method
Disposal of soil if contaminated	No	Remediated or landfilled?

Table 3-6 Main Impacts Associated with the Disposal of the Machinery using Mineral Oil

4 Software Requirements and LCIA Methodology

4.1 Introduction

Once the inventory data for an LCA have been collected there will typically be several hundred pages of input data to be analysed, for which commercially available software exists. The SimaPro package was used in this study.

This chapter gives information about the software used and the databases contained within it. This includes databases for the inventory and the impact assessment stages. Information about the LCIA methodology used in the case studies is also included in this chapter.

4.2 SimaPro

As stated in Burrows et al., (1998) Rice et al., (1997) undertook a review of the main LCA software packages on the market. He concluded that there were only four "serious players" in the market, of which SimaPro was one. SimaPro was chosen for this research on the basis of cost, the incorporated databases and the way in which the data could be analysed and interpreted within the software. Many of the software packages on the market at the beginning of the project would have been acceptable for use in this study. However, SimaPro, developed by PRé consultants, was deemed to be the best overall for the purposes of the project.

The use of software allows different life cycle impact assessment methodologies to be used. SimaPro contains a large database of some of the more commonly used materials and this can be easily amended, updated and added to as extra data become available. The information can be displayed in tabular, graphical and flow chart form and can be exported into other formats. This facilitates transportation and sharing of data and allows results to be presented in an convenient manner. SimaPro allows the LCA to follow the SETAC guidelines and also to comply with the ISO standards.

SimaPro includes different life cycle impact methodologies, and also different characterisation, valuation and normalisation data. According to ISO 14040 and ISO 14042 the use of the LCIA is intended to improve the understanding of results from the inventory stage. Many methodologies have been suggested, even within the scope of the SETAC guidelines. This research has focused on the EcoIndicator 95 methodology but the EcoIndicator 99 method has been used in the sensitivity analysis (Chapter 8) to determine the sensitivity of the results to the different impact assessment methods.

4.3 SimaPro Databases and Methodology

SimaPro contains databases for the Inventory stage of the LCA and for the Impact Assessment stage of the LCA. These will be outlined separately.

4.3.1 Inventory Databases

This section outlines the structure of the databases within SimaPro and the describes the data used within the software.

4.3.1.1 Structure

Within the SimaPro software a ***process record*** is used to define the inputs and outputs of a ***process*** and there is an option to enter additional information. The processes are separated into seven categories

- Material
- Energy
- Transport
- Processing
- Use
- Waste Scenario
- Waste Treatment

Each category has its own sub-categories which can be user-defined. The processes are then grouped in ***process databases*** and ***projects***. Process databases contain processes that can be used in all projects.

The software comes with three standard inventory databases. These contain LCA information about various products and processes. Care must be taken as the data are of wildly varying quality.

4.3.1.2 The PRé Database

This contains data from BUWAL, the Delft University of Technology, the Handbook of Emission Factors, Milieu-inventarisatie verpakkingsmaterialen, Chalmers Insustritechnik, SPIN (RIVM), ETH (Zurich), and PWMI/APME ecoprofiles. Full reference details and ordering information can be found in the SimaPro database manual (PRé 1997).

4.3.1.3 Buwal 250 Database

This was developed by EMPA for a study commissioned for the Swiss Ministry of the Environment (BUWAL). The Buwal Report "Oekoinventare für Verpackungen", Schriftenreihe Umwelt Nr. 250/1+2 can be ordered from BUWAL, Dokumentationsdienst, CH 3003 Bern, Switzerland.

4.3.1.4 IDEMAT database

This was developed by the faculty of Industrial Design Engineering of Delft University of Technology. It is based mainly on Dutch sources: further information, can be obtained from j.a.m.remmers.waal@IO.TUDelft.NL.

4.3.2 Life Cycle Impact Assessment Databases

The most frequently used LCIA within this research, EcoIndicator 95 is based on damage-orientated approach to impact assessment. EcoIndicator 99 is also used as a basis for comparison. EI95 was used during the main study, but EI99 was used in the sensitivity analysis to highlight the impact of using a different assessment methodology. Both of these methods represent a "top down" approach rather than the "bottom up" approach described in the SETAC and ISO standards. The "bottom up" approach is seen in a traditional LCA where the inventory results are listed and then interpreted. The "top down" approach was first mentioned by Braunschweig et al., (1996) and starts by defining the required result of the assessment, for example, the impact towards greenhouse gases or human health. This has been done because PRé Consultants, who developed the SimaPro software, argue that with the bottom up approach it is almost impossible to overcome ambiguity in the weighting procedure. If all the data are collected, classified, and then a weighting is added this will be subjective, as previously discussed. However, they argue that with a top down approach, which is designed around the weighting procedure, this problem is addressed. This research has not used the final valuation stage and so the impact of this difference is not seen in this study.

In EI99 the number of environmental problems is limited to three and the final results are described as damage to human health, to ecosystem quality and to resources. These are easier to comprehend and can give better comparative results than a single number. However, it does mean that if this weighting method is used the definition of additional impact categories to be studied is no longer possible. PRé believe that the top down methodology will steer LCA in the future. This may be the case if people want to assign values to their data, but will probably not happen if the data are left in a more objective state. At present LCA needs to be as objective as possible if it is to be accepted by industry. Additional subjectivity should not be introduced by incorporating extra valuation. A full examination of both methodologies can be found in the PRé literature (PRé, Methodology Report 1999).

4.3.3 EcoIndicator 95

EcoIndicator 95 (EI95) was devised by the Dutch-based PRé Consultants who devised SimaPro and it is a well-known LCIA methodology. In accordance with LCA practice, it examines impacts towards certain environmental issues, namely ozone layer depletion, heavy metals, carcinogens, summer smog, winter smog, pesticides, greenhouse effect, acidification and eutrophication. It also follows the accepted main stages of goal definition, inventory, impact assessment and evaluation (or improvement assessment). PRé has written extensive information about the method, most of which is published in "Eco-Indicator 95, Final Report" which is available from their website (www.pre.nl). However, most of this information deals with the valuation stages of a study which have not been used in this thesis because they are highly subjective. The author argues that it is best to leave the information in as objective a form as possible and let the decision-maker use those data to determine their response. Once the information has been analysed it is then possible to carry out whatever valuation stage is deemed necessary. However, the presentation of a single number to represent an impact can lead to incorrect decisions. For this reason, the data presented in this thesis are mainly shown in a normalised format.

The inventory stage is a data-gathering process and this is not amenable to the use of a software package. Software can provide a method for storing the data that is compatible with other formats and which is transferable, in accordance to the SPOLD methodology. SPOLD outlines that all data in an LCA should be easily accessible and transferable, and suggests a format for data storage so that the LCA database can be built up reasonably quickly. Data availability is one of the major problems within LCA, therefore if an assessment contains a lot of data it makes sense that these should be made available for use within other LCAs.

EI95 makes the following assumptions within its methodology:

- Only those effects that damage human health and ecosystems on a European scale are assessed.
- Raw material depletion and the space needed for waste disposal are not included in any of the valuated results (including the normalised results).
- Emissions from waste processing and raw material extraction are included.
- The impacts felt solely within a workplace are not examined.

The characterisation data used in EI95 are shown in Table 4-1. It is important that this information is shown in any study because the method by which data from the inventory can be allocated into the chosen categories should be clear and not seen as a "black box".

Greenhouse gases			**Ozone Depletion**		
Substance	Weight	Unit	Substance	Weight	Unit
1,1,1-tricholoroethane	100	Kg	1,1,1-trichloroethane	0.12	Kg
CFC (hard)	7100	Kg	CFC (hard)	1	Kg
CFC (soft)	1600	Kg	CFC (soft)	0.055	Kg
CFC-11	3400	Kg	CFC-11	1	Kg
CFC-113	4500	Kg	CFC-113	1.07	Kg
CFC-114	7000	Kg	CFC-114	0.8	Kg
CFC-115	7000	Kg	CFC-115	0.5	Kg
CFC-12	7100	Kg	CFC-12	1	Kg
CFC-13	13000	Kg	CFC-13	1	Kg
CO2	1	Kg	HALON-1201	1.4	Kg
dichloromethane	15	Kg	HALON-1202	1.25	Kg
HALON-1211	4900	Kg	HALON-1211	4	Kg
HALON-1301	4900	Kg	HALON-1301	16	Kg
HCFC-123	90	Kg	HALON-2311	0.14	Kg
HCFC-124	440	Kg	HALON-2401	0.25	Kg
HCFC-141b	580	Kg	HALON-2402	7	Kg
HCFC-142b	1800	Kg	HCFC-123	0.02	Kg
HCFC-22	1600	Kg	HCFC-124	0.022	Kg
HFC-125	3400	Kg	HCFC-141b	0.11	Kg
HFC-134a	1200	Kg	HCFC-22	0.055	Kg
HFC-143a	3800	Kg	HCFC-225ca	0.025	Kg
HFC-152a	150	Kg	HCFC-225cb	0.033	Kg
Methane	11	Kg	Methyl bromide	0.6	Kg
N20	270	Kg	tetrachloromethane	1.08	Kg
tetrachloromethane	1300	Kg	**Acidification**		
trichloromethane	35	Kg	ammonia	1.88	Kg
Summer Smog			HCl	0.88	Kg
1,1,1-trichloroethane	0.021	Kg	HF	1.6	Kg
1,2-dichloroethane	0.021	Kg	NO	1.07	Kg
acetone	0.178	Kg	NO2	0.7	Kg
acetylene	0.168	Kg	NOx	0.7	Kg
alcohols	0.196	Kg	SO2	1	Kg

aldehydes	0.443	Kg	SOx	1	Kg
benzene	0.189	Kg	**Eutrophication**		
caprolactam	0.761	Kg	ammonia	0.33	Kg
Chlorophenols	0.761	Kg	nitrates	0.42	Kg
Crude oil	0.398	Kg	NO	0.2	Kg
CxHy	0.398	Kg	NO2	0.13	Kg
CxHy aliphatic	0.398	Kg	NOx	0.13	Kg
CxHy aromatic	0.761	Kg	phosphate	1	Kg
CxHy chloro	0.021	Kg	COD	0.022	Kg
dichloromethane	0.021	Kg	NH3	0.33	Kg
Diethyl ether	0.398	Kg	NH4+	0.33	Kg
Diphenyl	0.761	Kg	Ntot	0.42	Kg
ethanol	0.268	Kg	phosphate	1	Kg
ethene	1	Kg	Ptot	3.06	Kg
Ethylene glycol	0.196	Kg	**Heavy Metals**		
Ethylene oxide	0.377	Kg	Cadmium oxide	50	Kg
formaldehyde	0.421	Kg	Cd	50	kg
Hexachlorobiphenyl	0.761	Kg	Heavy metals	1	Kg
Hydroxy compounds	0.377	Kg	Hg	1	Kg
isopropanol	0.196	Kg	Mn	1	Kg
ketones	0.326	Kg	Pb	1	Kg
methane	0.007	Kg	As	1	Kg
Methyl ethyl ketone	0.473	Kg	B	0.03	Kg
Methyl mercaptane	0.377	Kg	Ba	0.14	Kg
naphthalene	0.761	Kg	Cd	3	Kg
Non methane VOC	0.461	Kg	Cr	0.2	Kg
PAH	0.761	Kg	Cu	0.005	Kg
pentane	0.408	Kg	Hg	10	Kg
petrol	0.378	Kg	Mn	0.02	Kg
phenol	0.761	Kg	Mo	0.14	Kg
Phthalic acid anhydride	0.761	Kg	Ni	0.5	Kg
propane	0.42	Kg	Pb	1	Kg
propene	1.03	Kg	Sb	2	Kg
Propoinaldehyde (propanal)	0.603	Kg	**Carcinogens**		
styrene	0.761	Kg	As	0.0044	Kg
terpentine	0.377	Kg	Benzene	0.000011	Kg
tetrachloromethane	0.021	Kg	Benzo[a]pyrene	1	Kg
toluene	0.563	Kg	Cr(6+)	0.44	Kg
trichloroethene	0.066	Kg	CxHy aromatic	0.000011	Kg
vinylacetate	0.223	Kg	ethylbenzene	0.000011	Kg
vinylchloride	0.021	Kg	fluranthene	1	Kg
VOC	0.398	Kg	Ni	0.44	Kg
xylene	0.85	Kg	PAH	1	Kg
Winter Smog			tar	0.000011	Kg
Dust (SPM)	1	Kg	**Pesticides**		
SO2	1	Kg	Disinfectants	1	Kg
Soot	1	Kg	Fungicides	1	Kg
			Herbicides	1	kg
			Insecticides	1	kg

Table 4-1 EI95 Characterisation Data

A detailed description of the methods for obtaining the characterisation data shown in Table 4-1 is given in the EI95 guide and is not repeated here. The method is not perfect, but it is one which is widely used. It has been updated and improved as new data have been collected and as new scientific research about the effects different chemicals and materials have on the environment is published. Some of this has been incorporated directly into EI95, and some into the new EI99 methodology.

4.3.3.1 Normalisation

Normalisation is a relatively objective step that allows an illustration of what effects are "important" in the environmental issues studied. It allows a more understandable value to be quoted when talking about LCA results. A value of 200kg of CO_2 equivalents is meaningful when compared with other values of carbon dioxide equivalents, but it is not helpful when compared with 200kg of CFC-11 equivalents for ozone depletion. The former may have a significantly different effect on global warming than the latter will have on ozone depletion. Therefore a normalisation stage should be incorporated to ensure that the numbers are more meaningful. In general, normalised data are compared with the total emissions of that particular material or the total use of the raw material in the country or area examined. This is the method that has been used in this research, the resultant unit is the "people emission equivalents" which is determined as follows:

$$\text{European emissions per capita} = \frac{\text{Total European output in each emission category}}{\text{Population of Europe}}$$

$$\therefore \text{People emission equivalents} = \frac{\text{Emissions from the process studied}}{\text{European emissions per capita}}$$

The data can also be compared with legislative limits for the particular emission or raw material. This legislation is generally set at similar levels for each of the impact categories. Data for the normalisation stage in EI95 were taken from a number of European sources. These are fully analysed within the PRé report. When data for a European country was missing a total emission was extrapolated based on the country's energy consumption on the basis that the energy consumption reflects the country's industrial structure and therefore its emission patterns. Eastern and Western European countries were calculated separately and then combined. Table 4-2 shows the final normalisation values used in EI95.

	Unit	Western Europe	Eastern Europe	Total	Per head of the population	Uncertainty
Greenhouse Effect	GWP kg	$4.8x10^{12}$	$1.7x10^{12}$	$6.5x10^{12}$	$1.31x10^{4}$	Small
Ozone layer depletion	ODP kg	$3.7x10^{8}$	$9.4x10^{7}$	$4.6x10^{8}$	$9.26x10^{-1}$	Large
Acidification	AP kg	$3.5x10^{10}$	$2.1x10^{10}$	$5.6x10^{10}$	$1.13x10^{2}$	Small
Eutrophication	NP kg	$1.4x10^{10}$	$5.1x10^{9}$	$1.9x10^{10}$	3.82	Moderate
Heavy Metals	Pb equiv. Kg	$2.1x10^{7}$	$5.9x10^{6}$	$2.7x10^{10}$	$5.43x10^{-2}$	Large
Carcinogens	PAH equiv. Kg	$4.3x10^{6}$	$1.1x10^{6}$	$5.4x10^{6}$	$1.09x10^{-2}$	Large
Winter Smog	SO2 equiv. Kg	$2.3x10^{10}$	$2.3x10^{10}$	$4.7x10^{10}$	$9.46x10^{1}$	Small
Summer Smog	POCP kg	$7x10^{9}$	$1.9x10^{9}$	$8.9x10^{9}$	$1.79x10^{1}$	Large
Pesticides	Activ ingr. kg	$3.8x10^{8}$	$9.8x10^{7}$	$4.8x10^{8}$	$9.66x10^{-1}$	Large

Table 4-2 Normalised Data. From The Eco-Indicator 95, Final Report.

The normalised data show that an amount of CO_2 equivalents and CFC-11 equivalents have different effects on their receiving environments. The previously used example of 200kg of CO_2 equivalents would produce a normalised value of $200 \times 1.31\times10^4 = 262 \times10^4$ GWP (Global Warming Potential) for greenhouse gases compared with a value of $200 \times 9.26\times10^{-1} = 185.2$ ODP (Ozone Depletion Potential) for the ozone depletion. It is these numbers that should be used to obtain an overview of the relative importance of contributions to the environmental issues under consideration.

Characterised data can be used to compare the same impact between different studies. Normalised data can be used to compare different environmental impacts within a study. It can also be used as a comparison between two or more studies.

Further valuation and weighting techniques can be used in SimaPro. These weighting techniques add together the normalised or characterised data in order to produce a single score number "answer" for the LCA which is subjective and is not used in this study. Many people use this weighting stage in order to make decisions between two products or methods but ISO 14042 states that single score weighting values should never be used in comparative assertions disclosed to the public. In this thesis the results are left in a normalised form, hence a detailed description of the weighting processes involved in the valuation stages is not included.

SimaPro allows the characterisation and normalisation data within the system to be changed thereby enhancing the adaptability of the software, for example, to include environmental impacts not considered within a previous study.

4.3.4 EcoIndicator 99.

EcoIndicator 99, or EI99, is used within this thesis as a comparative mechanism to show the different results that can be reached when using different LCIA methodologies (see Chapter 8), but it has not been used elsewhere. EI99 differs from EI95 in its approach to the LCIA stage of LCA and also considers different environmental impact categories; most notably it includes land use and raw material use which should be considered in an LCA. The use of raw materials is important when examining the sustainability of a product, and the use of land is becoming a very important issue, especially in European countries where land is a scarce commodity. Although these are welcome additions to the methodology it must be noted that the data used to produce these categories are not necessarily of a high enough standard to use conclusively in an LCA study. For example, land use in EI99 is determined by the local and regional effect of land conversion, and the local and regional effect of land occupation. However, these data are based on the Dutch environment, and is unlikely to be representative of all countries in Europe. Determination of the local impact of land occupancy and conversion is very difficult.

4.3.4.1 Cultural Theory

One of the other main differences in the EI99 method compared with EI95 is the incorporation of cultural theory which originated from Hofstetter (1998). According to this theory there are five types of people: fatalists, hierarchists, egalitarians, individualists and autonomists. The theory examines the strength these people have, their peer group and the degree an individual's life is influenced by externally imposed prescriptions. According to PRé these types of people can be summarised by their characteristics:

1) **Individualists**: they are free from strong links to both their group and externalities. All limits are provisional and subject to negotiation. Individualists are often relatively free of control by others but are often engaged in controlling others.

2) **Egalitarians**: they have a strong link to the group, but a weak link to externalities. There is no internal role differentiation and relationships between group members are often ambiguous. Conflicts can occur easily.

3) **Hierarchists**: they have a strong link to the group and externalities. People are both controlled by others and control others. The hierarchy creates a high degree of stability in the group.

4) **Fatalists**: they have a strong relation to externalities but not to the group. These people act individually and are usually controlled by others.

5) **Autonomists**: this is the smallest group and it is assumed that they escape the manipulative forces of both externalities and their peer group. They neither control or are controlled.

The first three groups can be modelled and are used within SimaPro's cultural theory in EI99. Fatalists and Autonomists are not included because they have no real opinion or preferences that can be captured as a group. The basic attitudes of the first three groups are shown in Table 4-3.

Archetypes: Predictions:	Egalitarian	Individualist	Hierarchist
Criteria	Argument	Experience	Evidence
Management Style	Preventative	Adaptive	Control
Distribution	Parity	Priority	Proportionality
Perception of time	Long term dominates short term	Short term dominates long term	Balanced distinction between short and long term
Intergeneration responsibility	Present < future	Present > future	Present = future
View of resources	Depleting	Abundant	Scarce
Perception of needs and resources	Can manage needs, but not resources	Can manage needs and resources	Can manage needs, but not resources
Energy future	Low growth (radical change now)	Business as usual	Middle of the road (technical fix)
Attitude to nature	Attentive	Laissez-faire	Regulatory
Attitude towards humans	Construct egalitarian society	Channel rather than change	Restrict behaviour
Attitude towards resources	Need reducing strategy	Manage needs and resources	Increase resources
Perception (myth) of nature	Natural ephemeral	Nature benign	Nature perverse/tolerant
Perception of human nature	Born good, malleable	Self seeking	Sinful
Attitudes towards risk	Risk averse	Risk seeking	Risk accepting

Table 4-3 Cultural theory perspectives, from EI99 Methodology Report

These differences may have an impact on the way an LCIA is carried out. In SimaPro these cultural theories have been transformed into the following different methodologies to avoid unwitting bias by an investigation.

1) **Individualist Version**: Only proven cause and effect data are included. When there is a choice, the short-term perspective is taken. For human health issues, age weighting is used as a person is valued higher between the ages of 20 – 40. The impact of resource loss is not considered in any of the weighting stages, because future loss of raw materials is not thought to be a problem to the individualist.

2) **Hierarchical Version**: Only facts that can be backed up by recognised scientific and political bodies are included. This attitude is common amongst politicians and within scientific communities; a typical example is the wide acceptance of the IPCC (Intergovernmental Panel on Climate Change) guidelines for climate change. This is the default version recommended method within SimaPro.

3) **Egalitarian Version**: The precautionary principle is adopted. If anything is in doubt it is included. A very long time perspective is taken. This is the most comprehensive version of the methodologies, but it also has the most data uncertainties.

In the past it was possible that people chose these perspectives unknowingly. Now the perspectives are clear to the user and the reader. The different versions could be used by people with different beliefs about what is and what is not important. The hierarchical version is recommended as a default as this is seen as the "middle of the road" method. This method has been adopted in this research, and is used in Chapter 8. A comparison of the different results given by the three methods is made in Chapter 8.

4.3.5 EI95 and EI99

EI95 represents the traditional method of LCA. EI99 incorporates more features and also more environmental categories. Although the addition of these categories is welcome, in many cases there is insufficient data to back up the methodology at this point in time. The ability to determine the damage a product or system will have is welcome with the incorporation of the three types of environmental damage - human health, ecosystem quality and resources. However, again it is possible that this can be misused as any damage is dependant on the receiving environment and this can be overlooked very easily when using this tool.

The incorporation of the cultural values into the methodology is a good way to ensure that assumptions made about the data used in the characterisation stage are minimised. However, the differences shown in Chapter 8 resulting from this are very small. Data inaccuracy in the inventory data is still far more significant than the sensitivity resulting from the differences in cultural perspective. It is important to minimise all possible data sensitivities, but perspective must be maintained over the importance of the role of cultural theory.

EI99 will become the more commonly used tool, but at the moment the data quality behind EI95 is better.

4.4 Disadvantages in the use of software

There are a number of disadvantages associated with the use of software:

- *The black box problem*

  Results can be generated very easily and quickly and users may be lulled into a false sense of security, thinking that the results are accurate and complete when they are not.

- *Not understanding the process*

  Untrained people can easily produce "LCAs" without understanding the process. This could lead to inaccurate LCAs being produced.

- *Data quality*

  Results can be obtained as soon as any data are put into a database, but this gives no assurance of its usefulness.

4.5 Concluding Remarks

Software packages allow a user to apply techniques and methodologies that would not otherwise be practical. For example, it would not be practicable to compare and contrast different LCIA methods without the use of a software package. It allows non-expert users to undertake LCA but care must be taken in the interpretation of the results.

LCA is a time-consuming process, requiring a lot of data. Whilst software allows everyone to get results quickly, it must be remembered that gathering sufficient data for a complete LCA takes diligence. An LCA study should include information about where the data were obtained and how accurate the data are. The fact that software can produce fast results should not be taken as an indication that a reliable LCA can be carried out in a short period of time.

SimaPro was chosen or this study as it has been used in many peer reviewed LCA studies and has a good reputation amongst academics and industrialists. The methodologies in SimaPro broadly comply with the ISO Standards for the LCIA stage. They allow examination of the results at all stages in the LCA and outcomes can be analysed before or after the valuation stage. This allows the user to decide to what stage they want to take the impact assessment.

EcoIndicator 95 and EcoIndicator 99 were used in this study for several reasons:

- They contained characterisation data from well respected sources.
- As tools for impact assessment methods they are well respected in the academic press.
- These methods are used extensively and allow comparison of methodologies with other LCA studies.

The software used enabled the research to focus on technical issues associated with LCA rather than on writing software. No commercially available LCA software is perfect, but it does allow the assessment to be carried out in a more manageable manner.

This chapter has outlined the methods used within the software, what it allows one to do and what it cannot do. The problems associated with the use of software as well as the benefits have been discussed.

5 Introduction to Fluid Power Systems

5.1 Introduction

This project is part of a research programme undertaken in the Engineering Design Centre in Fluid Power Systems at the University of Bath. Hydraulic power is transmitted by controlled circulation of a pressurised fluid to a motor that converts it into a mechanical output. Hydraulic systems have a greater flexibility than mechanical or electrical systems. Brahmah was the first to exploit this power in 1795 (Burrows, 1995) when he produced a press that was used to crush seeds to produce vegetable oil. These original systems used water but as early as 1858 problems associated with the freezing of the water were addressed with the addition of methylated spirits. The fluid changed to mineral oil as the hydraulic specifications became too demanding for the water run systems. However, in recent years concern for the environment has led to a re-introduction of water-based systems, particularly by Danfoss, as well as the introduction of biodegradable oil based systems.

Use of biodegradable fluid has implications for fluid power systems (see for example, Burrows, 2000; M^cManus et al., 2000(a&b) and Hudson, 1999). A key need is to examine the environmental benefits claimed for biodegradable fluid against the backdrop of these issues. In this research this has been achieved through the use of LCA.

5.2 Mobile Fluid Power Applications

Hydrostatic systems are used extensively in mobile systems (forestry equipment, excavators, etc.) because of the inherent factor of high power to weight ratio and their versatility. However, the use of fluid power units in mobile systems poses problems that do not arise in static units. In static installations it is easier to protect pipes and hoses and they are not subject to the same levels of vibration as in mobile equipment. Mobile equipment makes extensive use of hoses which are one of the most easily damaged components. This must be recognised when considering system design, for example, it is necessary to ensure that there is full freedom of movement to prevent damage to the hose, whilst avoiding the possibility of snagging.

Mobile systems are subjected to more extremes of temperature than static systems which imposes design constraints. Also they are often designed to obtain the maximum power from the smallest and lightest unit (John Deere, 1992). Constant operation at the limit of performance leads to mobile equipment being more prone to develop leaks compared with static systems. This is exacerbated by high levels of vibration. The difficulty of designing ideally leak-free mobile equipment has led manufacturers to examine the use of biodegradable fluids. Instinctively, it is felt that if there is a spill of hydraulic oil then the environmental consequences will be less if the oil is biodegradable. This is discussed further in Sections 3.2.2 and 5.9. Biodegradable fluids are being used more extensively, thus the current study has been undertaken to evaluate the true overall environmental impacts of the oils used in mobile applications.

Ideally systems should be leak-free: that is the best environmental option. However, in spite of extensive research, leakage is still a fundamental issue in hydraulic systems and poor maintenance is a major contributory factor. Experience has shown that the quality of the maintenance of mobile equipment is often far from satisfactory. The research described here is not concerned with trying to improve upon hydraulic design in terms of leaks; rather, it is an attempt to establish the true environmental impacts of the use of different types of oil in hydraulic systems. This information can then be used to improve the usage and the design of hydraulic systems for the whole life impact of the machine.

5.3 The purpose of a Hydraulic Fluid

The primary duty of a hydraulic fluid is to transfer energy but there are further requirements placed upon a fluid in modern, high pressure and high temperature hydraulic machines. It is important that the fluids have high lubricity and are not corrosive. These requirements resulted in the initial move from traditional water hydraulics towards mineral oil although even in the 19^{th} Century, experiments were made with additives to modify the fluid properties. Mineral oils are highly flammable and have minimal biodegradation properties. A range of fire resistant fluids have been used but these are often environmentally aggressive. With the current increase in concern for the environment, the lack of rapid biodegradation has led to a surge of interest in "biodegradable" hydraulic fluids. Mineral oils are *inherently* biodegradable, but only over a long period of time and they do not meet important aspects of environmental acceptability, for example, aquatic toxicity (Marougy & Helduser, 1992). Biodegradable fluids are designed to biodegrade rapidly, and have been prepared to meet stringent criteria; they should not pollute groundwater, soil or surface water when accidentally leaked from hydraulic machines. The use of biodegradable fluids is becoming more common; especially in mobile machines, such as tractors, forestry machinery and reed-cutting machines.

Hydrostatic systems operate with relatively large volumes of oil under high pressure and so, if there is a spillage large volumes of oil may escape and pollute the environment. It is for this reason that many forestry machine users, particularly in Scandinavian and Germanic countries, are now using the more readily biodegrading oil.

5.4 Fluid Properties

There are many properties to consider when choosing hydraulic oil. The main considerations are outlined here (from FP1, University of Bath):

5.4.1 Viscosity Index

The viscosity of the fluid is the first thing to consider and the primary factor is the requirements of the pump. The viscosity index affects the operating conditions and is the deciding factor when choosing an oil.

5.4.2 Wear protection

Anti wear additives are usually added to base oil in order to enhance the natural protection provided.

5.4.3 Foam prevention

If the fluid foams in the reservoir then the foam will be drawn into the pump or other components. This can lead to high wear rates, as there will be insufficient lubrication.

5.4.4 Air release

If entrained air is not released quickly from the reservoir it can cause oil and air bubbles to form. In high-pressure situations this can ignite and cause spherical carbon products. The oil turns black and the filters block. The system can then fail.

5.4.5 Demulsibility

If oil becomes contaminated with water it is desirable for the water to be able to separate readily so that it can be drained off.

5.4.6 *Corrosion control*

It is necessary to protect the components of the hydraulic system from corrosion. Additive packages are usually added to the base oil to enable this.

5.4.7 *Thermal stability*

Fluids need to be able to withstand high temperatures without breaking down or oxidising.

5.4.8 *Pour point*

This is the temperature at which the oil solidifies. It needs to be considered in relation to cold starts and storage conditions.

5.4.9 *Hydrolytic stability*

If the oil becomes contaminated with water the fluid (including the additives) should be stable enough not to react and form deposits that can block filters.

5.4.10 *Shear stability*

This is related to oils with additives such as viscosity index (VI) improvers. These additives are polymers and can be sheared in pumps and valves. It is important to choose additives that are resistant to shearing. Otherwise, the additives will not last in the system and will become useless very quickly.

5.4.11 *Seal compatibility*

The oils and additives should be compatible with the seal (and hose) material that is in common use. Otherwise it is possible that these materials will degrade and there will be leakage and/or system failure.

5.5 *Mineral Oil Fluids*

Mineral oils are still the most commonly used hydraulic fluid. They are relatively inexpensive, are widely available and can be offered in suitable viscosity grades. They are inherently biodegradable, but are not readily biodegradable, and they are not sustainable. The optimal temperature for mineral oil use is 40°C: above and below this temperature they can suffer chemical breakdown with a loss of lubrication. Lower temperatures usually result in higher pressure losses. However, waxes can be produced that block filters. Most mineral oils contain an additive package that counteracts this problem. In general, mineral-based hydraulic oils can be produced with a number of additive packages. These packages enable mineral-based oil to be satisfactorily used in all hydraulic systems, but the addition may be particularly harmful to the environment.

5.6 Biodegradable Fluids

There are two main types of biodegradable fluids:

1. Those based on vegetable oils
2. Those based on synthetic fluids (these can either be mineral- or vegetable-based, and it is often difficult to ascertain the source of the base fluid)

Those based on vegetable fluids (normally rapeseed oil) are called natural esters and are given the designation HETG. Those based on synthetic fluids can either be ester (HEES) or Polyglycol (HEPG) (H = hydraulic, E = environmental, TG = triclycerid, ES = esteroil synthetic, PG = polyalynglycol).

5.6.1 Vegetable fluids (HETG)

Rapeseed oil is readily biodegradable and is classed as non-toxic. There are many advantages to the use of rapeseed from an economic point of view; the government is trying to reduce dependence on imports and also to reduce the overproduction of food by farmers. Therefore, there have been incentives, in the form of grants given to farmers to grow non-food crops, for example rapeseed, in their fields. The U.K. Government has been looking at the possibility of using more crops for energy purposes (see for example M^{c}Manus et al., (1999) and Parliamentary Office of Science and Technology, (1995)). Rapeseed hydraulic oil is about twice as expensive as mineral oil but it is the least expensive of the "environmentally friendly" oils.

5.6.2 Synthetic esters (HEES)

These have good technical properties as well as environmental acceptability. The cost of these fluids is approximately five times higher than mineral oils, and so to date their use has been minimal in most countries. However, synthetic ester has a longer useful life than mineral oil and so some of the higher costs can be offset. It is generally thought that synthetic esters are the best of the environmentally friendly fluids because they last well in hydraulic systems but no production data for these fluids could be obtained so they have not been included in this study.

5.6.3 *Polyglycols (HEPG)*

Polyglycols were used a number of years ago, but their use is in decline due to incompatibility with mineral oil and also incompatibility with some sealing materials and paints. Polyglycols do, however, have exceptional temperature stability, from -45°C to +250°C. Different oils would not generally be used in the same system, if a user wished to change from mineral oil to a polyglycol the machine would have to be completely stripped down and cleaned which is prohibitively expensive.

5.7 *The Performance of Rapeseed and Mineral oil within Hydraulic Systems*

Mineral oil and rapeseed oil will be compared within this study. The use of synthetic esters has not been considered due to the lack of data about their production. Mineral and rapeseed oils do not have the same performance characteristics when used within hydraulic systems. This is a controversial issue, with some manufacturers claiming that rapeseed oil does not need to be replaced any more frequently than mineral oil and some users claiming that the fluid needs to be replaced three times as often as mineral oil. As the use of rapeseed oil is still a relatively new and uncommon occurrence it is difficult to obtain accurate data for this. Marougy & Helduser (1992) from Vickers Hydraulics carried out some wear tests on environmentally acceptable fluids. Two anti-wear tests were carried out based on the vane pump test with Vickers pump V-104-C10 standardised in DIN 51389 and the ASTM D2882-83 and IP 281/72, and the FZG-Gear-rig test, DIN 51354/2. These tests showed excellent anti-wear properties for the rapeseed oil. The results showed that rapeseed oil could perform as well as mineral oil. These tests were carried out with "new" rapeseed oil and there was no testing done on how the oil would perform when the fluid starts to age or becomes contaminated. The total lifetime of the fluid was not addressed in the study. However, the paper does point out that if the vegetable oil were contaminated with a few percent of a high-dispersancy lubricant then the hydraulic system would fail due to a loss of lubricity. Vickers went on to field trials and examined the use of the rapeseed oil within a forwarder machine. A PVE35 piston pump was tested with rapeseed oil. After 3500 hours of service there was no obvious wear of the pump. Cheng et al. (1992) also carried out tests on a vegetable oil. These tests showed excellent properties for the oil in most cases, apart from the durability tests. Here the results indicated that if vegetable oil were to be used in a system where the fluids were expected to work over a long period of time there may be problems with the wear pattern of the hydraulic fluids. These tests were performed at a temperature of 70°C. Many applications run at a higher temperature than this. Eichenberg (1994) has concluded that rapeseed oil is a good hydraulic fluid, but the high temperature stability is critical. According to Eichenberg, high temperature operation causes oxidation, oil deterioration and viscosity increase. Low temperatures cause thickening of the oil which reduces the capability of the oil to flow in the machine.

Few studies have compared directly the use of mineral and rapeseed (or any biodegradable fluids) in hydraulic systems. Some have compared the use of biodegradable fluids, but few have included the use of mineral oils (with the exception of Hudson, 1999). For this reason it is very difficult to determine the exact comparability of the fluids. Much information has been gathered informally through conferences and meetings. Many workers, for example, Lämsä (1999) and Whightman et al., (1999) have stated that rapeseed oil performs as well as mineral oil in hydraulic systems. Although documented evidence for this was requested by the author none was received. Some users (for example, in the Forestry Commission, the National Trust for Scotland, and Bath and North East Somerset Council (BANES)) have stated that they need to replace rapeseed oil and some of the hydraulic components more frequently than they would if they were using mineral oil. The stated rate of change varied from one-and-a-half times to three times as frequently. It is therefore difficult to determine exactly how often the hydraulic fluids have to be changed.

Much informal advice was obtained by the author through meetings with industry at the University of Bath. The research described here was performed within the Engineering Design Centre (EDC) in Fluid Power Systems. The research was part of a large research programme in the design of fluid power systems for which a "Steering Group" of industrialists was set up. Part of their role was to review the research at four-monthly intervals. The steering group consisted of senior industrialists with a specialist knowledge in fluid power. Thus any assumptions made within this research have been discussed with the steering committee at regular intervals. A list of the members of the steering committee and their affiliations is shown in Appendix 2.

Sauer Sundstrand who were part of the Steering Group, performed a comparison of the use of mineral, rapeseed and synthetic esters in hydraulic pumps (Hudson, 1999) as part of a product development programme. The performance of the mineral oil varied little across the tests, and was satisfactory in all tests. Two rapeseed oils were tested. One was successful when tested at 50°C, one failed. Neither type of rapeseed oil met performance requirements when tested at temperatures above 50°C.

Laboratory testing (Hudson, 1999) showed that rapeseed oil did not perform as well as mineral oil at high temperatures and pressures. Rapeseed oil was shown also to degrade faster than mineral oil. Some manufacturers stated that the oil performed as well as mineral oil, but did not substantiate their claims with data. Informal meetings with hydraulic system users elicited the information that rapeseed oil-run systems use between one-and-a-half and three times as much oil as those run on mineral oil. For this LCA study, therefore, it has been assumed that the rapeseed oil will be replaced twice as often as mineral oil when used in a hydraulic system. The consequences of this are shown in Chapter 8. It is also assumed that the components in a hydraulic system will be replaced once for a system running on mineral oil and twice for a system running on rapeseed oil. This is an over-simplification as some components in the system will be replaced more than this and some not at all. However, this was thought to be an adequate representation of the maintenance schedule. A sensitivity analysis (shown in Chapter 9) has been carried out showing the results of the case studies if the rapeseed oil were replaced at the same rate as the mineral oil, one-and-a-half times as frequently, and three times as frequently in the life of the machine.

The differences in opinion concerning the performance of rapeseed oil is due to many things. Rapeseed fluids are not always consistent in their performance due to the additives and the quality of the base oil. This can vary from one crop to another and from one year to the next depending on weather, storage and treatment conditions. Also, the performance of the rapeseed depends on the way in which it is used within a system. Although manufacturers of fluids and equipment set out maintenance schedules, it is probable that in many situations these are not strictly adhered to. If a system running on mineral oil is not maintained accurately according to specification, in many cases this will not lead to operational problems. This may not be the case for systems running on rapeseed oil. Systems running on rapeseed oil may well be able to perform to the same specifications as mineral oil if maintained properly and used at low temperatures and pressures.

Information about the replacement frequency of rapeseed oil was obtained from people in the field, responsible for specific hydraulic equipment. It is possible that these machines are subjected to far harsher conditions than those used in laboratory tests.

Moreover, in the field operators are not always careful when topping-up systems so there can be an ingress of contaminants which lead to system degradation. Tests have shown that at constant temperatures some rapeseed oils can perform well, but at low temperatures the oil thickens, and at high temperatures the oil can degrade and cause problems. The machines examined in this study were used and often stored outside. The contrast between low overnight temperatures and high working temperatures may cause the oil to perform less well than anticipated but this suggestion has not been tested. Data concerning the performance of rapeseed oil are hard to obtain but opinions on the performance of the oil are plentiful. This research proceeded by using the best information available and subjected the outcome to critical appraisal both at internal meetings with industrialists and at major conferences.

5.8 *Fluid Power System Maintenance*

Fluid power system maintenance starts before the oil is put into the system. Oil drums should be stored in a horizontal position to prevent water or other contaminants collecting around the bung. The fluid should also be pre-filtered before being added to the system.

Once the oil is in the system it is important that it is examined at regular intervals. The frequency of these intervals depends on the machine and its operational schedule. In general manufacturers will specify an oil change after a certain number of hours, some will specify that a sample of the oil should be sent back to a laboratory for testing to determine if it needs replacing. Filters in the system also need replacement at regular intervals. If the filters are not maintained well the system will become contaminated. Small particles in the oil can severely damage hydraulic components. It is well known that in some fields of application, for example, farm machinery, poor maintenance is a major factor in machine malfunction.

Other hydraulic components will need servicing and possible replacement, and must be included in the maintenance schedule. The frequency with which these need to be replaced is in many respects correlated with how well the rest of the maintenance programme is carried out and also to environmental factors. If the system is kept clean, with filters regularly checked and replaced then the replacement rates for the oils and components will be reduced.

5.9 Local Impacts

The reason that some machines are being switched to operate on biodegradable fluids is due to the environmental impact when mineral oil is spilled from a system. When rapeseed oil is spilled into the environment it will biodegrade faster than a spillage of mineral oil, but more importantly, the biodegradable fluid is less toxic than mineral oil. Both mineral and rapeseed oil can be removed with booms if spilled in a river if the clean up takes place immediately. Mineral oil can then sometimes be reused but the rapeseed oil will be contaminated with water and cannot be reused. A large spill of either fluid will cause ecological damage. If spilled into a waterway and not cleared up, rapeseed oil will biodegrade quickly. This may cause a depletion of oxygen in the water and cause damage to the local ecology. The effect will depend on the amount of oil spilt and the size and sensitivity of the receiving environment. A small amount of mineral oil can cause significant damage to a waterway as it will cover the water very quickly denying oxygen to the local ecology. Recovery is more rapid from a spill of rapeseed oil on soil than it is from a spill of mineral oil. Large mineral oil spills in soil may result in contaminated land which is very costly to remediate.

It is worth noting that a spill of either type of oil will result in ecological and environmental damage. Oil is released at high temperature and pressure, therefore plants and animals will be burned and scorched with a significant spill of oil of any type. The use of rapeseed oil within a system is not a licence to minimise maintenance procedures and worry less about spillage into the environment. Spillage of rapeseed oil may result in a faster recovery, but it will still cause environmental damage.

5.10 Concluding Remarks

There are many properties to be considered when choosing a hydraulic oil. Synthetic esters are perhaps the best biodegradable oil, but have not been examined in this research as there are little data available. The performance properties of rapeseed oil are very controversial and it is difficult to access independent research in this area. All the assumptions made in this research about the use of the rapeseed in fluid power systems have been discussed with the EDC Steering Group at the University of Bath to enable a balanced view to be taken. However, as the performance data are so controversial a full sensitivity analysis has been carried out as discussed in Chapter 8 in an additional attempt to ensure objectivity.

The maintenance of fluid power equipment and of the oil plays a crucial part in the performance of the fluids. To maintain the best working conditions of the fluids and the equipment it is important that the systems undergo regular maintenance checks.

It will be necessary to reassess the outcome of the research when biodegradable fluids have been in use for a longer period of time and in a wider range of applications. That may lead to manufacturers of the fluids and hydraulic equipment being less protective of the performance data that are collected. The data availability then may extend to data for synthetic esters which could then also be considered in the study. Results, ideally free from commercial content, will then help to populate more densely the available databases.

6 Production of the Hydraulic Fluids

6.1 *Introduction*

This chapter outlines the methods used to determine the impact of the production of the rapeseed and mineral oils. The results obtained in this chapter are then incorporated into the following chapter to assess the total environmental impact of the case studies examined.

As previously discussed, there are many different types of hydraulic fluids used within the fluid power industry. These can be categorised as: mineral oil; fire resistant (water based and non-water based) and ecologically acceptable. Within the ecologically acceptable group of oils there are further subdivisions, the main ones being synthetic esters and vegetable oils. In general the vegetable oils are rapeseed, but can be olive or linseed. This chapter outlines the processes involved in the production of both mineral and rapeseed oils. For mineral oil, this covers the extraction of the mineral oil from the ground, its transport, storage, refining and processing. For the rapeseed oil it covers the growth of the seed, transportation, drying and crushing.

The data for the production of mineral oil are less detailed than those for rapeseed oil; the data for the former oil are not broken up into stages of extraction, distillation and refining. This is perhaps because mineral oil is a traditional product and older data have been used and updated in order to assess environmental effects. Each stage is complex and has not been independently researched, and where it has, the data have not been made publicly available. It should be emphasised that this does not necessarily mean that the available data are inaccurate, but the lack of detail about the separate stages of production is a shortcoming. The discrepancy between the level of detail in the data for the two oils is common to many studies comparing mineral and rapeseed products, e.g. Ceuterick and Spirinckx (1997), and Wightman et al., (1999).

6.2 *Methodology and Data*

The biggest problem encountered during this study was the lack of data. Many contacts were made through the university, at conferences and through papers published in related fields. Despite many promises of help it was, in general, unforthcoming. In any LCA the data gathering phase is the hardest and longest stage and that was the case in this study. The original intention was to include the use of synthetic esters. Information about the use and the disposal of these oils was available but there were no data for their production. A month-long trip to the Technical University of Braunschweig, Germany, was made in order to gather such information but this proved no more successful than efforts on the UK.

6.2.1 Mineral Oil

6.2.1.1 Mineral Oil Data

The data for this stage of the LCA were collected in a number of ways. Unfortunately oil companies rarely want to give out information about their processes, emissions and raw materials, therefore up-to-date data collection is rarely possible. Information about mineral oil production processes was gained through personal communications with representatives of oil companies and through the industrial liaison group at the University of Bath. Although many of these conversations ended with a promise of data, nobody honoured their promise despite being reminded. Therefore, previously published data had to be used, some of which were published in 1993, making it probable that they were ten years out of date. During that period the methods for production may have changed but this could not be accounted for. Newer data were used for the frequency of oil spills because the method of reporting oil spillage changed in the mid 1990s from a system where industry reported events to a system in which spillage was detected by satellite. Unsurprisingly the amount of recorded spills rapidly increased!

6.2.1.2 Mineral Oil Methodology

After the mineral oil data had been collected they were entered into the SimaPro software. The data were entered into one data sheet.

6.2.2 Rapeseed Oil

6.2.2.1 Rapeseed Oil Data

The data for the rapeseed oil were collected from a number of sources. Originally they were collected from Ceuterick and Spirinckx (1997). This was augmented, updated and compared with some data obtained from Cargill (1997 & 1998) for the crushing stages. This was then discussed with Wightman and Carruthers from the Scottish Agricultural College, Aberdeen. The soil/rapeseed growth emission data used in the early stages of the study did not take into consideration the fact that these emissions were not only related to rapeseed: some of the emissions would occur if the soil were left fallow or if other crops were grown. However, data for the such emissions were hard to access. Discussions with Wightman (1999), Dobbie (2000) and Hopkins (1999) along with referenced material (Jarvis & Pain (1998) and Bauwman (1990)) enabled an estimate of these figures to be made. This is further discussed in Chapter 8. Much of the data used in this chapter are based on personal correspondence and not on published data, so it is difficult to verify their accuracy. However, wherever possible the data used were compared with other data, obtained through personal communication or from slightly out of date published data.

Many companies may have gathered these data in order to comply with legislation for the Environment Agency, to comply with ISO 14001 or to satisfy an internal Environmental Management System (EMS). None of these systems would require the data to be published publicly. Indeed, many companies were unwilling to release data due to commercial sensitivity.

6.2.2.2 Rapeseed Oil Methodology

The data in this section were more detailed than in the mineral oil section, therefore it was possible to enter them into separate sections in the SimaPro software. For example, there were separate data sheets for the fertilisers, pesticides, crushing, growth, drying, etc. It was not possible to add together all of these data sheets to obtain a final impact result, because the data for the crop protection, the fertilising, etc. were for a whole field. Rapeseed oil was not the only product from the field and so the impact of the whole of these processes could not be allocated to the rapeseed oil. The way in which the data were collated is shown in Section 6.4. which allows the different stages of the production process to be examined individually.

6.3 Mineral Base Oil

Much of the data for mineral oil used in this report is from technical papers produced by Dr Ian Boustead for the European Centre for Plastics in the Environment and the Association of Plastics Manufacturers in Europe, and from Shell UK (Shell, 1997 and 1998). The main stages in the production of mineral oil are shown in Figure 6.1.

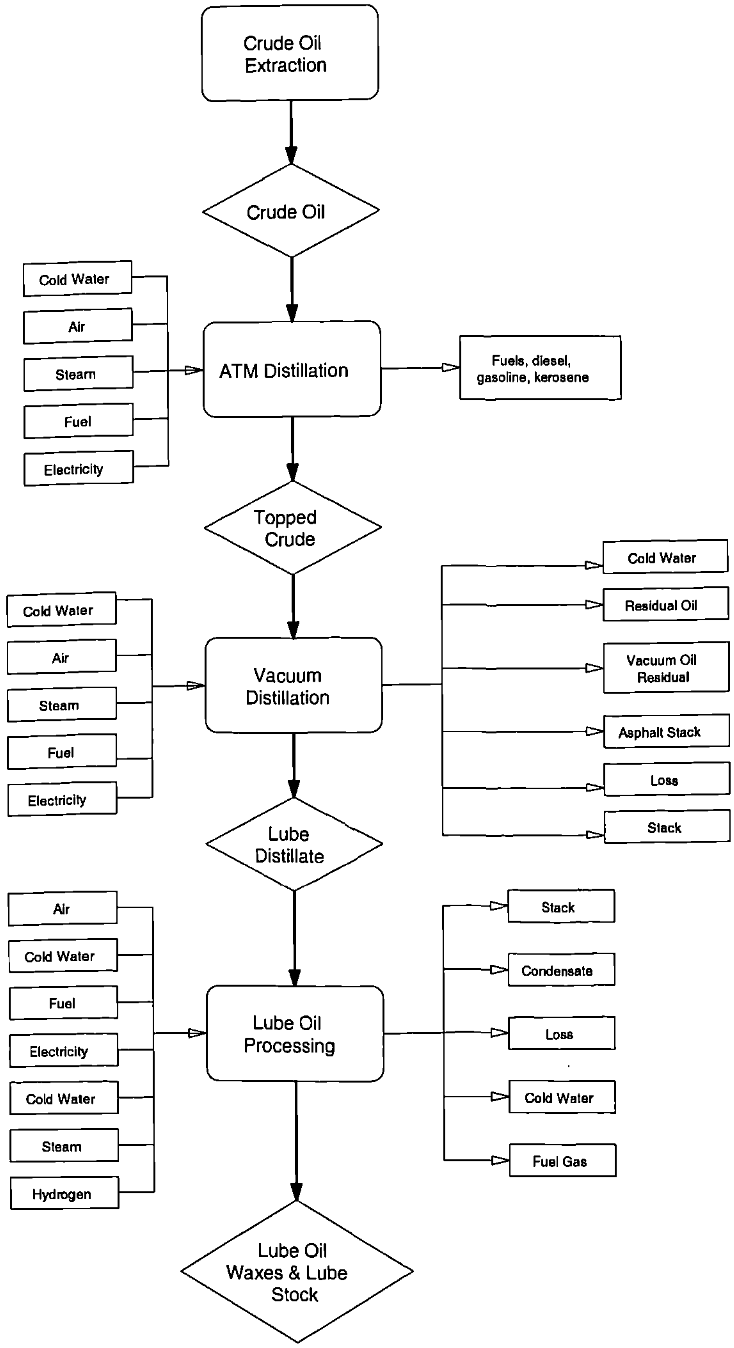

Figure 6.1 Stages in the Production of Mineral Oil

Oil and gas deposits occur worldwide and most countries obtain their oil and gas from various sources for economic reasons. United Kingdom crude oil can command a higher price than other international crude oils due to its lower levels of contaminants such as sulphur. It also contains a higher proportion of the lighter hydrocarbon molecules which results in a higher yield of products such as motor spirits and other transport fuels (Deparment of Energy, 1999). Approximately 15% of the oil used in the UK at present is obtained from the North Sea. Approximately 80% of the natural gas used in the UK is from the North Sea. The remainder of the oil and gas is largely obtained from the Middle East. Mineral oil is used for very many purposes and only a small fraction of the oil produced in the UK or bought from the Middle East will end up being used as a hydraulic fluid.

6.3.1 Mineral Base Oil Production Processes

The production of mineral base oil involves six stages: *exploration, drilling and extracting, transportation and storage, and refining*. These, and their LCA impacts, are described.

6.3.1.1 Exploration

Time and effort is put into exploration by oil companies because of the high economic value of oil and gas. Much of the exploration is contracted out to geophysical companies. There are many potential environmental impacts from this stage, the energy required to transport ships across the world being one of the most important. In addition, seismic equipment is used to determine the geology of the seabed and this can cause problems with marine life. The noise from this equipment is thought to disturb whales and dolphins. Although the exploration companies claim to stop surveying when they see whales or dolphins, it is likely that they still cause damage to these animals' communications. No impacts associated with exploration have been taken into account within the study due to a lack of usable data.

6.3.1.2 Drilling and Extracting

Drilling is the first step of the production stage. It is only by drilling down into a potential field that the presence of oil can be finally determined. Once an economically viable reservoir has been found the surrounding oil-bearing rock is perforated with explosive charges so that the reservoir oil can flow into the well. Then, once the necessary valves and control equipment has been put into place the well can go into production. In most cases the reservoir's own internal pressure is enough to drive the oil to the surface. If this natural force is not enough, secondary recovery has to be put into place. This involves the injection of gas or water into the reservoir to maintain pressure. Should this be insufficient, Enhanced Oil Recovery (EOR) is used. This technology can involve heat, special chemicals, and solvents all of which can potentially harm the environment.

6.3.1.3 Transportation and Storage

Crude oil is one of the largest internationally traded commodities, thus its transportation represents a significant global industry. Crude oil is moved either by large seagoing tankers or by pipeline. Often both forms of transport are used at different stages of transporting the fluid from the oil field to its destination at a refining centre. Crude oil is kept moving along pipelines by pumping stations at regular intervals.

As well as the impacts associated with the use of energy during transportation there are also impacts associated with spillage. There have been many highly publicised oil spills, including the Braer, Shetland in 1993; the Exxon Valdez, Alaska in 1989; and the Treasure in South Africa in 2000. Tanker spills have a varying effect on the environment depending on the amount of oil spilled, the area in which it is spilled, the weather at the time of the spill, the effectiveness of the clean-up operation and the time of year of the spill. The sinking of the Treasure, for example, occurred during the penguin breeding season and put over sixty thousand penguins at risk of oil contamination. Only an extensive rescue programme managed to save some of the penguins. Impacts such as this are very difficult to incorporate into an LCA but this does not mean that the impacts ought to be ignored.

Crude oil arrives at refineries and distribution points in large quantities, therefore it has to be stored in large volume. The usual form of storage is in large cylindrical steel storage tanks. In certain areas it is stored in old coal mines and caverns and at times of low demand in tankers. In some areas this last option is used to provide semi permanent floating storage.

6.3.1.4 Refining

Crude oil in its unrefined form has very few uses because there are too many hydrocarbon components. Refining is used to distil the crude oil into a series of fractions with a molecular mass less than that of the original crude oil, to remove unwanted impurities, such as sulphur, and to recover trace metals which are present in the original oil. In general, crude oil, once refined, yields four basic groupings of products: gas and gasoline, middle distillates (gas oil), fuel oil and residue cuts. The middle distillates form kerosene, light gas oil, heating oil, diesel oils and waxes and light lubricating oils. Light lubricating oils are used as hydraulic fluids. The proportion of light, middle and heavy distillates obtained from the oil varies enormously from one crude oil to another. In general a refinery will try to obtain as many of the light and middle distillates as possible. This is due to economic benefits and as a result refinery processes are continually modified and companies introduce more complex and expensive processes to gain more of the lighter products from the heavier and residual parts of the crude oil. These changes make it difficult to keep the complex LCA data up to date.

There are two main stages in the refining process. The first step is *distillation* which is often referred to as the primary refining stage. This involves separation of different hydrocarbon compounds that occur naturally in a crude oil. Heated crude oil is separated out in a distillation column or fractionating tower. The lighter, more volatile products separate out higher up the column while the heavier products separate out at the bottom of the column. For some crude oils, diesel fuels and heavy fuel oils can be produced in this way and marketed directly. However, a secondary refining process has been developed to improve the quality of some of the products. The second step is called *cracking and reforming*. This alters the products from the distillation into new components through a combination of heat and pressure in the presence of catalysts. This is applied mainly to the heavier distillates.

6.3.2 Mineral Base Oil Data and LCA Results

Table 6-1 shows the inputs and outputs for the production of 1kg of refined oil.

Category	Inputs/outputs	Amount
Fuels (input)	Coal	0.15MJ
	Oil	1.41MJ
	Gas	3.34MJ
	Hydro	<0.01MJ
	Nuclear	0.01MJ
	Other	0.00MJ
	Total fuels	4.92MJ
Feedstock (input)	Oil	45.00MJ
Raw Materials (input)	Iron ore	140mg
	Limestone	140mg
	Water	210000mg
	Bauxite	320mg
	Sodium Chloride	140mg
	Clay	30mg
	Ferro-manganese	<1mg
Air Emissions (output)	Dust	340mg
	Carbon Monoxide	80mg
	Carbon Dioxide	284000mg
	Sulphur Oxides	1800mg
	Nitrogen Oxides	2900mg
	Hydrogen Chloride	5mg
	Hydrocarbons	2900mg
	Metals	1mg
Water Emissions (output)	COD	10mg
	BOD	5mg
	Acid as H+	30mg
	Nitrates	1mg
	Metals	5mg
	Ammonium Ions	1mg
	Chloride Ions	10mg
	Suspended Solids	60mg
	Hydrocarbons	20mg
	Other Nitrogen	1mg
Solid Waste (output)	Industrial Waste	310mg
	Mineral Waste	2200mg
	Slags and Ash	2500mg
	Non-toxic chemicals	170mg

Table 6-1 Inputs and Outputs associated with refined Mineral Oil (collated from Bousted, 1993)

These figures have been analysed using SimaPro LCA software as discussed in Chapter 4. The analysis uses EcoIndicator 95 and the characterised data for the production of 1kg of mineral oil are shown in Table 6.2. The two main impacts from the production are the use of energy and the contribution to greenhouse gases, but there is also a relatively large contribution to acidification and winter smog. None of these impacts are surprising as they are all generally related to the production and use of energy. The amount of ozone-depleting gases, carcinogens and summer smog-producing chemicals are shown to be small for the production of the mineral oil, but as discussed in Chapter 2, the same weight of different chemicals will not necessarily have similar results with respect to their impact on the environment. Therefore, in order to determine their significance it is beneficial to also look at the normalised data. These are shown in tabular form in Table 6.3 and also in graphical form in Figure 6.2.

Class	Total	Unit
Greenhouse gases	3.56	kg CO2
Ozone Depleting gases	$8.9x10^{-12}$	kg CFC11
Acidification	$3.83x10^{-3}$	kg SO4
Eutrophication	$3.78x10^{-4}$	kg PO4
Heavy Metals	$5.02x\ 10^{-7}$	kg Pb
Carcinogens	$1.62x10^{-12}$	kg B(a)P
Winter Smog	$1.8x10^{-3}$	kg SPM
Summer Smog	$1.61x10^{-8}$	kg C2H4
Pesticides	0	kg active substance
Energy	5.94	MJ LHV
Solid Waste	$5.19x10^{-3}$	kg

Table 6-2 Characterised Data for the Production of 1kg of Mineral Oil

The normalised data in Table 6.3 and Figure 6.2 show that although the predominant impact relates to greenhouse gases there is also a significant impact on energy use, acidification, eutrophication, heavy metals and winter smog. Solid waste shows no impact because the respective amount of solid waste produced is minimal compared with the total waste produced in Europe.

Class	Total *("People Emission Equivalents")*
Greenhouse gases	$2.73x10^{-4}$
Ozone Depleting gases	$9.61x10^{-12}$
Acidification	$3.41x10^{-5}$
Eutrophication	$9.89x10^{-6}$
Heavy Metals	$9.23x10^{-6}$
Carcinogens	$1.49x10^{-10}$
Winter Smog	$1.91x10^{-5}$
Summer Smog	$8.96x10^{-10}$
Pesticides	0
Energy	$3.73x10^{-5}$
Solid Waste	0

Table 6-3 Normalised Data for the Production of 1kg of Mineral Oil

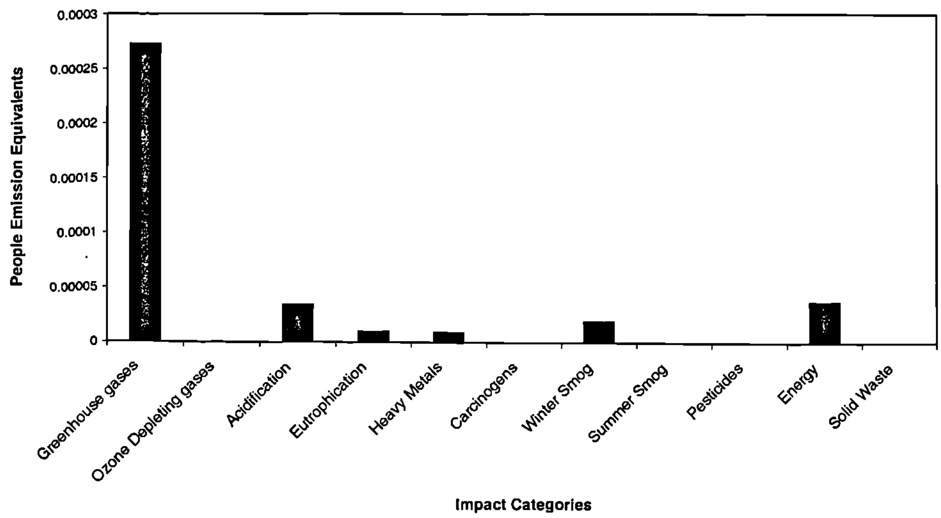

Figure 6.2 Normalised Data for the Production of 1kg of Mineral Oil

The significant contribution towards greenhouse gases from the production of crude oil is not due to any of the processes described in this chapter. Carbon dioxide is contained within mineral oil and was taken out of the atmosphere in previous ages when the oil was formed. By extracting the oil, this CO_2 becomes part of the present day environment and when the oil is disposed of it will be released into the atmosphere. Although it would be possible to allocate this CO_2 to a different stage of the LCA process it was thought to be more easily understood if it were allocated here and shown in the production graphs, since this is the stage when the CO_2 is 'returned' to the environment. It is not included in the rapeseed data because the CO_2 contained in the rapeseed comes from the present day environment and is therefore deemed to be "sustainable".

It is worth noting that when the oil was produced and the growth on the planet was left to decompose naturally there was no cultivation of the soil or land. In this age we have accelerated many processes and take crops from the land and reduced the number of trees and forests on the planet. Therefore, the setting down of oil deposits for future use is likely to be slower than in previous ages (as we harvest all the crops we grow and remove the growth from the land) and the recycling of CO_2 in our atmosphere may be artificially high. Therefore, the production of rapeseed may not be completely "CO_2 neutral", although it is considered as such in this study.

6.4 Rapeseed Base Oil

The cultivation and refining of the base rapeseed oil for use in hydraulic systems depend on many life cycle stages. The soil must be prepared, the fertilisers and pesticides have to be produced and applied, the crop must grow, then be harvested. Then the straw must be separated, and the seed dried, cleaned and pressed. The press cake is separated out and the rapeseed oil is processed. These main stages are shown in Figure 6.3. The data for this stage of the study was mainly taken from personal communication from Cargill Plc. (1997 & 1998) and Ceuterick & Spirinckx (1997).

6.4.1 Rapeseed Base Oil Production Stages

The production of the rapeseed requires seed bed preparation, sowing, fertilising, crop protection (pesticide use), rapeseed growth, harvesting, drying and storing and finally crushing and refining. These stages are discussed here.

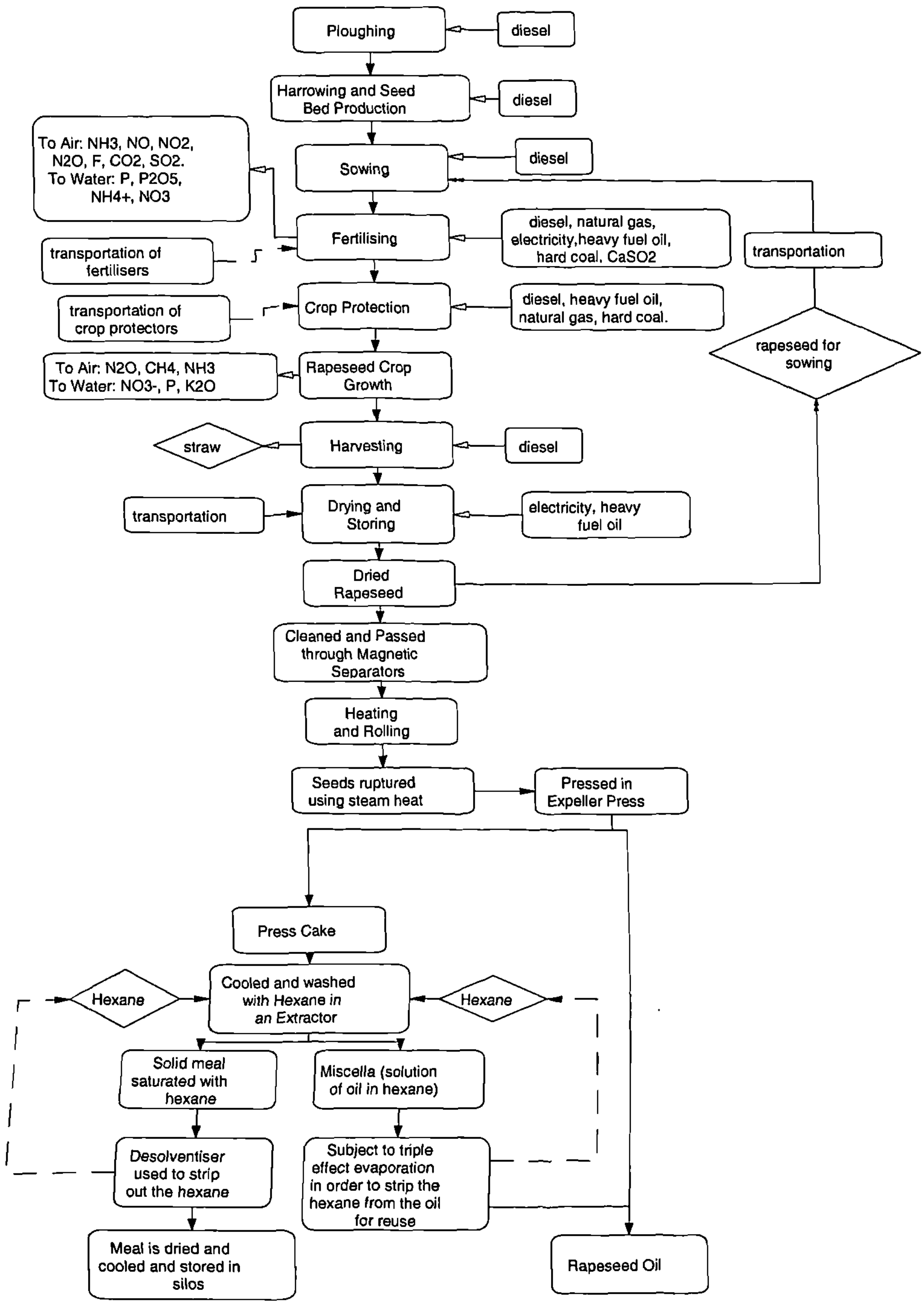

Figure 6.3 Cultivation and Refining of Rapeseed Oil

6.4.1.1 Seed bed preparation

Before rapeseed is planted soil needs to be prepared and this involves ploughing, harrowing and seed bed preparation. There will obviously be a localised impact related to this treatment, for example, the potential for poaching; (compaction of the soil as a result of cattle or machinery imposing weight on the soil especially when the soil is wet) or soil erosion which depends on the situation of the field and the length of time the field is left fallow. In this study only the direct impact of the use of the machinery has been considered. For a field of $10000m^2$ approximately 34kg of diesel is used in the ploughing, harrowing and seed bed preparation stages. The data for the impact of diesel were taken from the IDEMAT database and for 1kg of diesel the LCA data are shown in Table 6.4. These diesel data were used for all the relevant stages of the LCA.

Resources	
Crude oil	1.031kg
Natural gas	0.06185kg
Coal	0.0051kg
Iron (ore)	0.14g
Limestone	0.14g
Water	210g
Bauxite	0.32g
Emissions to Air	
CO2	284g
CO	0.08g
SOx	1.8g
NOx	2.9g
HCl	0.005g
CxHy	2.9g
metals	0.001g
Dust (SPM)	0.34g
Emissions to Water	
COD	0.01g
BOD	0.005g
H2	0.03g
N-tot	0.001g
Metallic ions	0.005g
Cl-	0.01g
CxHy	0.02g
Solid Emissions	
slag	2.5g
Final waste (inert)	2.2g

Table 6-4 Diesel LCA Data (from IDEMAT)

6.4.1.2 Sowing

Four kilograms of seeds are applied per hectare of land for the growth of a field of rape. It is assumed (as shown in Figure 6.3) that the seed is used from the field product. This will not always be true since farmers will wish to change the type of rapeseed grown as varieties change and improve. During sowing, 4.9 litres of fuel are consumed. In the context of the present LCA this has been incorporated in the ploughing phase.

6.4.1.3 Fertilising

The use of fertilisers is to compensate for the loss of nutrients in the soil. A natural growth cycle involves decomposition of plants back into the soil, but under cultivation a crop is grown and harvested so that the nutrients are removed from the soil. Fertilisers are used to increase the growth and yield of crops.

There are negative effects associated with the use of fertilisers which depend on the method and timing of the application, the soil structure, climate, proximity to waterways and the intensity of cultivation. The data given in Table 6-5 were used for the LCA study to determine the fertilisation used to produce one hectare of rapeseed, and 7.6 litres of diesel were used in the application of the fertilisers. The amounts of fertilisers used are based on recommendations of agricultural organisations, principally the French and Belgian Farmers' Association (Ceuterick & Spirinckx, 1997). These have been slightly adapted in accordance with the UK Fertilisers Manufacturers Association (FMA) (Jane Salter, 1998). The quantities are only an average and the amounts specified vary according to which survey is considered. For example, the quantities stated by MAFF in the 1997 British Survey of Fertiliser Practice show slightly different data. It is probable that the different results reflect mainly the different soil conditions across the UK.

Although lime is aggregated in the table with the fertilisers, it is not used for the growth of the crop, but to maintain a stable pH. The amount of lime needed is dependent on the crop structure and type and will vary throughout the country. The amount used in this study is based on an average European value that is very similar to that given by the FMA.

Fertiliser	Amount (kg)	Comment
Potash Fertilisers	130kg	These are produced from potash ores. These occur as sylvanite, carnalite, rock salt and kainite. Sylvanite can be used directly as a fertiliser.
Magnesium Fertilisers	80kg	These are mainly produced from keiserite which is a constituent of raw potash salt.
Nitrate Fertilisers	187kg	This is produced from ammonia which is processed by steam reforming of natural gas. Approximately 0.46kg is needed to produce 1kg of NH_3.
Phosphorous Fertilisers	70kg	Phosphate rock is the raw material used in the production of this fertiliser. Approximately 14.7 kg of the rock is needed to produce 1kg of the fertiliser.
Lime	500kg	Its production relies on the mining, crushing and calcining of limestone in furnaces. For 1kg of CaO 1.89kg of lime has to be mined. A major environmental issue associated with this process is the amount of dust emission. The local impacts from this are hard to incorporate into an LCA but must not be forgotten.

Table 6-5 Fertilisers used for growing 1 hectare of oilseed rape (Adapted Ceuterick & Spirinckx, 1997).

The production of fertilisers has various environmental effects. There will be localised impacts, such as an increase in dust levels near factories, which may cause eye irritation but these localised effects are not considered in LCA. The main inputs and outputs for fertiliser production considered in this study are shown in Table 6.6. It is calculated that the fertiliser will be transported over an average distance of 158km (Ceuterick & Sprinckx, 1997).

Type of Fertiliser	Nitrogen	Phosphorous	Potash	Magnesium	Lime
Energy Used in Production	65MJ	15MJ	8MJ	6MJ	5.26MJ
Emissions to air	6.07g NH3 5.83g NO + NO_2 7.855g N_2O	0.135g F	Unknown	Unknown	800kg CO_2 - 1.62kg SO_2 *(this amount has to be subtracted as SO2 from the fuel is trapped within the lime)*
Emissions to water	3.214g NH_4^+ 11.071g NO_3	4.58g P 1.15g P_2O_5	Unknown	Unknown	Unknown
Solid waste	Unknown	70kg $CaSO_4$	Unknown	Unknown	Unknown
Raw materials	0.46kg Natural gas	Unknown	Unknown	Unknown	Unknown

Table 6-6 Inputs and Outputs for the Production of 1kg of the lime and fertilisers

6.4.1.4 Pesticides

Pesticides are also required for the growth of rapeseed. These are utilised in the form of herbicides, fungicides and insecticides. Data for the amount of pesticides used on the crops were obtained from the Pesticide Usage Survey Report (Thomas et al., 1996) which was produced by MAFF and the Scottish Office of Agriculture (Environment and Fisheries Department). Unlike the data obtained for the fertilisers, the European data used by VITO (Ceuterick and Spirinckx, 1997) vary greatly from that obtained for the UK. The UK data were used in the study; the European data suggest that far more pesticides are used on crops than the UK figures indicate. A comparison is shown in Table 6.7.

	Ceuterick and Spirinckx, 1997	Pesticide Usage Survey Report 141
Herbicide	2.20kg	0.87kg
Insecticide	0.7kg	0.04kg
Fungicide	1.85kg	1.2kg
Growth Regulators		0.06kg
Molluscicides		0.07kg
Mixed Seed Treatments		0.09kg

Table 6-7 Pesticide Use on a 1 hectare Rapeseed Crop

There is more detail within the UK data; however, the molluscicides can be incorporated into the insecticide parameters giving a value of 0.11kg per hectare. There is little information available about the production of pesticides. They are mostly very complex chemical products containing fillers, emulsifiers and colouring agents as well as the active ingredient. The energy required to produce the pesticides for one hectare of rapeseed is 477.65MJ. The average distance that the pesticide will have to travel is 158km on highways and rural roads (Ceuterick & Spirinckx, 1997).

As well as the pesticide production there will also be an impact from the pesticide runoff. Some figures suggest that between 0.5% and 5% of the applied pesticide will end up as runoff (Cashmore & Cobb, 2000). Some of the more modern pesticides are very mobile and therefore a figure of 10% or more may be applicable. The amount of runoff is hard to predict - some say impossible (Beaumont, 2000) - as it depends on the weather, the soil and the equipment used. However, for this study, it has been assumed that the pesticide runoff is 5%, this representing an 'average' of the estimates.

6.4.1.5 Rapeseed Growth

During the growth of the rapeseed there are air emissions due to conversion processes in the soil. The main gases emitted from the soil are nitrous oxide, methane and ammonia. At an early stage of the research figures from Ceuterick and Spirinckx (1997) were used in the study but after consultation with Wightman (1999) it was established that these figures did not take into consideration the natural emissions of these gases which would be emitted from the soil whether or not there was a rapeseed crop on the land. The nitrous oxide content of the atmosphere increased by about 25% last century, about two thirds of that is thought to be due to the combustion of coal and oil, the remainder is due to agricultural processes. Nitrous oxide is released during the process of denitrification, which is fuelled by the presence of nitrates in the soil. Although much of this is attributable to the use of fertilisers, denitrification also occurs in non fertilised areas, for example, tropical forests are significant producers of nitrous oxide. Soil is also a known source of methane, although most of this seems to occur in the anaerobic conditions found in swampy areas, from rice paddies or from termites (Brady, 1990). An estimate of the emissions from the soil without any planting has been subtracted from the original data within this study. This should give a more realistic view of the emissions from a field of rapeseed. A more detailed examination of the sensitivity of the results to the soil emission data is given in Chapter 9.

6.4.1.6 Harvesting

In order to harvest the crop a combine harvester is used, which typically uses 17 litres of diesel per hectare. A total of 3500kg of rapeseed is gained from one hectare of land and 7000kg of straw are also produced. The percentage of water content within the straw and the rapeseed is not the same, rapeseed is 85% dry matter, straw is 50% dry matter. Therefore, the dry weights produced are: 2975kg of rapeseed, and 3500kg of straw. Allocation of the impacts from the previous stages is made according to the dry weight since this is the weight of useful product.

6.4.1.7 Drying and Storing

Rapeseed has to be dried before storing, otherwise there may be formation of undesirable colour and odour, and in extreme cases the seeds may coagulate in the storage silo. Seeds are dried by heat which is usually provided by an oil-fired burner, and ventilated by an electric fan, this consumes 0.505MJ per kg of rapeseed. After drying the seeds are stored in ventilated concrete silos. 4kg of seed is needed to plant one hectare of rapeseed field and so this is taken from the total production weight, assuming a completely closed loop, providing 2971kg of dried rapeseed from the one hectare field. The rapeseed is then transported an average of 250km to the oil production plant (Ceuterick & Sprinckx, 1997).

6.4.1.8 Crushing and Refining

When rapeseed arrives at a mill there is still residue in the seed which must be removed. Metallic residue is removed by passing the seeds over a magnet which removes any small pieces of ferrous metal. The seeds are dehulled by a process of rolling and the seeds are commuted and thermally pre-treated so that the fat is isolated to an acceptable yield. Conditioning deactivates the enzyme myrosinase and improves the quality of the oil. Then the seeds are pressed which separates the oil from the solid phase - the meal. These processes are shown in Figure 6.3. The seeds are then subjected to solvent extraction which is carried out with hexane. The introduction of the Environmental Protection Act (1990) means that there is a legal requirement to keep the hexane use below 2kg per tonne of seed processed (Cargill, 1997/1998). On average, about 0.2 - 0.3% of this hexane is lost, the rest is recycled. In this study the maximum hexane usage is considered, with a loss rate of 0.2%. The production of the hexane was assumed to be comparable with that of naphtha production as the production processes are very similar.

After the solvent extraction with hexane the seeds can be desolventized by toasters heated with steam. After drying and cooking, this meal can be used as an animal feed component. From the crushing process 1188.4kg of oil is produced and 1782.6kg of meal is produced (40% and 60%). For this reason only 40% of all the proceeding burdens can be allocated to the rapeseed oil production, which then needs to be refined.

Phosphatides, gums and other colloidal compounds can promote hydrolysis of an oil during storage and so they are removed by degumming. This is a pre-refining process where steam is used to remove contaminants: this requires 10kWh of electricity and 80kg of steam per tonne of crude oil.

6.4.2 *Rapeseed Base Oil Data and LCA results*

These data were analysed using the LCA techniques described in Chapter 2. Table 6.8 shows the characterised data for all the production stages. These are also shown graphically in Figure 6.4.

	Pesticides (crop protection)	Growth	Fertilising	Preparation	Ploughing	Harvesting	Drying	Crushing
Greenhouse Gases (kgCO2)	0.243	37.1	133	0.641	0.795	0.712	58.2	90.1
Ozone Depleting Gases (kg CFC11)	0	0	0	0	0	0	0	5.05×10^{-07}
Acidification (kg SO4)	0.00328	1.24	0.513	0.00865	0.0107	0.00961	0.528	1.2
Eutrophication (kg PO4)	0.000326	0.616	0.268	0.000852	0.00106	0.000947	0.051	0.0891
Heavy Metals (kg Pb)	0	0	0	0	0	0	0	0.000446
Carcinogens (kg B(a)P	0	0	0	0	0	0	0	7.74×10^{-08}
Winter Smog (kg SPM)	0.00182	0	0.0517	0.00483	0.00599	0.00537	0.294	0.782
Summer Smog (kg C2H4)	0.000982	0.000924	0.0513	0.0026	0.00323	0.00289	0.108	0.386
Pesticides (kg active subs)	0.014	0	0	0	0	0	0	0
Energy (MJ LHV)	102	0	3.14×10^{03}	104	129	115	1.36×10^{03}	1.64×10^{3}
Solid Waste (kg)	0.00397	0	2.05	0.0106	0.0132	0.0118	3.05	3.61

Table 6-8 Characterised Data for the Production of 1kg of Rapeseed Oil

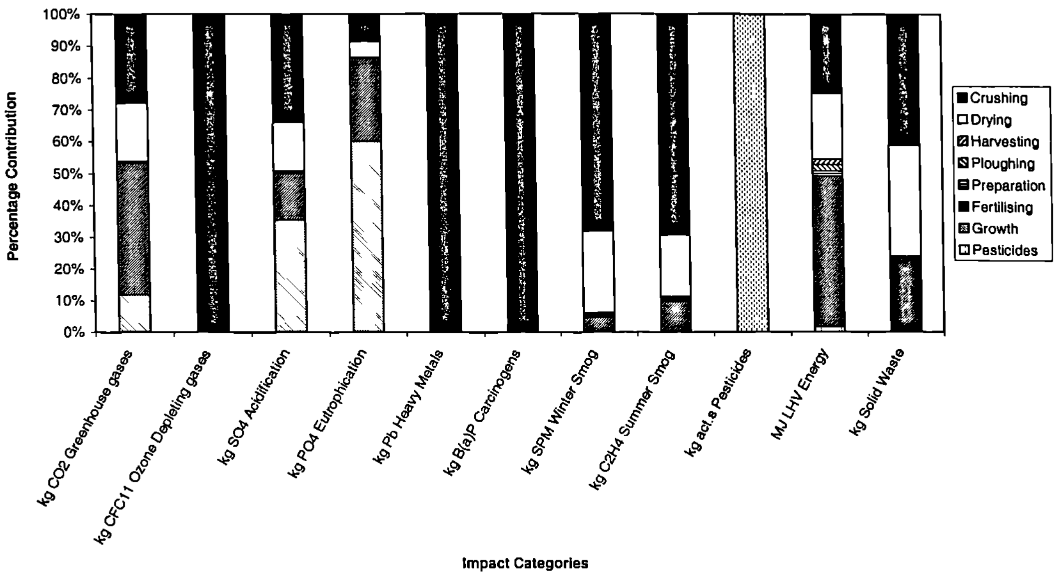

Figure 6.4 Characterised *Data for the Comparison of the Production Stages in* Rapeseed Oil

Table 6.8 and Figure 6.4 show that the crushing stage is the only contributor to ozone depleting gases, heavy metals and carcinogens. Therefore, if these effects are to be reduced, one must work on improving the crushing stage of the process. The crushing stage has a significant impact upon winter and summer smog and also contributes towards greenhouse gases, acidification, energy use and solid waste. The only contributor to pesticides is the crop protection stage. The growth stage makes a significant contribution towards acidification and eutrophication and also has an effect on greenhouse gases. Fertilising has an impact on energy use and solid waste. The drying stage makes a contribution towards greenhouse gases, acidification, eutrophication, winter and summer smog, energy use and solid waste. The harvesting, ploughing and preparation stages only have minor effects on the various impact categories.

In order to determine the significance of any of these impacts it is necessary to analyse the normalised data which are shown in Table 6.9 and Figure 6.5.

Class	Pesticides	Growth	Fertilising	Preparation	Ploughing	Harvesting	Drying	Crushing
Greenhouse gases	1.86×10^{-05}	0.00284	0.0101	4.90×10^{-05}	6.09×10^{-05}	5.45×10^{-05}	0.00445	0.0069
Ozone Depleting gases	0	0	0	0	0	0	0	5.45×10^{-07}
Acidification	2.91×10^{-05}	0.011	0.00455	7.68×10^{-05}	9.54×10^{-05}	8.54×10^{-05}	0.00469	0.0106
Eutrophication	8.53×10^{-06}	0.0162	0.00703	2.23×10^{-05}	2.77×10^{-05}	2.48×10^{-05}	0.00134	0.00234
Heavy Metals	0	0	0	0	0	0	0	0.00821
Carcinogens	0	0	0	0	0	0	0	7.12×10^{-06}
Winter Smog	1.93×10^{-05}	0	0.000548	5.12×10^{-05}	6.35×10^{-05}	5.69×10^{-05}	0.00311	0.00829
Summer Smog	5.48×10^{-05}	5.16×10^{-05}	0.00286	0.000145	0.00018	0.000161	0.00604	0.0215
Pesticides	0.0146	0	0	0	0	0	0	0
Energy	0.000642	0	0.0197	0.000653	0.000811	0.000726	0.00855	0.0103
Solid Waste	0	0	0	0	0	0	0	0

Table 6-9 Normalised Data for the Production of 1kg of Rapeseed Oil

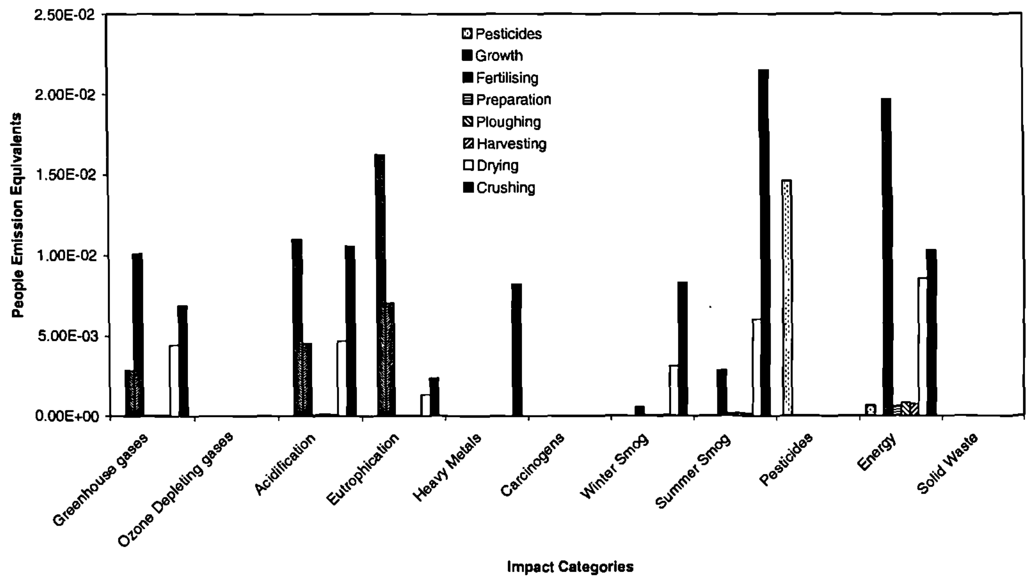

Figure 6.5 Comparison of Normalised Data for the Production Stages in Rapeseed Oil

Data in table 6.9 show that the contribution to carcinogens and ozone depleting gases associated with the production of 1kg of rapeseed oil is minimal. Figure 6.5 shows that the significant stages within this part of the life cycle are the crushing, fertilising and crop growth. The crop growth makes a relatively large contribution towards acidification and eutrophication whereas fertilising makes a relatively large contribution towards greenhouse gases and energy use. The crushing stage contributes to most of the impact categories, but has a particular significance in terms of greenhouse gases, acidification, heavy metals, carcinogens, winter and summer smog and energy.

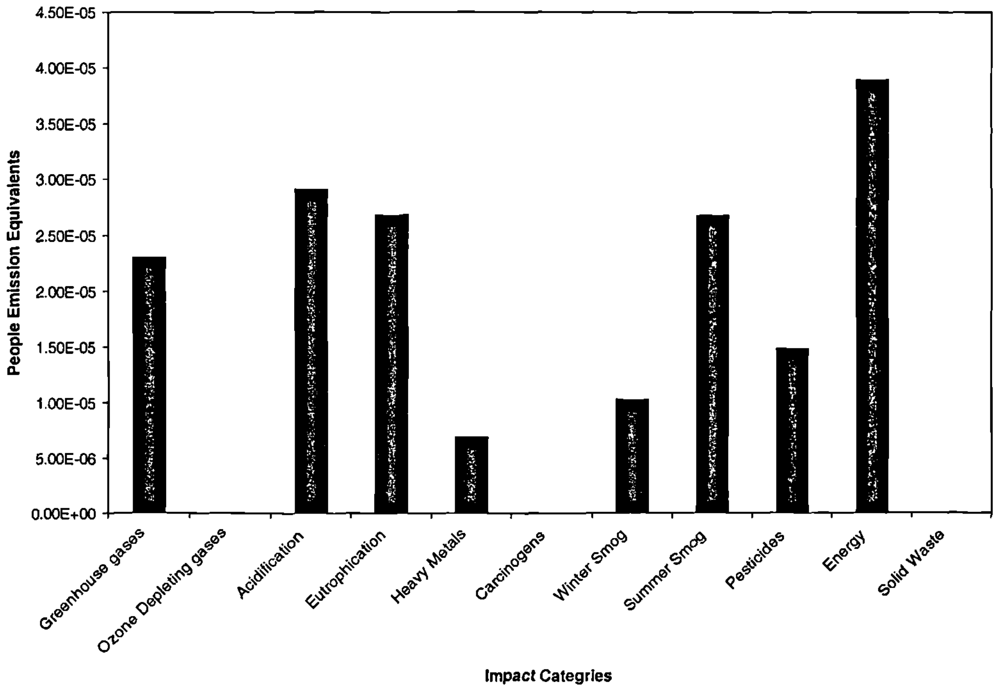

Figure 6.6 Normalised Data for the Production of 1kg of Rapeseed Oil

Aggregated characterised and normalised data are shown in Table 6.10. The normalised data are shown graphically in Figure 6.6. In the characterised data greenhouse gases and energy are by far the most abundant impacts, but they assume a lesser significance in the normalised data. The most significant normalised effect is energy use, followed by acidification, eutrophication, summer smog and greenhouse gases. Figure 6.4 shows that the main contributing stages towards these impacts are crushing, growth, drying and fertiliser production. Therefore, in order to reduce the overall environmental impact of the base rapeseed oil production one ought to try to improve the efficiency of the crushing, drying and fertilising stages. Crop growth is another area for examination and the issues associated with this were discussed earlier in this chapter. Sensitivity analysis on this stage is carried out in Chapter 9.

Class	Unit (for Characterised Data Only)	Total Characterised	Total Normalised
Greenhouse gases	kg CO2	0.3	$2.30x10^{-05}$
Ozone Depleting gases	kg CFC11	$4.25x10^{-10}$	$4.59x10^{-10}$
Acidification	kg SO4	0.00327	$2.91x10^{-05}$
Eutrophication	kg PO4	0.00102	$2.68x10^{-05}$
Heavy Metals	kg Pb	$3.75x10^{-07}$	$6.90x10^{-06}$
Carcinogens	kg B(a)P	$6.52x10^{-11}$	$5.99x10^{-09}$
Winter Smog	kg SPM	0.000976	$1.03x10^{-05}$
Summer Smog	kg C2H4	0.000479	$2.67x10^{-05}$
Pesticides	kg act.s	$1.43x10^{-05}$	$1.48x10^{-05}$
Energy	MJ LHV	6.18	$3.89x10^{-05}$
Solid Waste	Kg	0.00773	0

Table 6-10 Characterised and Normalised Data for the Production of 1kg of Rapeseed Oil

The use of genetically modified rapeseed may have an impact on the results in the future, for example modified rapeseed may be more easily crushed. The study of the potential impacts of genetical modification is beyond the scope of this study.

6.5 The Use of Additives

Until the 1940s, base mineral oil was used in hydraulic systems without any additives but with an increasing demand for higher quality fluids additives began to be used. The additives vary between rapeseed and mineral base oil. There is more than one type of mineral oil on the market and also more than one type of rapeseed oil, hence the additives also differ within the oil types because different manufacturers make the different oils and also because oils are made-up to different specifications. The main additive types are oxidation inhibitors, anti-wear, rust inhibitors, demulsifiers, anti-foam, metal passifiers, viscosity modifiers and detergents.

There is very little public domain information or data about the additives used in hydraulic oils. Much of the information used in this thesis was obtained from the Technical Committee of Petroleum Additive Manufacturers in Europe (ATC). Data were obtained through a visit from members of the ATC to the University of Bath and also from their publication, ATC-Hydraulic Fluid Module (Korff et al., 199?).

In general, the base oil will comprise 94% of the total fluid volume. A viscosity modifier will comprise 5% of the volume and the additive package will comprise 1% of the volume. The amount and types of additives will change with the oil type and specification of the fluid product. A typical mineral oil will contain oxidation inhibitors, anti-wear agents, rust inhibitors, demulsifiers, anti-foam agents, corrosion inhibitors, viscosity modifiers and may or may not include detergents. A rapeseed oil will typically contain oxidation inhibitors, anti-wear agents, rust inhibitors, demulsifiers, anti-foam agents and viscosity modifiers. These specifications are often bound by industry standards.

Additive Type	Mineral Oil	Rapeseed Oil
Oxidation Inhibitors	✔	✔
Anti wear agents	✔	✔
Rust inhibitors	✔	✔
Demulsifiers	✔	✔
Anti foam	✔	✘
Corrosion Inhibitors	✔	✘
Viscosity Modifiers	✔	✔
Detergents	?	✘

Table 6-11 Additive Types in Mineral and Rapeseed Oil

Both mineral oil and rapeseed oil can cause wear to components during use. When rapeseed oil was first introduced as a hydraulic fluid there were many problems associated with its wear properties. However, the addition of an anti-wear additive can help to alleviate that problem. The ZDTP family of additives is based on sulphur/phosphorus compounds and are used for anti-wear. They are very effective in reducing the wear in moving components such as pumps and actuators and they also have anti-oxidant and anti-rust properties. Members of the ZDTP family are classified as hazardous, therefore their addition to any oil renders it toxic. Whether the oil is biodegradable or not does not have a bearing on its toxicity.

No production data were found for any of the additives and manufacturers of mineral and rapeseed oil were not willing to comment on the specific contents of their additives. It is known that Hydrogen Sulphide (H_2S) and Hydrochloric Acid (HCl) sludge are produced during the purification of polymer VI improvers (Herdan, 1997). Rapeseed oil manufacturers claim that their oil requires fewer, and a smaller quantity of, additives than mineral oil, whereas mineral oil companies make a contrary claim. The opinion of the ATC was that the amounts required were probably about equal which is the view taken by the author in this study.

Most of the environmental research carried out on hydraulic oils and their additives has concerned their effect on the environment if they are spilled during use. No data were found for any emissions or raw materials used in the production of additives for this study. This is an obvious shortcoming in the study. However, as the research was primarily of a comparative nature between mineral and rapeseed oil, and it is presumed that the amounts and types of additives used in the oils are approximately equal, and can be discounted in this particular analysis without having too much of a detrimental effect on the final results.

6.6 Comparison of Mineral and Rapeseed Base Oil Production

Examination of the characterised results in Table 6-12 shows that the production of mineral oil makes a significantly greater contribution towards greenhouse gases, and also a greater contribution towards acidification, heavy metals and winter smog than rapeseed oil. The production of rapeseed oil makes a greater contribution towards ozone depleting gases, eutrophication, carcinogens, summer smog, pesticides, energy use and solid waste.

Class	Unit	Rapeseed	Mineral
Greenhouse gases	kg CO2	0.3	3.56
Ozone Depleting gases	kg CFC11	4.25×10^{-10}	8.90×10^{-12}
Acidification	kg SO4	0.00327	0.00383
Eutrophication	kg PO4	0.00102	0.000378
Heavy Metals	kg Pb	3.75×10^{-07}	5.02×10^{-07}
Carcinogens	kg B(a)P	6.52×10^{-11}	1.62×10^{-12}
Winter Smog	kg SPM	0.000976	0.0018
Summer Smog	kg C2H4	0.000479	1.61×10^{-08}
Pesticides	kg act.s	1.43×10^{-05}	0
Energy	MJ LHV	6.18	5.94
Solid Waste	kg	0.00773	0.00519

Table 6-12 Characterised Data for Mineral and Rapeseed Oil Production

The significance of these results can be seen clearly when they have been normalised as in Table 6-13 and Figure 6.7. These show that the impact on greenhouse gases from the production of the mineral oil far outweighs any of the other impacts in either of the production stages. This is due to "old" carbon dioxide being released into the atmosphere during the oil disposal.

Class	Rapeseed	Mineral
Greenhouse gases	$2.30x10^{-05}$	0.000273
Ozone Depleting gases	$4.59x10^{-10}$	$9.61x10^{-12}$
Acidification	$2.91x10^{-05}$	$3.41x10^{-05}$
Eutrophication	$2.68x10^{-05}$	$9.89x10^{-06}$
Heavy Metals	$6.90x10^{-06}$	$9.23x10^{-06}$
Carcinogens	$5.99x10^{-09}$	$1.49x10^{-10}$
Winter Smog	$1.03x10^{-05}$	$1.91x10^{-05}$
Summer Smog	$2.67x10^{-05}$	$8.96x10^{-10}$
Pesticides	$1.48x10^{-05}$	0
Energy	$3.89x10^{-05}$	$3.73x10^{-05}$
Solid Waste	0	0

Table 6-13 Normalised Data for Mineral and Rapeseed Oil Production

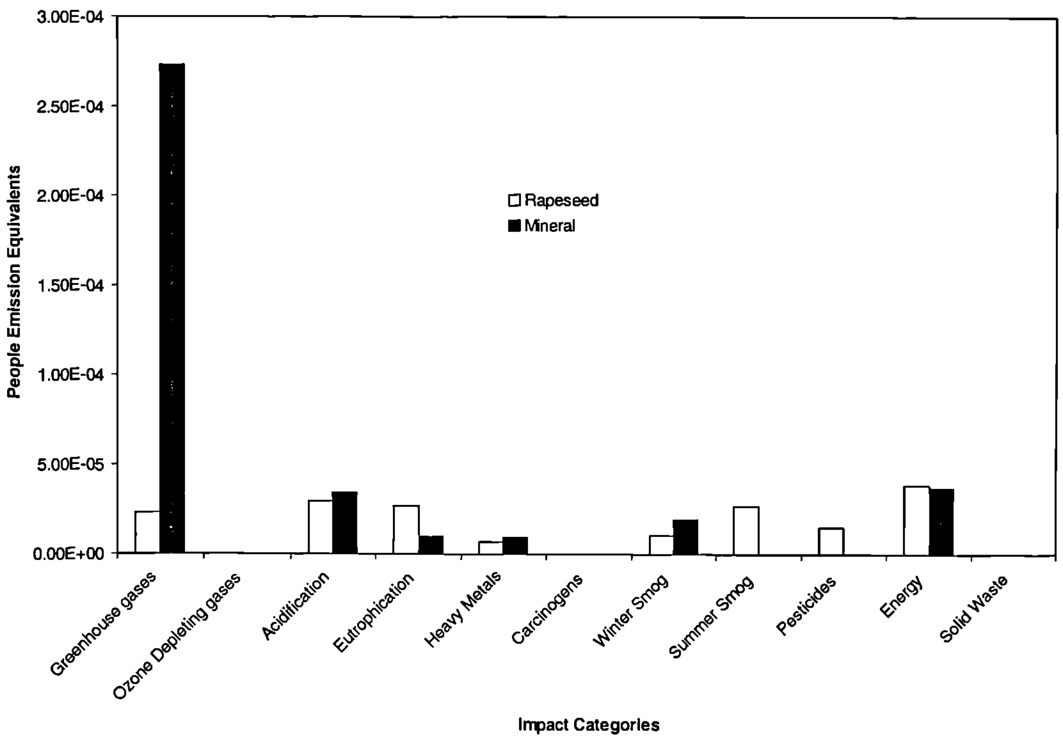

Figure 6.7 Comparison of Normalised Data for the Production of Mineral and Rapeseed Oil

The production of mineral oil also has a greater impact on acidification, heavy metals and winter smog, but on a more modest scale. The production of the rapeseed oil has a larger contribution towards eutrophication, carcinogens, ozone depletion, summer smog, pesticides and energy.

If one were to add together all the characterised or normalised results for the rapeseed oil then clearly the highest "total" number would be for the mineral oil. This is due mainly to the very high result for the unsustainable greenhouse gases. However, LCA studies cannot really be useful if concentrated into one number. If one were concerned about greenhouse gases, then clearly, on the basis of these results, one ought not to use the mineral oil. However, if one were concerned about eutrophication, for example, then with these results one would recommend the use of mineral oil rather than rapeseed oil. Excluding greenhouse gases, the comparative environmental impacts of both oils are similar, with the rapeseed making a greater overall impact. However, by including the impact on greenhouse gases, mineral oil has by far the worst overall environmental impact.

6.7 Findings

The results show that the *production* of mineral oil has a larger environmental impact than rapeseed oil in the fields of greenhouse gases, acidification, heavy metals and winter smog. The impact towards greenhouse gases is far larger for the mineral oil than for the rapeseed oil. The rapeseed oil has a larger impact towards ozone depleting gases, eutrophication, summer smog pesticides and energy. Which oil is "best" is dependant on which of these categories is chosen to be the most important.

The findings show that different environmental impacts result for each oil and it is not possible overall to say that one is better than the other, although the much larger contribution to greenhouse gases made by mineral oil may lead to the view that mineral oil has the larger overall environmental effect. This inconclusiveness is indicative of LCA when a valuation stage is not carried out. A valuation stage would attribute a single number answer to which oil was better, but it would obscure all the rest of the data. A further analysis of this problem is undertaken in Chapter 8.

6.8 Recommendations

From these results it is impossible to assess conclusively the relative environmental impact of the two oils in the production process. To undertake an LCA in the oil industry it is necessary to ensure that there is access to the required data. Much time was spent in this study trying to obtain data for the production of the oils. It is recommended that further work is performed in this phase. Ideally this work would be undertaken by a group with full co-operation from the oil industry.

6.9 Concluding Remarks

The data for the production of mineral and rapeseed base oil is incomplete. Much of the data used in this thesis was gathered from different sources, but there is a sufficient degree of compatibility to enable the results to be meaningful. The data for the rapeseed oil are more detailed; however, that does not mean that these are in any way more complete or accurate.

Additive packages are required for both fluid types, but data are not available for their production. According to the ATC the amount of additives required for each oil is similar, so this omission will not be detrimental to the final results of this comparative study.

The production (including the CO_2 disposal) of the mineral oil produces a significant amount of greenhouse gases due to the release of "old" CO_2 into the atmosphere. This impact far outweighs any of the other impacts associated with either mineral or rapeseed oil. Therefore, if all the environmental impacts studied are considered together, the production of mineral oil shows a far higher environmental impact than that for the rapeseed oil. If, however, individual environmental issues are examined then some of the environmental impacts are greater for the rapeseed than for the mineral oil.

7 Two Case Studies

7.1 *Introduction*

Two case studies were chosen for this research. As the aim of the research was to determine the life cycle impact of hydraulic systems running on mineral and rapeseed oil, case studies were chosen where rapeseed was either used as a hydraulic fluid, or it was conceivable that rapeseed oil would be used in the near future due to the sensitive environment in which the system worked. The first case study was based on forestry machinery; a harvester and a forwarder, the second case study on road sweepers.

Although detailed information was sought for the production of the machines it proved very difficult to obtain. Over a hundred letters were sent out to machinery manufacturers in the initial stages of the research. In many cases these letters were unanswered. Most of the letters that were answered simply wished the researcher luck in the project, with very few containing offers of help. This data acquisition problem is not unique to this LCA and appears to be a major stumbling block to the progression of LCA as a quality environmental management tool. Therefore, all the results and conclusions shown in this chapter, and indeed throughout this thesis, are only a representation of the material obtained. An LCA should constantly improve as data are gathered and added to the study and this has been the approach adopted throughout this study. Many companies are reluctant to release the type of data required for an LCA mainly because they do not have such data available, but in some cases it is because data are commercially sensitive. Best estimates were often used within this study as detailed in the thesis. If these are incorrect, then, obviously, the corresponding results are invalid. In order to reduce uncertainty a sensitivity study has been carried out to see what the impact on the final results would be if the input data were incorrect. This is discussed in Chapter 8.

Stage in the Life Cycle of the Machinery	*Covered in the Research?*	*Comment*
Production		
Extraction of Raw materials	Yes	Data for most of the raw materials were available through publicly accessible data bases. However, these are by no means comprehensive.
Transportation of raw materials to factory	Yes	Data for the transport of raw materials to the country in which the machinery is made has been considered. The data is not site specific.
Manufacture of raw materials into workable components for the manufacture of machinery	Yes	The publicly available databases normally incorporate this information.
Transportation of components to machine assembly factory	No	Transportation to the country was considered for materials which were sourced from outwith the country. No more detailed information was available.
Emissions and raw material use at the factory where the machinery is made	No	No factory specific information was available.
Production of mineral oil	Yes	Data for the production of mineral oil were taken from many publicly available sources.
Production of rapeseed oil	Yes	Data for the production of rapeseed were taken from other LCA's, personal communication and publicly available databases.
Use		
Transportation of machine to point of use	Yes	Transportation from the main factory site to the distributors in the UK was included.
Diesel/oil use	Yes	The average amount of diesel and hydraulic oil used in a lifetime was included.
Manufacture of replacements	Yes	This was included to the same standard as the production data above.
Transport of replacements to site	No	It was unclear whether all the replacements would be sourced from abroad or whether they could be sourced in the UK.
Spills of oil/diesel during use	Yes	Information about this was collected, however, the incorporation of local impacts into LCA is very difficult.
Energy used during maintenance	No	No data about this were available.
Disposal		
Transport of machinery to disposal site	No	Forestry machinery is normally kept until it is near the end of its life and is then either sent out on short term contracts or cannibalised for other machines. Sweepers have a shorter life and are often shipped out to Africa once they have finished their useful life in the UK. Both are very difficult to incorporate into an LCA and will not differ as a result of the hydraulic oil used.
Energy required to dispose of/recycle the machinery	No	
Disposal / recycling of oil	Yes	In the UK at the present moment both mineral and biodegradable fluids are disposed of in the same way, either used in road building (bitumen) or as a lower grade oil.
Transport of oil to disposal site	No	Many companies cannot say where their oil goes.

Table 7-1 Environmental Significance of the Main Stages of the Machine Manufacture

Although the results obtained are only a representation of the (limited) data obtained, the research was continued in an effort to examine the use of LCA methodology in an engineering environment. It is thought that enough data were obtained to show a reliable estimate of the environmental impact of the systems, but obviously the LCA can always be improved. Table 7-1 shows the main stages in the machine manufacture. It outlines the significance of the stages and whether they have been included in the thesis. One of the major shortcomings in this section of the study was the lack of information about the energy used and the emissions created by the machine assembly process. Detailed information about this was not available from the manufacturers, but this problem is not specific to this study within LCA. Many manufacturers make several different products on one site so it is often impossible for them to determine which of the production processes is associated with emissions or energy use. Many factories only have data for emissions for which they have a legal requirement.

This chapter examines the production and use of typical forestry machinery and the sweepers. The disposal of these machines is also examined, but not in as great detail as their production and use because the disposal mechanisms are less well known. Moreover, the machinery will be disposed of in the same manner whether mineral oil or rapeseed oil is used. The chapter discusses the use of oils in the machines and the performance of both fluid types. Use of the machinery is compared using both oil types.

7.2 Data Collection and Methodology

Extensive efforts were required to collect sufficient data to be able to determine the environmental impacts of the forestry machines. For this stage of the study contact was made with the UK suppliers of the forwarders and harvesters because it was impossible to obtain information directly from the Scandinavian suppliers. Data sheets were obtained which outlined the machine specifications and components. From these contacts with the suppliers, and the expertise of colleagues it was possible to estimate the weight of all the different components. Data for the production of these components were taken from the databases contained within SimaPro. Some of this information was modified, for example, data for aluminium production were amended in accordance with recommendations from the European Aluminium Association.

Information about the use of the forestry machines came from personal communication with the Environment Agency, the Forestry Commission and the National Trust for Scotland. Data published on the different uses of hydraulic oil in the field are scarce, but a number of papers contain information about laboratory testing of these fluids (see, for example, Cheng et al., (1992), Feldmann & Hinrichs (1995) and Echenberg (1994)), but it is not always possible to determine from these tests how the fluids will perform in the field. Fluids in the field are exposed to larger temperature ranges and in some cases short periods of more aggressive working conditions followed by periods of rest. These extremes of working conditions are not always replicated in laboratory tests.

The data were stored in SimaPro and the EI95 methodology was used in the analysis.

7.3 Forestry Machinery

At the start of the study a contact in the UK Forestry Commission made it possible to obtain data for forestry machines study. The Forestry Commission made use of biodegradable fluids, mainly as greasing agents and chain lubricants and to a lesser degree in hydraulic systems. The Forestry Commission have to tender for work on their own land. If the Forestry Commission do not produce the most competitive tender they will not win the contract. This means that they will only use biodegradable oil when necessary, and it also means that very few of the non Forestry Commission workers will use the biodegradable oils.

Approximately 10% of the United Kingdom is covered with forests, of which some 35% is owned by the Forestry Commission (Forestry Commission, 1997) which is a public body. The processing of timber inevitably results in some impact upon the environment. Hydraulic systems adapted for mobile logging equipment have the potential to leak, and thereby damage the ecology of the forest and the waterways within the forested area. Much of the UK forest is in upland areas where water flow is fast, therefore this means that any contaminants may be swept into the major waterways relatively quickly. The speed of the water flow may be increased by compaction of the ground by logging vehicles, and the ridge system adopted by foresters in order to plant trees more easily. Forests are often planted around lochs and lakes many of which are important ecologically. These often act as water supply reservoirs, and it is therefore important to determine the environmental impact of oil spillage originating from the machinery use.

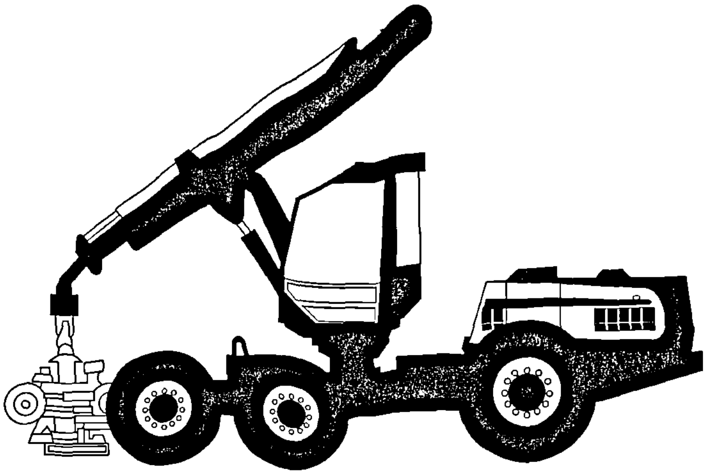

Figure 7.1 The Harvester

The Forestry Commission has a "non-draining" policy for hydraulic oils which means that they do not drain and replace oil during the life time of the machine but they continually top-up the oil. Despite this, more hydraulic oil is used (and therefore lost) within the Commission's forests than from engine or gear oils, which are drained and disposed of "correctly".

In recent years the Commission has started to look at the forest environment in terms of oil spillage, and has estimated that approximately 340,000 litres of hydraulic oil is spilt on the forest floor every year. This represents a spillage of 0.14 litres per hectare, but spills are not evenly spread out over the forest floor. If a machine leaks one drop of hydraulic oil every second, this is equivalent to a loss of 950 litres per year and highlights the importance of preventative maintenance. This type of leakage rate is not uncommon. Contamination of the forest floor may also be caused if empty containers are discarded. Despite policies that stipulate containers are not to be left in the forests after work has been carried out, it is not always easy to incorporate such policies into the working practice.

The harvester (Figure 7.1) is a machine that is used within the forest to fell the trees. There are two primary parts of a machine which include hydraulic systems; the main body and the cutting head. The forwarder (Figure 7.2) takes the cut logs to the side of the road ready for collection by lorry. There is only one hydraulic system in a forwarder.

In order to carry out an LCA, information about the production, use and the disposal of the systems had to be examined. Although the research is primarily concerned with the hydraulic systems, it is important that the rest of the machine is also examined so that the environmental impact of the hydraulic systems can be put into context.

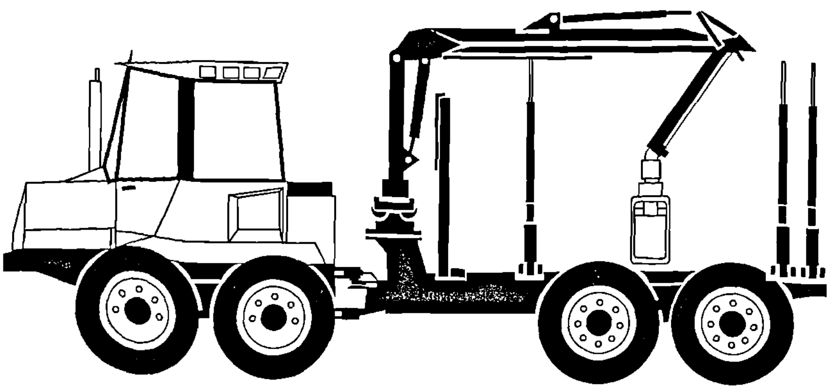

Figure 7.2 A Forwarder

7.3.1 Forestry Machine Production

The machines examined were produced in Scandinavia. Therefore their transportation to the UK has to be taken into consideration in an LCA. For the machines, the use of container ship and land transportation is considered. It should be noted that the maintenance data used do not include transport from Scandinavia because although some parts will be shipped in from Scandinavia there are many replacement parts sourced in the UK.

There is a number of manufacturers who produce similar machinery so the choice of manufacturer is insignificant, but the Forestry Commission, who use these machines, were able to supply use and maintenance data about the machines selected. Contact was made with the UK distributor of the machines and the author visited the company to gather information about the machines, their life expectancy, maintenance records, disposal techniques and production methods. General information was given and the company offered to contact the Scandinavian manufacturer to try to gather further information about the impact of the production of the machines. It was thought that the factories in Scandinavia would have some emissions and energy requirement data for their sites, but they were unable to provide any detailed data about their factory processes. Other forestry machinery manufacturers were contacted, but they were only able to provide a similar level of data. In the absence of more detailed information from other producers the original machines were used in the study.

Data for the production of the machinery were gathered from general specifications for the machines and augmented by information from the manufacturers. A list of all the components was gathered. The total weight of the machines was known, as was the weight of some of the components. As stated earlier, best estimates for the material components were determined.

	Components and total weights (kg)		
Main Machine (14996kg)	Axles(1800kg)	Steel (1000kg)	
		Iron (800kg)	
	Brakes(105kg)	Iron (45kg)	
		Steel (60kg)	
	Chassis(6000kg)	Cast Steel (3000kg)	
		Cast Iron (3000kg)	
	Drive Shaft(400kg)		Steel (400kg)
	Electrical System(90.5kg)	Battery	Lead (72kg)
			Sulphuric Acid (4kg)
			Plastic (4kg)
		Alternator	Steel (3kg)
			Aluminium (0.5kg)
			Iron (3kg)
			Copper (4kg)
	Engine(1142.5kg)	Actual Engine	Steel (170kg)
			Aluminium (60kg)
			Cast Iron (340kg)
		Fuel Tank	Steel (40kg)
		Transmission	Steel (200kg)
			Iron (100kg)
		Gears	Steel (100kg)
			Iron (100kg)
		Fuel Pump	Steel (0.5kg)
			Aluminium (4kg)
		Radiator	Copper (3kg)
		Clutch Assembly	Steel (25kg)
	Hydraulic System(336kg)	Piston pump	Steel (71kg)
		Actuator	St. Steel (160kg)
		Valves	Steel (40kg)
			Iron (15kg)
		Hydraulic Reservoir	Steel (20kg)
		Pipes	Rubber (30kg)
	Main Body(2195kg)	Steel (800kg)	
		Sheet steel (1000kg)	
		Glass (395kg)	
	Steering(50kg)	Steel (50kg)	
	Wheels(1727kg)	4 small	Rubber (417kg)
			Steel (610kg)
		2 big	Rubber (297kg)
			Steel (403kg)
Cutting Tools	Chain saw(15kg)	Steel (15kg)	
	Cutting motors(32kg)	Steel (32kg)	
	Hydraulic System(45kg)	Actuators	St Steel (30kg)
		Pipes	Rubber (15kg)
	Knives(15kg)	Steel (15kg)	
	Main body (893kg)	Steel (493kg)	
		Sheet steel (400kg)	
	Rollers (150kg)	Steel (50kg)	
		Rubber (100kg)	
Transport	Container ship (15650tkm)		
	Trailer (21910tkm)		

Table 7-2Harvester Components

Components and weights (kg)		
Engine (462.5kg)	Actual Engine (340kg)	Steel (102kg)
		Aluminium (34kg)
		Cast Iron (204kg)
	Fuel Tank (10kg)	Steel (10kg)
	Gear Box (80kg)	Steel (72kg)
		Aluminium (8kg)
	Clutch Assembly (25kg)	Steel (25kg)
	Fuel Pump (14.5kg)	Steel (0.5kg)
		Aluminium (4kg)
	Radiator (3kg)	Copper (3kg)
Steering (50kg)	Steel (50kg)	
Main Body (2214.5kg)	Steel (800kg)	
	Steel Sheet (1000kg)	
	Glass (414.5kg)	
Hydraulic System (240kg)	Piston Pump	Steel (50kg)
	Actuator	St. Steel (120kg)
	Valves	Steel (30kg)
		Iron (10kg)
	Hydraulic Reservoir	Steel (10kg)
	Pipes	Rubber (20kg)
Electrical System (115kg)	Alternator (15kg)	Aluminium (1kg)
		Copper (6kg)
		Iron (4kg)
		St. Steel (4kg)
	Battery (100kg)	Lead (90kg)
		Sulphuric acid (5kg)
		Plastic (5kg)
Drive Shaft (400kg)	Steel (400kg)	
Chassis (6250kg)	Cast iron (3125kg)	
	Cast steel (3125kg)	
Brakes (70kg)	Iron (30kg)	
	Steel (40kg)	
Axles (400kg)	St. Steel (100kg)	
	Iron (300kg)	
Wheels (8) (2064kg)	Small Wheels (8)	Rubber(838.08kg)
		Steel (1225.92kg)
Transport	Container Ship (12500tkm)	
	Trailer (17500tkm)	

Table 7-3 Forwarder Components

Table 7-2 and Table 7-3 show the components considered in the machines. The data for the component production for the machines were compiled from the software used and from publicly available datasets as previously discussed.

7.3.1.1 Results – Harvester Manufacture

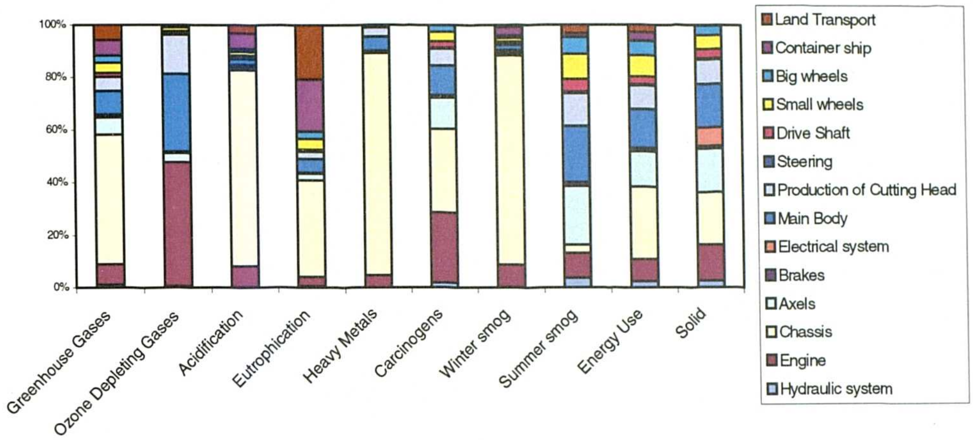

Figure 7.3 Characterised Data for Harvester Production

Figure 7.3 portrays the characterised results for the manufacture of the harvester. It shows that the chassis makes a particularly large contribution towards greenhouse gases, acidification, heavy metal and winter smog. The emission of particulates in iron and steel production contributes to smog. Transportation (both road and sea) contributes significantly towards eutrophication. The impact towards eutrophication is mainly due to the large amount of diesel used in the transportation as diesel refining releases nitrates. The engine manufacture has a significant impact on ozone depleting gases. The production of the hydraulic system does not have a significant effect on any of the categories. However, the characterised data only looks at the percentage contribution to each category and does not examine the significance of the categories themselves with respect to total emissions of the substances in Europe for which the normalised results must be studied.

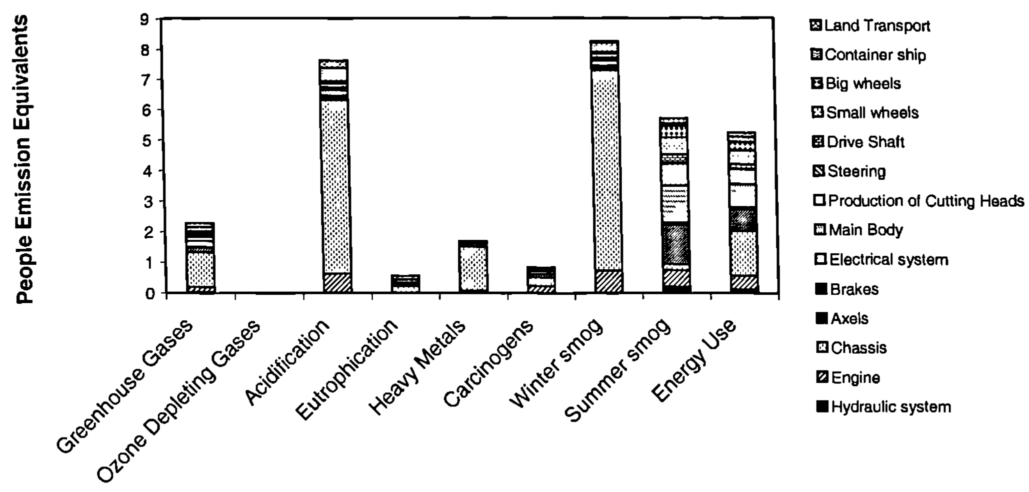

Figure 7.4 Normalised Data for Harvester Production

The normalised results (Figure 7.4) show that the categories in the harvester manufacture with the largest impacts are winter smog, acidification, summer smog and energy use. The largest contributor to these environmental issues is the chassis manufacture: in order to reduce the environmental effect of the manufacture of the harvester significantly, it is necessary to try to improve manufacture of the chassis. This could be done by reducing the quantity of material needed or by changing the materials involved to those with less of an environmental burden. Improving the processes involved with producing the cast iron and steel by reducing the particulate emissions would reduce the environmental burden.

The engine has a contribution towards greenhouse gases, acidification, carcinogens, winter and summer smog and energy use. The axle manufacture has a contribution towards summer smog and energy use, as does the production of the main body of the machine. Transportation impacts on greenhouse gases, acidification, eutrophication, winter and summer smog and energy use. The production of the cutting heads and of the wheels make a contribution towards energy use and summer smog.

7.3.1.2 Results – Forwarder Manufacture

The same analysis was undertaken for manufacture of a forwarder and Figure 7.5 shows the characterised data. Again, it shows that chassis production is the major contribution to many of the environmental issues considered. There are only two categories, ozone depleting gases and summer smog, where the chassis production is not the most significant contributor to the total. The engine production has a significant effect on ozone depleting gases and carcinogens. As with the harvester production, the transportation of the machine has a large impact on eutrophication. The impact of the wheels is greater for the forwarder; because there are more wheels on a forwarder than on a harvester, although some of the harvester wheels are larger than those for a forwarder. The production of polymer products in the rubber in the wheels contributes to acidification. The impact of the hydraulic system is not significant in any of the categories but can be seen in eutrophication, heavy metals, carcinogens, summer smog, energy use and solid waste.

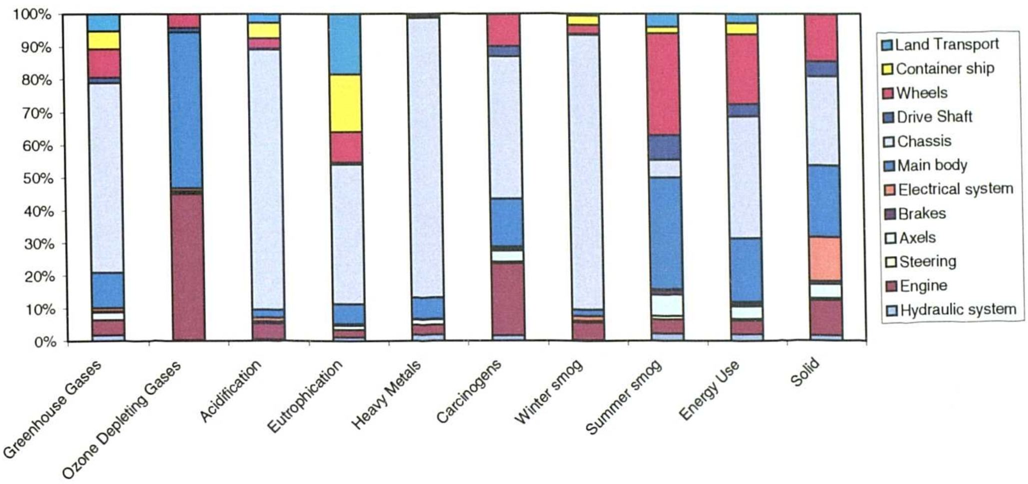

Figure 7.5 Characterised Data for Forwarder Production

The normalised chart in Figure 7.6 shows the significance of the results with respect to total emissions in Europe. The most significant environmental issues considered are acidification, winter smog, energy use and summer smog. The greatest contribution to these categories is the chassis. Chassis production has a significant effect on greenhouse gases, acidification, heavy metals, winter smog and energy use and this is due to the use of cast iron and steel. The main body of the forwarder has a significant contribution towards summer smog and energy use. The wheel production affects summer smog and energy use and the transportation impacts greenhouse gases, acidification, winter and summer smog and energy use. The production of the hydraulic system does not have a significant impact on any of the categories studied.

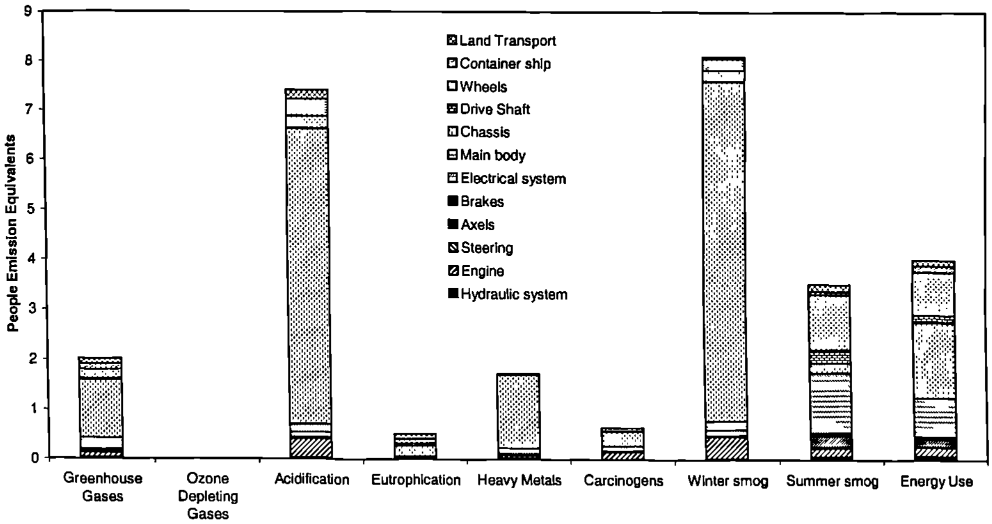

Figure 7.6 Normalised Data for Forwarder Production

7.3.2 Use of Forestry Machines

Although this study focuses on the use, and environmental impact of, hydraulic fluids, it is important to note that forestry machines are powered by diesel engines and this has a significant effect, both in terms of the amount of diesel used and the emissions. Figure 7.7 shows the environmental impacts of the production of the harvester, the production of the hydraulic oil (mineral) used in the lifetime of the harvester and the production of the amount of diesel required to run the machine for its lifetime. It can be seen that the environmental impact of the diesel use is far greater than any of the impacts examined in this research. This must be remembered when assessing the environmental impact of hydraulic oil. In order to substantially reduce the environmental impact of forestry machinery, the amount of diesel used must be decreased and this highlights the need to increase the efficiency of the engines or to use alternative fuels with may introduce other problems.

As discussed in Chapter 6 the life expectancies of mineral and rapeseed oil are not comparable. Mineral oil will last longer in a system than rapeseed oil and the component replacement is less for mineral oil. In this case study the relative ratio of change has been taken as two to one, that is, for every time the mineral oil and hydraulic components in a system using mineral oil are changed, there will be two changes of rapeseed oil and associated hydraulic components within the life time of the machines. A sensitivity analysis has been carried out on this in Chapter 8.

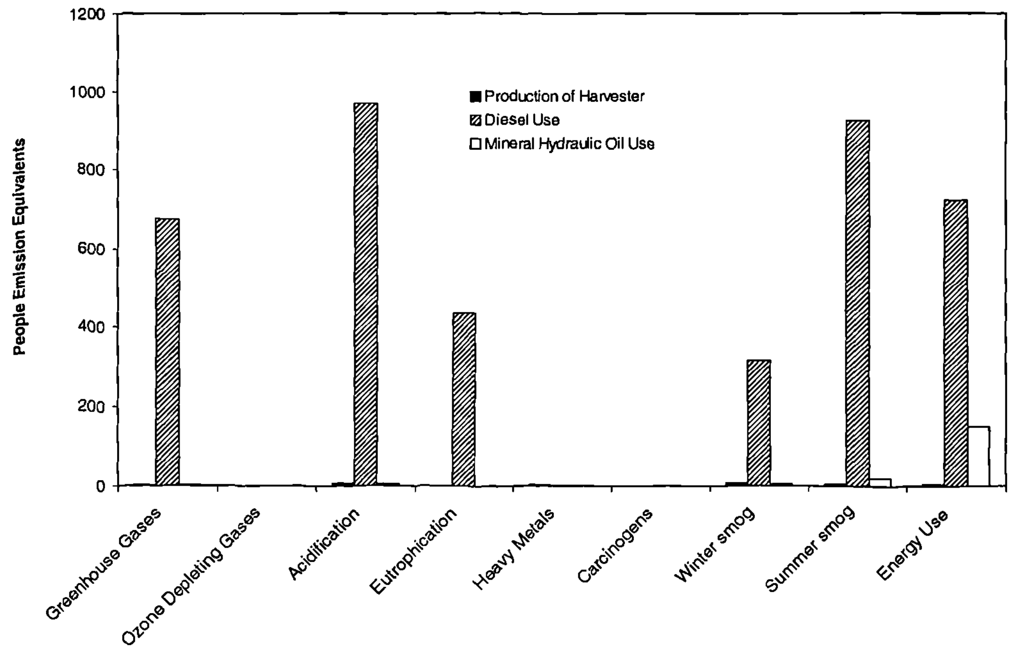

Figure 7.7 Normalised Comparison of Production and Use of the Harvester

Components of other parts of forestry machines also have to be replaced due to wear but these are not affected by the different types of fluid used and so are not included here. Seals and filters need replacing most often on a hydraulic system. Filters should be replaced regularly as a matter of routine maintenance. The Forestry Commission admit to not changing the oil, which is also recommended as a part of routine maintenance, so it is doubtful that the filters are changed as often as recommended. This problem is not limited to the Forestry Commission.

Hoses and pipes also need replacing when they become damaged. When there is a major spillage of hydraulic fluid it is often due to a hose failure. Hoses need be replaced several times during a lifetime, although the exact number depends upon many factors and is a matter of conjecture. Failure to replace can lead to contamination sufficient to cause pump failure. Within a mobile system the oil can become contaminated very easily because dust can be drawn into the system when an actuator is retracted, or there can be an ingress of contaminated oil into the reservoir.

It was impossible to collect reliable replacement and maintenance data for the forestry machinery. The Commission has maintenance schedules but these are often ignored in practice. Therefore, estimations had to be made about the replacement schedules. It was estimated that each component in the hydraulic system will be replaced once in the lifetime of the machines using mineral oil. This is an extreme simplification but it gives an estimation of the environmental impacts. This assumption was discussed at University Steering Committee meetings and at conferences and it was concluded that, in the absence of better data this was a simplification that could be used: once it has been included field data can be substituted as they become available.

It is known that when using rapeseed oil replacement rates are higher than when mineral oil is used. The same principles were followed but for the rapeseed oil it was assumed that they would all be replaced twice during the life time of a machine.

Similar assumptions were made for the life of the oil. The Forestry Commission were able to give data for the amount of mineral oil used. They were not able to specify how much rapeseed oil was used in the lifetime of a machine. This is because the machines that are run on these fluids are new and have not undergone a whole lifetime of running yet; therefore, all data are based on assumptions. However, it was possible to estimate the fluid consumption from data gathered from the Forestry Commission, the Environment Agency and the National Trust for Scotland. The assumption made in this study is that a system will use twice as much rapeseed oil than mineral oil. The same assumptions were made for both machines, the forwarder and the harvester. The "use" phase includes the production of the machines.

7.3.2.1 Results – Harvester Use

Figure 7.8 shows the normalised results of the comparison of the two oils used in the harvester over its lifetime. The impact on greenhouse gases of the system run on mineral oil far outweighs any of the other impacts considered. However, for every other category the impact of the system using rapeseed oil is greater than the impact of the system run on mineral oil. This shows that when considering a "cradle to gate" rather than a "cradle to grave" life-cycle, i.e., not yet including data for the disposal of the systems, there is no definite environmental benefit gained by using rapeseed oil, unless one is particularly concerned about the impact on greenhouse gases.

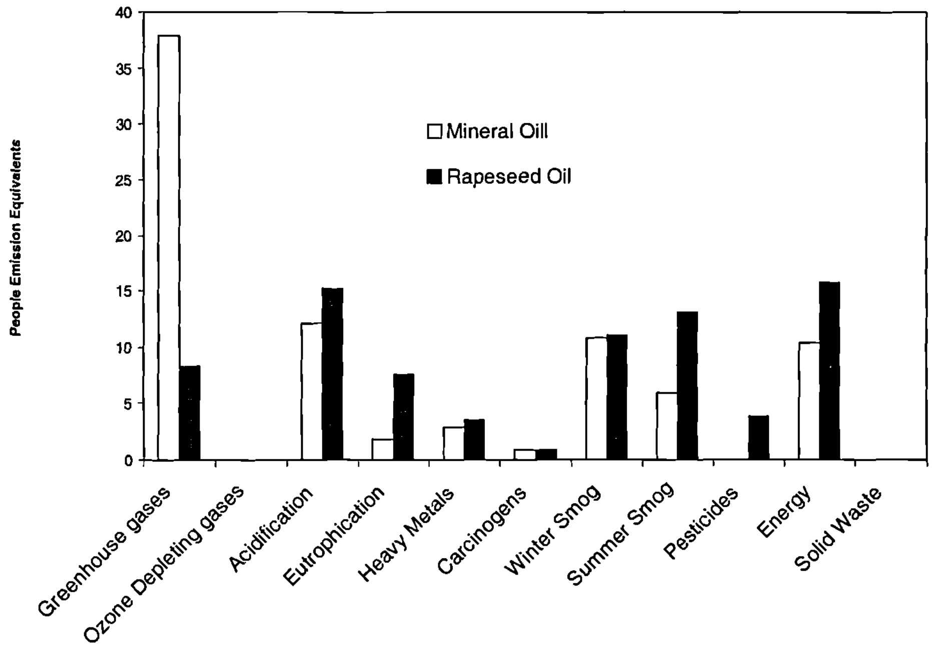

Figure 7.8 Comparison of Normalised Data for the Use of the Harvester

7.3.2.2 Results – Forwarder Use

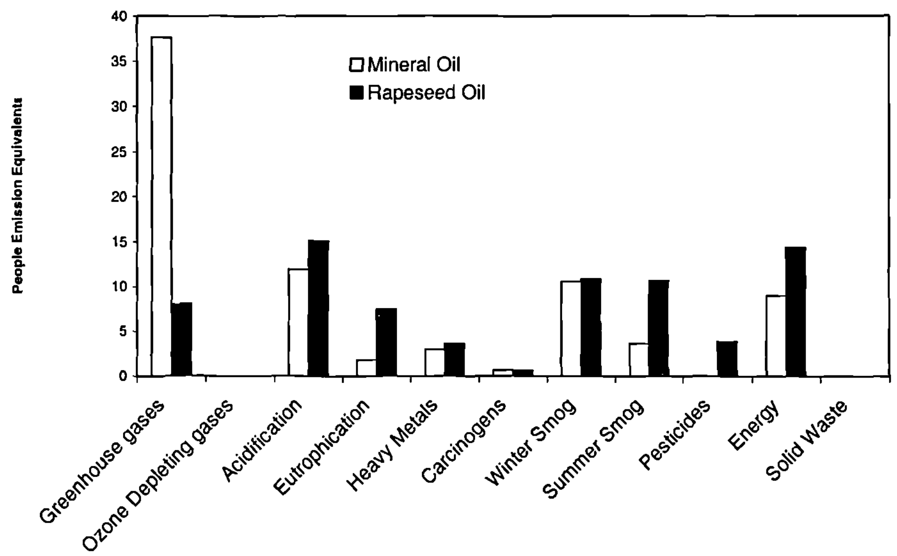

Figure 7.9 Comparison of Normalised Data for the Use of the Forwarder

Figure 7.9 shows the normalised results for the comparison of the two oils used in the forwarder. The impact of the system running on mineral oil far outweighs any of the other impacts considered. Again, for every other category the impact of the rapeseed oil is greater than the mineral oil.

7.3.3 *Disposal of the Forestry Machinery*

Forestry machines are generally run until they are no longer able to work efficiently. This is approximately fifteen years, after which they are usually used or sold for spares, or sold for scrap. No detailed records for this were obtained. Although none of the machines running on rapeseed have yet been disposed of it is unlikely that these machines will be disposed of in any different manner. Therefore the assumption has been made that the disposal mechanisms will have no effect on the comparison of the two hydraulic systems. The disposal of the machines has not been included in the study as there were not enough data to avoid complete speculation.

7.4 *Road Sweepers*

Road sweepers are used in most towns and cities in order to keep the streets, gutters and pavements clean. Their inclusion in the study was due to suggestions from many hydraulic users and manufacturers when the author requested information about the use of bio-fluids in hydraulic systems and invited ideas for case studies. Sweepers work in urban areas which are constantly subjected to small spills of diesel and petrol from cars and lorries, litter and other pollutants. The areas which are affected are generally tarmac or paved surfaces and it may be argued that the environmental effect of a spillage on these areas may not be significant. However, all of these areas have good drainage systems devised to channel water from urban areas in times of rainfall so that puddles and localised flooding do not form in the road or pavement. Many of these drains lead directly to rivers and so any pollutants contained within them will also go into the rivers. Some of the more modern, expensive drainage systems do have holding tanks which can separate out some of the pollutants but these tanks are uncommon and most of the water and pollutants that are carried away in the drainage system end up in the rivers. Therefore, a large spill of hydraulic oil from a road sweeper could cause a significant effect.

The case study was based on a typical road sweeper, shown in Figure 7.10 which is used by Bath and North East Somerset (BANES) council. Vehicle maintenance and running data were collected from BANES and details of the hydraulic system was also obtained. A representative from its UK supplier was contacted through BANES.

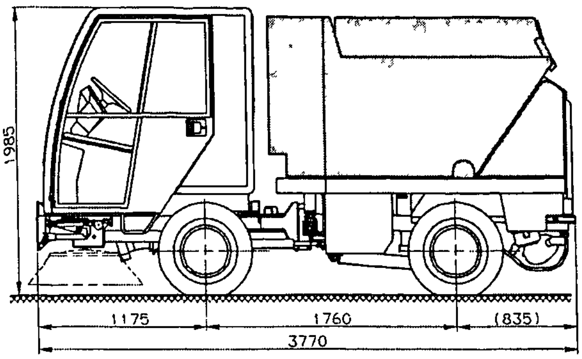

Figure 7.10 A Road Sweeper

7.4.1.1 Road Sweeper Production

The machines are Swiss-made, but are supplied and maintained within the UK. The machine parts needed in maintenance are transported from Switzerland.

Details for the manufacture of the machine itself were obtained from Jack Allen literature and service personnel. An outline of the component list of the sweeper is shown in Table 7-4. More detailed information was sought from the manufacturer and distributor, but was not forthcoming. Table 8.4 was sent to the manufacturer and the distributor together with a covering letter. The letter stated that these data had been gathered and that would be used in the LCA study. A request was made for further details or comments on the information in the table, for example, the specific types of rubber used, or the specific weights of any of the components, however, no further information was received.

The information shown in Table 7-4 was that used to analyse the production of the sweeper. Figure 7.11 shows the characterised results for the production of the different components of the machine. A table of these data is shown in Appendix 4 which shows that the main environmental emissions and raw material requirements are due to the production of the main cab, the engine and the chassis. The production of the hydraulic system does not have a significant influence on any of the categories, but is manifest in the greenhouse gases, acidification, eutrophication, heavy metals, winter and summer smog, energy use and solid waste categories. The main cab has a particularly significant effect on heavy metals and carcinogens and the chassis production makes a particular contribution to summer smog. However, as these are characterised data the significance of these emissions and raw material requirements cannot be analysed; therefore, the same data have been shown in a normalised form in Figure 7.12.

Road Sweeper			
Battery	36kg	32.4kg lead	
		1.8kg Sulphuric Acid	
		1.8kg Plastic	
Alternator	9.6kg	0.48kg Al alloy	
		3.84kg Copper	
		2.64kg Iron	
		2.64kg Stainless Steel	
Radiator	2kg	Copper	
Fuel Tank	5kg	Steel	
Gearbox	60kg	54kg Steel	
		6kg Aluminium	
Clutch Assembly	20kg	Steel	
Fuel Pump	10kg	7kg Steel	
		3kg Aluminium	
Chassis	1000kg	(steel frame welded from rectangular tubular steel)	
Axles	180kg	54kg Steel	
		108kg Iron	
Wheels	80kg	48kg Steel	
		32kg Rubber	
Brushes	50kg	30kg Steel	
		20kg Polypropylene	
Water Tank	20kg	Stainless Steel	
Hopper/collection unit	45kg	Stainless Steel	
Hydraulic System	140kg	Pumps	35kg Steel
		Actuators	65kg Stainless Steel
		Valves	15kg steel
			5kg Iron
		Hydraulic Reservoir	5kg Iron
			5kg Steel
		Pipes	10kg Rubber
Main Cab	510.4kg	450kg Aluminium	
		10kg Safety Glass	
		50.4kg Plastic	
Engine	232kg	139.2kg cast iron	
		69.6kg steel	
		23.2kg alloy	

Table 7-4 Sweeper Component List

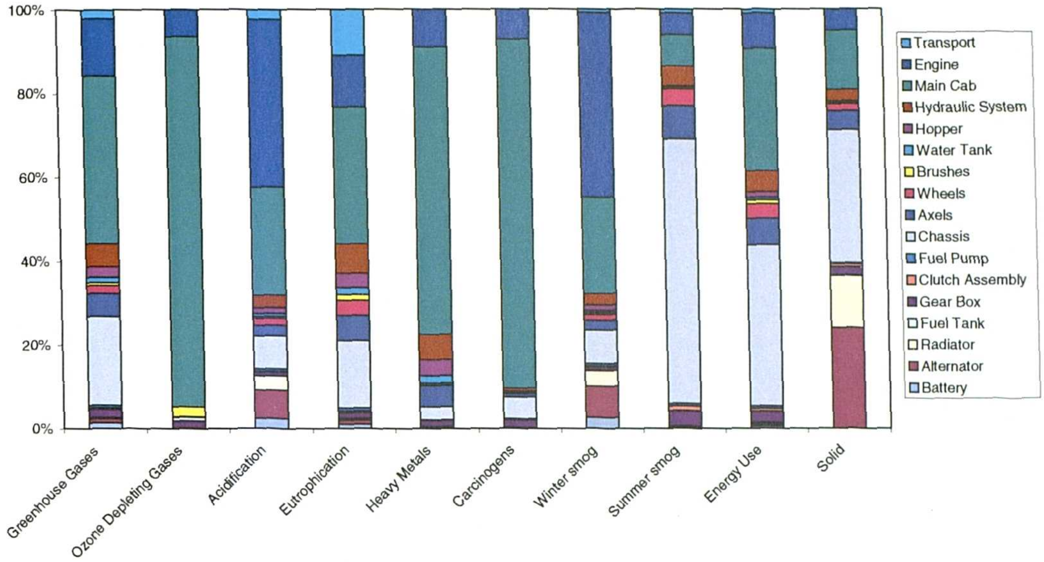

Figure 7.11 Characterised Data for Sweeper Production

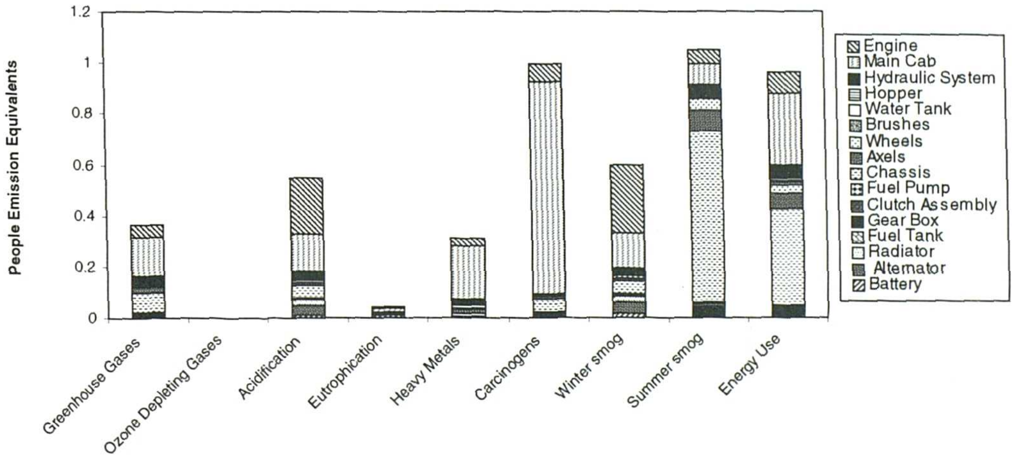

Figure 7.12 Normalised Data for Sweeper Production

7.4.1.2 Results – Sweeper Production

Figure 7.12 shows that the main environmental impacts upon carcinogens, summer smog and energy use are due to the production of the main cab, the engine and the chassis. The production of the hydraulic system has a small effect on greenhouse gases, acidification, eutrophication, heavy metals, carcinogens and winter smog, and a slightly larger effect on summer smog and energy use. The production of the hydraulic system is not particularly large in any of the environmental categories. If the processes involved in the production of the main cab and chassis in particular could be improved then the total environmental impact of the production of the machine would be reduced. The main cab has a large effect on carcinogens due to the amount of aluminium used. Aluminium production results in the emission of PAH's and benzo[a]pyrene which are known carcinogens. These emissions occur in the smelting process as a result of a practice called anode baking and it is the largest source of PAH emissions in the UK. Further examination of the sensitivity of the results are discussed in Chapter 8.

7.4.2 Use of the Sweeper

More specific maintenance data for the sweepers were obtained than for the forestry machinery. To date all of these machines work on mineral hydraulic oil, but it is probable that many of these machines will be changed to run on biodegradable hydraulic oils in the near future due to the sensitive, and very public, nature of their work. All the figures described in this section about maintenance therefore are based on the use of the mineral hydraulic oil. Unfortunately data for the diesel use in the sweeper was not obtained, therefore a comparative study was not able to be made. However, it is probable that the environmental impact of the diesel use will be greater than that of hydraulic oil.

The machines work an average of six hours a day for five days a week. The hydraulic filters are changed every 800 hours and the engine filters every 200 hours. The machines work in dusty environments and on average there will be approximately two hose failures a year within a fleet of seven machines. The hoses are the components within the hydraulic system most prone to damage as they are exposed to the elements all year round. However, there has only been one serious failure of a hose within the BANES fleet - it caused several cars, buildings and people to be sprayed with hydraulic fluid. This failure happened in a new machine and was due to a faulty fitting. The actuators are also prone to damage as a result of the high pressures to which they are subjected. This will not result in a large spill of fluid but a slow weeping over a long period of time.

It is recommended by the manufacturer that the hydraulic oil be replaced at least every two years. With a tank capacity of 60 litres this means that within the lifetime of each sweeper with BANES 120 litres of oil will be needed. However, there are leaks and spills from the system and, in reality, the levels are checked approximately every 50 hours. It is assumed that in the four years of working life, 17 litres will be lost due to a failure (based on the assumption of an average loss of a quarter of a tank per failure at an average rate of 1.14 failures per machine in the four year period (two a year with seven machines) and an added 17 litres loss from small leaks. This means that, through maintenance, failure and leakage, approximately 154 litres of oil will be used per sweeper over the four years.

Figure 7.7 shows the relative contributions of the different aspects of the life cycle of the harvester. It shows that the use of diesel fuel far outweighs the production of the machine and the use of the hydraulic oil. This is probably also true for the sweeper, although exact data for the amount of diesel fuel used were not obtained. However, Figure 7.7 also shows that the environmental impact for the production of the machinery and the use of hydraulic oil yields similar results in many of the environmental categories. Figure 7.13 shows that this is not the case for the sweeper. The sweeper uses far less oil over its lifetime than the forestry machinery. Comparatively therefore the oil use has far less of a significant effect over the life cycle of the whole machine.

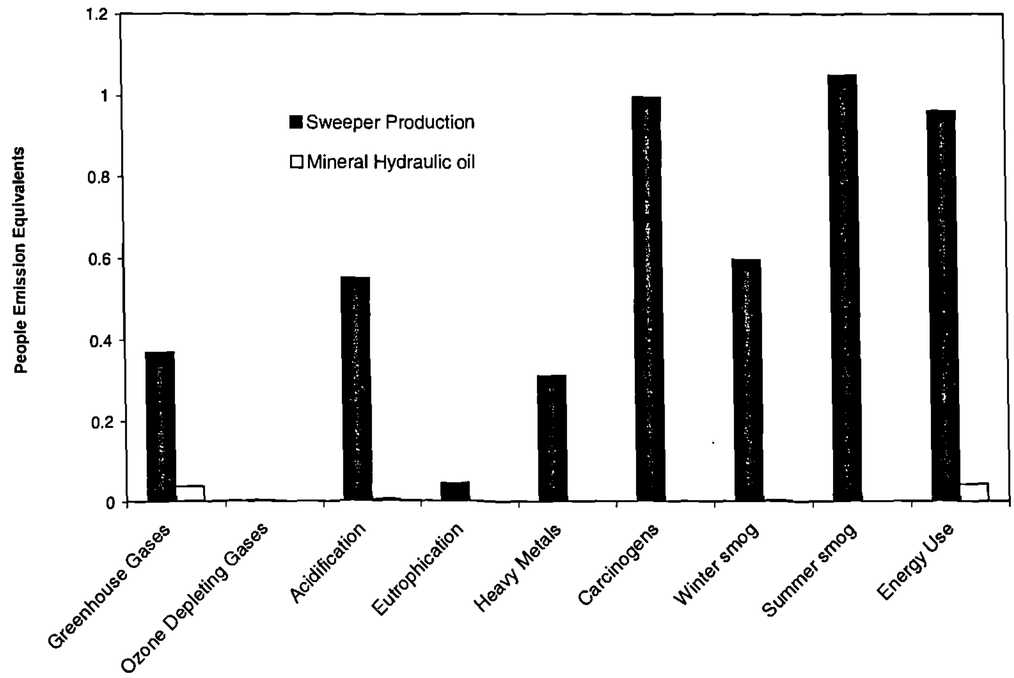

Figure 7.13 Normalised Comparison of Sweeper Production and Hydraulic Oil Use

7.4.2.1 Results – Sweeper Use

Figure 7.14 shows the normalised results for the comparison between the use of mineral and rapeseed oil in the sweeper. The impact of greenhouse gases from the use of the mineral-run system is far less pronounced than when used in the forestry machines. This is because there is less oil used over the entire life of the machine, as discussed above. However, the sweeper shows the same trend as both the forestry machines. For the greenhouse gas category the environmental impact is larger for the system running on mineral oil. For every other category the system running on rapeseed oil has a greater impact.

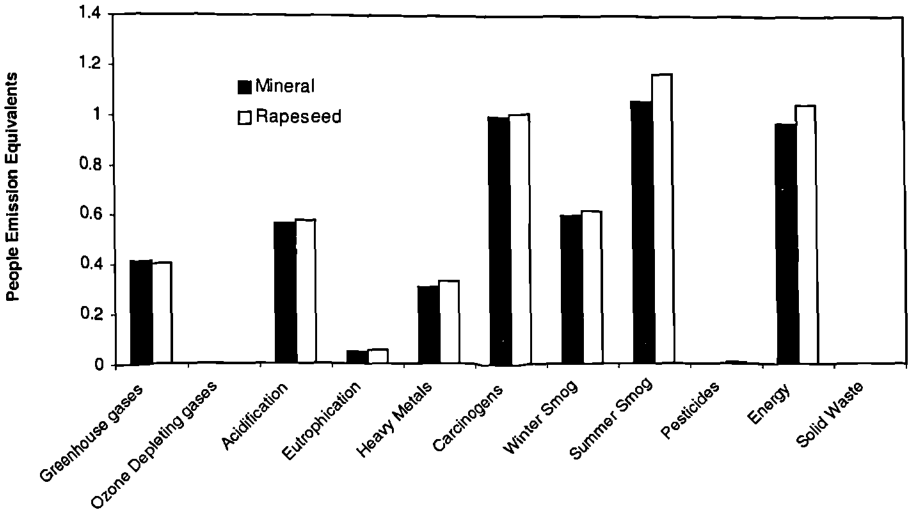

Figure 7.14 Normalised Comparison of Different Oils in a Sweeper

7.4.3 Disposal of the Sweepers

BANES use the sweepers for four years, after which they are sold at auction. They will normally be reconditioned or used for spare parts. It has not been possible to gain any further data for this period in the sweeper's life, therefore disposal of the machines has not been taken into consideration. The machines will have a useful life longer than four years and so in this study the LCA is not taking into consideration the whole life. If the LCA comparison were being made with some other form of street cleaning equipment then it would clearly be impossible to end the LCA at this stage. However, the comparison is made within the same machine, only working with different oils. There is no evidence to suggest that the lives will differ dramatically due to the oils. However, this is obviously a shortcoming in the study.

7.5 Oil Disposal

At present in the UK there is no separate disposal mechanism for mineral and rapeseed oils, but this is not the case in many European countries. In the UK all oil is collected together and is disposed of together. Much of the oil is burned or used in asphalt making, some is re-refined to be used as lower grade oils. There is no comparative difference and as there was no information about the emissions or raw material requirement for this process it has not been included. This is an obvious shortcoming in the study, but it should not have a detrimental effect on the comparative study performed.

It is unusual for mineral hydraulic oil to be re-refined as a hydraulic oil in the United Kingdom. Much of the oil which is re-refined is used as a lower grade oil. This, again, is not the case in other European countries. In Germany, for example, oil is collected and re-refined and can be used as hydraulic oil but rapeseed based oil cannot be re-refined in this manner. This means that if the processes were to change in the UK to become more like the German processes, the large difference in the impact towards global warming could be reduced. If the mineral oil could be used more than once then the impact towards global warming would be reduced. This scenario is not currently the case in the UK and so does not apply to the case studied in this research.

7.6 Valuation

If a valuation stage were to be carried out and an "aggregate impact value" was given for the LCAs based on each environmental impact assessed being given equal weighting, then for the forwarder and the harvester the overall number would be higher for the system run on mineral oil than for the system run on rapeseed oil: 78.16 for the mineral oil run system versus 74.85 for the rapeseed oil run system for the forwarder. These values are obtained by simply adding the characterised numbers together. This produces an equally weighted value. The number is higher for the mineral oil because of the very large impact the mineral oil system has with respect to greenhouse gases. For all categories other than one, in both the harvester and forwarder case, the rapeseed oil-run system places a larger burden on the environment than does the system run on mineral oil, yet a one number result indicates that the mineral oil system has a larger impact. This obviously shields a lot of the results.

A weighted "single number" answer could give other results depending on the values given to the various classification categories. If this were to be done then the steps taken in the valuation stage would have to be clearly identified. The author believes that one should discourage the use of this and that it is better for the data to be left at this stage so that all the information is presented and made available for evaluation. These criticisms would equally apply to the use of Multi Criteria Decisions Analysis because on scientific grounds it is difficult to assign appropriate weighing factors.

7.7 Discussion and Conclusions

This chapter has outlined the production method for a harvester, forwarder and sweeper. Although the data are not complete, and there are areas which could be improved, it is considered that enough information is available to provide an adequate summary of the environmental impacts associated with the manufacture of these machines. For all of the machines, it was shown that the main environmental impacts lay with the production of the chassis and the main body of the machine which are the largest parts. In no case did the production of the hydraulic system make a large contribution to the environmental impact of the production of the machines.

The environmental impact of the use of the machines then showed that apart from the impact upon global warming the systems using rapeseed oil had a greater impact upon all the environmental issues considered. The impact upon global warming far outweighs any other impact for the harvester and the forwarder. This is not the case for the sweeper as less oil is used over its lifetime and so, the production of the machine, which is the same for both systems, assumes a greater prominence.

It is a surprising result that the environmental footprint of the systems running on rapeseed fluid is often greater than that of those running on mineral oil. This is due to the performance characteristics of the rapeseed oil. Rapeseed fluids do not last as long under pressure and temperature as their mineral counterparts. They also have a more destructive effect on some of the hydraulic components (for example, rubber seals and hoses), and so they have to be replaced more frequently, causing more of an environmental burden.

No information about the disposal of the machines or the fluids used was included in this study. Although that is a shortcoming in the research it should not have any detrimental effect on the comparative nature of the study.

The case studies have shown that it is not necessarily environmentally beneficial to use rapeseed oil in fluid power systems. However, the local impacts have not been considered within the LCA. The local impacts are the reason that machine users have started to use such fluids. This study shows that unless there is a likelihood of a spill in a sensitive area then it is not environmentally beneficial to use a rapeseed oil based hydraulic system in either forestry machinery or sweepers.

8 Data Quality, Availability and Sensitivity Analysis

8.1 Introduction

A Life Cycle Assessment study is subject to error and uncertainty in many areas. It is impossible to gather accurate data for each and every stage associated with the life of a product or a system. Accuracy of data within an LCA is a very important issue. Not only has one to be certain that the raw inventory input data are correct, but it is necessary to be aware of possible data gaps and data inaccuracies. It is impossible to collect information about all the inputs and outputs from a product or system, so it is as important to know what has been left out as to know the accuracy of what has been included. This is difficult because processes are often reported incompletely or inaccurately. Ideally therefore, each section and stage of an LCA should be reviewed by an expert in the relevant field, but this is impossible in most cases due to time and money constraints. The quality of each LCA will therefore depend on both the quality of the input data and the knowledge of the percentage of the input data that has been made available for the study.

This chapter will outline the main areas for sensitivity within this study. Chapter 7 showed that the main impacts upon the environment during the production of the machinery were felt during the manufacture of the chassis and the main body of the machines. Therefore, a full examination of the production of these components is undertaken here. The amount of oil used within the machines was a controversial issue therefore a study of different replacement rates has been examined.

The Life Cycle Impact Assessment (LCIA) stage is also important within LCA with respect to data quality, availability and sensitivity. As was discussed in Chapter 2 the methodology used in this stage has not been universally accepted and different people have used different impact assessment methodology in different LCAs. This chapter will examine the impact of using slightly different LCIA methodologies for the case studies already discussed and it will examine the effect of using different characterisation data.

Initial inventory input data is not the only area for concern over data quality in an LCA. Data are used which may not be initially apparent to the reader of an LCA report. Characterisation data are needed for the impact assessment stage and, if carried out, the valuation stages. Data variation can lead to changes in final results in a study with comparable inventory input data. The environmental impact categories studied can also have an effect on the final results of a study.

This chapter is broken down into three main sections:

- Sensitivity of the inventory data - machinery manufacture
- Sensitivity of the inventory data - machine use
- Sensitivity of the LCIA (characterisation) data

8.2 Sensitivity of the inventory data - machinery manufacture

An investigation was undertaken into the sensitivity of the case study results with respect to the data used in the machine manufacture, oil production, and field data for the use of machinery. Normalised data are shown within the text, full tables of the characterisation data are given in Appendix 4.

The total weight of the machines in the case studies was known, but the weights of the constituent components had to be estimated. The results described in Chapter 7 outline which parts of the machines contribute the largest environmental effect for each of the machines. These were used to determine on which components a sensitivity analysis would be used. Two methods were proposed for the sensitivity analysis:

- Vary the individual component weight and accept that the total weight will not remain the same (Method A).
- Vary the individual component weight and keep the total weight the same by also varying other components (Method B).

Both of these methods have problems associated with them. The first method is simplistic and unrealistic in that it does not maintain the one variable that is known. The second is problematic because many variables are changed at once and it is impossible to know to what these changes are attributable. When none of the inputs are absolute it is impossible to find a solution to this problem, therefore, both methods were used in this study. This was done to highlight some of the problems associated with sensitivity analysis in LCA. ISO 14042 recommends that a sensitivity analysis should to be carried out on an LCA, but it is difficult to determine how to do this when so many of the input data are variable or unknown.

The first approach to sensitivity analysis was fairly straightforward; the weight of a chosen component was varied by the chosen amount, the LCIA was undertaken and the new results were compared with the original results. The second method was slightly more complex. In order to maintain the total weight when varying an individual component, the weight of other components have to change and this can be dealt with in several ways, none of which is perfect. One method would be to arbitrarily choose another of the inputs and reduce or increase it by the same amount as the chosen component: this is simple but the disadvantage is that the arbitrarily chosen component has just as much impact on the final results as the selected component. Another method is to reduce the weight of all the other components by an equal proportion. An adapted version of this method was used in the second sensitivity analysis. It is known that some of the components are correct to within a given percentage and this determined the allowed maximum variation. For example, it is known that the data for the wheels are correct to within 5%, therefore the weight of the wheels was not allowed to vary by more than 5%.

If the total weight is T, and there are N components, then

$$\sum_{i=1}^{N} x_I = T .$$

If given component series x_I has a percentage error E_i, x_I is perturbed by E_I but the total of the series must remain equal to T. This is achieved by perturbing all the other component weights in the series by some percentage λ. This is given by equation 8-1 whose basis is determined in Appendix 5.

$$\lambda = 100\left[\frac{T - x_I\left(1 + \frac{E_I}{100}\right)}{T - x_I} - 1\right] . \qquad \text{Equation 8-1}$$

Although all the data are to some extent uncertain, there are components about which more is known. These data have less uncertainty attached to them. If one wants to assign a maximum variation for these values then the following equation, derived in Appendix 5, must be used:

$$\lambda = 100\left[\frac{T - x_I\left(1+\frac{E_I}{100}\right) - x_J\left(1-\frac{\lambda_0}{100}\right)}{\left(\sum_{i=1} x_I\right) - x_I - x_J} - 1\right].$$ Equation 8-2

When:

E_I	= known percentage error
λ	= percentage correction for all other data
T	= The sum of the values of the series
$x_1, \ldots, x_n$	= members of the series
x_I	= value to which applying error
x_J	= limiting change value
λ_0	= maximum percentage change for x_J

So, for example, if one wanted to vary the weight of a component weighing 6000kg by 20% in a machine that weighed 14996kg and one knew that the weight of the one component weighing 1727kg was correct to within 5% one would use the equation as follows:

$$\lambda = 100\left[\frac{14996 - 6000\left(1+\frac{20}{100}\right) - 1727\left(1-\frac{5}{100}\right)}{14996 - 6000 - 1727} - 1\right]$$

$\lambda = 15.32\%$.

Therefore, the other components in the machine will have to be changed by 15.32% in order to maintain the weight of the machine when the component under scrutiny is changed by 20% and the limit of change on one of the components is 5%.

A full description of the mathematics underlying this method is given in Appendix 5.

8.2.1 Harvester Manufacture

8.2.1.1 Chassis Sensitivity

Figures 7.3 and 7.4 show that the production of the chassis is the predominant contributor to the environmental impacts associated with the manufacture of the harvester. It was estimated that the weight of the chassis could be incorrect by a factor of

± 20% and an analysis was carried out to determine the sensitivity of the final results to this error. Using the first methodology, the total weight of the machine was also changed. The results of this analysis are shown in Figure 8.1 and shows that when the weight of the chassis is increased the environmental impact of all the categories is increased which is not surprising because the weight of the machine was considered to be increased. The biggest changes are seen in the acidification and the winter smog. With a reduction in weight the impact on the environmental issues considered is reduced. The environmental issues most sensitive to a change in the weight of the chassis are acidification, winter smog, greenhouse gases, heavy metals and energy. The weight change does not result in a large change towards eutrophication, ozone depletion, carcinogens, summer smog or pesticides.

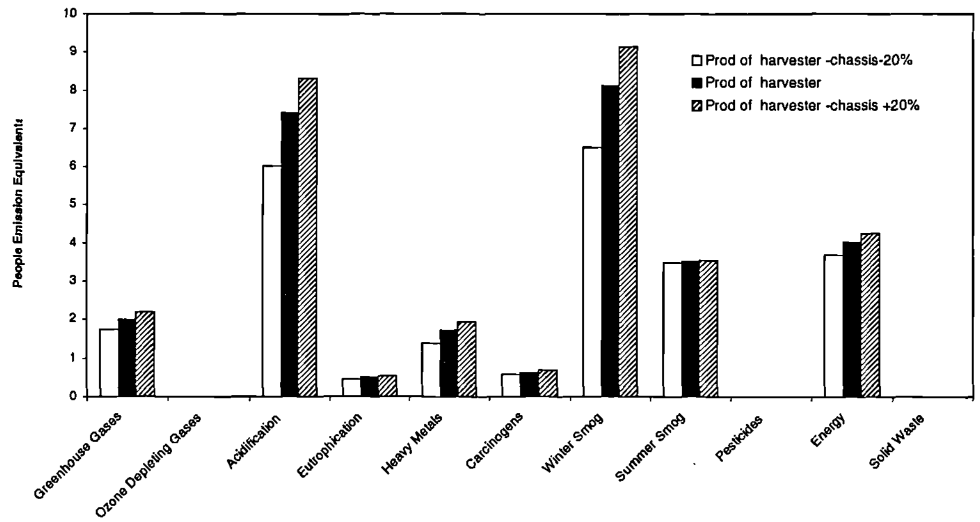

Figure 8.1 Normalised Chassis Weight Sensitivity in a Harvester using Method A

When the second sensitivity analysis method was used the weight of the wheels was kept to within 5% because the data used for the wheels were very accurate. Again, the weight of the chassis was varied by 20%, but the total weight of the machine was kept constant.

	Total -20%	Total - original	Total +20%
Greenhouse Gases	1.91	2.01	2.11
Ozone depleting gases	0.000632	0.000549	0.000465
Acidification	5.97	6.93	7.89
Eutrophication	0.314	0.34	0.365
Heavy metals	1.45	1.69	1.94
Carcinogens	0.876	0.847	0.813
Winter smog	6.78	7.9	9.02
Summer smog	6.13	5.44	4.7
Pesticides	0	0	0
Energy Use	5.1	4.92	4.72
Solid Waste	0	0	0

Table 8-1 Normalised Chassis Weight Sensitivity in a Harvester

The results of this approach are shown in Table 8-1 and Figure 8.2. When the weight of the chassis is reduced by 20% the impact towards greenhouse gases, acidification, heavy metals and winter smog are reduced markedly which are similar to the results from the first sensitivity analysis method. However, the results from this method differ markedly in their impact towards carcinogens, summer smog and energy use compared with the first method. In the second methodology the impact towards carcinogens, summer smog and energy use decrease when the chassis weight is increased because the impact of the decrease in weight of all the other components has a greater impact on the results than the increase of the chassis weight. This shows how sensitive the results are to the sensitivity analysis method used.

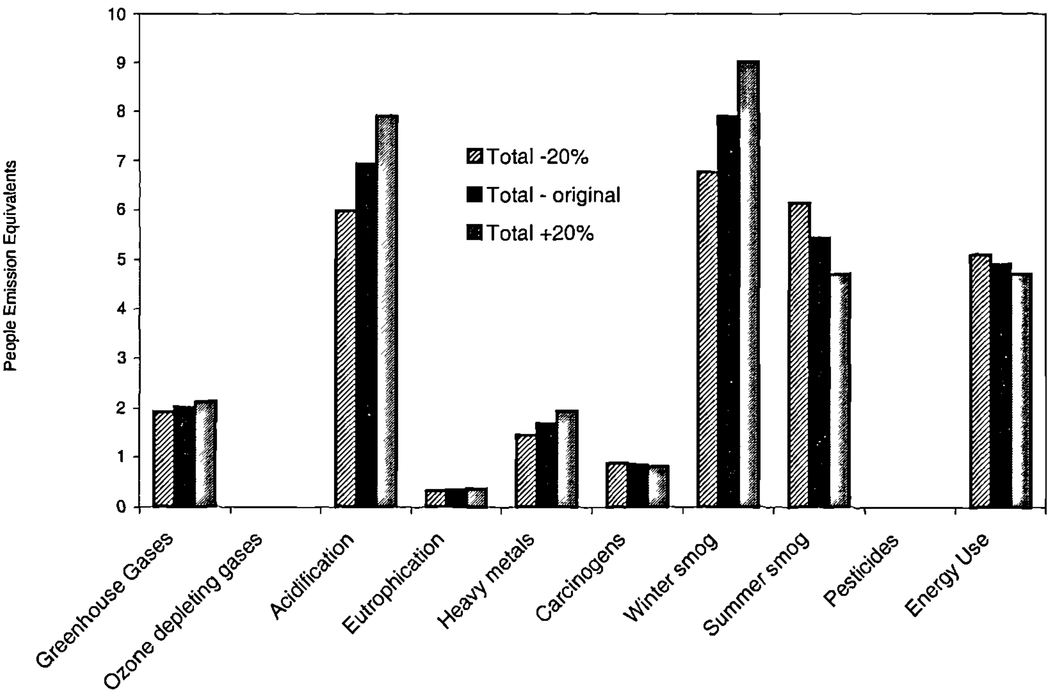

Figure 8.2 Normalised Chassis Weight Sensitivity in a Harvester using Method B

	Total-20	Total - original	Total+20
Greenhouse gases	2.15	2.01	1.98
Ozone depleting gases	0.000643	0.000549	0.000539
Acidification	7.21	6.93	6.74
Eutrophication	0.366	0.34	0.33
Heavy metals	1.78	1.69	1.65
Carcinogens	0.896	0.847	0.846
Winter smog	8.2	7.9	7.69
Summer smog	5.92	5.44	5.55
Pesticides	0	0	0
Energy use	5.3	4.92	4.9
Solid waste	0	0	0

Table 8-2 Normalised Axle Weight Sensitivity in a Harvester

8.2.1.2 Axle Sensitivity

Figure 7.4 shows that the production of the axles also plays a significant part in the contribution towards summer smog and energy use. For this reason the sensitivity of the final results to changes in the weight of the axles has also been examined. The results using the first sensitivity analysis methodology, Figure 8.3. show that the environmental impact is not greatly affected by the change in the axle weight; the only discernible sensitivities are towards summer smog and energy. Here the impact is slightly reduced when the weight of the axles is reduced but the sensitivity does not appear to be large.

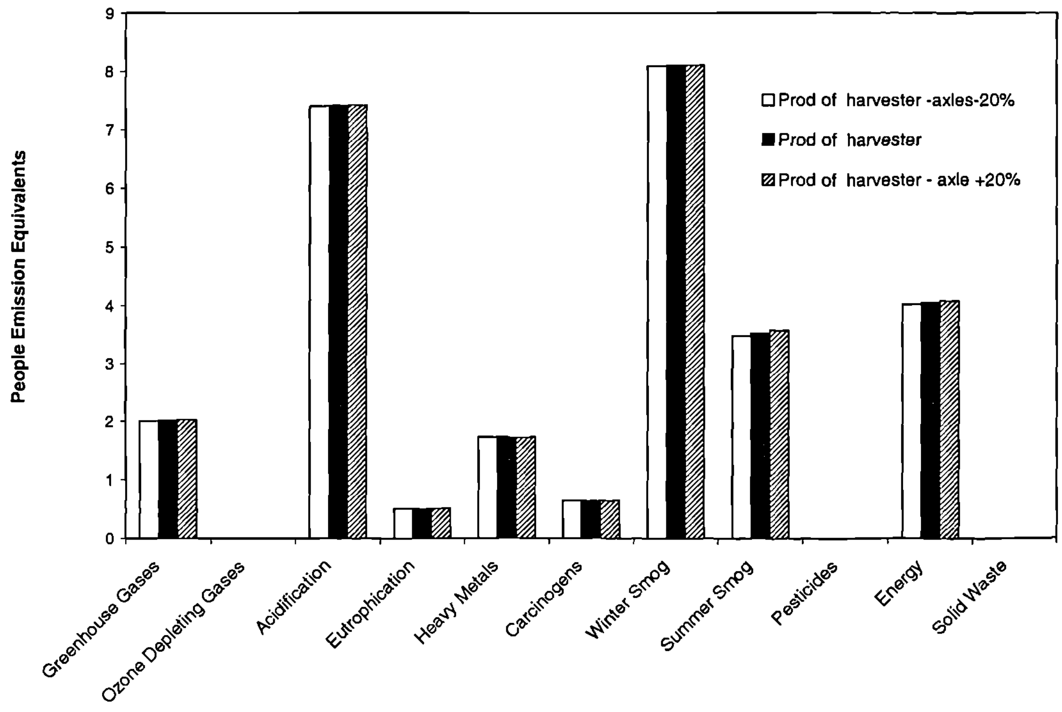

Figure 8.3 Normalised Axle Weight Sensitivity in a Harvester using Method A

The results from the second methodology are shown in Figure 8.4 and Table 8.2. Figure 8.4 shows that if the weight of the axles is increased by 20%, the impact on greenhouse gases, ozone depleting gases, acidification, eutrophication, heavy metals, carcinogens, winter smog and energy use is decreased. The impact of summer smog is increased. The impact towards summer smog is increased when the axle weight is increased or decreased. Again, the difference between the results from the two methodologies is quite marked. This suggests that there is a fine balance between the components of the axle and the components used to make up the total weight. Most of the results show that there is a more significant impact on the final results when the weight of the axles is decreased than when it is increased by the same amount. This indicates that the components of the axles (steel and iron) have a less significant impact on the overall environmental impact than the other components do.

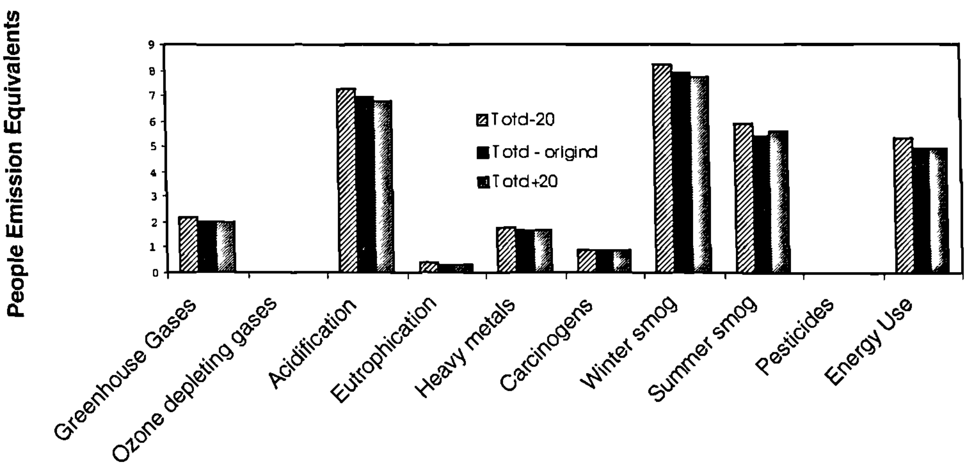

Figure 8.4 Normalised Axle Weight Sensitivity in a Harvester using Method B.

8.2.1.3 Mainbody Sensitivity

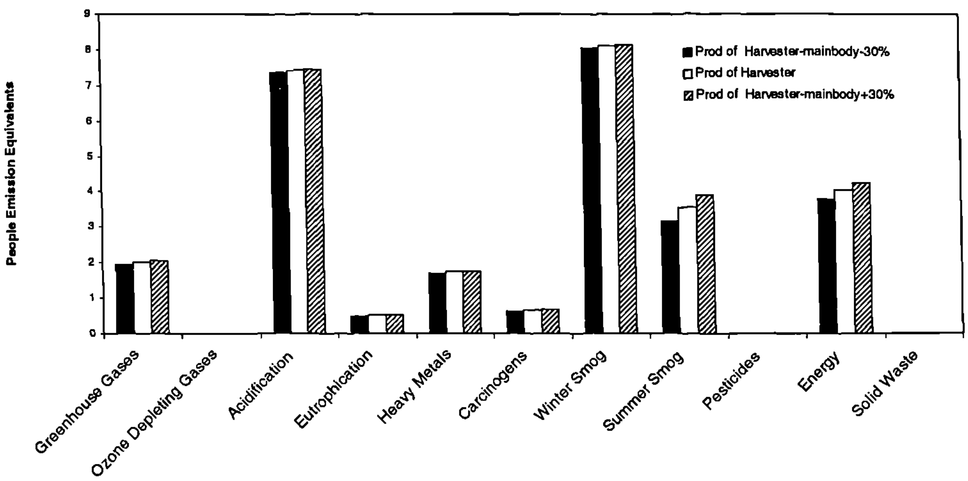

Figure 8.5 Normalised Mainbody Weight Sensitivity in a Harvester using Method A

The weight of the main body had to be estimated therefore, the sensitivity of the final result to changes in this was also examined. Results from the first sensitivity analysis methodology, Figure 8.5, are not very sensitive to change in the weight of the mainbody. The largest changes appear in the impact towards summer smog and energy use and these impacts are always increased when the weight of the component in question is increased and decreased when the component's weight is decreased.

The results from the second methodology, Table 8-3 and Figure 8.3, show that the final results are less sensitive to changes in the main body weight than to changes in the weight of the chassis. There are no significant changes to the greenhouse gases, ozone depleting gases, eutrophication, heavy metals or carcinogens. When the weight is decreased by thirty percent the impact on acidification, and winter smog increases, the impact towards summer smog is slightly reduced. When the weight is increased by thirty percent the impact towards acidification, and winter smog is reduced and the impact towards summer smog and energy use is increased.

For acidification and winter smog the results are reversed between the two methodologies. This is because the impact of the change in weight of all the other components is greater than the impact of the actual component variation.

It is obvious that although the final results are sensitive to changes in the weights of the chassis, axles and main body, none of the changes to the final results is very significant. This means that any changes to the components in the machines will not have a highly significant effect on the final results. However, this may not be the case for the manufacturing processes which could not be included in this study for reasons discussed in Chapter 7.

	Total-30%	Total - original	Total+30%
Greenhouse Gases	2.04	2.01	2.12
Ozone depleting gases	0.000505	0.000549	0.00059
Acidification	7.23	6.93	6.82
Eutrophication	0.347	0.34	0.37
Heavy metals	1.74	1.69	1.65
Carcinogens	0.846	0.847	0.883
Winter smog	8.25	7.9	7.72
Summer smog	5.31	5.44	6.42
Pesticides	0	0	0
Energy Use	4.91	4.92	5.61
Solid Waste	0	0	0

Table 8-3 Normalised Mainbody Sensitivity for the Harvester

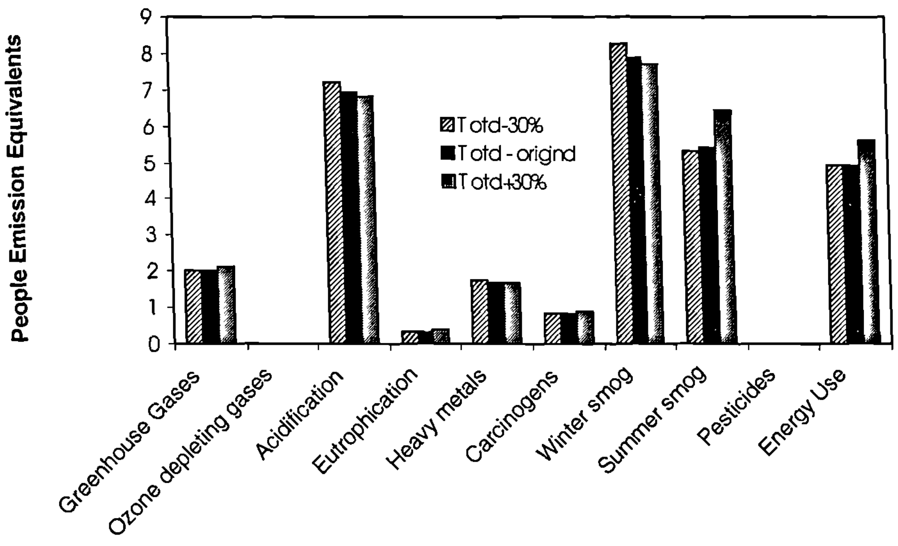

Figure 8.6 Normalised Mainbody Weight Sensitivity for the Harvester using Method B.

8.2.2 Forwarder Manufacture

8.2.2.1 Chassis Sensitivity

Following the result of Chapter 7 which showed that the chassis had the largest impact for the forwarder the sensitivity of the final results to changes in this factor were examined. The weight of the chassis was varied by 20%. The results of the first sensitivity analysis, Figure 8.7 shows that the main sensitivity is in acidification and winter smog; when the chassis weight is increased all the environmental impacts are increased.

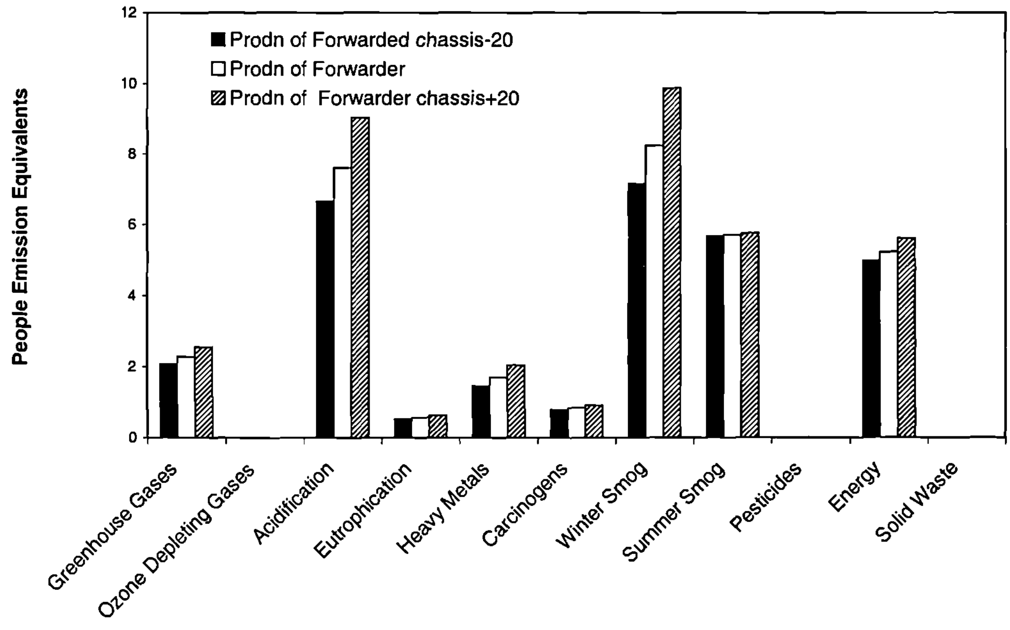

Figure 8.7 Normalised Chassis Weight Sensitivity for the Forwarder Using Method A.

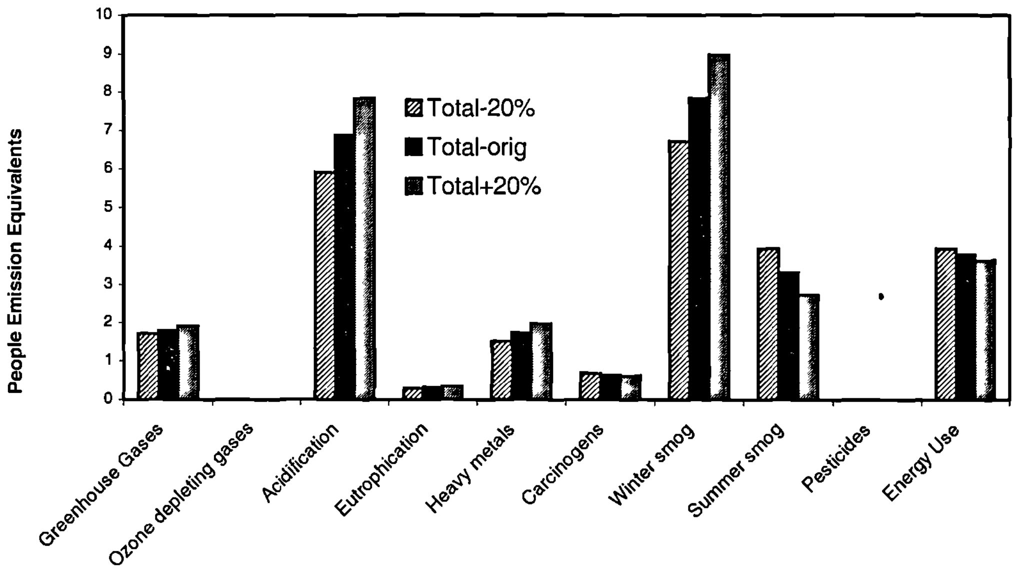

Figure 8.8 Normalised Chassis Weight Sensitivity for the Forwarder using Method B.

The results from the second sensitivity analysis were obtained when the weight of the chassis was varied by 20%, and the variation of the wheels was kept within 5%. Table 8.4 and Figure 8.8 show that the significant impacts occur in acidification and winter and summer smog. When the total weight of the chassis is reduced the impact towards greenhouse gases, eutrophication, heavy metals and winter smog is reduced and when it is increased the impact towards ozone depleting gases, carcinogens, summer smog and energy use is decreased.

8.2.2.2 Wheel Sensitivity

For the forwarder, the impact of the wheels is another significant part of the machine manufacture. Data for the wheels were correct to within 5%; Figure 8.9 shows the results of varying the weight of the wheels by 5% using the first sensitivity analysis methodology. None of the impacts towards the environmental issues is changed greatly by a variation of 5% in the wheels' weight.

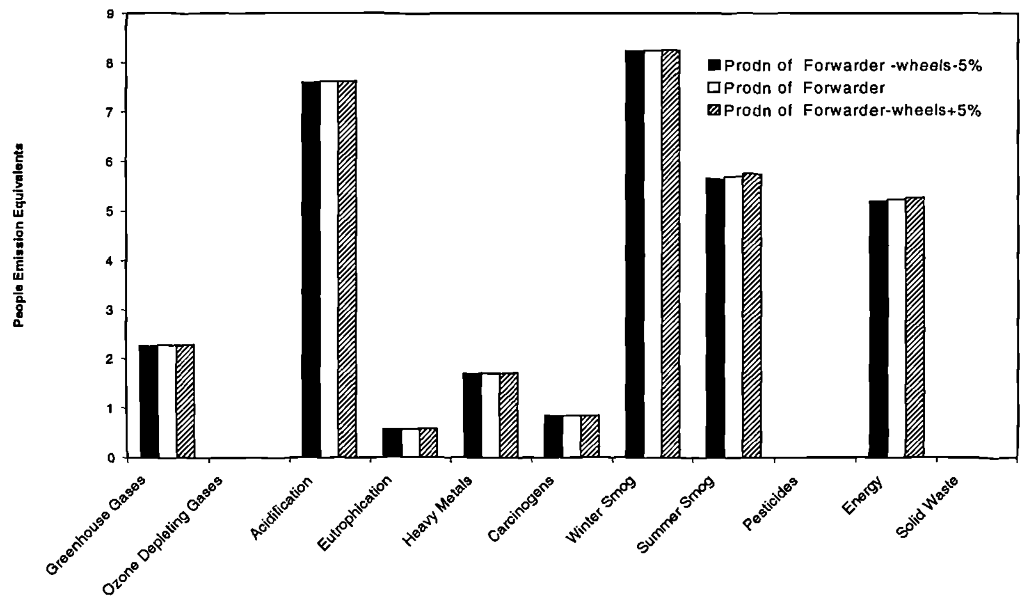

Figure 8.9 Normalised Wheel Weight Sensitivity for the Forwarder using Method A

Table 8.5 and Figure 8.10 show the impact of increasing and decreasing the weight of the wheels by 5% using the second sensitivity analysis methodology. There are only slight changes in any of the impacts.

8.2.2.3 Mainbody Sensitivity

As with the harvester, the least reliable estimate is that of the main body of the machine. Figure 8.11 shows the result of changing this parameter when using the first sensitivity analysis method. The variation in the results is not great, with the impact towards summer smog and energy use causing the most change.

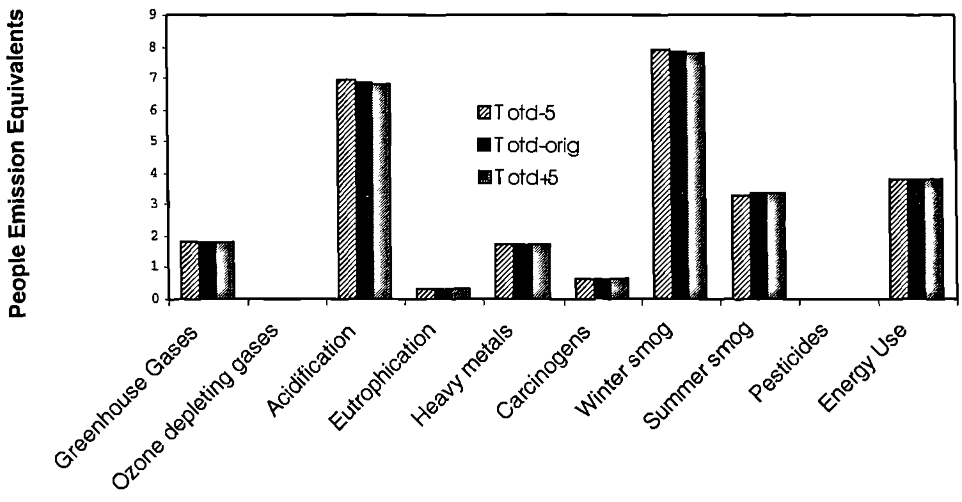

Figure 8.10 Normalised Wheel Weight Sensitivity for the Forwarder using Method B

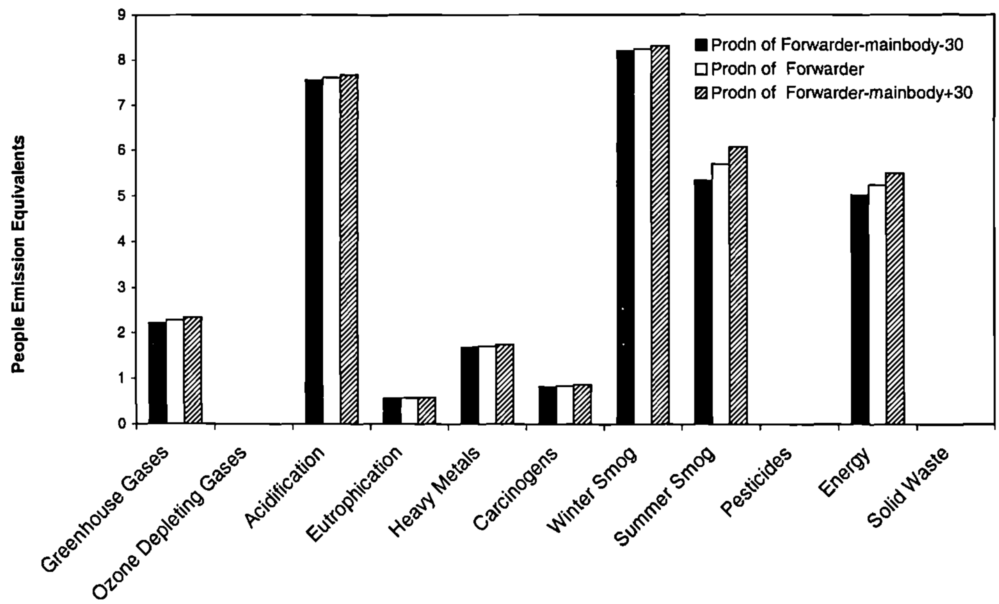

Figure 8.11 Normalised Mainbody Weight Sensitivity using Method A

Figure 8.12 shows the impact of increasing and decreasing this weight by 30% using the second sensitivity analysis methodology. Again, the impact of this is not large, with discernible changes being in acidification and winter and summer smog. When the weight of the main body is reduced the impact towards acidification and winter smog is increased. When the weight is increased the impact towards acidification and winter smog is decreased and the impact towards summer smog is increased. The different results obtained when using the two methods mirror those for the harvester.

	Total-20%	Total-orig	Total+20%
Greenhouse Gases	1.71	1.8	1.9
Ozone depleting gases	0.000525	0.000409	0.000295
Acidification	5.91	6.87	7.83
Eutrophication	0.303	0.326	0.35
Heavy metals	1.51	1.74	1.97
Carcinogens	0.684	0.649	0.615
Winter smog	6.72	7.84	8.96
Summer smog	3.94	3.33	2.73
Pesticides	0	0	0
Energy Use	3.94	3.79	3.64
Solid Waste	0	0	0

Table 8-4Normalised Chassis Sensitivity for the Forwarder

	Total-5	Total-orig	Total+5
Greenhouse Gases	1.81	1.8	1.8
Ozone depleting gases	0.000413	0.000409	0.000406
Acidification	6.93	6.87	6.82
Eutrophication	0.327	0.326	0.326
Heavy metals	1.75	1.74	1.72
Carcinogens	0.652	0.649	0.646
Winter smog	7.9	7.84	7.77
Summer smog	3.3	3.33	3.36
Pesticides	0	0	0
Energy Use	3.78	3.79	3.8
Solid Waste	0	0	0

Table 8-5 Normalised Wheel Sensitivity for the Forwarder

	Total-30	Total-original	Total+30
Greenhouse Gases	1.85	1.8	1.76
Ozone depleting gases	0.000365	0.000409	0.000454
Acidification	7.29	6.87	6.46
Eutrophication	0.337	0.326	0.316
Heavy metals	1.82	1.74	1.66
Carcinogens	0.658	0.649	0.64
Winter smog	8.32	7.84	7.35
Summer smog	3.1	3.33	3.57
Pesticides	0	0	0
Energy Use	3.75	3.79	3.83
Solid Waste	0	0	0

Table 8-6 Normalised Mainbody Sensitivity for the Forwarder

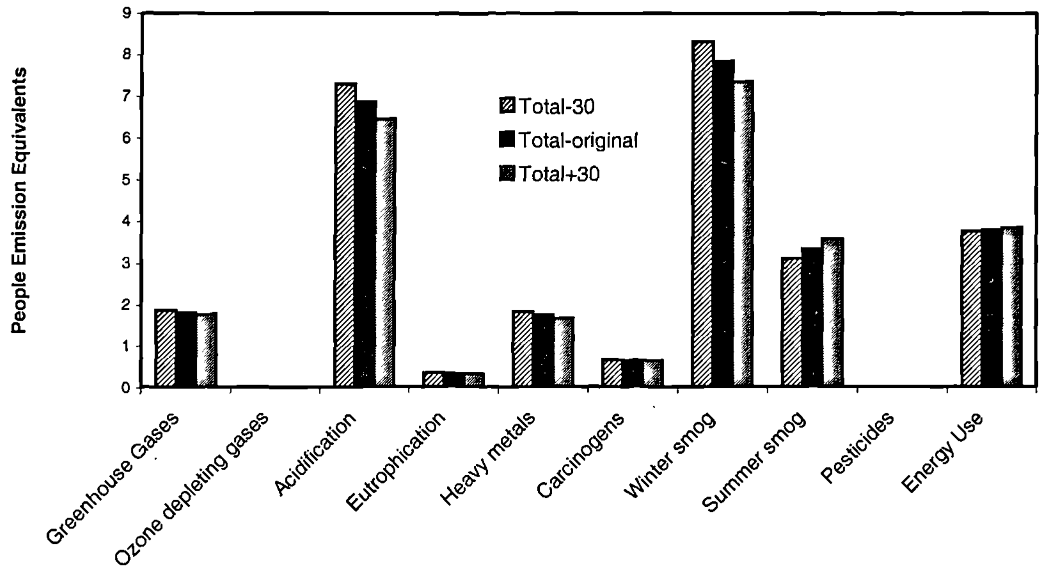

Figure 8.12 Normalised Mainbody Weight Sensitivity for the Forwarder using Method B

8.2.3 Sweeper Manufacture

Figures 7.11 and 7.12 show that the main contributors to the environmental impact associated with the production of the road sweeper are the main body of the machine and the chassis. Using the same methods applied for the harvester and sweeper the sensitivity of the overall environmental impact of the machine to changes in the weight of these components was assessed.

8.2.3.1 Chassis Sensitivity

Using the first methodology the weight was varied by 20% and the results are shown in Figure 8.13. The greatest sensitivities lie with the summer smog and energy use. The other environmental issues are not very sensitive to change in the chassis weight.

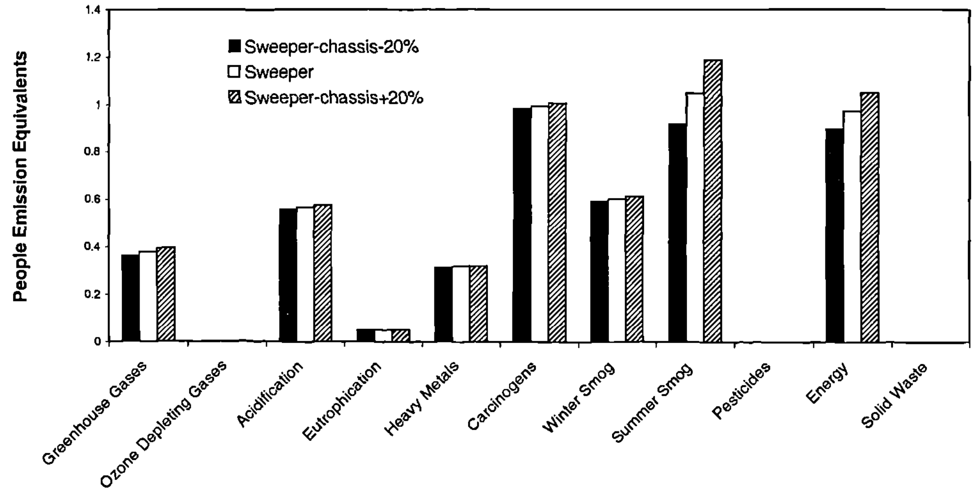

Figure 8.13 Normalised Chassis Weight Sensitivity for the Sweeper using Method A

Using the second sensitivity analysis the weight of the chassis was varied by 20% which meant that the other components within the system had to be varied by 14%. Table 8.7 and Figure 8.14 show the results of this analysis. When the chassis weight is increased, the environmental impacts are in general decreased. This means that the decrease of the weight of the other components has more of an effect than the impact of the increase in the chassis weight. This is true for all of the issues except summer smog on which the steel production in the chassis has a large detrimental effect. Although the sensitivity of the final results to the change in chassis weight is noticeable, it is not particularly significant for any of the issues.

8.2.3.2 Mainbody Sensitivity

The manufacture of the main cab also has a significant contribution to the overall environmental impact of the machine. When the main body weight is varied by 20% there is a noticeable impact on carcinogens, shown in Figure 8.15 using the first methodology for sensitivity analysis, and in Figure 8.16, for the second method. Figure 8.15 shows that the sensitivities of the other environmental issues are not very large.

Figure 8.16 shows that the impact towards greenhouse gases, ozone depleting gases, eutrophication, carcinogens, winter smog and energy is increased with a 20% increase in the main body weight and a decrease of 5.4% in the rest of the components' weights. Only the impact towards summer smog is reduced by an increase in the main body weight. Figures 7.11 and 7.12 indicate that the impact towards carcinogens is largely due to the main body of the machine. This is further shown by the sensitivity of the results to the variation of main body's weight. The main body comprises aluminium, safety glass and plastic. It is the use of the aluminium which causes the impact towards carcinogens.

Class	Sweeper-chassis+20	Sweeper	Sweeper-chassis-20
Greenhouse gases	0.357	0.379	0.407
Ozone depleting gases	0.00122	0.00141	0.00161
Acidification	0.504	0.566	0.631
Eutrophication	0.0479	0.051	0.0551
Heavy metals	0.279	0.317	0.361
Carcinogens	0.875	0.996	1.12
Winter Smog	0.535	0.603	0.673
Summer Smog	1.14	1.05	0.98
Pesticides	0	0	0
Energy	0.971	0.973	0.988
Solid waste	0	0	0

Table 8-7 Normalised Chassis Weight Sensitivity for the Sweeper

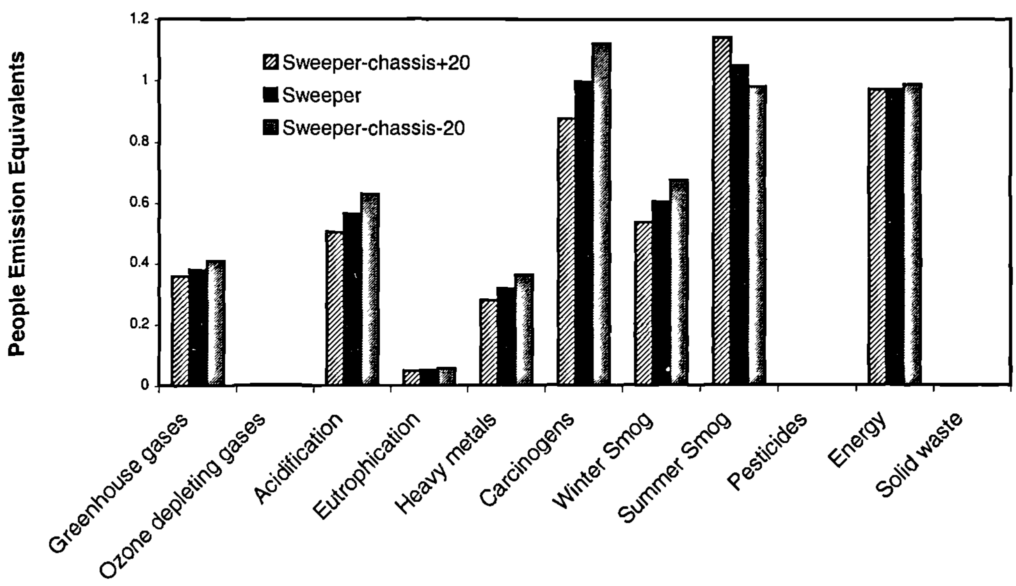

Figure 8.14 Normalised Chassis Weight Sensitivity for the Sweeper using Method B

8.2.3.2.1 The Use of Aluminium

When the study was carried out the manufacturer was contacted about the use of aluminium in the machine. It is used because it is lightweight and strong, but it does cause many carcinogenic substances to be released. When Figure 8.14 and Figure 8.16 are compared with Figure 8.6 and Figure 8.10 for example, it is seen that the carcinogen impact is far greater for the manufacture of the sweeper than the forwarder and harvester. Although it is known that the aluminium used did contain a recycled component, the sweeper manufacturers were unable to state the percentage of recycled material in the aluminium used. Consultation with both them and the European Aluminium Association resulted in the presumption that it probably contained 50% recycled material. This is the normal value for the type of aluminium used in machines such as the sweeper; but it could be up to 80% recycled or as little as 25%. Therefore, a sensitivity analysis was carried out on the recycled component of the aluminium in the main body of the machine, shown in Figure 8.17. Unsurprisingly the impact on the carcinogens is very sensitive to the amount of recycled component. With 80% recycled aluminium the environmental impact is much reduced. The rest of the environmental issues examined are not nearly as sensitive to the change in the recycled component, but they are all reduced with an increase of the recycled aluminium used in the machine.

Class	Sweeper(tot)-mainbod+20	Sweeper	Sweeper(tot)-mainbod-20
Greenhouse gases	0.401	0.379	0.366
Ozone depleting gases	0.00165	0.00141	0.00117
Acidification	0.576	0.566	0.563
Eutrophication	0.0534	0.051	0.0501
Heavy metals	0.358	0.317	0.285
Carcinogens	1.15	0.996	0.841
Winter Smog	0.609	0.603	0.605
Summer Smog	1.03	1.05	1.1
Pesticides	0	0	0
Energy	1	0.973	0.964
Solid waste	0	0	0

Table 8-8 Normalised Sensitivity of the Main Body in the Sweeper

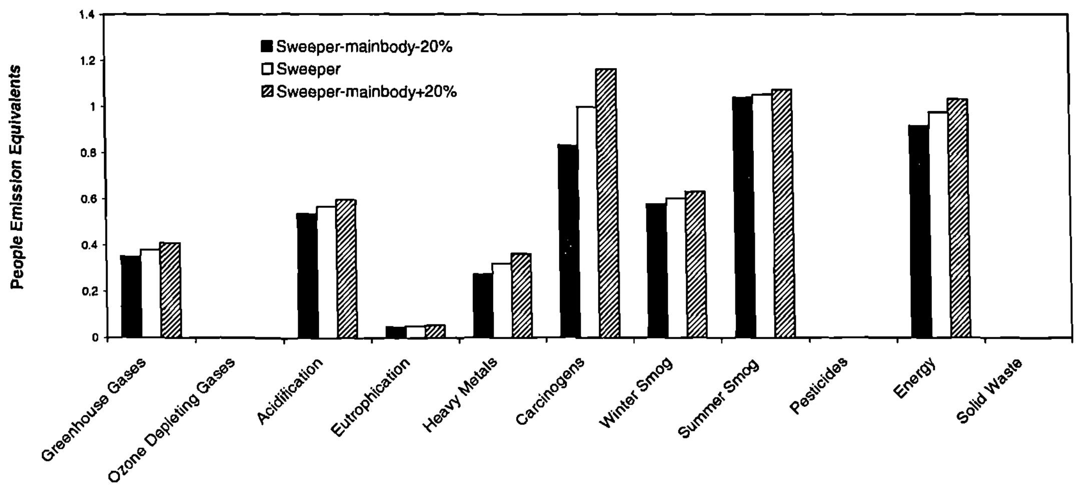

Figure 8.15 Normalised Mainbody Weight Sensitivity for the Sweeper using Method A

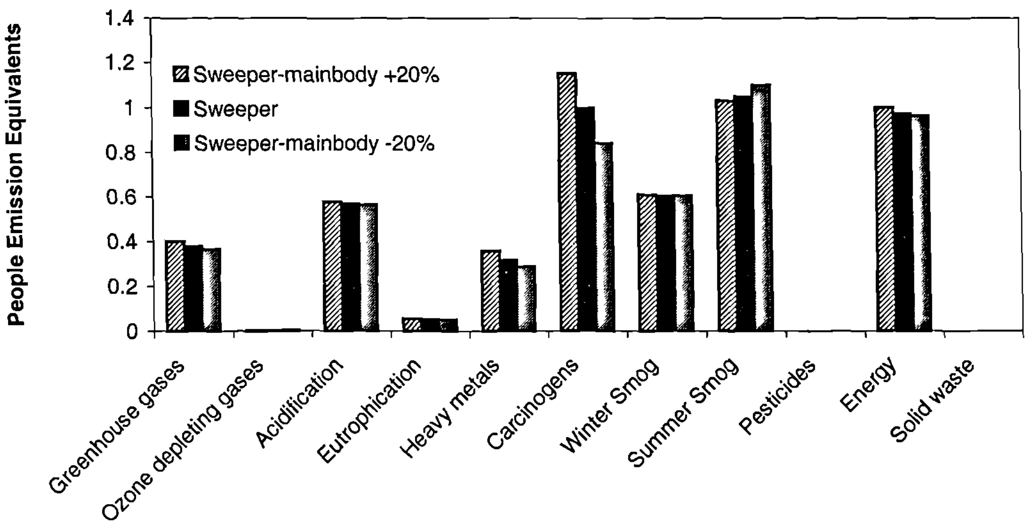

Figure 8.16 Normalised Main Body Weight Sensitivity for the Sweeper using Method B

The machine manufacture is far more sensitive to the amount of recycled aluminium than it is to a change in weight of either the body or the chassis. Hence, to decrease the environmental impact of sweeper manufacture one might try to increase the recycled component of the aluminium or change the material used in manufacture. It would be necessary to consider any changes in weight to the machine and any corresponding factors, for example, fuel consumption.

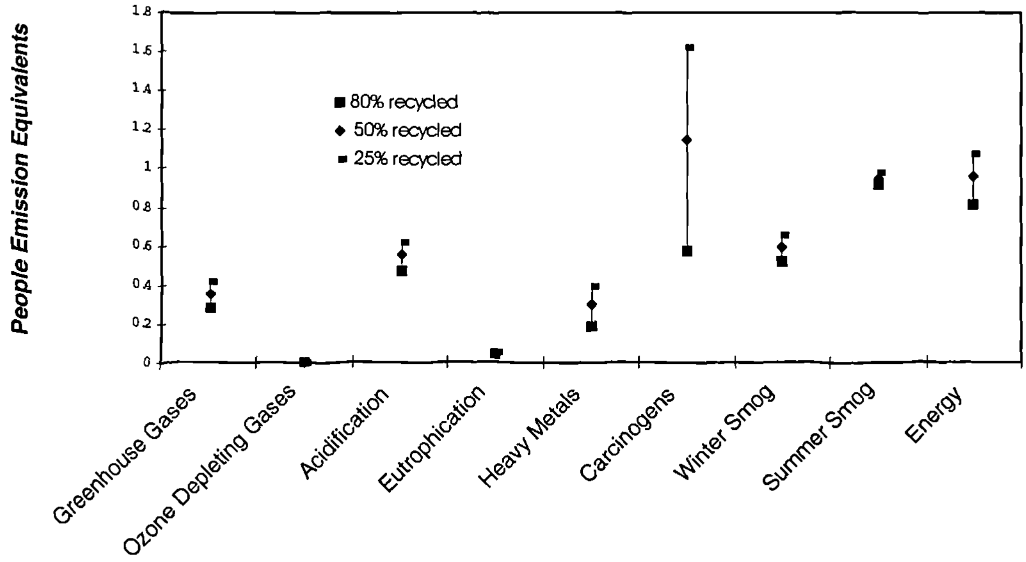

Figure 8.17 Normalised Sensitivity of the Sweeper to Recycled Aluminium Component

8.2.4 Discussion and Conclusions for the Machine Manufacture

This section has demonstrated that the use of sensitivity analysis within LCA is very important. Its use highlights which data should be focused upon for improvement in the overall impact of the machine manufacture, but the use of sensitivity analysis in this stage of LCA is not simple.

Inventory data in all LCAs is uncertain and it is likely that many LCAs will encounter the same problems highlighted in this research. Both the methods could yield different results as seen in the previous sections. Neither method is perfect, both have their advantages and both certainly have their disadvantages. The difference in results seen in this research is due to the relative importance of the variables being varied in the analysis. This is made clear in this study, but it is possible that in some LCAs thought will not be given to the potential impacts of the type of sensitivity analysis chosen. It is therefore recommended that further work ought to be carried out on the use of sensitivity analysis in LCA.

The overall environmental impact of the harvester production is sensitive to a change in weight of the chassis, the axles and the main body of the machine. However, even with twenty percent variations in the weights of these components, the overall impact was not changed very significantly. The forwarder is also sensitive to changes in the chassis weight, wheel weight and main body weight. The main body and chassis variations result in larger variations in the final environmental impact than does the variation of the wheels. The sweeper showed sensitivity towards variation in both chassis and main body weight. However, the most significant sensitivity in the sweeper was not the weight of any of the components, but the amount of recycled aluminium used in the main body of the machine. If the component of recycled aluminium is increased then the impact towards carcinogens is significantly reduced. This study shows that although the variations in weights of different components may have an effect on the overall environmental impact of the manufacture of the machines, the actual materials used in the system can have a far greater impact.

8.3 Sensitivities in the Use of Oil

The manufacture of the machines has a varying significance on the overall life cycle impact of the systems as shown in Chapter 7. The sweeper machine manufacture has a larger impact on the whole life of the sweeper than the production of either of the forestry machines on their life cycle impact.

In Chapters 6 and 7 the properties of fluids were discussed. According to some machine users and some component manufacturers, more rapeseed oil is needed over the lifetime of a hydraulic system than mineral oil because rapeseed oil has to be replaced more frequently that the mineral oil due to difference in performance properties. However, this is a contentious issue. In the main case study it was assumed that the volume of rapeseed oil needed in the machinery over its entire lifetime was twice that of mineral oil. However, estimates gathered from people using the machines, and some testing data have outlined that it is possible that rapeseed oil needs replacing three times more often than mineral oil. In contrast, some oil manufacturers and published test data show that rapeseed oil performs as well as mineral oil: it is difficult to reconcile these two opinions. It is the author's opinion, based on work discussed in Chapter 6, that rapeseed oil does *not* perform as well as mineral oil in the applications studied.

Given the conflicting opinion, a study has been made of the effect on the overall result if the performance of the mineral oil was taken to be equal to, one and a half times, double and three times better than the rapeseed oil.

8.3.1.1 Sensitivity of the Harvester to Oil Performance

Figure 8.18 shows the use and manufacture of the harvester with different oil performance scenarios. For each of the different rapeseed oil performance scenarios, the impact of the mineral oil on greenhouse gases remains by far the most significant because the CO_2 component of the mineral oil is non-renewable, and as such is unsustainable. For all the other environmental issues considered, when the rapeseed is changed as frequently as the mineral oil, the impacts towards ozone depleting gases, eutrophication, summer smog, pesticides and energy use are larger for the system running on rapeseed oil. The impacts towards greenhouse gases, acidification, heavy metals and winter smog are greater for the system running on mineral oil. The impacts towards carcinogens and ozone depleting gases are very similar for both oils.

When the rapeseed oil is replaced one and a half times as often as the mineral oil, once again the impact on greenhouse gases is dominated by the mineral oil. Impacts towards ozone depleting gases, acidification, eutrophication, heavy metals, carcinogens, summer smog, pesticides and energy use are greater for the system running on rapeseed oil. The impact towards greenhouse gases and winter smog is greater for the system running on mineral oil.

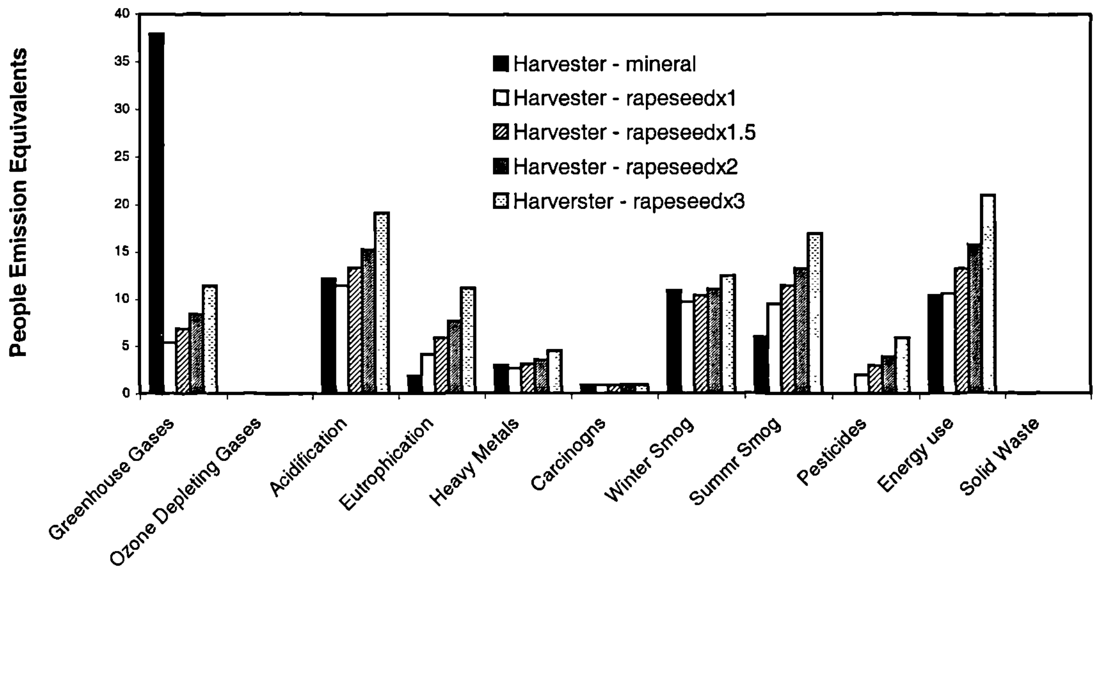

Figure 8.18 Normalised Sensitivities for the Oil Performance Scenarios

When the scenario used in the case study is adopted, and the mineral oil is deemed to perform twice as well as the rapeseed oil, the impact towards ozone depleting gases, acidification, eutrophication, heavy metals, carcinogens, winter smog, summer smog, pesticides and energy use is greater for the system running on rapeseed oil. Only the impact on greenhouse gases is larger for the system running on mineral oil. Again, with the mineral oil assumed to perform three times as well as rapeseed oil, only the environmental impact on greenhouse gases is larger for the system running on mineral oil.

8.3.1.2 Sensitivity of the Forwarder to Oil Performance

Figure 8.19 shows the performance of the forwarder with different oil performance scenarios. Again, all the other impacts are far outweighed by the impact of the mineral oil on greenhouse gases. If the mineral and rapeseed oil are assumed to perform equally in the system, then a system running on mineral oil will have a larger impact towards greenhouse gases, acidification, heavy metals and winter smog. It will have a smaller impact on ozone depleting gases, eutrophication, carcinogens, summer smog, pesticides and energy use.

When the scenario requiring one and a half times more rapeseed oil than mineral oil is used a system running on rapeseed oil will have a larger impact towards ozone depleting gases, acidification, eutrophication, heavy metals, carcinogens, summer smog, pesticides and energy. When twice the amount of rapeseed is needed the impact from a rapeseed oil-run machine will be larger for ozone depleting gases, acidification, eutrophication, heavy metals, carcinogens, winter and summer smog, pesticides and energy use. The mineral oil system will only have a larger impact towards greenhouse gases. If three times the amount of rapeseed oil is needed, then again, the only impact the mineral oil will have larger than the rapeseed system is greenhouse gases.

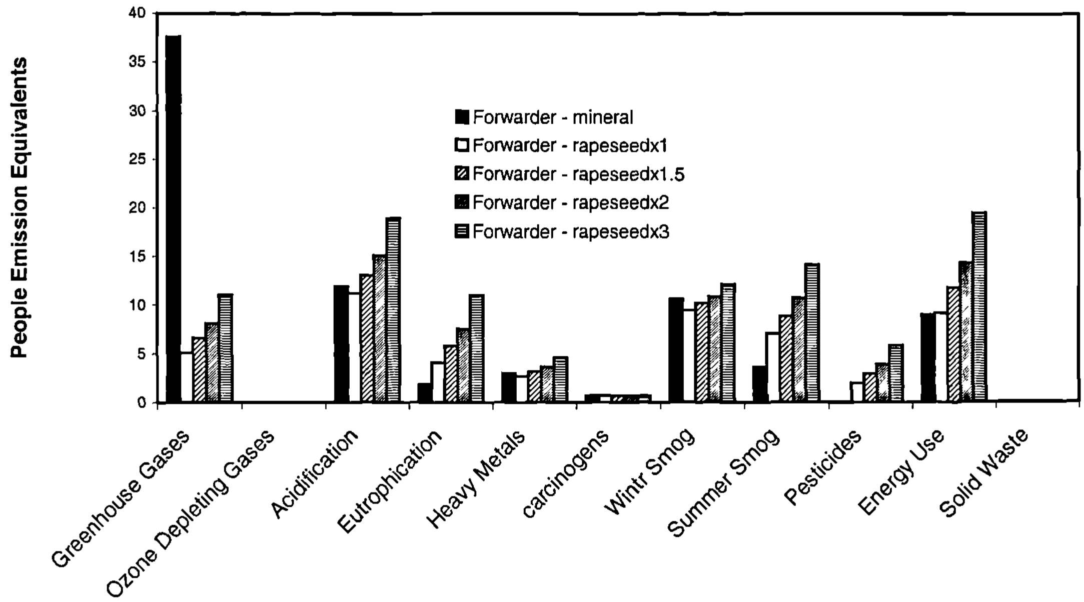

Figure 8.19 Normalised Sensitivity of the Forwarder to Different oil use scenarios

8.3.2 Sensitivity of the Sweeper to Oil Performance

Figure 8.20 shows the sensitivity of the sweeper performance to the different oil performance scenarios. It shows a different overall result to Figure 8.18 and Figure 8.19. The impact of the mineral oil towards the greenhouse gases is not nearly as profound for the road sweeper because the manufacture of the machine makes a far greater contribution to the whole life of the machine. When the two oils are replaced at the same rate the environmental impacts are very similar for most of the issues considered. The rapeseed system has a greater impact on eutrophication, summer smog and pesticides. The impact towards greenhouse gases, ozone depletion, heavy metals and carcinogens is the same for both fluids. Mineral oil has a greater impact towards acidification, winter smog and energy use. However, all the results in this scenario are very close. This is because of the machine production and the fact that the sweeper uses a lot less oil during its lifetime than either of the forestry machines does.

When the rapeseed oil is replaced one and a half times more often than mineral oil there is a more noticeable difference in the graph: the impact of the rapeseed machine is greater for greenhouse gases, acidification, eutrophication, carcinogens, summer smog, and pesticides. The impacts towards ozone depletion, carcinogens and energy use are equal, the mineral oil only has a greater impact towards winter smog. When the rapeseed is changed twice as often as mineral oil the environmental impact for the system running on rapeseed oil is greater for all the environmental categories. This is repeated when the system needs three times as much rapeseed oil than mineral oil.

Class	Sweeper use with min oil (CO2)	Sweeper with rapeseed oil x1	Sweeper with rapeseed oil x1.5	Sweeper with rapeseed oil x2	Sweeper with rapeseed oil x3
Greenhouse Gases	0.415	0.382	0.384	0.402	0.423
Ozone Depleting Gases	0.00141	0.00141	0.00141	0.00142	0.00142
Acidification	0.571	0.57	0.572	0.58	0.598
Eutrophication	0.0523	0.0546	0.0564	0.0564	0.063
Heavy Metals	0.318	0.318	0.318	0.336	0.353
Carcinogens	0.996	0.996	0.996	1.01	1.01
Winter Smog	0.606	0.605	0.605	0.62	0.635
Summer Smog	1.05	1.06	1.06	1.15	1.2
Pesticides	0	0.00199	0.00298	0.00398	0.00597
Energy Use	0.978	0.978	0.98	1.05	1.1
Solid Waste	0	0	0	0	0

Table 8-9 Normalised Data for the Sensitivity of the Oil use scenarios with the sweeper

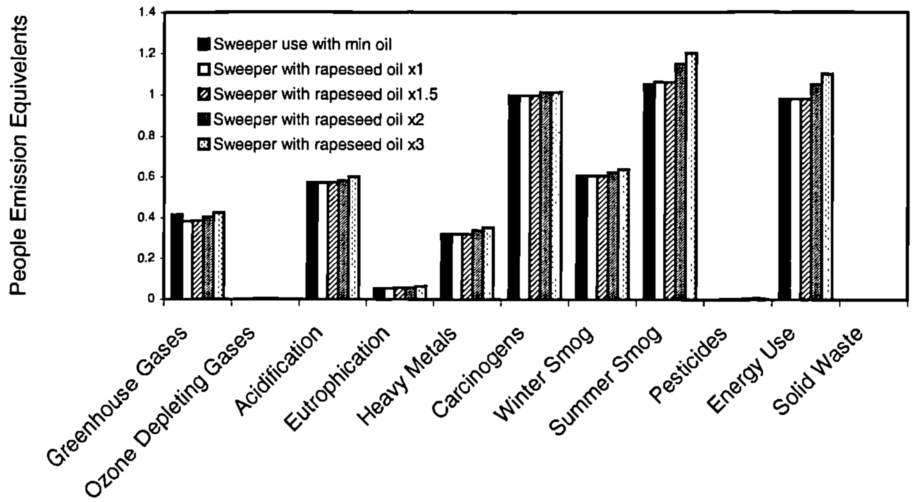

Figure 8.20 Normalised Sensitivity for the oil use scenarios in the sweeper.

8.3.3 Discussion and Conclusions for the Machine Use

For all the systems studied, when the performance of mineral oil is taken to be three times better than that of rapeseed oil, the systems running on rapeseed oil are shown to have a greater impact on every environmental category, except greenhouse gases, than mineral oil. When twice as much rapeseed oil is used than mineral oil, most of the categories in each system (and all categories in the sweeper's case) have a larger impact from the rapeseed run system.

When the oil performance is taken to be the same for the sweeper the results are very similar, there would be no relative benefit in using either of the oils. When the oil performance is assumed equal the forestry machinery then the environmental impact is lower for the machines using rapeseed oil. This shows that the results from this study cannot automatically be carried over to other mobile hydraulic systems. It also shows that the results are sensitive to the assumptions made about the oil performance.

8.4 Sensitivities in the Oil Production.

The level of detail for the oil production is not the same for both oils. There is a far greater level of detail about rapeseed oil production. This made it easier to analyse each step of rapeseed oil production compared with mineral oil production stages.

8.4.1 Mineral oil Production

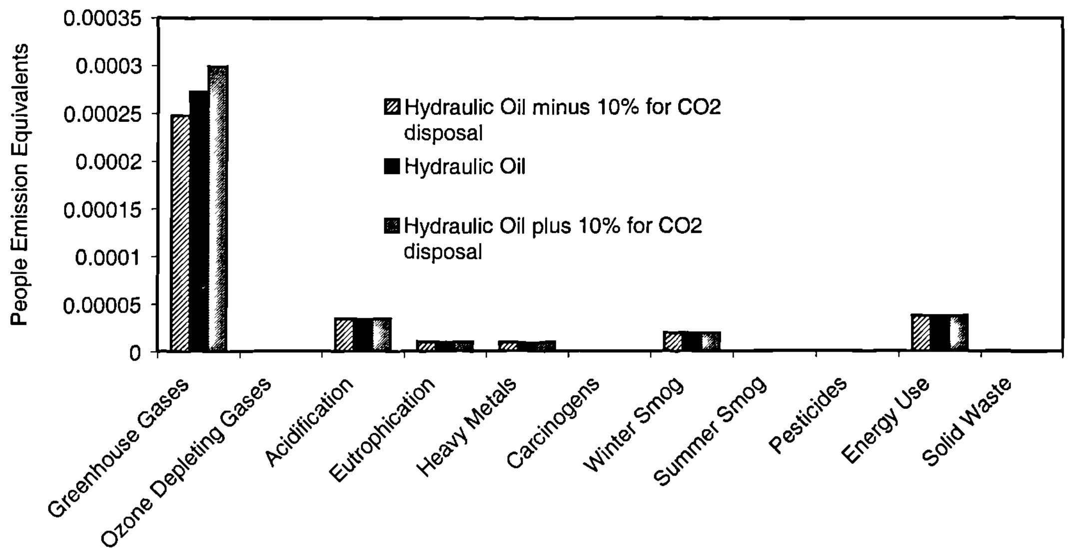

Figure 8.21 Sensitivity of Mineral Oil to Carbon Dioxide Disposal

The data for the mineral oil production were taken from APME. As mentioned, there is little detailed information about the individual stages of the mineral oil production, therefore, it is impossible to conduct a sensitivity analysis on these data. As discussed in Chapter 7, the production of the oil includes information about the carbon dioxide released when the oil is disposed of. The calculation of the amount of CO_2 in mineral oil is based on the density of the mineral oil, 870kg/m^3 It is estimated that there is 65 ± 10% kmol CO_2 in 1m^3 of mineral oil (R.Rathbone, 1999), therefore, for one cubic metre of oil 2860kg of CO_2 is produced [2]. The sensitivity of the environmental impact of the production of the oil was examined with respect to this. The results of this are shown in Figure 8.21. The environmental contribution to every environmental issue considered, apart from that to greenhouse gases, remains the same. The impact towards the greenhouse gases increases as the amount of CO_2 released is increased.

8.4.2 Rapeseed oil Production

The data used for the rapeseed oil production are more detailed than that used in the mineral oil production. It is therefore possible to carry out sensitivity analysis for stages in the production process.

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[2] This is obtained by multiplying the molecular mass of the CO_2 (12 + (16x2) = 44) by the number of moles of CO_2 contained in the mineral oil, then 1kg of oil will produce 3.28kg of CO_2. As the 65kmol CO_2 was accurate to ± 10% it is therefore possible that the amount of CO_2 per kilogram of oil ranges from 2.96kg to 3.62kg.

8.4.2.1 Pesticide Runoff

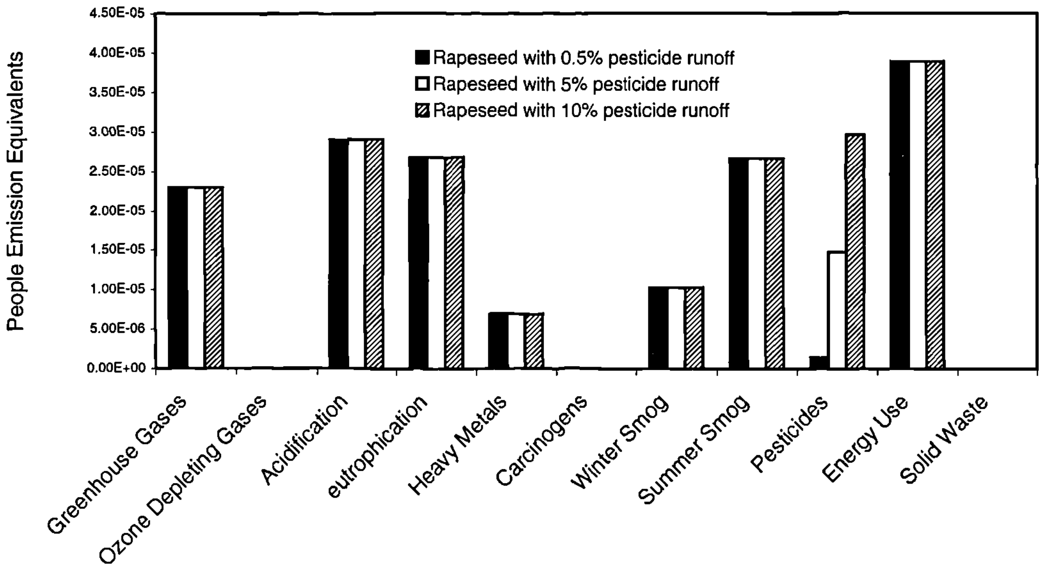

Figure 8.22 Normalised Sensitivity of the rapeseed oil production to pesticide runoff.

Figure 6.5 shows that some of the main contributors to the environmental impact of the rapeseed production are the fertiliser, drying, crushing, growth and the pesticide used. The information about runoff of pesticides from fields is very difficult to obtain, and its accuracy is not high. This is because the runoff rate is dependent on soil conditions, weather conditions, geology and crop type. The amount of runoff is probably somewhere between 0.5% and 10% for most applications. In the case study a value of 5% was used. Figure 8.22 shows the effect of altering the amount of runoff from 0.5% to 5% to 10%. The impact is significant towards the pesticides category with a value of 1.48E-6 for 0.5% runoff, 1.48E-5 for 5% runoff and 2.97E-5 for a runoff value of 10%. As the only part of the LCA with an impact towards the pesticide category is the rapeseed oil production, none of the LCA comparisons in any of the other categories is affected by this.

8.4.2.2 Soil Emissions

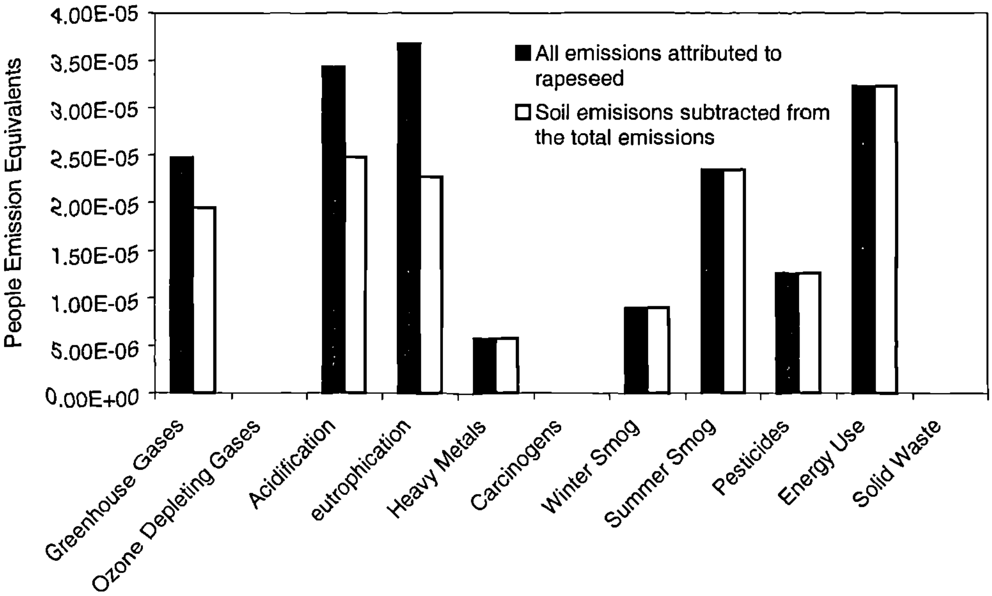

Figure 8.23 Sensitivity of Rapeseed Production to soil emissions

One of the other areas of data about which there is significant uncertainty is the soil emissions which is a complex issue. Soil is always in the process of gas exchange of some sort, and this is hard to assess because it depends on the soil moisture, the soil type and the vegetation growing on it. Originally all the emissions from the rapeseed were used in the LCA but the soil would emit some of these gases whether or not a crop was growing on it. Therefore this approach is unrepresentative of the actual environmental impact of the rapeseed growth. An estimation of the emissions was difficult to make because there are many factors contributing to such emissions, as indicated above. Table 8.10 shows the total emissions and those which take into consideration the emissions from the soil without the rapeseed growth. This is an estimation and further work ought to be carried out to determine the exact impact this can have on the production of renewable crops.

	Total emissions	Estimated rapeseed emissions
Emissions to air		
N_2O	3140g	1000g
Methane	2190g	1000g
Ammonia	10kg	5kg
Emissions to water		
Nitrate	50kg	25kg
P-tot	0.35kg	0.17kg
K	20kg	10kg

Table 8-10 Soil Emissions per hectare per year

The impact of using these two sets of data on the final rapeseed production data is presented in Figure 8.23 which shows that the impact on greenhouse gases, acidification and eutrophication is affected by the differing emission data. The differences shown are for 1kg of the rapeseed oil. Much more rapeseed than this is used within a system during its lifetime, therefore the effect on the total life cycle impact would be significant. As the precise amount of emissions is not known, Figure 8.24 shows the effect of reducing and increasing the estimated rapeseed emissions by 20%. The differences may not appear very significant, but when the amount of oil used in a machine is considered their significance becomes apparent. More accurate soil and crop emission data would therefore be very beneficial in any further study.

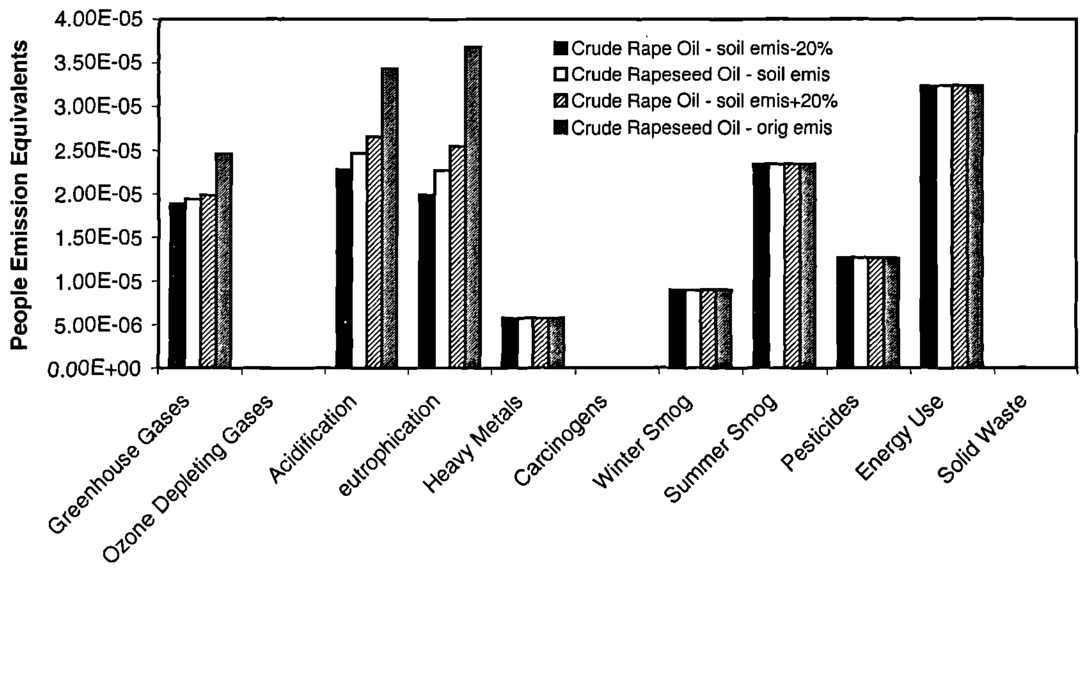

Figure 8.24 Sensitivity of the Rapeseed Oil Production to soil emissions.

8.5 *Sensitivities in the Life Cycle Impact Assessment*

Most studies comment on the data quality of the inventory data, but it not the only type of data within an LCA to be subject to inaccuracies. Data used within the Life Cycle Impact Assessment (LCIA) can also have a significant influence on the final results. In many cases most of these data are "hidden" in the software and many users are not fully aware of the potential problem. Comparison of some of the characterisation input data used within SimaPro EI95 and other data which may be used as characterisation data show significant differences. Comparisons of the Global Warming Potential data, as used by SimaPro (CML data) and data generated by the International Panel on Climate Change (IPCC) are shown in Table 8.11. This reveals that many of the substances given a GWP weighting in the CML data are not even considered in the IPCC data and vice versa. Substances frequently have different GWP values in the two sets of data. The same is seen in Table 8.12 where the CML Ozone Depleting Potential (ODP) data is compared with the US Environment Protection Agency ODP data.

The author approached a number of people about this, including the UK Met office, AEA Technology, IPCC, the US EPA, the Climate Research Unit at the University of East Anglia and SimaPro. Nobody was able to offer reasons why the data are so different. The IPCC data is based on 1995 values, the CML on 1992 values but it is unclear when the US EPA data were compiled. Some of the differences in the data will be due to increasing legislation which outlaws many of the chemicals considered. Whatever the causes of these differences, these data sets are publicly available and widely used. It is possible that people are using these datasets without realising their impact.

Figure 8.25 and Figure 8.26 show the impact these different characterisation data sets have on the total environmental impact of the road sweeper system. It could be argued that these differences are unimportant when comparing the use of rapeseed oil and mineral oil because either of the datasets will yield the same conclusion. However, it is important to try to understand the data behind every LCA study. If this is not achieved then scientists and engineers may well dismiss its use as a decision making tool in the future.

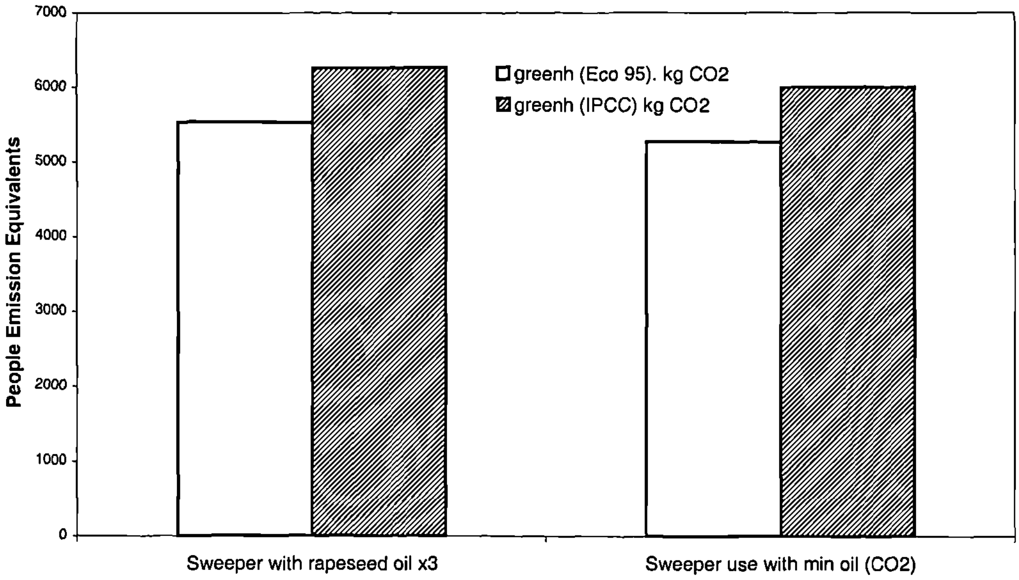

Figure 8.25 Sensitivity of the greenhouse gas results to LCIA data.

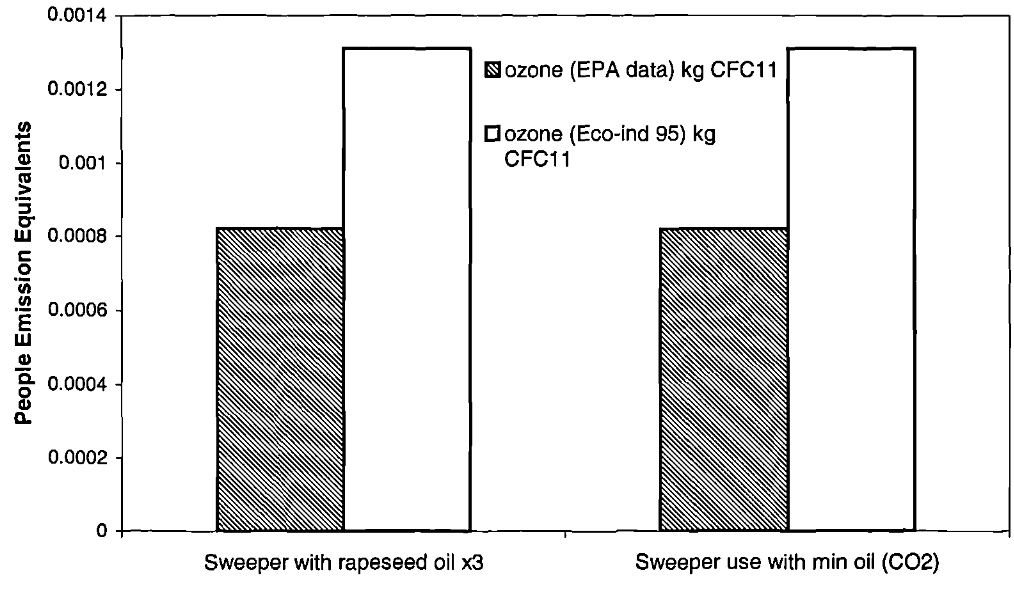

Figure 8.26 Sensitivity of the Ozone depleting gas results to LCIA data

8.5.1 Different LCIA methodologies

Changes in assumptions and input data have thus far been considered. However, alterations in the methodology and data handling can also have a large effect on the final results of a study. The software tool adopted for the study, SimaPro, provides the user with alternative methodologies. The data presented by the author employs the Eco-Indicator 95 (EI95) methodology. However, Eco-indicator 99 (EI99), the new methodology from PRé Consultants, has been incorporated in the latest version of SimaPro. EcoIndicator 99 uses a damage assessment approach, moving away from the simple "less is better" ideology in EI95 towards a more accurate assessment of damage to ecosystems, health or resources. Although EI99 is good in principle, there are problems in practice, for example, the damage to ecosystem quality caused by acidification or eutrophication via airborne emissions is based on a Dutch model. This is clearly a limitation: there are few rocky areas and no hills or mountains in the Netherlands and much of the natural ecosystem is based on sand dune-like features and these are not representative of other parts of Europe. Therefore, emissions which produce a certain change in plant life in the Netherlands may not have the same effect in other countries and geographic areas. As with all LCA products, though, EI99 is a new tool and it will obviously be improved over time.

One problem with analysing and comparing Life Cycle Assessments is the inability to determine how the LCIA has been carried out. The traditional classification, characterisation and valuation stages may not be carried out in an LCA and it may be unclear what is used in their place. The environmental impact categories included in a study are easy to determine because they are always shown in the results. The reasons why they have been chosen may be less clear and the actual emissions and raw materials that have been included in the LCIA may be very difficult to ascertain. This poses questions such as: "have all of the emissions that could possibly affect the greenhouse effect been included in the category for greenhouse gases or are only the gases which are "scientifically proven" to have an effect included?" EcoIndicator 99 may make this process simpler by trying to include the three major "mind sets" related to emission impacts and their importance. It employs three categories based on what is termed "cultural theory". These sub-groups arise from the different approaches to the complex choices about which emissions should be included in an LCIA. PRé Consultants argue that there are three main methods for determining impacts (These were discussed more fully in Chapter 4.):

- **Individualist (I)**
- **Hierarchical (H)**
- **Egalitarian (E)**

The inclusion of these three alternatives highlights the main options in data analysis. The choice of one or other approach serves to act, in effect, as a sensitivity analysis. This is because decisions are constantly being made within the LCA process as to which emissions should be allocated to which impact category. Decisions are made, perhaps unconsciously, due to a practitioner's understanding of a particular issue and also due to his or her belief of how important the issue is. Knowledge of the significance of the contribution that will be made by the emission or use of the raw material will also play a part in the decision-making process. The use of the three approaches enables a practitioner to be more aware of the decisions made within the LCIA. It ensures that LCA practitioners are aware of the different perspectives upon the impacts of certain emissions and allows them to see the impact on the final results when these different methods are employed.

Figure 8.27 presents the same data as displayed in the earlier Figure 6.7, but EI99 is used instead of EI95. The hierarchal method has been used because this is deemed to be the "default" method, the "middle of the road" method. The use of EI99 yields different results compared with EI95. When using EI99 mineral oil compares unfavourably with rapeseed oil in terms of climate change, but there is a "new" impact category, land use, which obviously shows a high impact for rapeseed. The labels HH, EQ and R on this figure refer to the damage categories examined: human health, ecosystem quality and resource extraction.

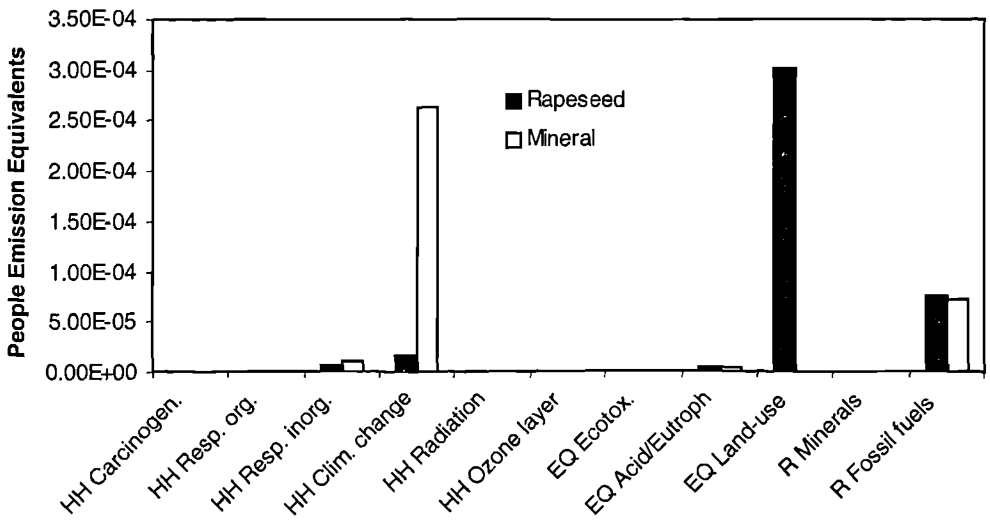

Figure 8.27 Oil production using EI99

Figure 8.28 shows the comparison of the life cycle of a harvester employing different hydraulic fluids when using the different impact methodologies adopted by EI99. The different methodologies within EI99 do not change the pattern of the overall comparative outcome for the use of the different oil types. Although the results here do not show that one oil type is better using one methodology and worse with the other the different socio-cultural methodologies do have an effect on the results. With either of these methodologies, the environmental impact of the systems using 3 times as much rapeseed is worse than for those using mineral oil. Although the same conclusion is reached using both methodologies, the results differ and indicate that care must be taken when selecting an impact assessment methodology. If different case studies were chosen the two methodologies might not lead to the same overall conclusions: this cautionary observation is based upon the differences shown in the results for the oil production.

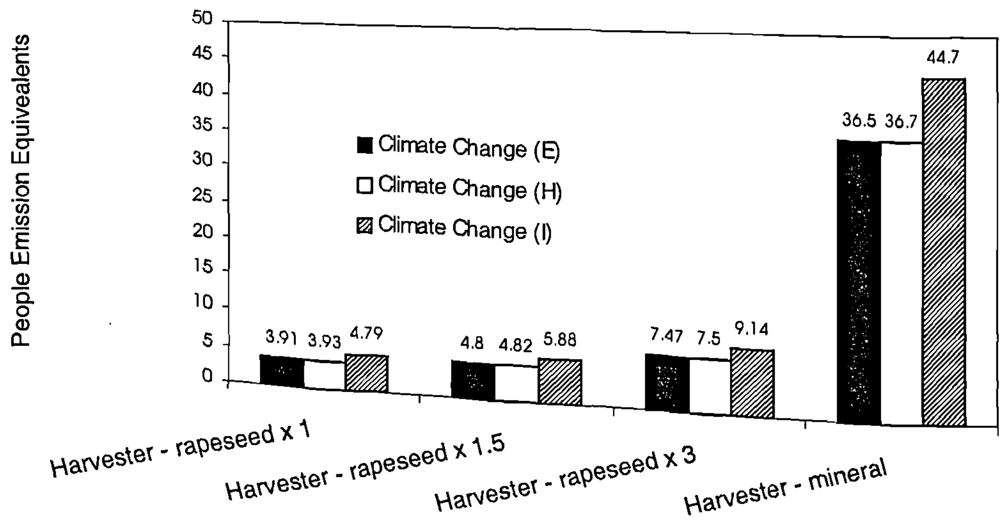

Figure 8.28 Sensitivity of the results to changes in the use of LCIA methodology and data

There are many sections within an LCA in which data quality can be questioned. Benefit would arise from obtaining further information about many data points in the study. Most studies focus on the sensitivity of the inventory data. This chapter has shown that this is indeed an issue worthy of study. It is important that the method of sensitivity analysis is chosen with care and that the implications of the choice are known. It is not possible to obtain a perfect method and this is something which requires further research within LCA.

The sensitivity analysis showed that the inventory data were sensitive to change and indicates data points for which it would be beneficial to obtain more accurate results. The use of two types of sensitivity analysis showed that it is difficult to determine the sensitivity of data when the total weight of a system is known and component weights are to be varied.

Characterisation input data can also cause sensitivity in the final results of an LCA. As these data are often hidden within software it is imperative that this area of sensitivity is highlighted. Different data used at this stage can result in otherwise identical LCA inventory data yielding different results. It is important that this is realised. Although the final results for the case studies are sensitive to change in the input data the final conclusions remain the same. The use of mineral oil in the three systems studied does not have a more significant overall environmental impact than the use of rapeseed oil. This is not necessarily true for all case studies, but even for these limited case studies this is an important result because there is a tendency in the fluid power field to assume that rapeseed oil is more environmentally friendly without asking any questions.

Substance	Weight factor - EI95 (CML)	Weight Factor - IPCC
1,1,1 - trichloroethane	100	x
CFC (hard)	7100	x
CFC (soft)	1600	x
CFC-11	3400	x
CFC-113	4500	x
CFC-114	7000	x
CFC-115	7000	x
CFC-116	6200	x
CFC-12	7100	x
CFC-13	13000	x
CFC-14	4500	x
CO2	1	x
CO2 (fossil)	1	x
dichloromethane	15	x
HALON-1211	4900	x
HALON-1301	4900	x
HCFC-123	90	x
HCFC-124	440	x
HCFC-141b	580	x
HCFC-142b	1800	x
HCFC-22	1600	x
HFC-23	x	11700
HFC-32	x	650
HFC-41	x	150
HFC-43-10mee	x	1300
HFC-125	3400	2800

HFC-134	x	1000
HFC-134a	1200	1300
HFC-143	x	300
HFC-143a	3800	3800
HFC-152a	150	x
HFC-227ea	x	2900
HFC-236fa	x	6300
HFC-245ca	x	560
methane	11	21
N2O	270	x
tetrachloromethane	1300	x
trichloromethane	25	x
Chloroform	x	4
Methyl Chloride	x	9
Sulphur hexafluoride	x	23900
Perfluromethane	x	6500
Perfluroethane	x	9200
Perfloropropane	x	7000
Perflurobutane	x	7000
Perfluropentane	x	7500
Perflurohexane	x	7400
Perflurocyclobutane	x	8700
Nitrous oxide	x	31
Trifloridomethane	x	<1

Table 8-11Comparison of CML and IPCC Global Warming Data

8.6 Concluding Remarks

The research is sensitive to many variables. The sensitivities in the production of the machines lie mainly in the larger components of the machines. The forwarder and harvester are sensitive to the production of iron and steel in the chassis and main body and the sweeper to the use of aluminium in the main body. The largest sensitivities are due to the assumptions made during the study about the emissions from the rapeseed growth and the replacement rate of the fluids. Overall, the study is most sensitive to the assumption about the oil replacement rate as this gives rise to the most significant changes in the final results. It is important that the assumptions in any LCA study are clearly identified and their implications are fully discussed.

Substance	Weight factor - EI95 (CML)	EPA
1,1,1-trichloroethane	0.12	x
CFC (hard)	1	x
CFC (soft)	0.055	x
CFC-11	1	1
CFC-113	1.07	0.8
CFC-114	0.8	1
CFC-115	0.5	6
CFC-12	1	1
CFC-13	1	1
CFC-111	x	1
CFC-112	x	1
CFC-212	x	1
CFC-213	x	1
CFC-214	x	1
CFC-215	x	1
CFC-216	x	1
CFC-217	x	1
HALON-1201	1.4	x
HALON-1202	1.25	x
HALON-1211	4	3
HALON-1301	16	10
HALON-2311	0.14	x
HALON-2401	0.25	x
HALON-2402	7	6
HCFC-123	0.02	0.02
HCFC-124	0.022	0.02
HCFC-141b	0.11	0.1
HCFC-142b	0.065	0.06
HCFC-22	0.055	0.05
HCFC-225ca	0.025	x
HCFC-225cb	0.033	x
methyl bromide	0.6	0.7
tetrachloromethane	1.08	x
CC14	x	1.1
Methyl chloroform	x	0.1
C2H2F2Br2	x	0.85
C2H2F3Br	x	1.15
C2H2FBr3	x	0.6
C2H3F2Br	x	0.65
C2H3FBr2	x	0.9
C2H4Br	x	0.085
C2HF2Br3	x	1.15
C2HF3Br2	x	1
C2HF4Br	x	0.95
C2HFBr4	x	0.55
C3H2F2Br4	x	1.15

C3H2F3Br3	x	2.9
C3H2F4Br2	x	3.9
C3H2F5Br	x	1.15
C3H2FBr5	x	1
C3H3F3Br2	x	1.3
C3H3F4Br	x	2.35
C3H3FBr3	x	1.6
C3H3FBr4	x	0.99
C3H4F2Br2	x	0.55
C3H4F3Br	x	0.87
C3H4FBr3	x	0.165
C3H5F2Br	x	0.435
C3H5FBr2	x	0.44
C3H6FBr	x	0.36
C3HF2Br5	x	1.05
C3HF3Br4	x	1.2
C3HF4Br3	x	1.35
C3HF5Br2	x	1.45
C3HF6Br	x	2
C3HFBr6	x	0.9
CHFBr2	x	1
CHF2Br (HBFC-22B1)	x	0.74
CH2FBr	x	0.73

Table 8-12 Comparison of CML and EPA data for Ozone Depletion

9 Recommendations and Conclusions

9.1 *Introduction*

Life Cycle Assessment is a powerful environmental management tool that will become more commonly used in future years. It is a simple, elegant idea, but it can become convoluted in practice. The amount of data required for an LCA is vast and there are often difficulties obtaining these data, however, as more LCAs are carried out and databases become more extensive this problem should be gradually alleviated.

This chapter re-iterates the research objectives outlined in Chapter 1 and discusses how they were met. It then considers the problems associated with LCA as a tool in general and discusses the use of sensitivity analysis in LCA. More specific comments are made on the case studies, with recommendations of areas that need to be improved and the scope for further work.

9.2 *Initial Research Objectives*

The main objectives of the research were:

- To examine the life cycle of fluid power systems when using biodegradable oil and mineral oil.
- To examine the comparative impact of these systems over their life cycles using two case studies.
- To determine whether Life Cycle Assessment (LCA) is a useful and suitable tool for use within fluid power engineering.
- To determine potential areas for improvement within the engineering design of mobile systems and LCA.

9.2.1 To examine the life cycle of fluid power systems using alternative media: biodegradable oil and mineral oil

The life cycle of two types of forestry machines and a road sweeper using rapeseed and mineral oil have been examined. This is described fully in Chapters 6, 7 and 8. The research has included production of the fluids and machines. It has examined the different use and maintenance records for the fluids, and the way in which the machines use the fluids. Disposal of the machines and the oil has been discussed, but not enough data were available for a full study of this stage of the life cycle to be included.

9.2.2 To examine the comparative impact of these systems over their life cycles using two case studies

This was fully examined in Chapters 6, 7 and 8. Both case studies show that the use of the rapeseed oil is not necessarily environmentally beneficial if the oil has to be replaced more frequently than the mineral oil. However, the research shows that the impacts are very dependant on the machine in which the fluid is used. The forestry machinery is far more sensitive to the amount of oil used in the system than the road sweeper, because of the different useful lives of the machines. The road sweeper has a shorter life than the forestry machinery and so the impact of the production of the machines on the environment is larger than the use of the oil, which is the converse of the case of the forestry machinery.

9.2.3 To determine whether Life Cycle Assessment (LCA) is a useful and suitable tool for use within engineering

The case studies used have shown that it is possible to use LCA in an engineering environment. They have also shown that it is very difficult to obtain sufficient data for such a study. For these case studies it has been shown where improvements in the design of the systems could be made in order to improve the overall environmental impact of the systems. Research at the University of Bath (Richards et al., 1999 & Richards et al., 2000) has created multi-media techniques to help the designers of fluid power systems. As the uncertainties are removed it will be possible to incorporate this LCA research into the multi-media activity. For example, one could choose the material from which a component is to be made and the performance, design and environmental implications would be depicted. Once a whole system has been built up in a multi media environment the components with the largest environmental burdens could be identified and alternatives considered. The impact of fluid selection could also be considered. When employed at this design stage the environmental impacts could be alleviated much more comprehensively than if the resulting environmental burdens have to be reduced after products have been manufactured.

9.2.4 To determine potential areas for improvement within the engineering design of mobile hydraulic systems and LCA

Chapters 6 and 7 examined the impact of different stages of the production and use of machines and different oils. The best way to improve the design of a hydraulic system from an environmental perspective is to minimise leakage. Although designers ought to strive constantly to make the systems more and more reliable and leak-free, this study has shown that the environmental impact of machinery can be affected by its components.

Rapeseed oil has a smaller impact on the environment than mineral oil if one only looks at the production phase. However, the operational properties of rapeseed oil are not as good as mineral oil and it requires more frequent replacement. This means that more rapeseed oil is used in a system than mineral oil, and the environmental impacts from the production phase have to be multiplied by the increased usage rate over the life of the machine in question. To reduce the environmental impact of a system running on rapeseed oil, it is necessary to improve the performance characteristics of the oil.

The production of machines also has a significant impact on the whole life environmental burden of the system. The production of the chassis and the main body of the machines has the largest overall impact. Hence it is important to assess the possibilities of weight reduction and hence reduce the consumption of diesel fuel.

The diesel consumption of machines has a larger environmental effect than the use of hydraulic oil. Although not considered in detail in this study, the use of an alternative power source, or increasing system efficiency may have a significant environmental benefit.

The work has demonstrated that LCA is a good tool for use within engineering systems but there are many areas open for improvement.

9.3 Problems associated with LCA

The main problems associated with LCA are the time it takes to complete and the limited availability of reliable, accurate inventory data. Moreover, the latter stages of LCA are still subjective. In order for LCA to become a reliable and trusted environmental management tool the subjectivity must be removed as much as possible.

There should be no "black box" scenarios within the process - all should be clearly visible.

The time taken to complete an LCA is the reason why many companies have failed to embark upon such studies in spite of the beneficial outcome. When the practice of LCA becomes more common there will be more readily accessible inventory data available for use and the time taken for completion will be reduced. The application of specific software allows a "baseline" LCA to be carried out relatively quickly but the data from which these outputs are generated may not be of the best quality. As with any system, the quality of the results is entirely dependant on the data used in the study.

The results of an LCA can easily be manipulated in the LCIA stage. Therefore it is important that the reason for choosing the environmental issues is clearly stated. It is also important that if a valuation stage is completed the methodology should be clearly described and that all the interim stages and results are shown.

9.4 The need for a comprehensive study of the local impacts

Life Cycle Assessments do not consider local impacts, only regional and global impacts. It is due to local impacts that the use of biodegradable oil has become popular in hydraulic systems, it is thought that the environmental effect of a spill of biodegradable hydraulic oil will be smaller than the effect of a spill of mineral oil.

Life Cycle Assessment does not have scope for the incorporation of localised impacts. This ought to be considered when an LCA is commissioned. If there are any significant environmental aspects to the study then an EIA or similar local environmental management tool ought to be used as a complementary assessment. LCA is only one of a suite of environmental management tools and ought to be used as such.

9.5 Synthetic esters

The research considers the use of mineral oil and rapeseed oil in hydraulic systems. However, the biodegradable fluid which is in greatest use is not rapeseed oil, but a synthetic ester. Research on the use phase of this fluid suggests that its performance is similar if not better than that of the mineral oil. However, it has proved impossible to obtain inventory data for the production of synthetic esters probably because much of this information is commercially sensitive. However, as companies become aware of the benefits of this type of research it is possible that they will release data so that their oils can be compared in a life cycle capacity to mineral and rapeseed oil.

9.6 Results from the Case Studies

9.6.1 Oil Production

The data used in Chapter 6 which examined the oil production stages of the study were incomplete. However, effort was made to ensure that as much data were included as possible and that these were as accurate and up-to-date as possible.

The production of mineral oil has a very large effect towards global warming compared with the production of rapeseed oil. This is because it is a non-sustainable product. Mineral oil also has a larger impact on acidification, heavy metals and winter smog. The production of the rapeseed oil has a larger impact on eutrophication, carcinogens, ozone depletion, summer smog, pesticides and energy use. However, all but the impact towards greenhouse gases are relatively similar.

9.6.2 Forestry Machinery

Chapter 7 outlines the impact of the production of the forwarder and the harvester and their use. The environmental impact of the production of both machines is dominated by the main cab and the chassis which are the heaviest parts of the machines. The impact of the use of diesel in these machines far outweighs the impact of the production of the machines and the use of hydraulic systems. For both machines, when the rapeseed oil is replaced twice as often as the mineral oil the environmental impact on every category considered, apart from greenhouse gases, is greater for the system running on rapeseed oil. This shows that it is not necessarily beneficial for the environment to use rapeseed oil in these machines.

9.6.3 Road Sweepers

Road sweepers are also examined in Chapter 7. The production of the sweeper is dominated by the aluminium cab. If the amount of aluminium used in this part of the machine could be reduced, or the recycled component of the machine could be increased (as discussed in Chapter 8) the environmental impact from this stage of the machine's life cycle could be reduced. The difference between the use of mineral and rapeseed oil in the sweeper is not as pronounced as it is in the forestry machinery because the life of road sweepers is such that production plays a larger role in the life cycle. The impact from the system running on rapeseed oil has a larger impact on every category other than greenhouse gases. In this case study the difference between the impact on greenhouse gases is less marked. This challenges the view that rapeseed oil is used "for the sake of the environment".

9.7 Assumptions

The assumptions made in a study can have a profound effect on the final results. It has been shown in this research that assumptions made about the performance of the oil in the systems can alter the environmental impact of the systems dramatically. It is imperative that any assumptions made in a study are clearly visible along with the reasons behind the choices made.

9.8 Sensitivity analysis

Chapter 8 outlined the sensitivity analysis carried out in this research. International Standard guidelines suggest that a sensitivity analysis ought to be carried out, but it has been shown here that this is not necessarily a simple task. When two types of analysis were used to determine the sensitivity of machine production to errors in the weights of some of the components the results could vary. This is because of the problems associated with uncertainty of so many components when the total weight is known.

The analysis showed that although the inventory data used in the research were not precise, the sensitivity of the final results to variations in these data did not lead to major changes in the final results.

Differences in the final LCA resulting from different characterisation data were larger than those from the inventory data. The characterisation data are not usually exposed to sensitivity analysis and so it is interesting to note that this can produce differences of this sort. The research has shown that it is important to understand the source of characterisation data that is used in a study which is being used to aid decision making.

Life Cycle Assessments can be sensitive to changes in the LCIA methodology used (Chapter 8). It is important that one knows why each environmental issue studied in an LCA has been chosen. These are often pre-defined in commercial software packages, therefore it is important that care is taken not to choose a set of impact categories that will either advantage or disadvantage one particular product or stage of a life cycle assessment.

9.9 Further Work

The research has shown that there is much work that should be done in this area. It is recommended that the following work is carried out:

- An environmental impact assessment type study on the impact of many of the hydraulic oils in different receiving environments
- Integrate the environmental burden data into a multimedia aid to design
- Investigate the life cycle of synthetic esters in fluid power systems
- Establish a conclusive methodology for sensitivity analysis in LCA
- Create a "complete" inventory database for fluid power systems
- Investigate fully the implications of using different characterisation data and LCIA methodologies

9.10 Concluding Remarks

Life Cycle Assessment is a very powerful tool, but it has obvious limitations. An increase in the use of LCA ought to mean that more accurate and up-to-date inventory databases are compiled and maintained so that LCA's will not be so time consuming and inaccurate.

Life Cycle Assessment can be incorporated into the design methodology once complete LCA's have been carried out. This will allow the environment to be considered at the start of every project, rather than being considered only when there is legislation to meet or a pollution event.

The use of LCA allows the "true" environmental decision to be made. Decisions are often made about the environment as a result of emotionally based information. LCA allows the whole "story" of the product or system to be examined. This should improve decision making processes.

Local impacts have not been considered in this study in spite of the fact that the use of biodegradable oil in hydraulic system has become so popular as a result of them. The local impacts may be very important, but they do not represent the complete story. LCA allows regional and global issued to be examined. In this study it has been shown that the regional and global impacts for rapeseed oil are often larger than they are for the mineral oil. This is a surprising result for a designated "environmentally friendly" fluid.

To summarise, LCA ought to be used within the fluid power engineering community and it would be beneficial if it were considered at the design stage. This research has shown that, contrary to general opinion, rapeseed oil may have a larger environmental impact than mineral oil when used in fluid power systems. The research has also highlighted the problems associated with using LCA, the problems associated with data quality and availability at all stages in an LCA. Sensitivity analysis has also been examined and used within the study. This is an important stage of LCA and ought to be researched further.

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APPENDIX 1
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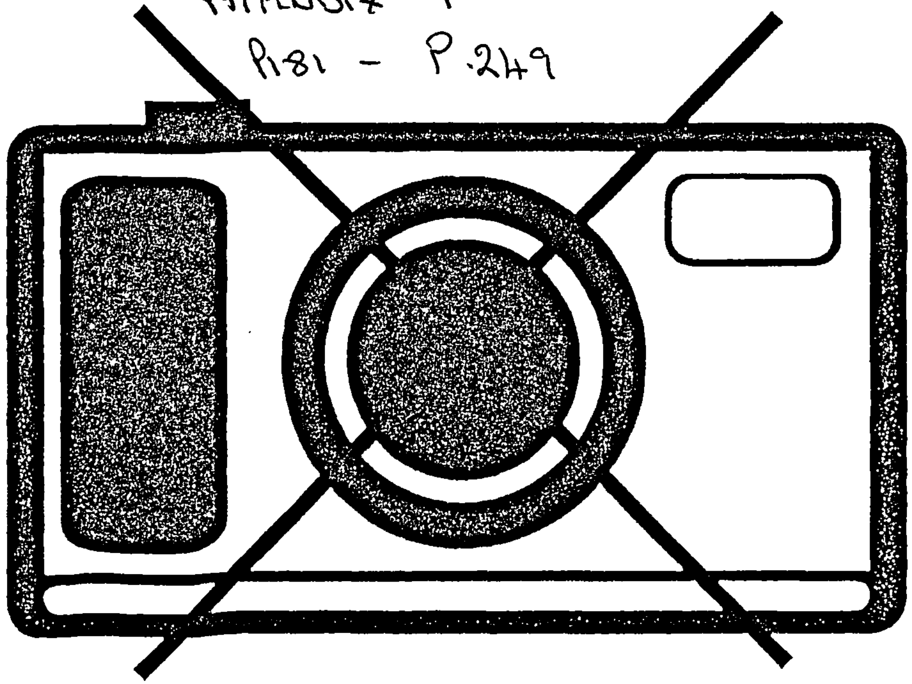

IMECE 98
International Mechanical Engineering Congress and Exposition
November 15-20 1998, Anaheim, CA

LIFE-CYCLE ASSESSMENT OF OIL 'HYDRAULIC' SYSTEMS FOR ENVIRONMENTALLY-SENSITIVE APPLICATIONS

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ABSTRACT

Life-cycle assessment (LCA) techniques have been used in order to evaluate the environmental impact of conventional oil 'hydraulic' systems in an ecologically-sensitive application; that of mobile forestry machinery typical of modern European design. A single-grip 'harvester' employed for logging and a 'forwarder' that subsequently transports the felled and cut-to-length timber out of the forest are analysed. The results of this indicative LCA provide insights into the relative magnitude of the complex range of environmental impacts arising from fluid power systems and their parent vehicles in the forestry context. It also suggests areas for future research, principally on the impact of diesel fuel and hydraulic oil (including their additives) on the forest ecosystem, on the balance between local, regional and global environmental effects, and on the developing methods of LCA itself.

INTRODUCTION

Background

In the aftermath of the Rio Earth Summit in 1992 there has been a heightened awareness of environmental issues world-wide, and in particular of the need to achieve sustainable development. This has filtered down to the design domain as it becomes recognised that developing products and processes with a low environmental impact over their whole life-cycle are preferable to cleaning up during and after operation. In the case of fluid power systems the market is currently dominated by those based on mineral oils as the working medium. There is also a significant market for synthetic oils used where fire is a hazard. Environmental pressures now make it timely to examine alternatives such as biodegradable fluids (or bio-oils) and water. Burrows (1995) has recently traced the historical development of fluid power systems design, and the sort of environmental imperatives that have led to a re-evaluation of, for example, water hydraulics. The Scandinavian countries are leading in the field in the application of environmentally-friendly fluids, and Germany is beginning to pay serious attention to these developments. It is likely that these trends will be given added impetus by new European Union (EU) legislation and international standards, for example ISO 14001. Several papers have been published at international conferences in Belgium, Finland and Germany giving preliminary results concerning the development of performance specifications and of the operational experience of companies using biodegradable fluids (see, for example, Tharp et al, 1998).

It is now widely recognised that in order to evaluate the environmental consequences of a product or activity the impact resulting from each stage of its life cycle must be considered. This has led to the development of a range of analytical techniques that now come under the 'umbrella' of life-cycle assessment (LCA). Along with other environmental management tools, LCA is becoming more widely adopted in the context of international environmental regulations, for example, that associated with eco-labelling. For a full LCA the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole-life cycle from "cradle-to-grave" (Graedel and Allenby, 1995). [In the present baseline study the disposal of the forestry machinery and related hydraulic oil has not been fully considered and so it might more accurately be termed a "cradle-to-gate" study.] LCA underpins the process of environmentally-sensitive design, or 'eco-design', that has very largely focused to date on products. In the case of fluid power systems based on oil hydraulics a network of interconnected components needs to be evaluated within a network, or circuit, systems analysis framework.

The Matter Considered

The findings of a 'baseline' study of the life-cycle environmental impact of conventional oil hydraulic systems are reported. In later research, to be described elsewhere (Burrows et al, 1998), the baseline results will be contrasted with fluid power systems utilising biodegradable fluids (such as rapeseed oil or synthetic esters) as their working media. It is anticipated that these may prove more ecologically benign, although this needs to be placed in the context of the particular application being considered.

In order to assess the environmental performance of conventional systems in an ecologically demanding situation, the case of mobile forestry machinery has been examined. Here the potential contamination of forest ecosystems by mineral or synthetic oils could prove particularly damaging. Two vehicles that are typical of modern European design are evaluated; a 'harvester' and a 'forwarder'. The LCA indicates the relative magnitude of the complex range of environmental impacts associated with the machines themselves and their fluid power systems. Areas for future research are identified in respect both to the impact of diesel fuel and hydraulic oil on forest eco-systems, as well as the development of LCA methods.

LIFE-CYCLE ASSESSMENT

Historical Development

In the field of economics it is often argued that cost-benefit analysis (CBA) is superior to life-cycle assessment. This view has been challenged by Hammond (1998), who has drawn attention to the limitations of CBA techniques for evaluating projects with significant environmental impact. Obviously there may be imperfections in the structure of the theoretical "perfect competitive market"; for example, social costs may be excluded from prices and externalities, such as pollution or waste disposal costs, might not be included. The various methods for valuing external costs and benefits in CBA are all open to criticism. Choice of different valuation methods can lead to a wide variation in the supposed costs and benefits. This valuation process is uncertain and potentially controversial, often relying on the determination of shadow prices. In the extreme, they result in methods for valuing human life and well being that are quite at odds with that perceived with by the individual or by society as a whole. Similar difficulties arise in valuing other elements of the biosphere. There are also likely to be uncertainties about the future, restricted information about technical possibilities and time lags, all of which might cause market prices to deviate from those which would lead to optimal investment decisions. Another reason for discouraging the sole use of CBA techniques is that it obscures rather than highlights the range of impacts that may emanate from a given project. Decision makers are presented with a single decision criteria (such as the discounted cost-benefit ratio), which actually hides many disparate environmental impacts. It is vitally important that the implications of these impacts are faced by design engineers rather than obscured by the methodology.

Life-cycle Assessment arguably originated from the techniques of 'energy analysis' (sometimes termed energy or fossil fuel accounting) that developed in the 1970's, following the so called 'oil crisis' (see, for example, Chapman, 1976, Roberts, 1978 and Slesser, 1978). The methodology of LCA follow closely that developed for energy analysis (Hammond, 1998), but evaluates the environmental burdens associated with a product or process over a their whole life-cycle. This requires the determination of a balance or budget for raw materials (outputs) emanating from the system. Energy is treated concurrently, thereby obviating the need for a separate energy analysis. LCA is a product or system based form of environmental auditing which is often geographically diverse, that is, the material inputs to a product may be drawn from any continent. Until recently there has been a lack of consensus on the best approach to LCA and consequently practitioners have, to some extent, developed their own methodology. This has allowed a great deal of subjectivity to develop in some studies. Only relatively recently has the methodology of LCA been codified under the auspices of the Society of Environmental Toxicology and Chemistry (SETAC) at a series of workshops in the early 1990's (Graedel and Allenby, 1995). In the USA it is sometimes referred to as 'resource and environmental profile analysis', or REPA (Canter, 1996). SETAC (1991 and subsequent publications) have largely defined the standard framework and this forms the basis of the draft ISO 14040 series.

LCA Methodology

The aim of the LCA is to identify opportunities for environmental improvement, by detecting the areas with the most significant impacts. This improvement potential can then be examined as part of the design process. SETAC (1991) has established a framework for LCA comprising of four main stages. These are illustrated schematically in Fig. 1, where it is shown to follow a logical sequence of goal definition and scoping, inventory analysis, impact assessment, and recommendations for improvement. There are many technical issues (Hammond, 1998) that need to be addressed while conducting this type of LCA (and about which Ayres (1995) and Lee et al (1995) have been particularly critical); the definition of system boundaries, the quality of data available, and the way in which the results are normalised. The goal definition process is very important as part of the planning stage for an LCA study. Gathering data for the inventory can be a time consuming task as many companies see such data as either confidential or simply do not have that sort of detailed records needed for a credible whole life study. The impact assessment is still undergoing refinement, the concepts employed in the SETAC methodology have been largely incorporated in the draft ISO 14040 standards. Three elements of the impact assessment stage are indicated in Fig. 1. Both the classification and characterisation elements were undertaken in the present study. Comparative valuation of emission data was not performed, although the data was normalised with respect to both European emissions and the output of felled logs from the forestry equipment. The improvement assessment process will only be completed when the impacts of alternative fluid paper systems have been determined in the follow-up study (Burrows et al, 1998). Much of the data utilised in the present study has, of necessity, been estimated, and will subsequently be refined.

In order to identify the life-cycle stages appropriate to the present study, a flow chart of the main areas of potential

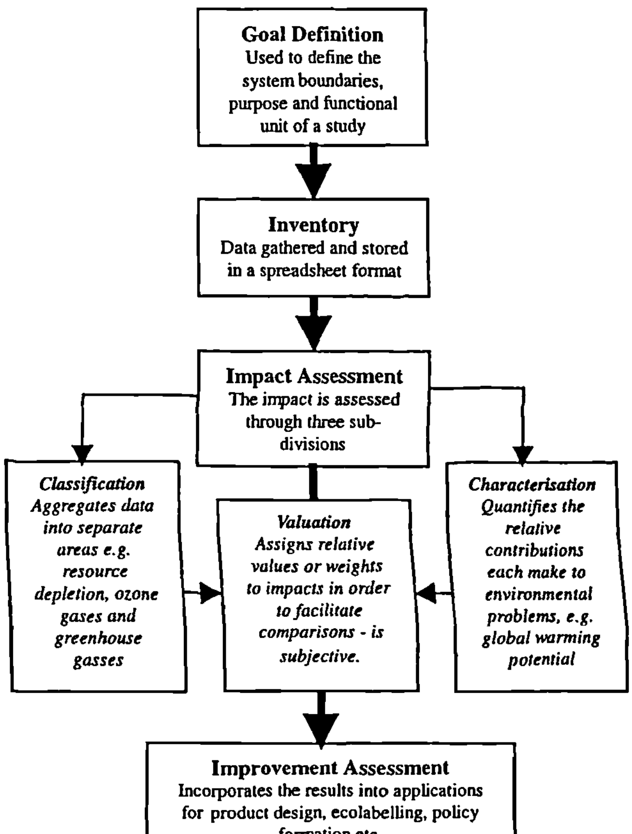


Fig. 1. Schematic Representation of the Life-cycle Assessment Methodology Defined by SETAC.

environmental impact was produced; see Fig.2. This shows the main boundaries of the complete study, encompassing both the baseline assessment of conventional oil hydraulic systems used in mobile forestry machinery and that with biodegradable ('environmentally-friendly') fluids. The type of logging equipment examined here is often refurbished and resold on the secondary market after its initial, or primary, use. There is insufficient information available at present from operations to enable this reuse to be accounted for in the present study.

Life-cycle assessment is still very much in the development phase, both in Europe and North America. The process of tracing the life-cycle environmental impact of a product or activity is complicated. It is greatly assisted by the use of spreadsheet programs, and several special purpose software packages have become commercially available. Rice et al (1997) recently undertook a review of the twelve main packages available in Europe. These were assessed in terms of a range of criteria, including the volume and quantity of data, evaluation methods for impact assessment, burdens allocation, software engineering practices, and cost. On the basis of this comparison, Rice et al concluded that only four of these packages were serious 'players' as environmental management tools. The present study has been undertaken using an updated version of one of the four recommended tools: SimaPro 4.0. It is a commercial package developed from that originally reported by Heijings et al, 1992 (see also Guinee et al 1993a and 1993b for related product-oriented LCA work at CML, Leiden University, the Netherlands), then known as version SimaPro 1.0. This choice has no particular significance, as any of the four packages recommended by Rice et al would have been suitable. In terms of the LCA stages illustrated in Fig. 1, the software has been mainly used as part of the inventory stage, although supplemented by specific data on the materials content and embedded energy related to the mobile forestry machinery considered here.

The database used for the inventory of the life-cycle assessment underpins the entire study. If this information is not reliable, then the credibility of the study will be greatly reduced. Data gathering for an LCA is very difficult and time consuming, due to the large amount of data required and because some data may be commercially confidential. In this baseline study typical data for the manufacture and operation (use) of the forestry machinery has been used, and this will be updated over time. The general database in the SimaPro software (such as energy efficiencies) comes from publicly available European sources. Its classification scheme has been largely adopted for impact assessment. The initial phase of valuation, the normalisation process, has been performed using both the method adopted for the software (comparison with European emissions) and by dividing the emissions data with output parameters specific to forestry management and timber transportation.

FLUID POWER SYSTEMS IN A FORESTRY CONTEXT

Forests and the Environment

Approximately 10% of the United Kingdom is covered with forests, of which some 35% is owned by a public body; the Forestry Commission (Forestry Commission, 1997). Processing timber will inevitably result in some impact from the machinery utilised. Hydraulic systems adapted for mobile logging equipment have the potential to leak, and thereby damage the ecology of the forest and the waterways within the forested area. Much of the UK forest is in upland areas where water flow is fast. This means that any contaminants may be swept into the major waterways relatively quickly. The speed of the water flow may be increased by compaction of the ground by logging vehicles, and the ridge system adopted by foresters in order to plant trees more easily. Forests are often planted around lochs and lakes into which run-off water and potential contaminants will flow. Many of these are important ecologically, and often act as water supply reservoirs. It is therefore important to determine the environmental impact of oil spills originating from the machinery use.

The Forestry Commission has a "non-draining" policy for hydraulic oils. Despite this, more hydraulic oil is used (and therefore lost) within the Commission's forests than from engine or gear oils, which are drained and therefore disposed of "correctly". In recent years the Commission has started to look at the forest environment in terms of oil spillage, and has estimated that approximately 340,000 litres of hydraulic oil is spilt on the forest floor every year. This only represents a spill of 0.14 litres per hectare, but they are not evenly spread out over the forest floor. If a machine leaks one drop of hydraulic oil every second, for example, this is the equivalent to a loss of 950 litres per year. This type of leakage rate is not uncommon. In Europe, 400 million litres of hydraulic oil is produced per annum, and only some 75% of this can be accounted for at any one time. Oil spills on the forest floor may also be caused if empty containers are left lying around. Despite policies that stipulate containers are not to be left in the forests after work has been carried out, it is not always easy to incorporate such policies into the working practice.

Mobile Logging Equipment Powered by Oil Hydraulic Systems

In the present study two types of forestry machinery were examined: a 'forwarder' that fells the trees and cuts the logs to predetermined lengths. The cut length depends on the current economic market and customer orders. In the case of the forests managed by the UK Forestry Commission considered here, logs are normally cut to approximately 2 m lengths. Vehicles typical of European design are illustrated schematically in Fig. 3. Hydraulic systems are employed in both systems; they are utilised in the cutting and moving part of the harvester, and in the forwarder arm adopted for moving the logs. These particular machines have more hydraulic components than those used elsewhere in the tree planting/felling process. It is estimated that these two machines account for more than half the hydraulic oil used by the Forestry Commission.

Hydraulic systems in mobile forestry units have a significant potential to leak. If this actually occurs within the forest, rather than at a depot, the implications of this can be great. It is obviously preferable to take mitigating action to avoid such spills before they happen, rather than to attempt to clean up during or after operation. However, the issue of hydraulic systems within a forest is not straightforward. The ongoing environmental effects of the complete logging machine in operation, or the environmental effects during its manufacture, may far outweigh the burdens due to the hydraulic systems alone. The use of LCA allows these issues to be studied, and enables a rational decision to be made as to whether it is desirable to alter the oil hydraulic system for use within such sensitive areas.

Although it is important to determine the environmental consequences of the hydraulic systems employed in forestry machinery, it is desirable to place these impacts in context. The risks involved with hydraulic oil usage within forestry must be put into perspective at an early stage. Ecological or environmental risk assessment (ERA) is becoming increasingly used as a formalised tool, partly due to the increased media interest in environmental disasters. The risk of spills from hydraulic systems must be considered along with the consequences of a spill. This environmental risk must, in turn, be contrasted with other potential hazards, such as the risk of diesel oil spills from the engine and its possible impact. Detailed research on the use of ERA in relation to logging equipment has yet to be carried out. Risk assessment may also take place within the impact identification stage of a life-cycle

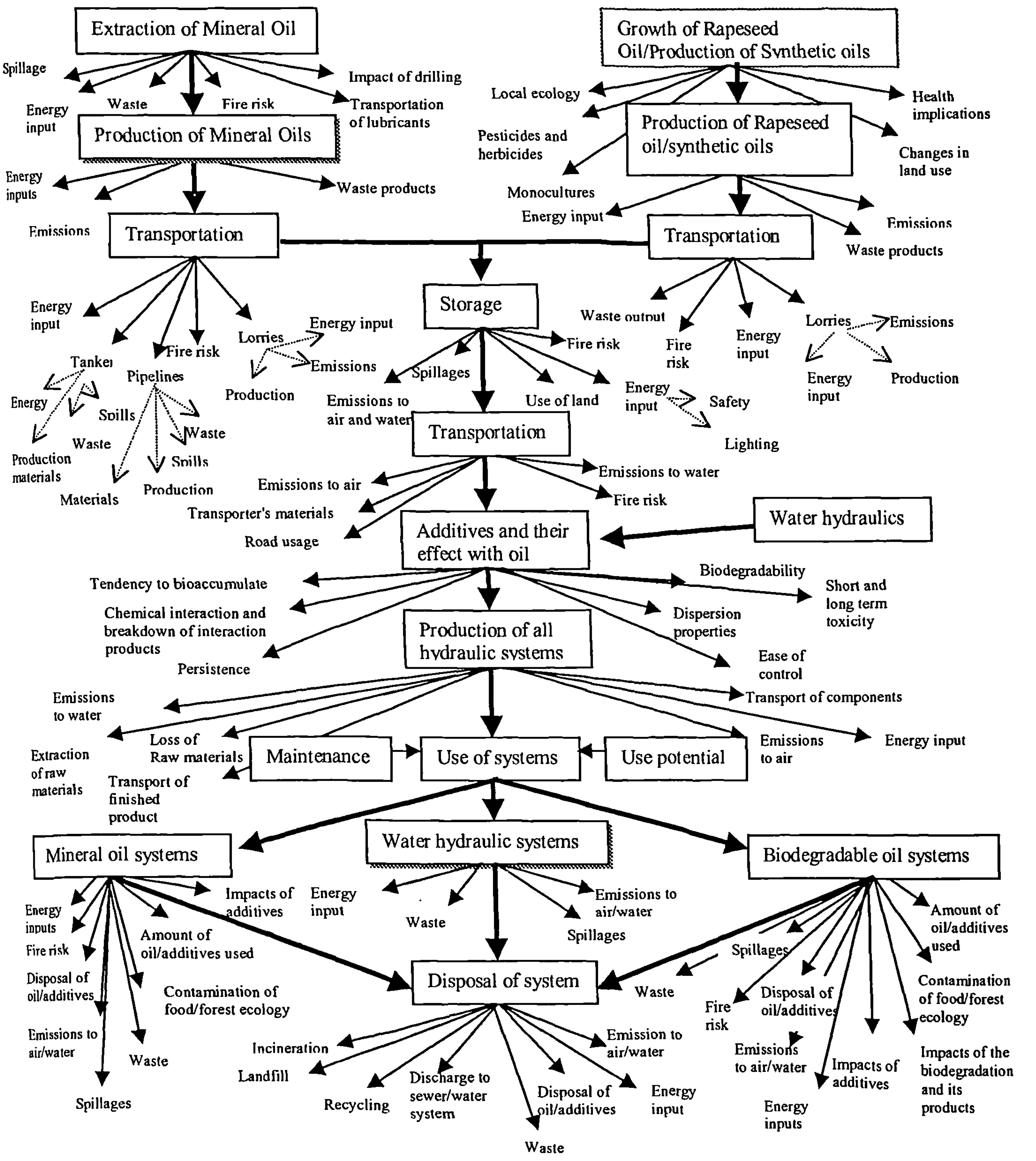
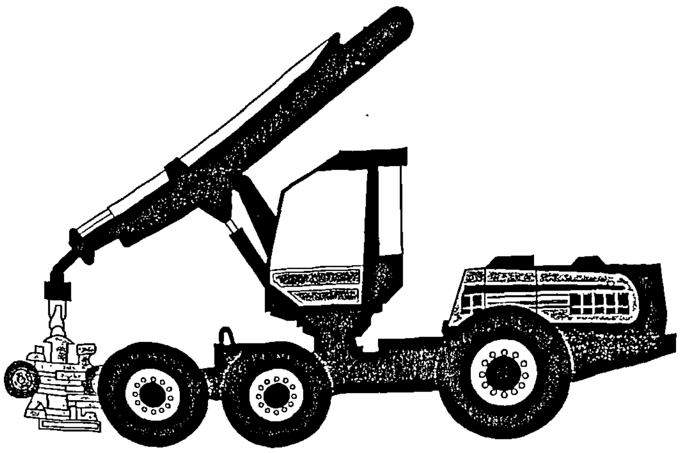


Fig. 2. Flow Chart of the Main Stages of Potential Environmental Impact



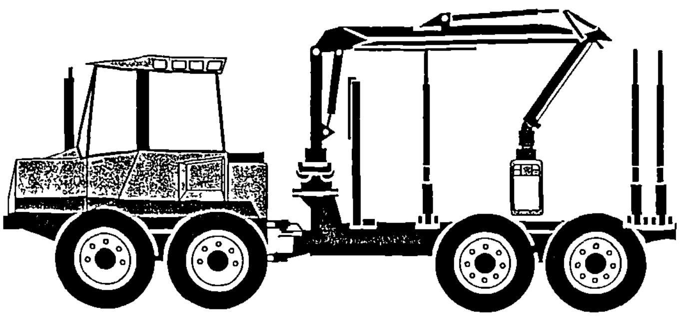


Fig. 3. Schematic Illustration of Mobile Forestry Machinery (of Modern European Design): top – a Harvester, and bottom – a Forwarder.

assessment (see Fig. 1) in order to determine the most appropriate valuation system relevant to the study.

Main Environmental Impacts of Timber Thinning and Felling

The process of timber felling and thinning is bound to have an effect on the local environment. Large machines enter areas hitherto relatively untouched since their original plantation. The soil will be compacted, and wildlife disturbed, and minor water courses changed. These effects cannot be avoided as they are integral to the timber harvesting process. However, the direct effects of the logging equipment may be minimised. The main effects on the forest ecology due to such machinery is caused by diesel emissions and fuel spills, the loss of lubricant from the chainsaw, and hydraulic oil spills and leaks.

CASE STUDY; MOBILE FORESTRY VEHICLES AND THEIR OIL HYDRAULIC SYSTEMS

Selection of the Case Study – Goal Definition

In life-cycle assessment, goal definition is the initial stage that sets out the aims and objectives of the study (see Fig. 1). Areas of significant environmental impact related to the manufacture and operation of forest machinery need to be outlined. This includes comparison between the impact of the whole vehicles and their hydraulic systems. The purpose of the present study was described in the opening section above.

Scoping Study of Mobile Logging Equipment

LCA scoping studies outline the significant areas requiring further study. The issues considered in the present case study are shown in the flow diagram illustrated in Fig. 2. These issues were examined in the light of the aim of the study, prior to the data being incorporated into the life-cycle inventory (see below). In the context of UK forest management, mobile logging equipment is commonly imported from continental European and Scandinavian manufacturers (for example, those in Germany and Norway). Consequently, the system boundary has been effectively drawn at the source of the raw material and energy inputs to the manufacturing process. That is around the mine or well, wherever this is geographically located. The system boundary in LCA studies is sometimes made coincident with that of the nation state for reasons of simplicity, but this would have been inappropriate in the present case.

The Life-cycle Inventory

The inventory process involves gathering information about all the emissions associated with the manufacture and operation of the machinery. Data on the materials composition of mobile logging equipment of European design and manufacture (both the forwarder and the harvester) were obtained from the manufacturer's specifications. The emissions associated with each stage of the process can then be readily determined by tracing them back to their origin. Information about the use of the vehicles was obtained principally from the Forestry Commission. It appears that the operation of both vehicles are very similar in terms of fuel use, and so for this study identical data has been used for the two machines.

Impact Assessment

In order to determine the environmental consequences of the manufacture and use of the mobile logging equipment, the data compiled for the 'Life-cycle Inventory' has to be classified into groups of emissions that contribute to a specific impact. This has been done in accordance with SETAC guidelines (1991) and the draft standard ISO 14042. Once classified, the data has to be assigned a weighting in order to obtain equivalence values, for example global warming gases are given a CO_2 equivalent value in order to rank them together. This data is shown in Table 1. However, such data is difficult to interpret, and so SETAC have suggested a further analysis stage as part of LCA valuation. In reality, few LCA studies to date have incorporated a valuation stage (Powell et al, 1997), due to the difficulty in overcoming the subjectivity of the task. Nevertheless, it is an important element of LCA and one that is currently attracting much attention. This includes a recent investigation of the valuation process (Braunschweig et al, 1996), which has been identified by SETAC as part of the initial stage of impact assessment.

The data obtained for the present study can be presented in several ways. Classified data grouped in terms of their potential environmental impact is given in Table 1. It indicates emissions data 'characterised' for manufacture and whole life operation of the harvester. Energy use and emissions data can subsequently be normalised in a variety of ways. Normalised data for the harvester is presented graphically in Fig. 4, using a similar practice to that adopted in the transportation field. Here average emissions are shown per tonne of cut-to-length timber over the life of the vehicle. Only the emission of the greenhouse gases and energy consumption appear significant issues according to this normlalisation. However, this does not give any indication of the amount of emissions produced compared with the total production of that pollutant. Nevertheless, it is a valid comparative mechanism and is used here to compare manufacture and use of the machines, as well as the production and use of their hydraulic systems. In Figs 5 and 6 the life-cycle energy requirement per tonne of logs produced annually for both the harvester and the forwarder (over an assumed 15 year life of the vehicles) is displayed. The comparison of the manufacture of the vehicle with that of their hydraulic system (see Fig 6) indicates that the parent machine has greater environmental effect. Notwithstanding this the use of hydraulic oil within the system is a significant part of the total use of the machinery.

Table 1. Characterised Data for Life-Cycle Assessment

	Manufacturer of Harvester	Manufacture of Forwarder	Manufacture of Hydraulic System for Harvester	Manufacture of Hydraulic System for Forwarder	Operation/Use of Machine (Diesel and Hydraulic Oil) over 15 years	Operation/Use of Hydraulic System (hydraulic oil) over 15 years
Greenhouse Gases (kg CO_2)	3E4	2.64E4	104	470	8.86E6	2.24E4
Ozone Depleting Gases (kg CFC11)	5.09E-4	3.7E-4	0	1.2E-6	0	0
Acidification Inducing Substances (kg SO_4)	903	891	0.866	3.25	1.1E5	683
Eutrophication Inducing Substances (kg PO_4)	22	19.6	6.6E-2	0.24	1.67E4	33.2
Heavy Metals (kg PB)	0.921	9.4E-2	4.5E-4	1.86E-3	0	0
Carcinogens (kg B (A) P)	9.9E-3	7.6E-6	1.49E-5	1.2E-4	0	0
Winter Smog Inducing Substances (kg SMP)	766	762	0.329	1.66	3E4	533
Summer Smog Inducing Substances (kg C_2H_4	104	64	0.108	1.41	1.7E4	358
Energy (MJ LHV)	8.88E5	6.65E5	2.48E3	1.3E4	1.42E7	2.47E7
Solid Waste (kg)	7.86E3	6E3	7.32	97.3	4E3	0

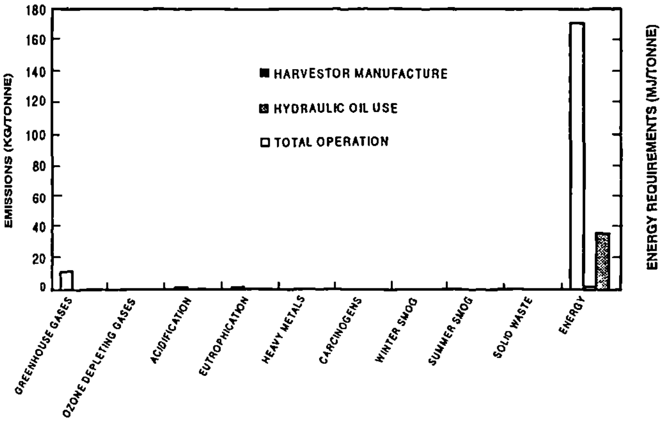


Fig. 4. Normalised emissions attributed to the single-grip harvester (over an assumed 15 year life); per tonne of cut-to-length timber.

A second method of normalisation is to compare the energy use and emissions with European (or other regional) emissions in each category per capita. This can be achieved using the notion of 'people emission equivalents' which can be defined for the present purposes as follows:-

European emissions per capita

$$= \frac{\text{total European output in each emission category}}{\text{population of Europe}}$$

∴people emission equivalents

$$= \frac{\text{emissions due to forestry machines}}{\text{European emissions per capita}}$$

An example of energy use and emission data for the harvester normalised in this way is shown in Fig. 7. It should be noted that the European emission per capita relate to one year only (in common with most regional statistics), whereas those emanating from individual vehicle use are over their 15 year life-cycle. Thus, the data in Fig. 7 exaggerates the emissions from the harvester by a factor of fifteen. Nevertheless this type of normalisation can illustrate the relative contribution that the manufacture and operation of mobile forestry equipment makes to overall European emissions. This can be used to outline areas in which comparatively large emissions are made. Data normalised in this way (See Fig. 7) shows that the use of the vehicles potentially contribute significantly to greenhouse gas emissions, acidification, eutrophication, winter and summer smog as well as energy consumption

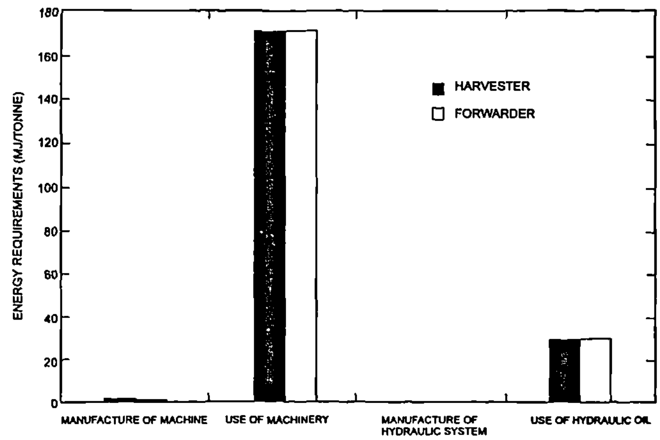


Fig. 5. Life-cycle, or gross, energy requirements for mobile forestry machinery and their fluid power systems (normalised per tonne of logs felled over an assumed 15 year life cycle).

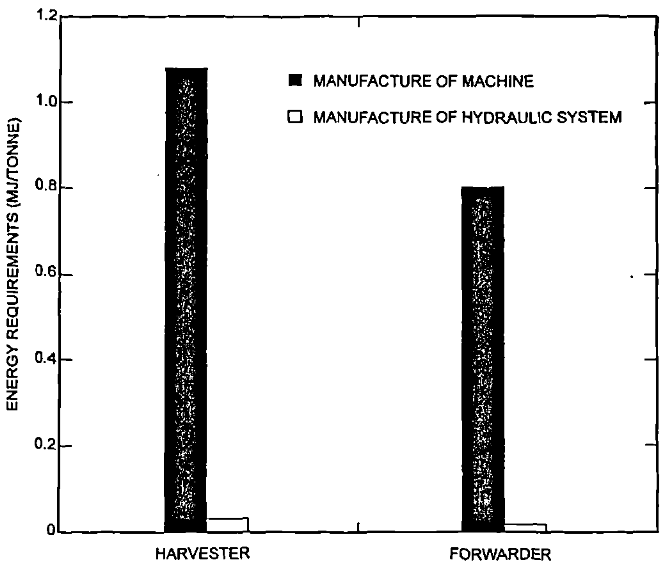


Fig. 6. Manufacturing, or process, energy requirements for mobile forestry machinery and their fluid power systems (normalised per tonne of logs felled over an assumed 15 year life).

Time plays a significant role in normalising emissions data. In the present study, data for use over a vehicle lifespan of fifteen years has been compared to the average emissions per capita in Europe over one year. Although this is common practice in LCA studies, it gives the impression that the impact of vehicle operation is much worse than it really is. If data was analysed for just one year of use it would change the scale on the resultant graph (such as Figs. 4-6), and suggest that manufacture was more important than it is over the life cycle. It would not, of course, change the relative importance of the various emissions during the operation of the vehicles. As there is no data for emission production levels in the future, and any other method of analysis would show constant weighting (or bias) towards the production. This type of presentation has been accepted as normal practice (Braunschweig et al, 1996).

The main areas of significant environmental impact relate to the use of the vehicles in the forest, and particularly the use of the hydraulic oil. Clear felling large areas of forest undoubtedly has major environmental effects. However, the present study aims to determine the long-term impacts of the machinery in the forest environment, rather than the consequences of felling itself. The only direct impacts on the forest ecology will be due to the running of the engine (diesel emissions) and the potential spills of diesel fuel or hydraulic oil. The operation of the machine raises the significant issue of acidification. This is a very important matter within forestry management, as the combination of the decomposition of pines and acid rain makes forestry areas particularly susceptible to high acidity. This in turn leads to the solution of heavy metals into the water in the soil and nearby waterways. Heavy metals in solution can be very toxic to aquatic ecology. Oil spills may also inhibit enzyme activity within the soil, which can effect the uptake of phosphorous, that is essential for plant growth in the soil (Kireeva et al). The potential impact of a combination of acidification and a spill of hydraulic oil clearly needs further examination by soil scientists.

The impact of a spill on the forest floor is likely to be potentially one of the most important environmental issues associated with the use of hydraulic fluid power devices within forestry. However, it is very difficult to quantify the effect that such

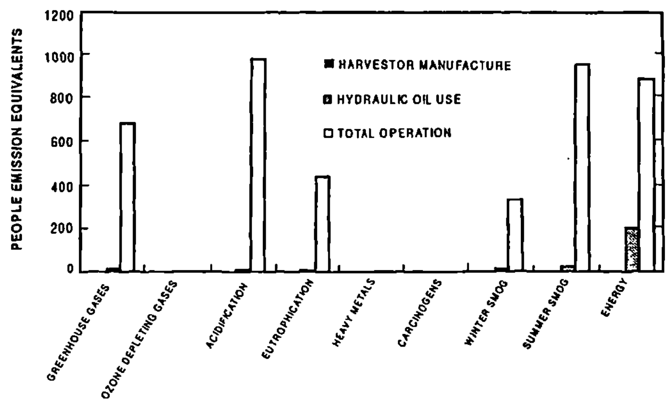


Fig. 7. Normalised Emissions attributable to the single-grip harvester (over an assumed 15 year life); compared with European emissions per capita.

spills will have, and incorporate this into the valuation stage of a LCA. Methodologies to achieve this will need to form an important element of future research aimed at evaluating the environmental impact of such systems in ecologically-sensitive applications.

CONCLUDING REMARKS

Life-cycle assessment techniques have been used in order to evaluate the environmental impact of conventional oil hydraulic systems in an ecologically-sensitive application; that of mobile forestry machinery. A single-grip harvester employed for felling cut-to-length timber and a forwarder that subsequently transports the logs out of the forest have been analysed. Both machines are typical of modern European designs. The energy and materials used to manufacture and operate the two vehicles, together with the associated pollutants and wastes released into the environment, were quantified over their whole life cycle. The results of this indicative LCA provide insights into the relative magnitude of the range of complex impacts emanating from the fluid power systems and their parent vehicles. It suggests that the operation and maintenance of the machines in the forest dominate the life-cycle environmental impact. This is much greater than that which is attributable to the production of the vehicles themselves, either from the extraction and refining of raw materials, or the manufacture and installation of the machines. Likewise, the impact of the oil hydraulic systems is generally small compared to their parent machines. Nevertheless, some of these pollutant emissions can cause significant damage to forest ecosystems via acidification and eutrophication processes.

The present study suggests areas for future research, particularly in regard to the impact of diesel fuel and hydraulic oil spills (including their additives) on the forest ecosystems. It has also highlighted the valuation problem associated with balancing potential environment impacts at the local, or forest, level with those that have regional and global consequences. The speculative contribution of greenhouse gases to global warming (Hammond, 1998) obviously falls into this latter category. Finally, it is clear that LCA methods have some way to go before that can be regarded as being an objective tool. They are rather better at identifying potential regional effects, than the sort of localised ones that are important in a forestry context. Ecological risk assessment may prove to be a useful adjustment to LCA for identifying hazardous doses of contaminant, and the uncertainty of the impacts.

ACKNOWLEDGEMENTS

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The author's names appear alphabetically.

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LIFE CYCLE ASSESSMENT OF SOME MOBILE HYDRAULIC SYSTEMS

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ABSTRACT

Life Cycle Assessment has been used to study the environmental impact of mobile hydraulic systems using both mineral and rapeseed 'hydraulic' oils. Rapeseed oil is far more readily biodegradable than mineral oil. It is for this reason that it has become popular for use in situations where a spill could cause significant environmental damage, for example, within forested areas. The case of a forest harvester has been studied in order to evaluate the whole life cycle impact of these alternative fluids, including their refining, field use and disposal. It is found that the production of rapeseed oil has a greater impact in relation to many environmental issues than the production of refined mineral oil. This is largely due to the energy required in the crushing stage of the oil's production. Rapeseed oil deteriorates more rapidly than mineral oil and so a larger quantity is required over the lifetime of the fluid power system. This means that the impacts associated with the production of the rapeseed oil is exacerbated when viewed over its life-cycle. The contribution to environmental issues for both oils has been assessed and it is found that there is a larger impact attributable to the rapeseed-based oil in respect to all the global and regional issues examined.

KEYWORDS: **Life Cycle Assessment, Mobile Hydraulic Systems, Hydraulic Oils, Biodegradability.**

1 INTRODUCTION

1.1 Background

It is estimated that approximately 400,000 tonnes of hydraulic fluids are produced in the EU annually [1]. Of this, it is estimated that 300,000 tonnes are lost due to leakage or accident. Population pressure in much of Europe means that pollution, particularly oil pollution (two pints spilled on water can cover approximately an acre of water), is increasingly important. However, this must not be allowed to overshadow other potential environmental impacts solely because it is the most visible. To date, most attention has been focused on biodegradable fluids because of the harmful effects of conventional mineral oil when it has been spilled (see, for example,[2] and [3]). In order to counteract the effects of a spill it may be argued that the hydraulic fluid ought to be changed to one that is more readily biodegradable. However, it is possible that the performance of these oils within a fluid power system and the processes involved in their production may outweigh the benefits of having a highly biodegradable fluid. The use of life cycle assessment (LCA) allows the potential environmental effects associated with the use of a hydraulic system to be examined and compared systematically over the entire life cycle of a material, product or system. This enables the true environmental impact of a system to be compared with an alternative.

1.2 The Issues Considered

Burrows et al [4] in their LCA study of mineral oil and 'hydraulic' systems found that the operation or use of forestry machinery in the field had a greater effect than its manufacture. The present work will expand on that 'baseline' study to focus on the production of both mineral and biodegradable fluids, their use within a particular hydraulic system and their disposal. One of the mobile forestry machines examined in the earlier study, a single grip harvester employed for logging (see Figure 1) is again used as a test case here. The elements of the production and processing of the different types of fluids are examined from an environmental perspective and the use and maintenance schedules of the systems with the differing fluids is assessed. This enables a whole life cycle comparison of the differing hydraulic fluids to be made. A brief overview of both types of fluid is presented before the more detailed comparison. Due to lack of adequate public domain data in some areas of the study this can not be classified as a full LCA. Areas where more data is needed are highlighted in the text, but the paper nevertheless gives a good indication of the life cycle impacts of both fluid types studied.

2 L.C.A. METHODOLOGY

Detailed state of the art methodology is described in many papers (see, for example, [5 - 9]) and was examined briefly in Burrows et al [4]. Consequently, only a brief outline of LCA methodology is given here. There are four main stages to LCA; goal scoping, inventory, impact assessment, and improvement assessment. These stages have now been broadly accepted and incorporated into the draft ISO standard series 14040. LCA aims to determine potential environmental impacts of a product or system from the "cradle to the grave" assessing impacts that arise from production, use and disposal.

The goal scoping stage is used to determine the boundaries of the study, for example, whether one ought to study the diesel engine used for powering the fluid power system. It is also used to highlight the outputs required from the study and the depth needed.

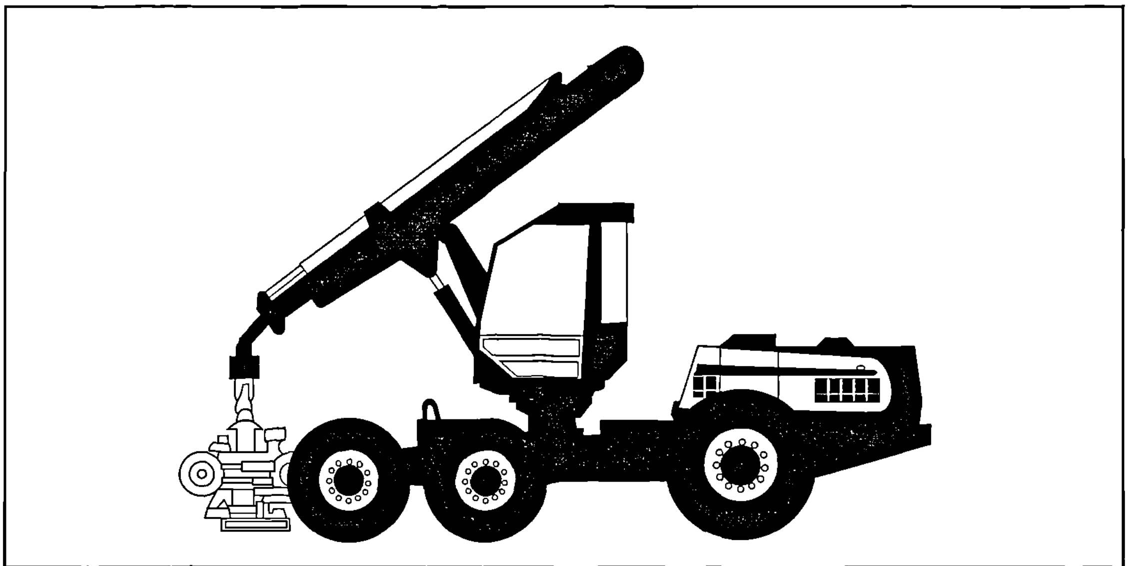

Figure 1. A Harvester

The 'inventory' is the stage in which all the data is collected. This is a time consuming process. Data is required for every stage of the process for emissions to air, water and soil, the raw material used, the energy required, and the solid waste produced. In many cases this information is either not available, or cannot even be readily estimated. In such situations best estimates ought to be made but it is imperative that this is made clear to the potential user. The data which is gathered during the inventory forms a large database which will inevitably be difficult to interpret.

The impact assessment stage of LCA is used to help with the interpretation. Environmental impacts cannot be classified as a single number, they have to be attributed to a specific known environmental consequence such as ozone depletion. The data gathered has to be attributed to pre-determined impacts which have been chosen by the LCA practitioner. This process is termed classification. All the data in each of the classes will not have the same effect. Both CO_2 and CH_4, for example, are greenhouse gases but CH_4 has a far greater effect than CO_2. Therefore, there needs to be a weighting factor applied so that the relative contribution to each category can be evaluated. Once this weighting, or characterisation, is completed then the result is a mass in kg of CO_2 equivalents for greenhouse gases and kg CFC-11 equivalent for ozone depleting gases. Data can be analysed at this stage to determine the impact of a system on each of the pre-determined categories. However, this comparison can be difficult. For example, 10kg of CO_2 equivalent will not have the same effect on global warming as 10kg of CFC-11 equivalent will have on ozone depletion. Therefore, normalisation is used. The most common method of normalisation is to compare the emissions with the average annual emissions of the country or countries in which the study is taking place. The normalised data is then used to highlight areas of potential improvement.

The notion of "people emission equivalents" has been used in the present study, following Burrows et al [4]. This can be defined as follows:-

$$\text{European emissions per capita} = \frac{\text{Total European output in each emission category}}{\text{Population of Europe}}$$

$$\therefore \text{ People emission equivalents} = \frac{\text{Emissions from process studied}}{\text{European emissions per capita}}$$

3 HYDRAULIC FLUIDS

3.1 Types of Hydraulic Fluids

There are two main types of hydraulic fluids - mineral oil and biodegradable fluids. The category of biodegradable fluids may be subdivided into synthetic esters, polyglycols and vegetable fluids (mainly rapeseed oil). Rapeseed oils, together with mineral oils are examined in the present work. Polyglycols and synthetic esters can be based on either mineral oil or vegetable oil. Polyglycols lack high biodegradability and are more toxic than synthetic esters when mixed with their additive packages. Synthetic esters, although more expensive than all other hydraulic fluids appear to have good lubricate and biodegradability characteristics. They will therefore be examined by the authors in further research.

3.2 Fluid Requirements

Traditionally, the important operational parameters for hydraulic fluids are their viscosity, wear protection, foam prevention, air release, corrosion control, thermal stability, pour point, hydrolytic stability, shear stability and seal compatibility. These are obviously still very important, but the environmental acceptability of the fluid is becoming more and more important as public awareness of environmental issues grows. The ability to perform as required along with being as environmentally benign as possible has now become an important consideration.

4 MINERAL OIL FOR MOBILE HYDRAULIC SYSTEMS

4.1 Mineral Base Oil Production

Data for the mineral oil production has been gathered by the European Centre for Plastics in the Environment [10]. This data represents the average gross inputs and outputs associated with the production of refinery products for the average European oil product. Here fifteen percent of the oil is derived from the North Sea and the remainder from other sources. It includes the extraction of the crude oil from the oil fields, transportation to the refinery, and the initial refining process. Although no specific data for the energy requirements and emissions for the production of hydraulic oils from this refined crude oil data has yet been found by the authors, data has been used for the energy requirements to produce heavy fuel oil [11] in the present studies. This is called the mineral base oil. It is of a similar weight to the lubricating oils and undergoes the same cracking process as shown in Figure 2. This means that the information available for both the rapeseed oil and the mineral oil is at a similar level of reliability. Data for the production of mineral oil cannot be so easily broken down as the data for the rapeseed oil. This is because the procedures are more complex and the data for the individual processes are not so readily available.

Data for emissions to air, water and soil as well as for energy use and solid waste from all the stages was collated and, using the SimaPro software package, the data was analysed. The software was chosen after evaluation of the main software packages. Rice et al [12] recently undertook a review of the twelve main packages available in Europe. These were assessed in terms of a range of criteria and on the basis of this comparison Rice concluded that there were only four main 'players' as environmental management tools. The present study has been undertaken using SimaPro 4 - an updated version of one of the recommended packages. This choice has no particular significance as any of the recommended tools would have been suitable.

4.2 Use

Mineral oil has been used in hydraulic systems for many years and is considered by many fluid power engineers to be the best option. It meets all the requirements for a hydraulic fluid as specified earlier. However, it is not readily biodegradable. It is for this reason that many manufactures and users have started to use more biodegradable fluids, that is rapeseed based fluids and synthetic ester based fluids.

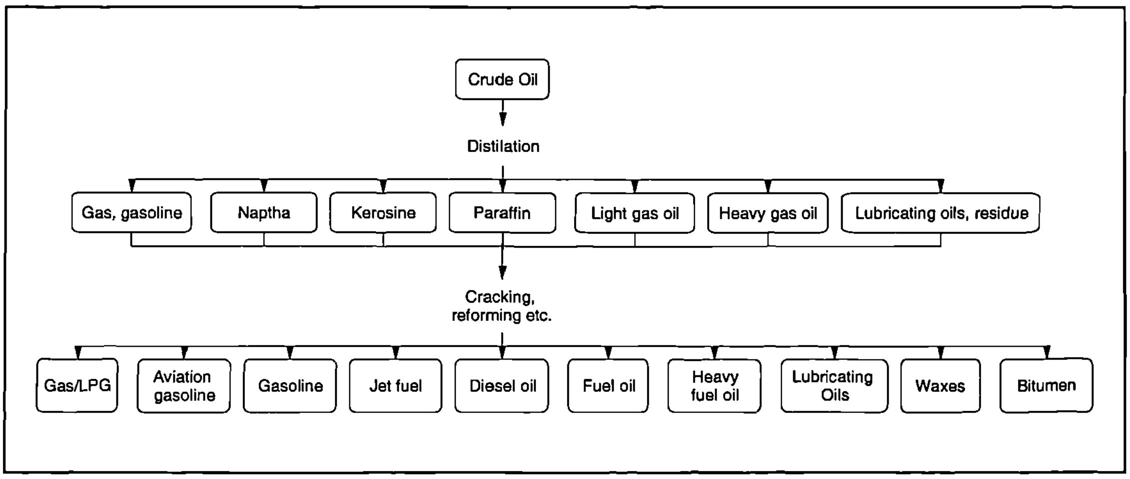

Figure 2. Mineral Oil Production. Adapted from OPEC [13]

4.3 Disposal

The most environmentally sensitive disposal method for mineral oil is to recycle or reprocess it. Hydraulic fluids are a very small percentage of the oil products sent for reprocessing and so they are mixed with all the other lubricants for reprocessing. The most common method of reprocessing is to heat the oil to 90°C and crack the water from the oil. This recycled product can then be resold as fuel oil. Exact details of this process are not precisely known. However, as it is the same process for both fluids (see Section 5.3) it will not have a differential influence in any comparison.

4.4 Spills

A spill of mineral hydraulic oil can cause environmental damage. Although many operators carry booms on their machinery for use after a spill this can only be employed when there has been a large spill. Small spills of mineral oil, if concentrated in a small area, may nevertheless have a large impact on the soil due to the lack of biodegradability of the fluid. This may have an effect on the re-growth of trees and smaller flora and may have a very large impact if spilled in a forestry area or, for example, on a golf course. Large amounts of oil spilled on water may be caught with a boom. However, if there are large amounts of a non-biodegradable fluid spilled on soil then it will seep down into the soil and the soil may consequently have to be lifted to avoid severe contamination. This can be a very expensive process.

5 RAPESEED FLUID FOR MOBILE HYDRAULIC SYSTEMS

5.1 Rapeseed Base Oil Production

The steps necessary for producing crude rapeseed are shown in Figure 3. This was compiled from data obtained from Cargill Plc [14] and Ceuterick and Spirinckx [15]. The impacts associated with the production of the farm and processing machinery has not been included within the present study as the machinery used is also used for other products. The main impacts associated with the ploughing and fertilising of fields cannot be directly attributed to crude rapeseed oil used for hydraulic purposes. The partitioning of so called 'co-products' is a significant area of difficulty in conducting accurate LCA studies. A commonly used basis for allocation between co-products is to use the mass of the different product streams. Much of the rapeseed grown on agricultural land will be used for 'vegetable' food oil, cattle feed or straw. Only 18% of the total environmental impacts associated with the processes shown in Figure 3 can be attributed to that used for rapeseed oil. Subsequently, only a very small amount of the rapeseed oil will be used as hydraulic oil. Data for the production of actual usable hydraulic oil from this base oil is not readily available. It is taken to have the same net energy requirements as the production of hydraulic oil from the base mineral oil used in this paper for comparison purpose. As more information and data is gathered the current findings will be updated.

Figure 4 shows the relative contributions the base rapeseed oil production has on the pre-determined environmental impacts. This data is for one kilogram of the oil and is normalised as described in Section 2 and shows that the most significant impact is due to energy use followed by its contribution to summer smog and acidification. In order to reduce the overall environmental effect of the base rapeseed oil production it would be necessary to reduce contributions to these areas. However, as can be seen from Figure 3 there are many stages involved with the base rapeseed oil production and so it is necessary to look at which of these give rise to the largest impacts. This disaggregation is shown in Figure 5. The main area of energy use is the actual process of crushing the oil from the dried rapeseed. Therefore, if it were possible to reduce the energy usage within the crushing process then this impact could be significantly reduced.

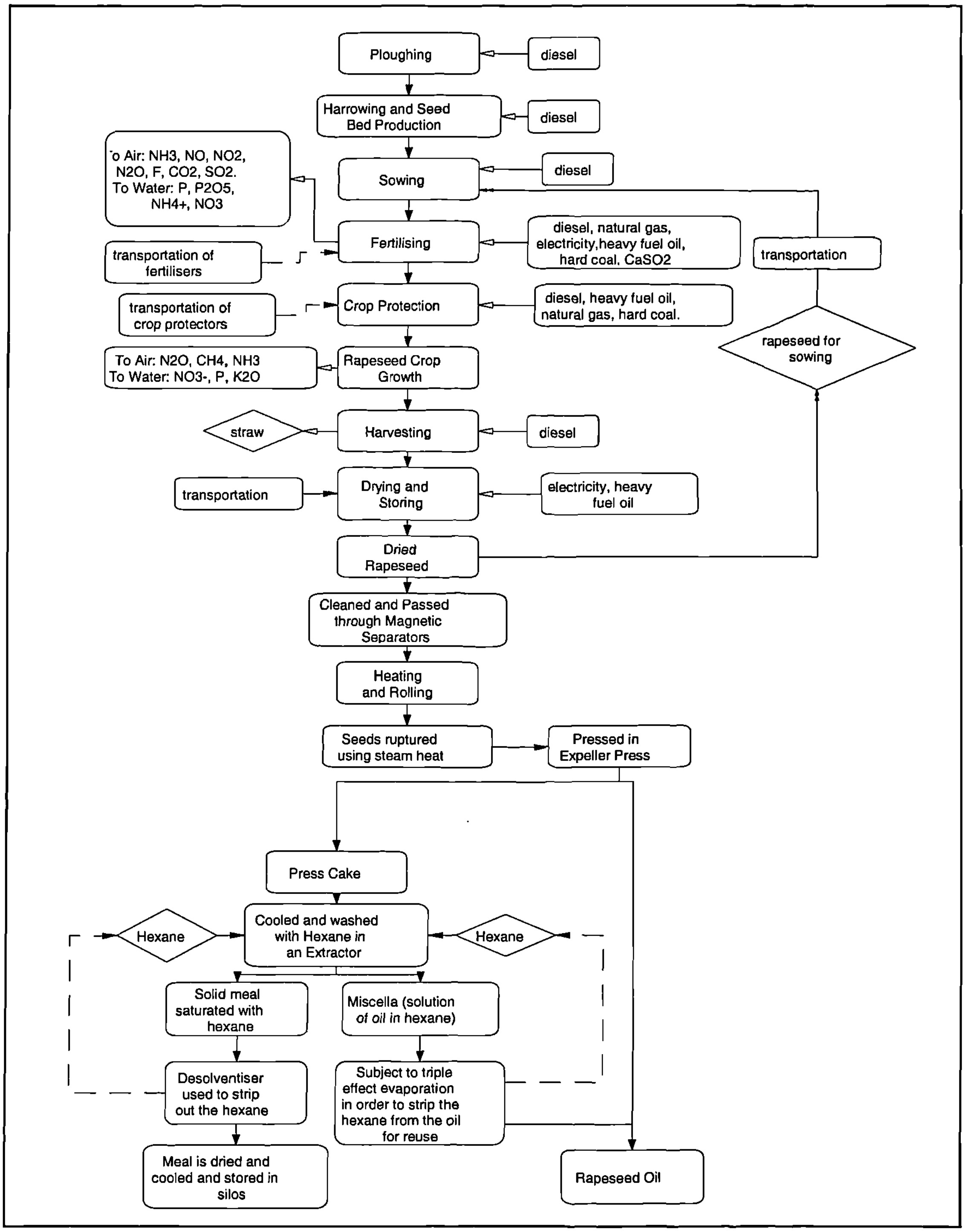

Figure 3. Rapeseed Oil Production (adapted Cargill Plc. and Ceuterick and Spirinckx [15])

5.2 Use

Vegetable oils have excellent lubrication qualities [16]. However, they have poor low temperature fluidity and exhibit rapid oxidation at high temperatures. The performance of fluids based on rapeseeds is generally considered to be inferior to that of mineral oils and it is generally thought that there is no technical benefit in using biodegradable fluids in areas other than sensitive ones [17].

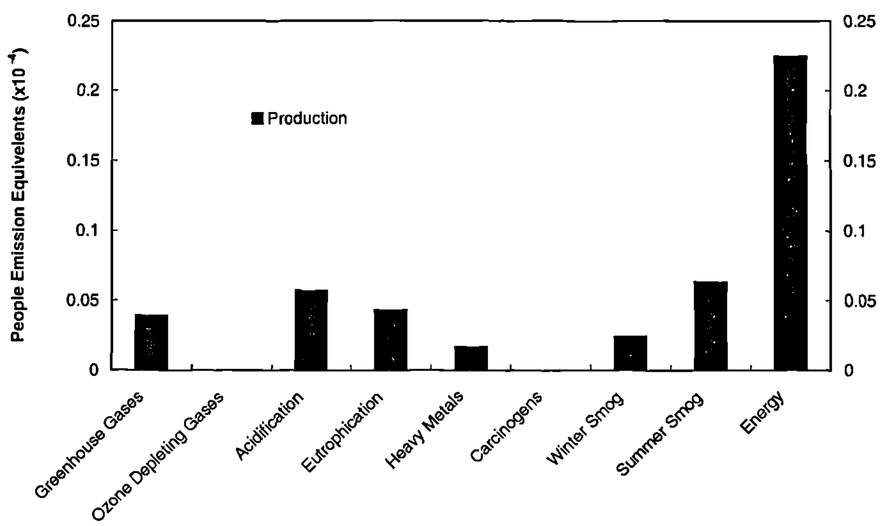

Figure 4. Normalised Data for Rapeseed Oil Production.

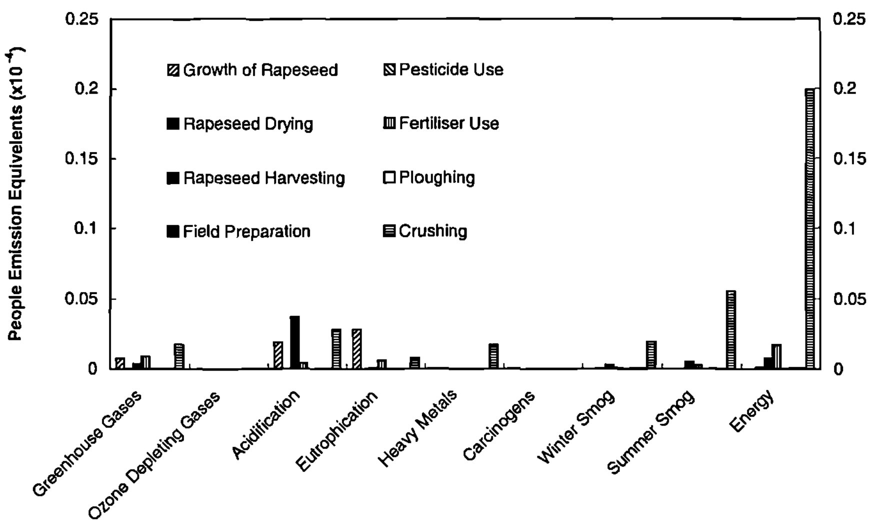

Figure 5. Detailed Normalised Data for the Base Rapeseed Oil Production

5.3 Disposal

It appears that there is currently no widely used method for the disposal of biodegradable oils separately from conventional oils. This means that when the fluid is sent for recycling it is mixed with the mineral oil and therefore any potential recycling benefits are lost. As mentioned in section 4.3 the fluids are reprocessed to form fuel oil in one of the many oil recycling or reprocessing plants. However, much of the hydraulic oil which is produced is unaccounted for, leading to the assumption that much of this is spilled [1].

5.4 Spills

Rapeseed oil is readily biodegradable. Rapeseed based hydraulic fluids are quoted as being from 70 to 100 percent biodegradable [3], [15], [18] and [19]. This obviously depends on the additive packages used with the base oil. Biodegradability is an important asset if the oil is to be used within an ecologically sensitive area where a spill could cause significant environmental damage such as within a forest or water environment.

6 COMPARISON OF THE TWO HYDRAULIC FLUIDS

6.1 Base Oil Production

A comparison between the various environmental impacts of the base oil production is shown in Figure 6. The data is shown for the production of one kilogram of base oil in both cases. This comparison does not incorporate the use or production of any additives. The impact of the rapeseed base oil production far outweighs that of the mineral oil. By far the largest difference is in terms of the energy requirements. A reduction in the energy requirements for the rapeseed oil would bring the two alternative hydraulic fluids closer in terms of life-cycle environmental impacts. However, the difference between the environmental impacts are still very large and it would take a lot of changes to procedures in order to achieve a more equal impact.

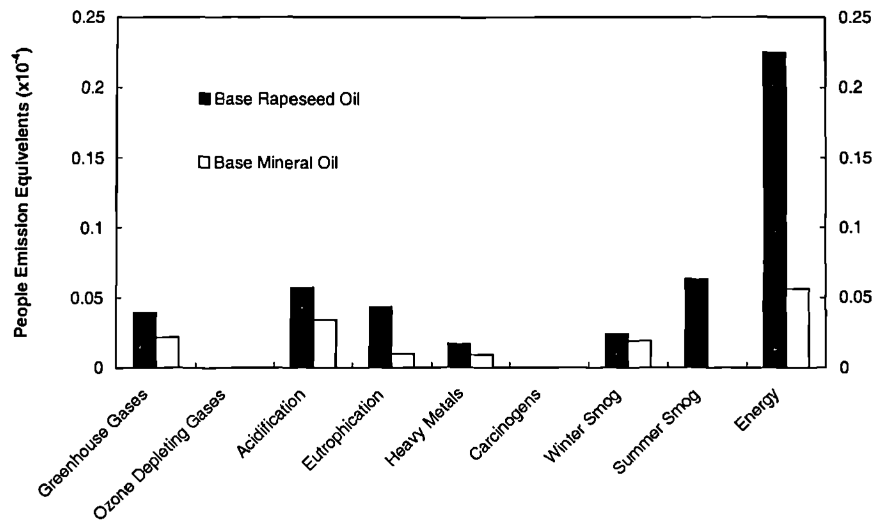

Figure 6. Normalised Comparison of the Base Oil Production.

6.2 Use

In neither case has the impact of the manufacture of the additives been taken into consideration. It is presumed that the fluids would be used with the additives and no tests are run on base fluids alone. Production of the additives is not considered here simply due to a lack of public domain data. This will be examined by the authors in further studies. It is assumed for the purpose of this study that the environmental impacts associated with the production of the additives will be similar for both base oils.

Test studies on the use of both mineral and rapeseed oil have been evaluated. Most of these studies suggest that both the fluids meet the minimum requirements for a hydraulic oil (see, for example [19 - 21]). This type of information is difficult to incorporate into an LCA. Ideally, a detailed account of the different maintenance schedules would be necessary so that the amounts of fluids used within a life time, and the repairs and replacements, could have been studied. However, this has not been possible here.

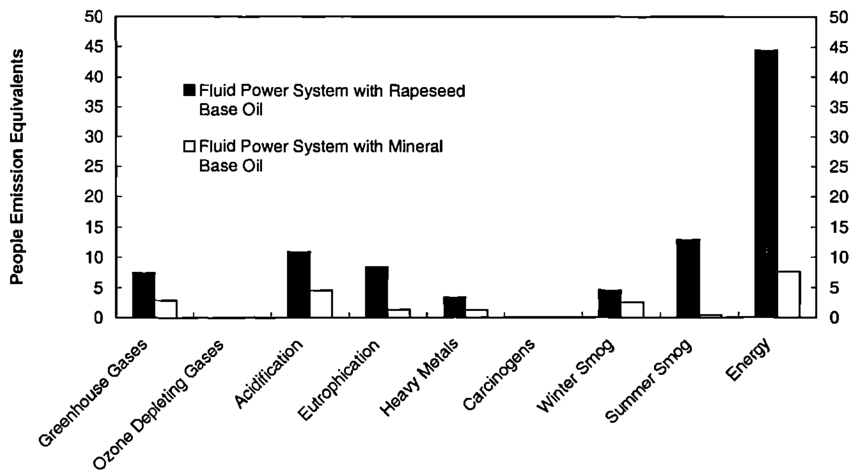

Figure 7. Normalised Comparison of the Life Cycles of a Harvester Hydraulic System Using Mineral and Rapeseed Base Oils.

A comparison of the life cycle impacts of the two alternative fluids as used in a harvester (a forestry machine used to fell trees as illustrated in Figure 1) is shown in Figure 7. The harvester is presumed to have a life of fifteen years. This shows data for the base oil and their subsequent use in the harvester. It also includes data for the manufacture and maintenance of the hydraulic system. Every component of the fluid power system using the mineral base oil is assumed to be replaced once over its life. For the system using rapeseed base oil it is presumed that all the components will be replaced one and a half times. This will obviously not necessarily be the case, but it is believed that this will give a plausible representation of the maintenance schedule. Some of the components will never need replacement whilst some will require more frequent renewal. It is also presumed that the fluid power system will use one and a half times more rapeseed based fluids than mineral based ones due to their lack of longevity. These presumptions are made on the basis that earlier studies show that although rapeseed fluid is acceptable it can have a shorter life due to the slightly higher corrosion caused by their poor oxidative stability. Again, the use of the rapeseed base oil has more of an impact on the environment that the mineral oil in every category.

A more detailed comparison of the environmental impacts resulting from the use of the two base oils and the maintenance of their fluid power systems as illustrated in Figure 8. This separates the life cycle impacts of the base oils from the life cycle impacts of the actual fluid power systems. It shows that the maintenance schedules on the systems themselves have a minimal impact. Consequently the presumption that the rapeseed oil will result in one and a half times more maintenance is not critical to the analysis in terms of the impact of the rapeseed oil. It would still far outweigh that of the mineral oil.

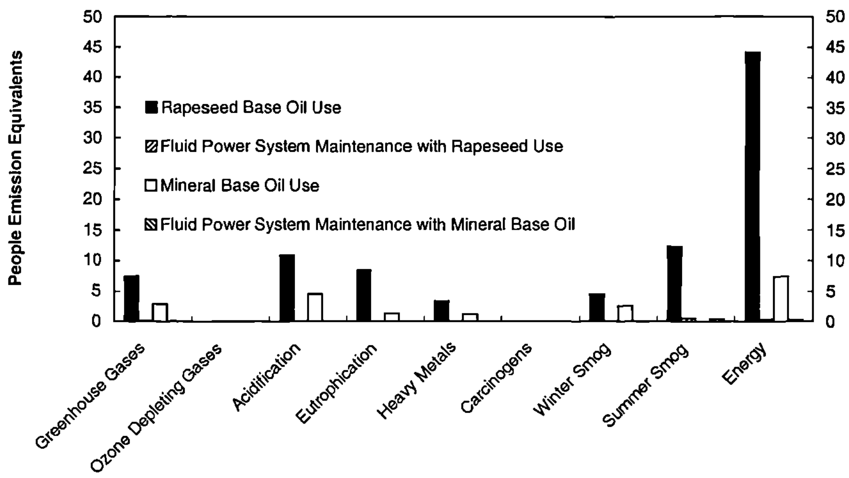

Figure 8. Detailed Normalised Comparison of the Life Cycles of a Harvester Hydraulic System Using Mineral and Rapeseed Base Oils.

6.3 Spills

Spills can and will happen with fluid power systems whether they are filled with biodegradable fluids or not. However, the effect of the spills will depend on the type of fluid, the amount of fluid and the location of the spill. If a spill occurs on or near a waterway then there is the potential for the machine user to contain much of the spill with booms. However, not all the oil will be contained via this procedure. If a small amount of the oil is left in the waterway then the impact of this would be far smaller if the fluid were biodegradable. Rapeseed oil is generally less toxic than mineral oil and will biodegrade faster. This means that the waterway will return to normal faster than if the fluid spilled was non-biodegradable. If a large spill occurs on soil then the chances of catching the oil are far smaller. If the fluid were biodegradable then the clean up operations will be far less costly than if it were not. Any large spill on vegetation will have an thermal impact, with high fluid temperatures causing vegetation to die. However, the re-growth will be far quicker with a biodegradable oil and the soil will not have to be dug up and treated. Small spills of fluid over a large area of soil will probably not have a significant environmental impact. However, if a contractor is working on the side of a hill where the groundwater and soil water - small pockets of water within the soil - will all be running into one catchment then there is the potential for accumulation from machine leaks if the fluids were non-biodegradable.

7 CONCLUDING REMARKS

It is not currently possible to incorporate local impacts into an LCA study. Therefore, it is difficult to incorporate the full significance of biodegradability into a study of this type. It has been shown that biodegradability of the fluids are very important in the case of mobile forestry machines. However, it has also been shown that the overall lifecycle impact of rapeseed fluids is far greater than that of mineral oil for all issues considered. This global and regional impact must then be balanced with the more local impact. It is felt, in this case, that although the local ecological impacts are obviously important, it is imperative that rapeseed oil is not employed for the "sake of the environment" without giving it whole life-cycle consideration.

It is worth noting that the oil used within fluid power systems, particularly in the case of rapeseed base oil, is a product of a process which produces many other products. This process would continue whether there was a market for the hydraulic oil or not. Therefore, it is doubtful whether global and regional environmental impacts would be reduced significantly if the rapeseed base oil ceased to be used within fluid power systems.

The use of synthetic esters may possibly be a better way to improve the environmental impact of hydraulic systems on both the local and global scale, particularly if they are based on mineral oil. This will be examined by the authors in future work. However, the fact that both mineral oils and synthetic esters are based on finite fossil fuels may colour our view on the regional and global impacts in future years. Genetic engineered rapeseed may eventually be grown without the use of fertilisers and crop protectors and will be designed so that the oil can be easily extracted. In these cases it is possible that the views presented here may need to be altered drastically in the longer term.

8 ACKNOWLEDGEMENTS

The work reported here was carried out by a multidisciplinary team with expertise/interests in fluid power system design and control (CRB), energy and the environment (GPH) and natural environmental science (MCM). It forms part of a major research programme funded by the UK Engineering and Physical Science Research Council to support the Engineering Design Centre for Fluid Power Systems (grant GR/L26858). The study has been greatly assisted by the provision of operational data by Sauer Sundstrand, the Environment Agency, the Forestry Commission and Cargill Plc.

The authors' names appear alphabetically.

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Life Cycle Assessment of Mobile Hydraulic Systems

M.C. McManus, G.P. Hammond & C.R. Burrows

IMechE Seminar - Environmental Impact of Fluid Power Systems
November 4th, Birdcage Walk, London.

Abstract

Life Cycle Assessment (LCA) techniques have been used in order to evaluate the environmental impact of some fluid power systems. The whole life impact of mineral and rapeseed oils are contrasted for the case of mobile forestry machinery typical of modern European design. Difficulties associated with the adoption of the LCA approach are identified including the problem of data acquisition and quality. Sensitivity analysis is employed in order to evaluate the accuracy of the computed emissions. It is shown that significant differences arise between the whole life impacts of alternative fluids and those related to their end use operation.

Introduction

Greater awareness of environmental issues and of the potential impacts that can occur from anthropocentric use of natural resources and the environment has meant that environmental management techniques are now more widely used within industry. Many of these tools focus on the direct environmental impact of an industry, a machine, or a production site. Life Cycle Assessment (LCA) is a technique that enables the environmental effects of a system or process to be examined over its entire life, not restricted within geographical boundaries, thereby giving a holistic picture, from the "cradle to the grave". Typical life cycle inputs and outputs at each process stage are shown in Figure 1.

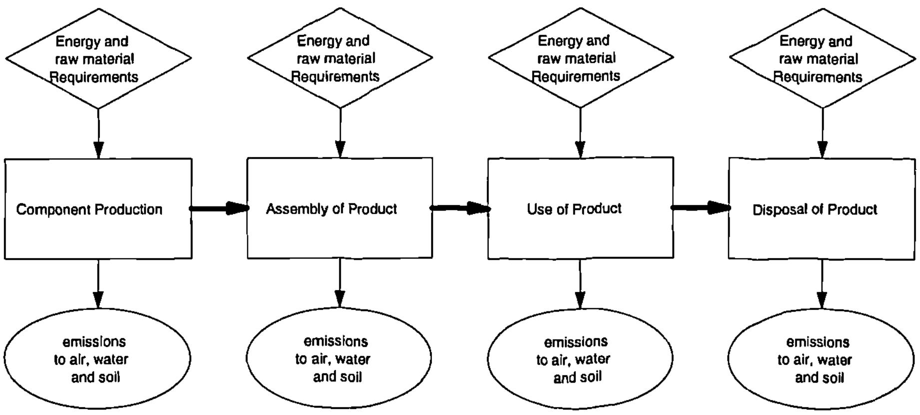

Figure 1. Inputs and Outputs considered in an LCA study. (Source, [1])

Fluid power, or "hydraulic", systems facilitate the transmission of large amounts of power or movement to areas where it is needed. Such systems have very high power to density ratio and so can be used in applications where space and weight are important considerations. Hydraulic devices are found in both mobile and static units. Static applications include those in the food processing industry, the manufacturing industry, and in docks where large loads have to be lifted and moved. In contrast, mobile machines are employed in diggers, lorries and trucks.

Mobile systems often work in "sensitive" environments, for example, near waterways (reed cutting machinery and reservoir machinery), in forests (harvesters and forwarders) and within populated urban centres (road sweepers). This means that any spill from a mobile machine has the potential to significantly effect its surrounding environment. It is popularly believed that the impact of spills within sensitive environments can be minimised if the fluid is readily biodegradable. Promotion of the biodegradable fluids has become popular as the impact of spills has been perceived as important. Consequently, some systems have been converted to use biodegradable fluids.

Systems cannot run on the different fluids without first being thoroughly cleaned out, with the possible replacement of seals and pipes. This can be expensive, although this must be compared with the potential cost of any clean-up. The demanding nature of a mobile machines task (often in harsh conditions with large temperature changes and little opportunity for maintenance) means that they are more prone to leaks and hose bursts than their static counterparts. This in turn means that the fluid placed in the machines is very important. There are three main types of fluids: mineral oil, vegetable-based biodegradable oil and synthetic ester based biodegradable oil. The present study is restricted to an examination of vegetable and mineral oil.

L.C.A. Methodology

The methodology of LCA has been outlined in many papers [e.g.,[2-4]] and so it is only briefly discussed here. The Society of Environmental Toxicology and Chemistry (SETAC) guidelines codify four main stages in the LCA process: Goal Definition, Inventory, Impact Assessment and Improvement Assessment (see Figure 2). The goal definition and inventory stages are fairly well established, but the others less so. Goal definition is the stage in which the scope of the project is outlined. Here the study boundaries are established and the environmental issues that will be considered are identified. An initial scoping study is therefore a prerequisite to a full LCA.

The inventory stage is where the bulk of the data collection is performed. This can be done via literature searches, practical data gathering or, most commonly, a combination of the two. Impact assessment is where the actual effects on the chosen environmental issues are assessed. This stage is further subdivided into three elements: classification, characterisation and valuation. The first two of these are fairly well established, although there is still ongoing research. However, the valuation stage is fairly subjective and still arouses debate in the literature. Classification is where the data in the inventory is assigned to the environmental impact categories. In each class there will be several different emission types, all of which will have differing effects in terms of the impact category in question. A characterisation step is therefore undertaken to enable these emissions to be directly compared and added together. The characterisation stage yields a list of environmental impact categories to which a single number can be allocated. These impact categories are very difficult to compare directly and so the valuation stage is employed so that their relative contributions can be weighted. This is subjective and difficult to undertake and many studies omit this stage from their assessment. Instead they employ normalisation as an intermediate step.

Improvement assessment is the final phase of an LCA in which areas for potential improvement are identified and implemented. Although this is an integral part of the function of an LCA, there have been few published studies to date that have included improvement assessments. This is principally due to problems with the completion of the preceding stages including difficulties with data collection and quality.

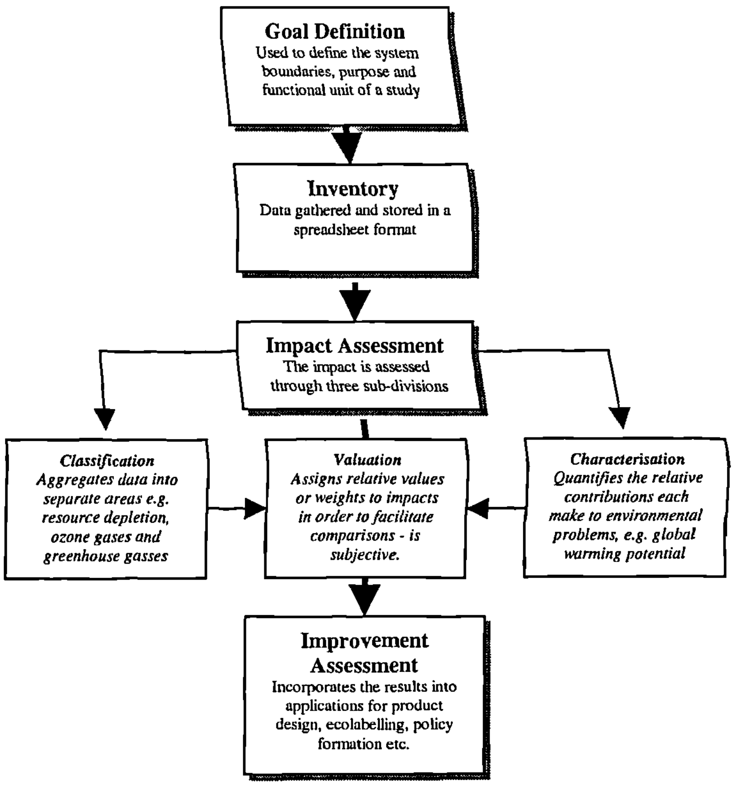

Figure 2. Schematic Representation of the Life Cycle Assessment Methodology Defined by SETAC (Source, [5])

Data has been normalised in the present study with respect to average European emissions. This can be achieved [5,6] using the notation of "people emission equivalents", which can be defined for the present purposes as follows:

$$\text{European emissions per capita} = \frac{\text{Total European output in each emission category}}{\text{Population of Europe}}$$

$$\therefore \text{People emission equivalents} = \frac{\text{Emissions from the process studied}}{\text{European emissions per capita}}$$

The main objective of LCA is to analyse the impacts of a product or system with respect to known environmental impact categories such as global warming, acidification, ozone depletion and so on. It is not possible, in practice, to analyse all known environmental problems and so it is important that the most appropriate ones are adopted for each given study. During the goal definition, or scoping, stage the relevant environmental impact categories should be outlined together with the reasons for their selection over other possible categories. Obviously, it is very bad practice to fail to include any environmental effect to which the system has, or could potentially have, an impact. It is obviously desirable that an LCA should be peer reviewed at appropriate stages. Ideally, this should involve the examination of each stage and of the data used for the study. In practice, this is often very difficult, if not impossible, to achieve. Academic studies are automatically subject to a partial peer review as part of the refereeing process that takes place prior to publication of material in scientific and technical journals or conference proceedings.

Life Cycle Assessment in a Forestry Context.

In the present study a forest "forwarder" has been examined. This is a machine which collects felled and chopped trees and moves them to the forest track or roadside ready for collection. It is shown schematically in Figure 3. The aim of the current work is to compare and contrast the environmental impact of the fluid power systems employed by a forwarder using both conventional mineral oil and rapeseed oil. In order to carry out an LCA the production of the machinery must be studied as well as the production of the fluids themselves. An outline flow chart of the resulting environmental impact is shown in Figure 4.

A literature survey on the use of the different hydraulic fluids revealed a number of relevant studies [7-24]. Contact was also made with the producers of fluid power devices (some of which run life tests using the different fluids), users of these systems and the producers of the fluids themselves. Information given about the comparative use of the fluids and their operational performance varied greatly between the different sources. It was therefore necessary to make estimates based on the opinions given, including placing uncertainty bands on the data. Over the fifteen-year life cycle of a forwarder it appears that the hydraulic systems using rapeseed fluid require replacement between one and a half and three times as frequently as those running on mineral oil. Likewise, the hydraulic components need replacing at a similar frequency. The consequences of these differing life characteristics have been assessed using sensitivity analysis. Obviously the maintenance schedules represent a simplification as some parts of the system will be changed more often and others less. However, these schedules appear to represent a realistic operating profile for a forwarder.

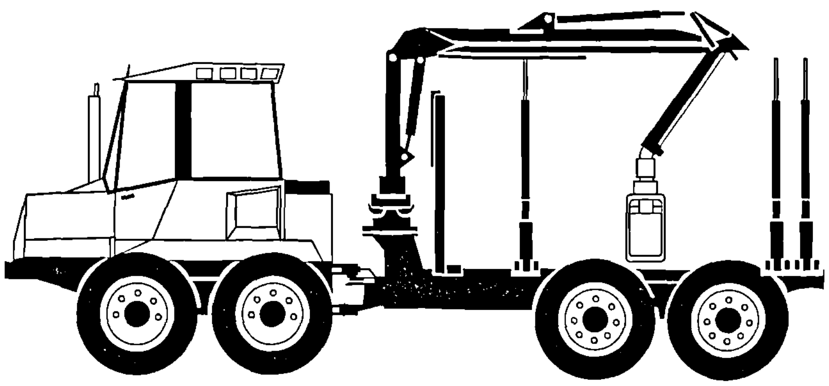

Figure 3. Diagrammatic representation of a forwarder

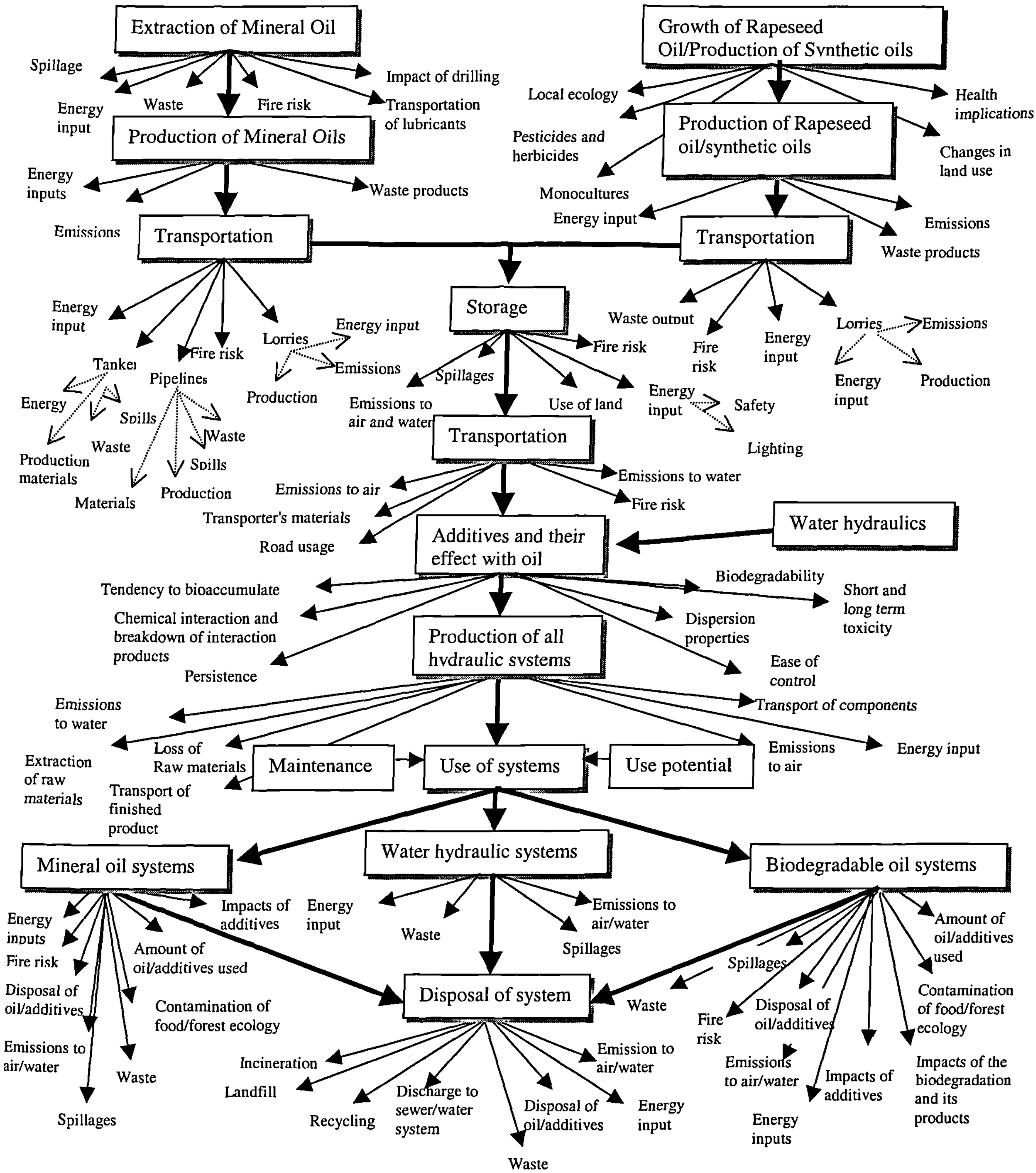

Fig.4. Outline Flowchart of Potential Environmental Impacts from Alternative Fluid Power Systems.

In order to ascertain the importance of any environmental impact associated with a fluid power system using different types of fluid it is important to examine the impacts of the parent machine or system. Table 1 shows the emissions attributed to the production of the forwarder, the hydraulic system, and the use of either mineral or rapeseed oil over the entire life. The data indicates that the use of diesel within the system far outweighs any environmental impact emanating from the rest of the machine. This suggests that any improvement in the overall energy efficiency of the forwarder will significantly reduce its life cycle impact.

	Units (Kg equivs)	Rapeseed oil use over 15 years	Mineral oil use over 15 years	Production of forwarder hydraulic system	Diesel use over 15 years	Production of the forwarder
Greenhouse Gases	CO2	4.82	2.84	0.036	676	2.02
Ozone Depleting Gases	CFC	0	0.00000125	0.0000013	0	0.000409
Acidification	SO4	6.73	4.44	0.0289	972	7.42
Eutrophication	POB	7.22	1.29	0.00628	438	0.51
Heavy metals	Pb	1.12	1.2	0.0342	0	1.74
Carcinogens	B(a)P	0	0.0000195	0.0107	0	0.65
Winter smog	SPM	1.75	2.49	0.0278	318	8.11
Summer smog	C2H4	4.61	0.000117	0.0786	929	3.54
Energy Use	MJ LHV	6.39	7.32	0.0815	726	4.04

Table 1. Normalised Data for Life Cycle Assessment (kg equivs)

A graphical representation of the data in Table 1 indicates a negligible contribution due to the production of the systems or the fluids. This is due to the relatively large impact of the diesel. The systems and fluids have consequently been examined separately and are shown in Figure 5. This indicates the effect of replacing the rapeseed oil one and a half times more frequently than mineral oil over its 15 year cycle. However, the impact of the maintenance and replacement of the hydraulic system components is not included here. For most of the environmental impacts studied, the largest contribution comes from the two fluids. However, the contribution to winter smog is dominated by the production of the forwarder. This also has a significant contribution to acidification and heavy metal use. These large impacts arise from the production of the chassis. These results will be discussed further in the Sensitivity Analysis section.

The use, and consequential environmental impact, of the two alternative hydraulic fluids are contrasted within Figure 6. Here the assumption is made that the rapeseed fluid and the associated hydraulic components are replaced one and a half times more often than when using mineral oil. It suggests that the contribution towards greenhouse gases, acidification, eutrophication and summer smog is greater for the systems using rapeseed fluids. In contrast, the effects on energy use and winter smog are greater for systems employing mineral oils. This data shows quite a substantial change from the authors' previous results which suggested the environmental impact in all categories was greater for systems using rapeseed fluids. Refinement of the original data shows that this is not the case. A more detailed breakdown for the production of the rapeseed fluid has subsequently been produced and is displayed in Figure 7.

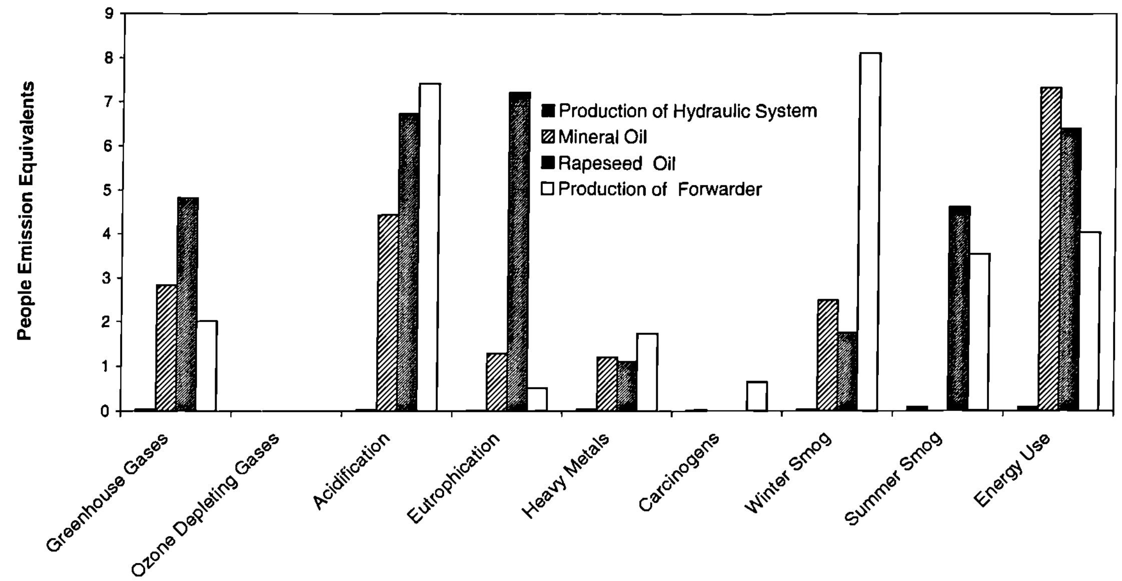

Figure 5. Normalised Comparison of the Production of the Forwarder, its Hydraulic System and the fluids on which it will run over a 15 year life cycle.

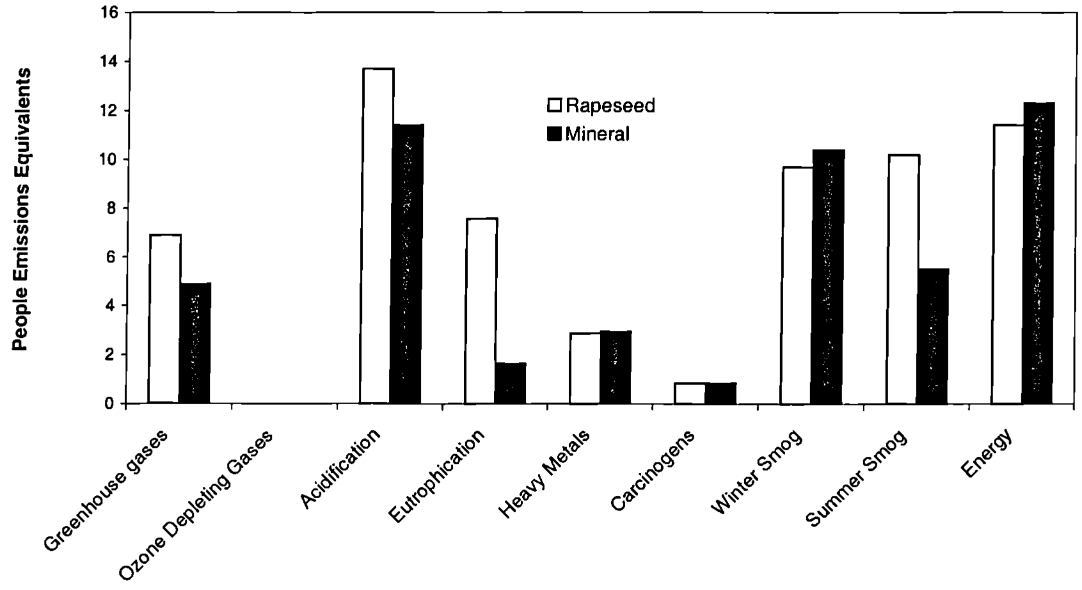

Figure 6. Comparison of a hydraulic system using mineral and rapeseed oil, including maintenance.

Figure 7 indicates that the main contribution to acidification and eutrophication, which are two of the largest areas of environmental impact, arise from the actual growth process for the rapeseed. The growth process cannot be altered without the help of techniques such as genetic modification. Its large effect is quite surprising and efforts have been made to verify the data which mainly originated from VITO [25]. It is difficult to obtain specific information about the growth of rapeseed. Every crop differs due to its variety, the soil in which it grows and the specific climatic conditions. During the growth stage nitrogen in the soil is partly converted into an

N_2O emission to the air. The N_2O emissions were calculated based on the amount of fertilisers used on the crops and used the Intergovernmental Panel on Climate Change (IPPC) N_2O emission methodology. N_2O is an important greenhouse gas and together with similar soil conversion emissions to CH_4 and NH_3 this accounts for the large impact of rapeseed growth upon greenhouse gases. The high eutrophication values are partially due to nitrates leaching from the soil. In the present study average European data for agricultural land was adopted, since no specific information for rapeseed leachate was available. It is clear that in order to improve the environmental impact of the rapeseed production attention must be focused on the lesser (in terms of environmental impact contributions), but still significant, parts of the production process. These include crop protection measures (herbicides and pesticides), the fertiliser production, growth and the crushing process.

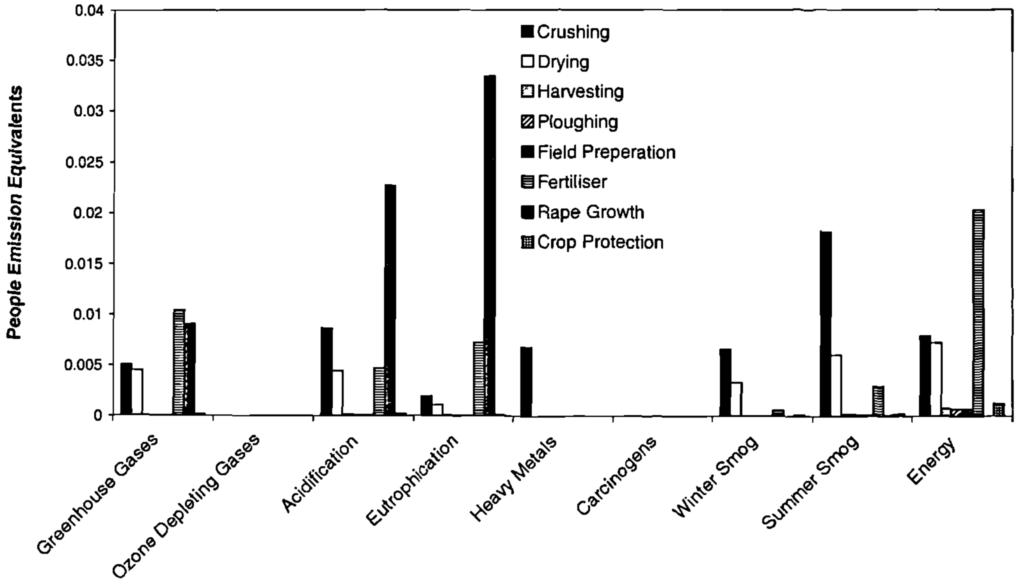

Figure 7. Detailed breakdown of the emissions due to rapeseed oil production

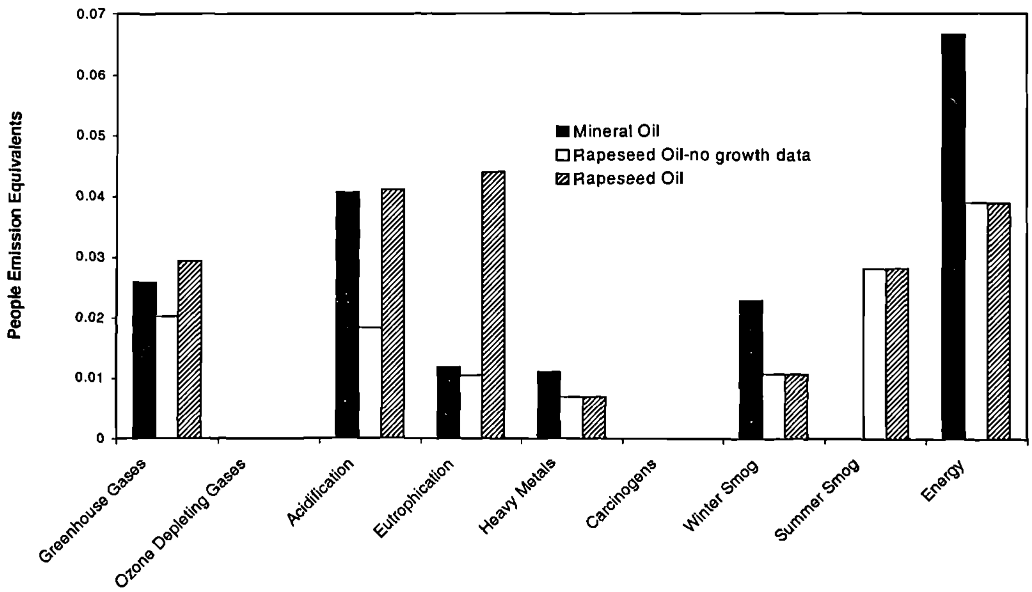

Figure 8. The Environmental Impact of the Production of Mineral Oil and of Rapeseed Oil with and without the Growth Stage

LCA enables "values of importance" to be attributed to the environmental impacts chosen in the study. However, value attribution has not been carried out in the present study. This is because it is believed that for this study no single impact has greater significance than any other. The normalised results have therefore been left for an open comparison by the reader.

Sensitivity Analysis

In view of the surprisingly large effect of rapeseed growth towards some of the environmental impact categories studied, a sensitivity study was undertaken. The rapeseed growth stage of the rapeseed oil production process mainly involves the conversion of soil components into emissions to air and water. Some of the nutrients originate from the fertiliser use on the fields. A "worst case scenario" has been adopted with the whole of the growth stage omitted to see what impact this would have on the earlier results and is shown in Figure 8.

When the growth stage is retained the impact towards greenhouse gases, acidification, eutrophication and summer smog is greater for the production of the rapeseed. The production of the mineral oil then appears to produce larger amounts of heavy metals and winter smog and higher energy use than the rapeseed oil. However, when the growth data is omitted the results change significantly and the impact to everything except summer smog is greater than for the production of mineral oil.

This data can then be incorporated into the life cycle of the machinery in order to determine the consequential whole life impact. Figure 9 depicts the use of the forwarder with both mineral oil and rapeseed oil with and without the growth data. It also shows the different effects of replacing the rapeseed oil and hydraulic components one and a half times more frequently than the mineral oil and three times as frequently as the mineral oil.

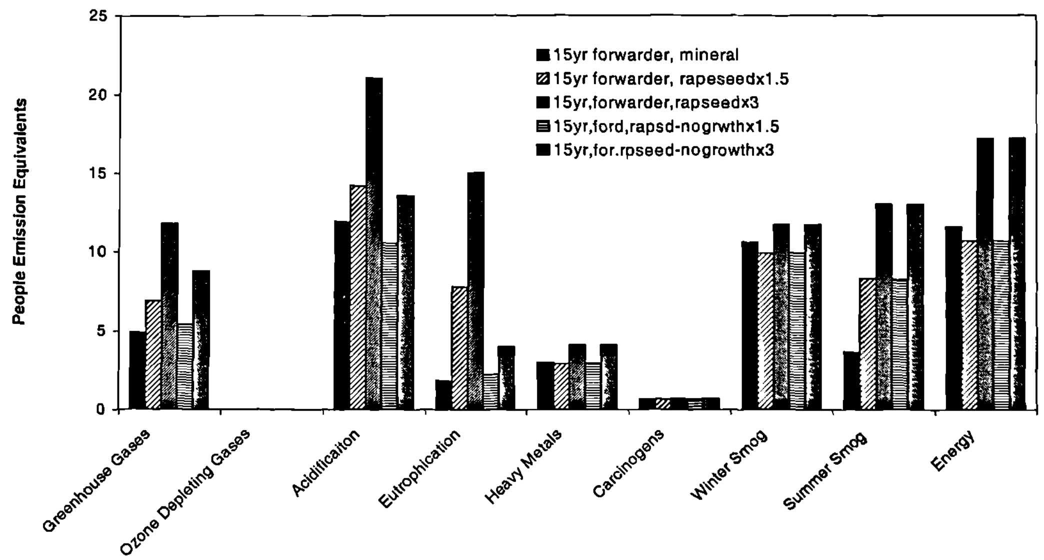

Figure 9. Comparison of the use of mineral, rapeseed and rapeseed with no growth data, within a forwarder.

It is clear that the results shown in Figure 9 are very sensitive to the growth data. The maintenance and fluid replacement schedule required is also very important. Nevertheless, it shows that for most of the scenarios, the use of rapeseed oil as a hydraulic fluid has a greater effect on the chosen environmental impact categories than does the mineral oil.

Figure 5 shows that the production of the forwarder makes a large contribution towards acidification and winter smog. This can be attributed to the production of the chassis. A sensitivity analysis for all the main components of this equipment was undertaken, although only that for the chassis is reported here. There are some components within the machinery for which very accurate data was available and during the sensitivity analysis these were held at the given value, or changed very slightly as appropriate. The total weight of the machine was known and so as the various components were altered, this value had to remain constant. The weight of the chassis itself was varied by ± 20% with the result shown in Figure 10. The chassis is a very substantial part of the machine and when its weight is reduced, the other parts of the forwarder begin to take on a more significant role. Those which originally have quite large impacts on summer smog and energy use are increased further as the weight of the chassis is decreased. Consequently the impact of the whole machine rises when the chassis weight is decreased. Contributions to greenhouse gases, eutrophication and energy use decrease whether the chassis weight is increased or decreased. This means that there is a fine balance between the impacts of all the different components. Over all, the change in the results given a 20% change in the weight of the chassis is not very significant. This was also the case for all the individual components examined.

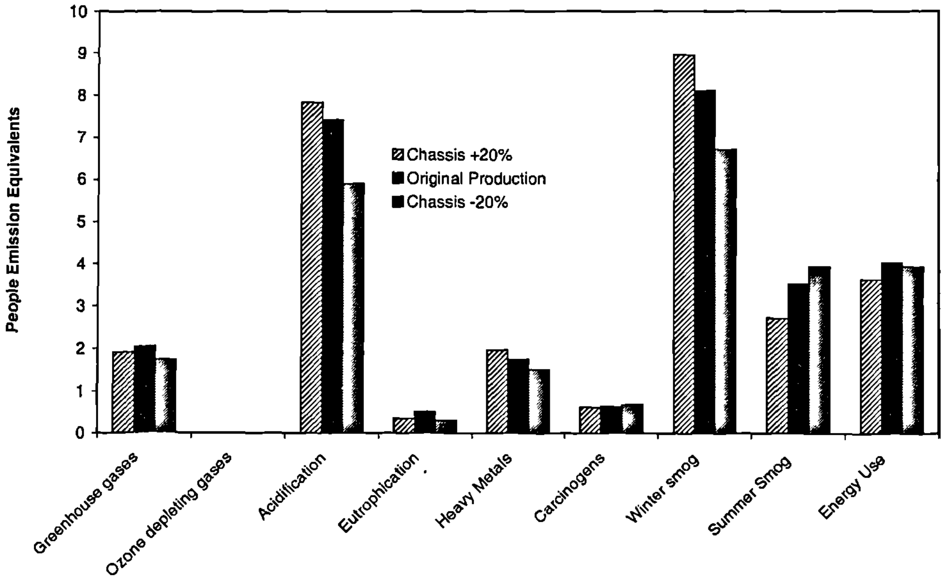

Figure 10. Sensitivity analysis results for variation in the forwarders chassis weight.

In its current form the process of gathering data for the impact assessment stage is rather cumbersome and is not practical for many industrial purposes. Better public databases will be necessary before the use of LCA will be able to grow and become a useful tool. It is possible that with the increased use of other environmental management techniques and the adoption of the ISO 14000 series standards, then companies and industries will stimulate the development of such a basic LCA database.

Local Impacts

So far all the impacts discussed have been at the regional or global level. That is the main focus of LCA as a long term tool, free of geographical boundaries. However, the main reason for industry adopting the use of biodegradable fluids is because of the perceived beneficial effects at a local level. It is important to consider this aspect.

If biodegradable fluids are spilled they will biodegrade rapidly. Hence the clean up costs and the impact on the environment will be less than if it were a spill of mineral oil. However, if a spill is in an area where recovery can be made quickly (for example, in a waterway where there are booms or bunding nearby), then recovered mineral oil can be reused. In contrast, rapeseed oil will have to be disposed of, as any contamination of rapeseed oil with water renders it useless. Biodegradable fluids will deplete oxygen levels within a river as they biodegrade. However, a similar amount of mineral oil left in a river could cause damage which would take far longer to remediate. If a spill were direct to soil the use of rapeseed fluids would result in a far quicker recovery time and may mean that the land would not have to be treated as contaminated.

Although over its entire life cycle the use of rapeseed hydraulic fluids within a hydraulic system should perhaps not be encouraged for environmental reasons, there are arguments in favour of biodegradable fluids. There are areas in which it is very beneficial to use the more biodegradable fluids and the life cycle assessment of the fluid suggests that the impact of the rapeseed is not too different from that of the mineral oil to discount the former on environmental grounds. The authors will carry out LCA's of the more popular synthetic esters so that a full comparison can be made.

Disposal/Recycling

The results reported do not constitute a full Life Cycle Assessment as the impact of the disposal of neither the fluids nor the machinery has been taken into account. In the UK both mineral and biodegradable fluids are disposed of/recycled in the same manner and so this will not make any difference to the comparison of the two systems. Similarly, the forestry machines operating on either oil are disposed of in the same manner and there will be no differential impact for the purpose of this study. This comment cannot be applied to other European countries where the use of biodegradable fluids is greater and separate disposal and recycling facilities exist.

Concluding Remarks

LCA requires a vast amount of data in order to produce a complete study. Unfortunately much of the data required is not readily available in the open literature. In the mid-nineties it was hoped that this problem would be alleviated slightly through the implementation of environmental standards such as EMAS and ISO 14001. However, frequently the data required for an LCA is far more detailed than that required for other environmental management tools. Unless a company is willing to put many person-hours of effort into the process of data acquisition it is impossible to complete a full LCA. It is for this reason that LCAs are mainly carried out within larger companies that have the resources to devote to environmental initiatives. This can mean that LCA is not a viable tool for small and medium sized companies or organisations.

LCA is a very powerful tool that can be used to obtain a more realistic picture of the effects that a product or system may have on the environment. However, as with all tools, the results can only reflect the accuracy of the available data. LCA is an extremely data-hungry tool and to gather sufficient data for an LCA is very time consuming and very difficult. Anyone undertaking an LCA must be prepared to constantly update and correct the data used. As data is such a significant issue, it is important that a sensitivity study is carried out on the results.

The paper shows that over an entire life cycle of a forwarder the use of diesel has by far the greatest environmental effect. The environmental effects of the use and production of the hydraulic system are far less significant. Therefore, any improvements to the over-all energy efficiency of the forwarder will have a large effect on the life time environmental impacts of the machine.

The hydraulic systems using mineral oil have less of a global and regional environmental impact than those using rapeseed fluids. However, the impact that the fluids may have on the local environment needs to be considered. A sensitivity analysis showed that even significant changes in the production of the forwarder had little effect on the environmental impact of it overall. However, change in the use and maintenance of the forwarder does have a significant effect on the over-all life cycle environmental impact. Also, significant changes in the data for the production of the rapeseed oil can yield large changes in the final results.

The data requirement of a Life Cycle Inventory is often extensive and the data quality often inadequate. This will only be overcome if there is a large increase in the number of LCA's undertaken and if the data used is made publicly accessible. Contradictory data from different sources also cause problems in specific cases. The data problems suggest the need for sensitivity analysis.

Although LCA is a useful tool, it is one which ought to be used with care. In sensitive environments there is still a local ecological advantage in the use of rapeseed oil over mineral oil. However, outwith such environments the use of rapeseed oil as a hydraulic fluid for environmental reasons is questionable. An extension to the research to study other biodegradable fluids will allow a fuller comparison of mineral and biodegradable fluids to be undertaken.

Acknowledgements

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LIFE CYCLE ASSESSMENT OF ALTERNATIVE HYDRAULIC FLUIDS FOR MUNICIPAL CLEANING EQUIPMENT

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Abstract

The use of biodegradable fluids in fluid power systems has become more popular as awareness of environmental issues has increased globally. Mobile machinery are prime candidates for biodegradable fluid adoption as they often work in sensitive environments. Life Cycle Assessment has been employed to determine the effects of using mineral and biodegradable fluids over the life time of municipal road sweepers. This shows that although biodegradable fluids may be beneficial, in local terms, if spilled in an environmentally sensitive area there are, nevertheless, environmental disadvantages to its utilisation when viewed over the whole life cycle.

Introduction

Life Cycle Assessment (LCA) is an environmental management tool that assesses the environmental impacts of a product or system over its entire life, from the cradle to the grave. It is a relatively new tool, the idea emerging mainly from the development of energy analysis in the 1970's following the initial "oil crisis". The overall aim of LCA is to identify opportunities for environmental improvement by detecting the parts of a product or system with the most significant environmental impacts. This improvement potential can then be examined as part of the design process and can be used to improve the overall environmental impact of a product.

LCA determines the environmental impact of a product or system over its whole life, through production, use and disposal. The impact resulting from the product can be examined with respect to known environmental effects such as global warming and acidification. SETAC [1] has established a framework for LCA comprising of four main stages; goal definition and scoping, inventory, impact assessment and improvement assessment. This is shown in Figure 1. The goal definition process is very important as part of the planning stage for an LCA study. This is where important issues such as boundary delineation and assumptions are made.

Gathering data for the inventory can be a time consuming task as many companies see such data as either confidential or simply do not have the detailed records needed for a credible whole life study. The impact assessment stage is still undergoing refinement although the concepts employed in the SETAC methodology have been largely incorporated in the draft ISO 14040 series of standards [2 - 5]. There are three main elements to this stage: classification, characterisation and valuation. Both the classification and characterisation elements were undertaken in the present study, whereas the valuation stage was only partially employed through the use of normalisation.

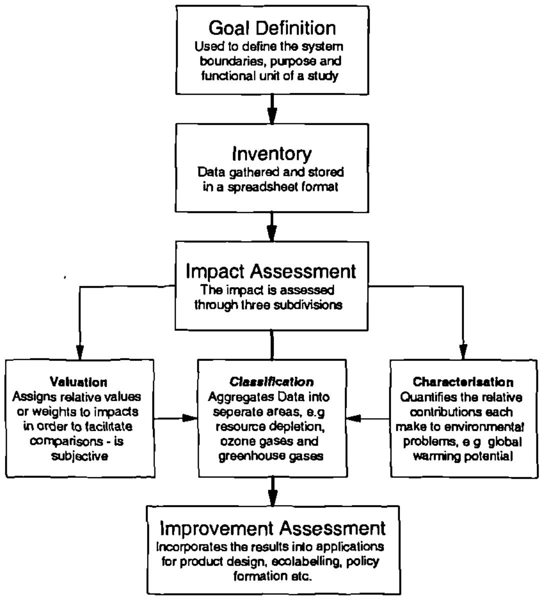

Figure 1. LCA methodology as outlined by SETAC.

The impact assessment stage of LCA aids the interpretation of the environmental impacts. Such impacts cannot be classified as a single number but have to be attributed to a specific known environmental consequence such as ozone depletion. The data gathered has therefore to be classified in terms of pre-determined impact categories chosen by the LCA practitioner. This process is termed classification. Obviously, all the data in each of the classes will not have the same effect or severity. Both carbon dioxide (CO_2) and methane (CH_4), for example, are greenhouse gases but CH_4 has a far larger global warming potential than CO_2. Consequently, there needs to be a weighting factor applied to the different emissions so that their relative contribution to each category can be evaluated. Once this weighting procedure, or characterisation, is completed then the result is a mass in kg of CO_2 equivalents for greenhouse gases, and similarly kg CFC-11 equivalent for ozone depleting gases. Data can therefore be analysed at this stage to determine the impact of a system on each of the pre-determined categories. However, this comparison can be problematic. For example, 10kg of CO_2 equivalent will not have the same effect on global warming as 10kg of CFC-11 equivalent will have on ozone depletion. In order to overcome this difficulty, a normalisation process is adopted. The most common method of normalisation is to compare the emissions with the average annual emissions of the country or countries in which the study is taking place. The normalised data is then used to highlight areas of potential improvement. In this study the following method has been used [6]:

European emissions per capita = total European output in each emission category / population of Europe

Therefore; people emission equivalents = emissions from the process studied / European emissions per capita

LCA is still very much in the development phase, both in Europe and North America. The elegant idea of tracing the life-cycle environmental impact of a product or activity quickly becomes convoluted in practice. Nevertheless, it has been greatly assisted by the use of spreadsheet programs, and several special purpose software packages have become commercially available. Rice et al [7] undertook a review of the twelve main packages available in Europe in the mid 1990's. These were assessed in terms of a range of criteria, including the volume and quantity of data, evaluation methods for impact assessment, burdens allocation, software engineering practices, and cost. On the basis of this comparison, Rice et al concluded that only four of these packages were serious 'players' as environmental management tools. The present study has been undertaken using an updated version of one of the four recommended tools: SimaPro. This choice has no particular significance, as any of the four packages recommended would have been suitable.

The database used for the inventory of the life-cycle assessment underpins the entire study. If this information is not reliable, then the credibility of the study will be greatly reduced. Data gathering for an LCA is very difficult and time consuming due to the large amount of data required and because some data may be commercially confidential. In this study typical data for the manufacture and operation (use) of the municipal machinery has been used, and this will be updated over time. The general database in the SimaPro software comes from publicly available European sources.

Road Sweepers

Road sweepers (Figure 2) are used in many towns in order to clean litter from the road sides. The sweeper described in this study is one of the larger road sweepers in which two people may sit. Dust and dirt from the road is lifted by two large brushes which are kept wet to minimise dust movement. The water is recycled through the machine, while the dirt and rubbish is sucked into the machine. Retained dirt is held in a hopper at the back of the machine and then it is emptied at the depot.

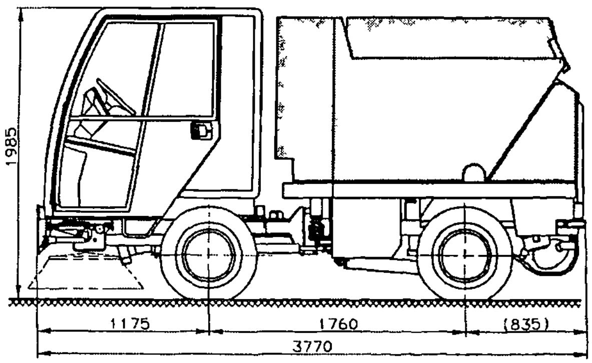

Figure 2. Schematic Illustration of Road Sweeper (of Modern European Design).

There are many types of sweeper in production. The sweeper studied here is a type manufactured in mainland Europe (principally in Germany) and shipped to the UK for distribution by a local company. An inventory of the components has been compiled and the environmental impact of the machine production has been assessed on this basis. Data for the production process was obtained from the manufacturer. Information about the specification of the road sweeper is shown in Figure 3. Once the inventory of all the components and their parent material had been compiled this was sent back to the manufacturer and the local distributor for verification (unfortunately, at time of writing, no feedback had been received).

Length	3770mm
Width	1280mm
Height	1958mm
Weight (empty)	2400kg
Payload	1600kg
Travel Speed	40km/h
Operating Speed	1 - 12km/h
Climbing Ability	30°
Engine	Low emission, 5 cylinder diesel engine.
Hydraulics	Adjustable, load-sensing controlled axial piston pump for suction fan and front attachments, gear pump for steering, auxiliary functions and side brush drive.

Figure 3. Road Sweeper Baseline Specification.

Figure 4 shows the contribution to the chosen environmental burdens resulting from the sweeper manufacture. The most significant impacts relate to carcinogens, summer smog and energy use. Production of the chassis and the main cab (in which the driver will sit) have the most significant effect in these categories. The chassis is structurally robust and heavy and so is always likely to have a fairly large environmental impact when compared with the rest of the machine. In the sweeper examined here the cab was fabricated from aluminium which is energy intensive to produce and has a very large contribution to environmental effects.

Aluminium is both light and strong and was adopted to maintain safety and strength. If an alternative metal (such as mild steel) was used for this it is likely that the overall environmental impact, particularly in regard to carcinogens, would be greatly reduced. Consequently, in order to reduce the environmental impact of sweeper fabrication the manufacturers ought to consider different structural material for the main cab. The production of the hydraulic system has only a minimal effect when compared with the rest of the machine.

Comparison of Alternative Fluids

The primary duty of a hydraulic fluid is to transfer energy. For this purpose any of the various hydraulic media would be suitable. However, there are further requirements placed on the fluid such as lubricity, the ability to work at low temperatures, and the prevention of corrosion. It was for this reason that the original water hydraulics, historically used in stationary applications, were replaced by a mineral oil with suitable additives. The use of mineral oil was commonplace over many years and would probably still be accepted had the oil stayed in the hydraulic system. However, fluid power systems are prone to leaks and once the oil has leaked there are disadvantages of the mineral oil and additive package. Such fluids are highly flammable and only minimally biodegradable. Consequently some users of mobile machines

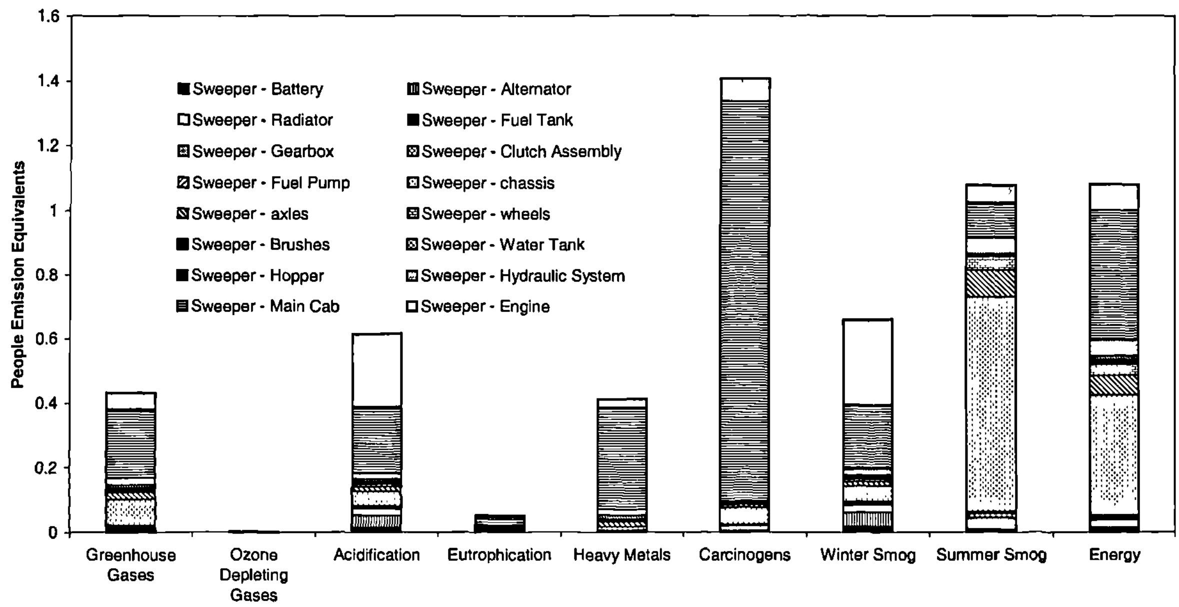

Figure 4. Normalised Environmental Comparison of Road Sweeper Manufacture

have begun to think about alternatives to the conventional mineral oil. Water hydraulics, albeit with additives, are being reconsidered for some (mainly stationary) applications while biodegradable fluids (based on either vegetable oils, e.g. rapeseed, or synthetic esters) are an attractive option for ecologically sensitive applications.

Hydraulic installations are generally optimised for use with mineral oil. Unfortunately, biodegradable fluids are not often compatible with all the components of a hydraulic system and so devices running on the biodegradable fluids often need to be specially modified. This,

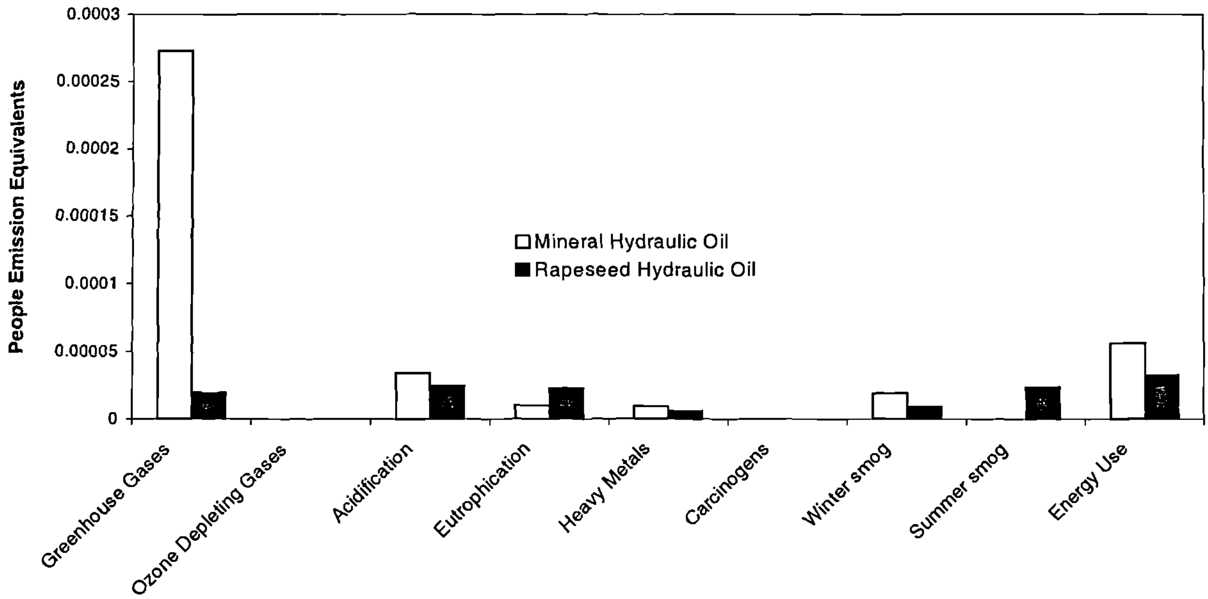

Figure 5. Environmental Comparison of the Hydraulic Fluid Production (mineral and rapeseed)

together with the higher monetary cost of the fluids means that the biodegradable fluid systems may be more expensive than those running on conventional mineral oil. It is for this reason that biodegradable fluids, in the UK, have only been commercially attractive for hydraulic systems operating in sensitive environments. Other countries in Northern Europe, particularly Germany and Scandinavia, have adopted a greater use of biodegradable fluids. These countries have generally displayed greater concern for environmental issues than the UK population.

It is generally accepted that in most cases a spill of biodegradable fluid will have less environmental impact on a local scale environment than a spill of mineral oil. In general, the biodegradable oils have also been formulated to be less toxic than the mineral oil although this need not always be the case.

Biodegradable fluids biodegrade more quickly than mineral oil - mineral oil will biodegrade, but over a longer period of time. However, spillage is not the only problem and there are also environmental impacts associated with the production, use and disposal of the fluids over their whole life, which are unrelated to spills of the fluid. These environmental impacts have been examined in the present study using LCA.

In the UK there are few, if any, sweepers that use biodegradable fluids. Nevertheless, the environment in which sweepers work is a sensitive one. If there is a spill of oil onto a road it will run quickly into the storm water drains. As these are designed primarily for diverting rainwater off the roads they often do not have much, or any, filtration. Therefore a spill may quickly find its way into nearby streams or rivers. For this reason the type of oil used in a system can be important. The adoption of biodegradable fluids has become more common in other industries, for example, the forestry industry. Consequently it was thought prudent to examine the potential effects that the use of both types of oil may have on municipal machinery and the environment in which they work. In present work the use of rapeseed based oil has been examined, although synthetic esters are more commonly used and their environmental impact will be evaluated in further LCA studies.

Mineral oil is a non-renewable resource and this, together with its lack of rapid biodegradability, is the main reason for examining the production and use of alternatives. In order to meet greenhouse gas emission legislation many countries are looking into the use of renewable fuels. It is often argued that the growth of a crop such as rapeseed is CO_2 neutral, as the CO_2 emitted from the plants when they decompose or are burnt is taken up again during the growth of the next crop. However, although this is true there is also a net CO_2 loss in the soil when land is turned over for cultivation. This releases more carbon dioxide into the atmosphere for the period the crop is growing until after the land is returned to its original state. For the purpose of this study it is assumed that the rapeseed oil is a simple CO_2 neutral product.

The disposal of mineral oil releases "new" carbon dioxide into the atmosphere, i.e. carbon dioxide that was not present in the current carbon cycle. This CO_2 is in fact ancient CO_2 which was trapped in soil and vegetation millions of years ago. All of the CO_2 emitted from the disposal of mineral oil is therefore "non natural" in terms of the current natural environmental cycle. However, the mineral oil used in the hydraulic systems is often recycled and re-used. It is therefore inappropriate to allocate all the CO_2 emissions from the disposal of the oil to the hydraulic oil. By re-using the oil the use of "new" oil is being negated. Unfortunately, there are no separate disposal or recycling methods for biodegradable and mineral oils currently employed in the UK. They are simply "bundled" in with conventional mineral oil disposal. If, in the future, there is a differential recycling regime for the two oils then the issue of separate emission allocation will have to be considered carefully.

Figure 5 shows the contrasting environmental impacts from the production of the mineral and rapeseed oil. It shows, subject to the assumptions stated above, that overall, the environmental impact of the production of mineral oil is greater than that of rapeseed oil. However, in the specific case of eutrophication and summer smog the production of rapeseed oil has a greater environmental impact. The large effect that the mineral oil has in terms of greenhouse gases is because of the associated release of carbon dioxide into the atmosphere as previously discussed. For all the other environmental categories the mineral oil is more benign, but it still has a greater over-all environmental effect compared with the rapeseed oil.

Maintenance of the Hydraulic System

It is recommended that the hydraulic fluid is changed at least every two years for the sweeper studied. Hydraulic fluid levels must be examined every fifty hours and hydraulic filters inspected every two hundred hours. The sweepers typically operate five days a week for six hours per day. The machine life for the local authorities is about four years after which they are sold on to other countries or for scrap. On average each machine has just over one hose burst in its four year life. Pumps and motors do not often fail on these systems, but there is sometimes a problem with the actuators leading to small leaks of the hydraulic fluid. This is due to the intense pressure to which they are subjected.

Performance of the Sweeper

Hydraulic systems are sensitive to the fluids on which they run. All modern systems have been specifically designed for use with mineral oil and although there is an increase in the use of biodegradable oils there are a number of changes that need to be made in order for a system to operate on rapeseed fluid. Biodegradable oils can be more aggressive towards seals, hoses and pipes. This necessitates different material requirements in production of machines to run on biodegradable fluids. Such fluids can also be more aggressive to the complete hydraulic system. Whole life testing in laboratories has shown that many components wear faster when a system is run on rapeseed oil [8]. Operating experience suggests that the fluids themselves also need replacing more frequently than mineral oils. Consequently more rapeseed oil is needed over the lifetime of the machine and the hydraulic components require replacement more frequently. However, these performance characteristics are viewed as controversial and some [9] say that the rapeseed oil will perform as well as a mineral oil. As the oil type and its performance is a very important part of the LCA the assumptions made about the performance of the fluids in each study must be clearly stated.

In the present work a range of assumptions about the life performance of the rapeseed oil were used. Although life testing in the laboratories [8] show that rapeseed does not perform as well as mineral oil it has been suggested by some researchers [9] that rapeseed oil and mineral oil perform very similarly. As the adoption of biodegradable fluids, at least in the UK, has been only a

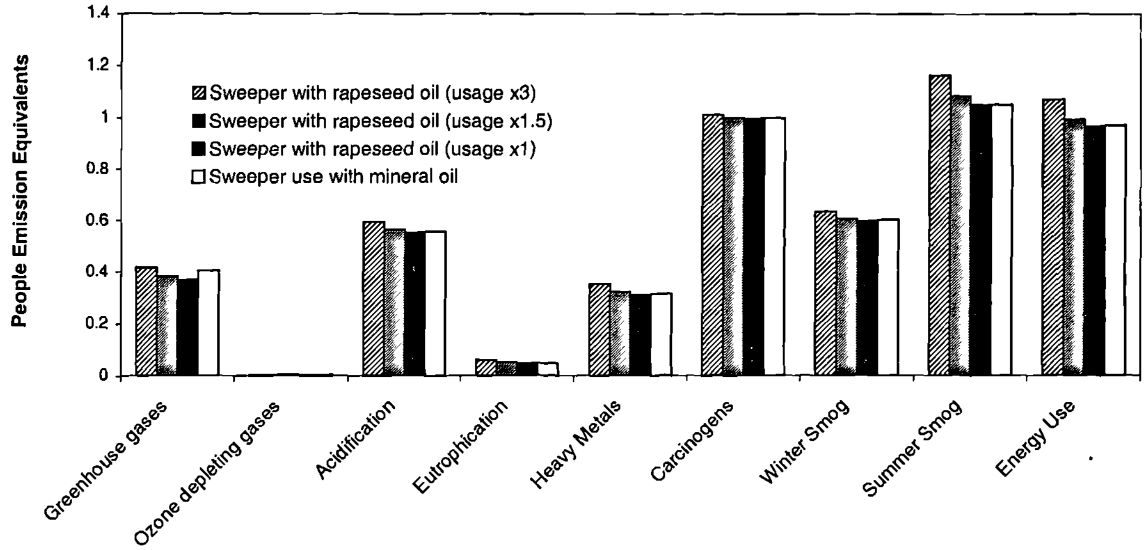

Figure 6. Environmental Comparison of Road Sweeper Operation (with mineral and rapeseed oils)

relatively new development it is likely that it will be some years before field trials and experience can determine how these fluids really perform in practice. The present authors believe that rapeseed oil does not perform as well as mineral oil due to its poorer oxidative qualities, its likelihood to cause extra wear in a system and its apparent shorter life span. However, a range of different life performances for the rapeseed oil have been adopted for comparative purposes.

Figure 6 shows the environmental impact of the production of the road sweeper and its use with both mineral and rapeseed hydraulic oil over four years. It also shows the environmental impacts if the rapeseed oil (and the corresponding hydraulic components) had to be replaced one and a half times and three times as often as the mineral oil respectively. Equal usage of mineral and rapeseed oil induces environmental impacts that are about equal. The contribution to greenhouse gases is marginally larger for the system based on mineral oil and the contribution to eutrophication is very slightly greater for the system run on rapeseed oil. If the rapeseed is replaced one and a half times as often as the mineral oil then the environmental impacts are greater for the rapeseed oil for every category except the contribution to greenhouse gases. Should the rapeseed oil be replaced three times as often then the impacts of running the system on rapeseed oil are higher in every category.

The use of LCA therefore shows that over the life of the hydraulic system the rapeseed oil based system has a slightly larger (negative) environmental impact than the system run on mineral oil. The "environmentally friendly" rapeseed fluid does not perform so well when the whole life of the system is considered. However, the reason for adopting this because it has good biodegradable properties and the local impacts a spill of the oil will be lower. The LCA methodology cannot yet account for local impacts and this has been neglected in this present study. It is hoped that with future research and refinement local impacts could be incorporated into the LCA methodology, recognising that potential local impacts are the main reason for the use of biodegradable fluids. Nevertheless, the present results indicate that unless there is a significant risk of a local impact it is not worth while, on environmental grounds, to adopt rapeseed fluids in hydraulic systems in preference to mineral oil.

For most of the environmental impact categories studied the differences between the environmental impact of the systems run on the different fluids is not very large. This differs from the authors' previous case study on forestry machinery [6 & 10]. The reason for this is that sweepers use comparatively little hydraulic fluid and the operational life of the machinery is quite short. Consequently, the impact of machine construction of the takes on a greater importance. Figure 7 shows a comparison between the manufacture of the sweeper, the production of the hydraulic system and the production of enough mineral and rapeseed oil to run the sweeper over its notional four year life (this presumes that the same amount of rapeseed oil is consumed as mineral oil). This illustrates that the manufacture of the road sweeper has by far the largest environmental effect. In most impact categories this is followed by the production of the hydraulic system. The production of the two fluids has a fairly insignificant impact overall. This accounts for the relatively small change in environmental impacts when comparing the sweeper running on the two different hydraulic fluids.

sweepers themselves are typically sold on to countries in East Africa if the machines are in working order or are sold for reconditioning and scrap.

The oils will be recycled as lower grade fluids or burnt in an incinerator [11]. There is no difference in the disposal of machines running on mineral or rapeseed fluids and so there will be no difference in the comparative results given here.

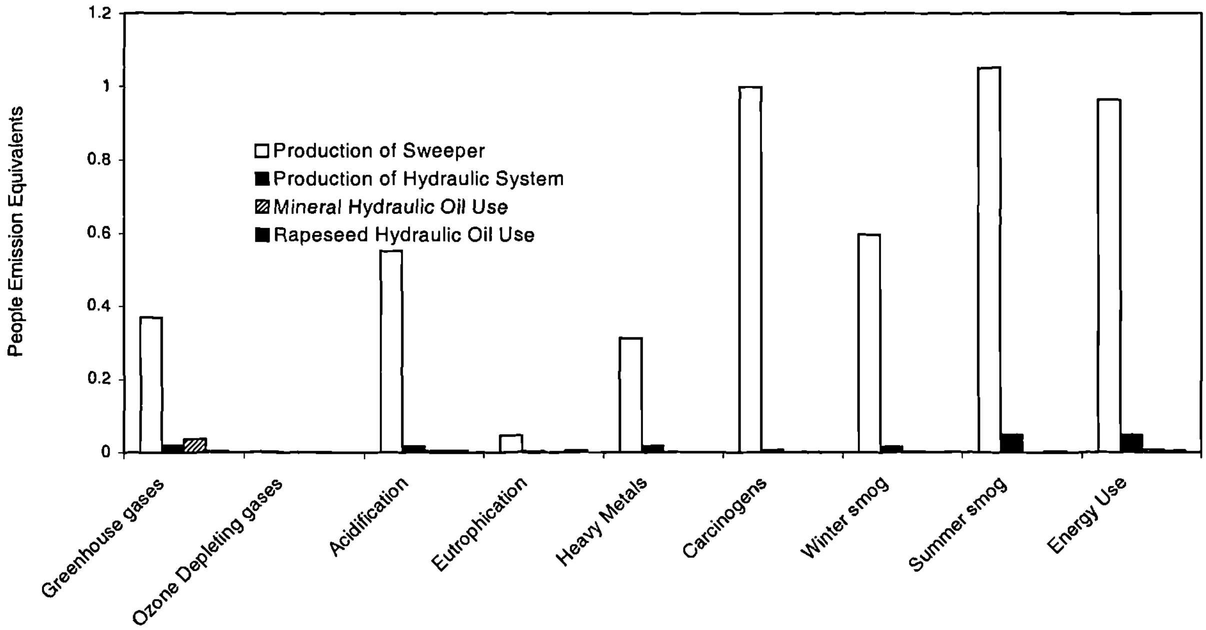

Figure 7. Road Sweeper Whole Life Environmental Impacts

In order to reduce the total environmental impact of the sweeper it would obviously be beneficial to concentrate on design improvement to the machine components and manufacture. As previously discussed, the chassis fabrication process and the aluminium cab are the main contributors to its environmental impact. Nevertheless, it should be borne in mind that the use of diesel in the road sweeper engine would far outweigh any of the impacts examined here.

Disposal

In the UK at the moment there is no separate mechanism for the disposal of mineral and biodegradable fluids. Most of the fluids are recycled as lower grade fuel oils or are burnt in the road building industry. In the present study the disposal of the machinery and the oils have not therefore been taken into account. In this respect it is not a full LCA. Likewise, the

Concluding Remarks

Although there is little or no use of biodegradable fluids in road sweepers in the UK there is a significant potential for their adoption due to the environment in which they work. The use of biodegradable fluids in fluid power systems has increased significantly over recent years as people become more environmentally aware. Their take up is currently much greater in mainland Europe than in the UK. It is likely that the UK will follow this as part of a general move towards lower impact lifestyles or European Union regulations. It has been shown that this trend in the use of rapeseed hydraulic oil may be counter productive in overall environmental terms. The whole life impact of hydraulic systems employing rapeseed oil is greater than those with conventional mineral oil.

The production of the rapeseed fluid has a lower environmental impact than the production of the mineral oil. However, it is their relative use in the hydraulic system that increases the overall environmental impact of systems running on rapeseed fluids. If these fluids could be improved so that their life performance was comparable to the current generation of conventional mineral oil then the use of rapeseed as a hydraulic fluid would be more beneficial.

The production of the sweeper, and in particular its cab, has a large environmental impact. Although aluminium has the advantage of being strong and light weight it is a very energy intensive material and it does have a very large environmental impact. It is possible that alternative materials could be found for the cab construction and this might reduce the impact of the system significantly. Nevertheless, it should be borne in mind that the use of diesel in the engine will far outweigh any of the impacts discussed in this paper.

LCA is a very data hungry process. All the data used in this study is publicly available. However, much of the data is based on best estimates and cannot be considered definitive. A complete data set for all components and processes is, at present, impossible to obtain. Any LCA ought to be continually updated over time and the present work should therefore be regarded as an initial or a "baseline" study.

Acknowledgements

The work reported here was carried out by a multidisciplinary team, with expertise/interests in fluid power system design and control (CRB), energy and the environment (GPH), and natural environmental science (MCM). It forms part of a major research programme funded by the UK Engineering and Physical Sciences Research Council to support the Engineering Design Centre for Fluid Power Systems at Bath (grant GR/L26858). This study has been greatly assisted by the provision of operational data by the Bath and North East Somerset Council and by Jack Allen.

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Life Cycle Assessment, Data Quality and Sensitivity Analysis:
The Case of Mobile Fluid Power Systems

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Abstract

Life Cycle Assessment (LCA) is quickly becoming a popular environmental management tool. However, data acquisition and data quality does not appear to be improving with the same rapidity. Studies are often based on out of date data and do not always have a comprehensive data set from which to work. This paper illustrates how sensitive the final results in an LCA can be to variation in the input data, the assumptions made within a study, and the methodology used in the Life Cycle Impact Assessment (LCIA) stage of the study. Although experienced LCA practitioners are aware of this, it is questionable whether the "lay reader" is aware of how dependent the final results are on these uncertainties. This implies the need for clarity in reporting the findings with the assumptions, the system boundaries, data acquisition, and the LCIA method adopted clearly set out. It is also desirable to undertake a sensitivity analysis in order to evaluate the influence of uncertainty.

Introduction

Life Cycle Assessment (LCA) is an environmental management tool that assesses the environmental impacts of a product or system over its entire life, from the cradle to the grave. The impact resulting from the product can be examined with respect to known environmental effects such as global warming and acidification. The overall aim of LCA is to identify opportunities for environmental improvement by detecting the parts of a product or system with the most significant environmental impacts. This improvement potential can then be examined as part of the design process and can be used to improve the overall environmental impact of a product.

The Society of Environmental Toxicology and Chemistry (SETAC) established a framework for LCA in the mid 1990's. This methodology has been widely accepted and comprises four main stages: goal definition and scoping, inventory, impact assessment and improvement assessment. Goal scoping is important as a planning stage of the LCA and the inventory is a time consuming process during which all the data is collected. Impact assessment is a complex stage which is further broken up into classification, characterisation and valuation. Classification assigns the data collected into the environmental impact categories chosen for the study and characterisation determines the relative contribution each of the inputs will make towards the chosen category. Valuation then assigns a value to these to determine their relative importance and this is a fairly controversial stage. The final stage in the SETAC methodology is the improvement assessment which is where the results are analysed in order to determine where improvements can be made to both the LCA and also to the product or system that is being studied.

The use of Life Cycle Assessment (LCA) has become more widespread in recent years. Despite this there are still significant problems in obtaining sufficient, good quality, data for studies. Some reports underplay these difficulties and so non-practitioners may view LCA with a false sense of precision and certainty. In reality this environmental management tool is complex: final results can be sensitive to relatively small changes in input data arising from either material type or numerical uncertainties. The findings can also be sensitive to changes in the Life Cycle Impact Assessment (LCIA) methodology. These issues are highlighted here using two case studies related to fluid power systems: forestry machinery and road sweepers.

An outline of the case studies and their importance is presented below, followed by a description of the LCA results. Finally, the issues concerning data quality and sensitivity analysis are discussed.

There are many software packages available for LCA and in the mid 1990's Rice et al (1997) undertook a review of the twelve main packages available in Europe. These were assessed in terms of the volume and quantity of data, evaluation methods for impact assessment, burdens allocation, software engineering practices, and cost. On the basis of this comparison, Rice et al concluded that only four of these packages were serious 'players' as environmental management tools. The present study has been undertaken using an updated version of one of the four recommended tools: namely, SimaPro, a commercially available package. This choice has no particular significance, as any of the four packages recommended would have been suitable.

Mobile Fluid Power Systems

The purpose of fluid power systems, commonly termed "hydraulic systems", is the transfer of energy. Hydraulic systems are preferred in a number of applications because they have a good power to weight ratio. Examples of fluid power applications include "diggers", the lifting components of refuse trucks, rides in fairgrounds, and aircraft. In the present study the environmental impact of fluid power systems used in forestry machinery and road sweepers has been examined. These are both mobile applications which means that the hydraulic systems are often put under greater mechanical stress than if they were in static applications. Fluid power systems are theoretically closed (or sealed) systems and, on the whole, run with mineral oil as their working fluid. However, the systems are often prone to leaks and spills in practice.

The environment in which a mobile system may find itself can vary greatly. Forestry machines often operate near waterways which are particularly sensitive to ecological damage. In contrast, road sweepers work in an "un-natural" environment where oil can be flushed away very quickly to a storm water run-off system. This contaminated water is not always treated before it is discharged into rivers, lakes or seas. Therefore, the potential environmental impact of spills from these systems can be quite large. Consequently, many firms in Northern Europe (particularly Germany and the Scandinavian countries) have started to use biodegradable fluids in mobile hydraulic systems. The authors have therefore examined the whole life impact of this change (see (Burrows et al., 1998 & 1999) and (McManus et al., 1999 & 2000)). The environmental impacts emanating from the production of the machinery and the alternative hydraulic fluids were examined together with

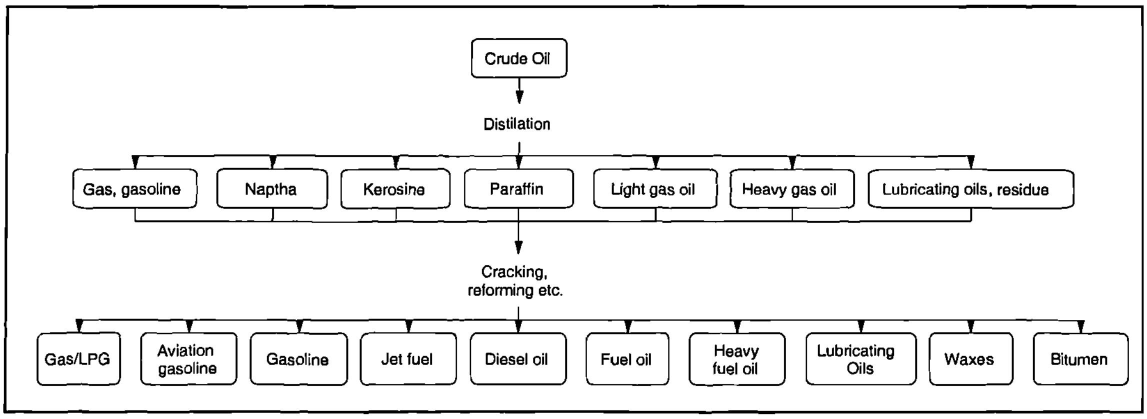

Figure 1. Mineral Oil Production.

various performance and maintenance schedules and disposal strategies for the fluids. The forestry machine has an average life of fifteen years, whilst a road sweeper runs for approximately four years before being sold for parts or to developing countries.

Alternative Hydraulic Oils

The fluids examined in the present study were conventional mineral oil and rapeseed-based oil. Many mobile machines requiring fluids that rapidly biodegrade use synthetic esters. Data for the production of synthetic esters are very hard to obtain but the researchers intend to extend the research to consider these in the future. Figure 1 shows the main stages involved in the production of conventional mineral oil. Data for this was taken from the Association of Plastics Manufacturers in Europe/European Centre for Plastics in the Environment (Boustead, 1993) and from the SimaPro 4 software used in the study. The main stages (based on data from Ceuterick & Spirinckx (1997) and Cargill Plc.) in the production of rapeseed oil is illustrated in Figure 2.

A comparison of the environmental impact attributable to the production of each of the two fluids is depicted in Figure 3. Overall, there is a greater environmental impact resulting from the production of mineral oil, particularly in relation to global warming. This is because mineral oil is not a renewable source (see (M^{c}Manus et al., 2000) for further discussion of this issue). However, it can be seen that for eutrophication and summer smog the production of the rapeseed oil has a higher environmental impact than the more conventional fluid.

Mineral and biodegradable fluids do not have the same engineering or physical properties when used in fluid power systems (Natscher, 1991). Tests have shown that rapeseed oil needs to be replaced more frequently than mineral oil. Rapeseed oil also causes more wear within a system and so certain hydraulic components need more frequent replacement when rapeseed oil is used than when mineral oil is employed (see, for example, Hudson, 1999). The precise amount of extra fluid and component maintenance necessitated by rapeseed oil use is uncertain as it is dependent on the standard of maintenance. The authors believe that an estimate of between one-and-a-half and three times as much fluid use and maintenance is typical of UK practice. However, there are those that disagree with these figures (Carruthers et al, 1999) and so a larger range is adopted here for comparison. Figures 4 and 5 show the comparative impact of the two fluids when they are utilised in forestry machinery and road sweepers respectively. These demonstrate how sensitive the final LCA results are to assumptions made during the Life Cycle Impact Assessment (LCIA) process. Although only oil replacement is mentioned in the discussion it must be remembered that this is coupled with an increased rate of hydraulic component replacement as well. The effect of this component replacement has been included in the study.

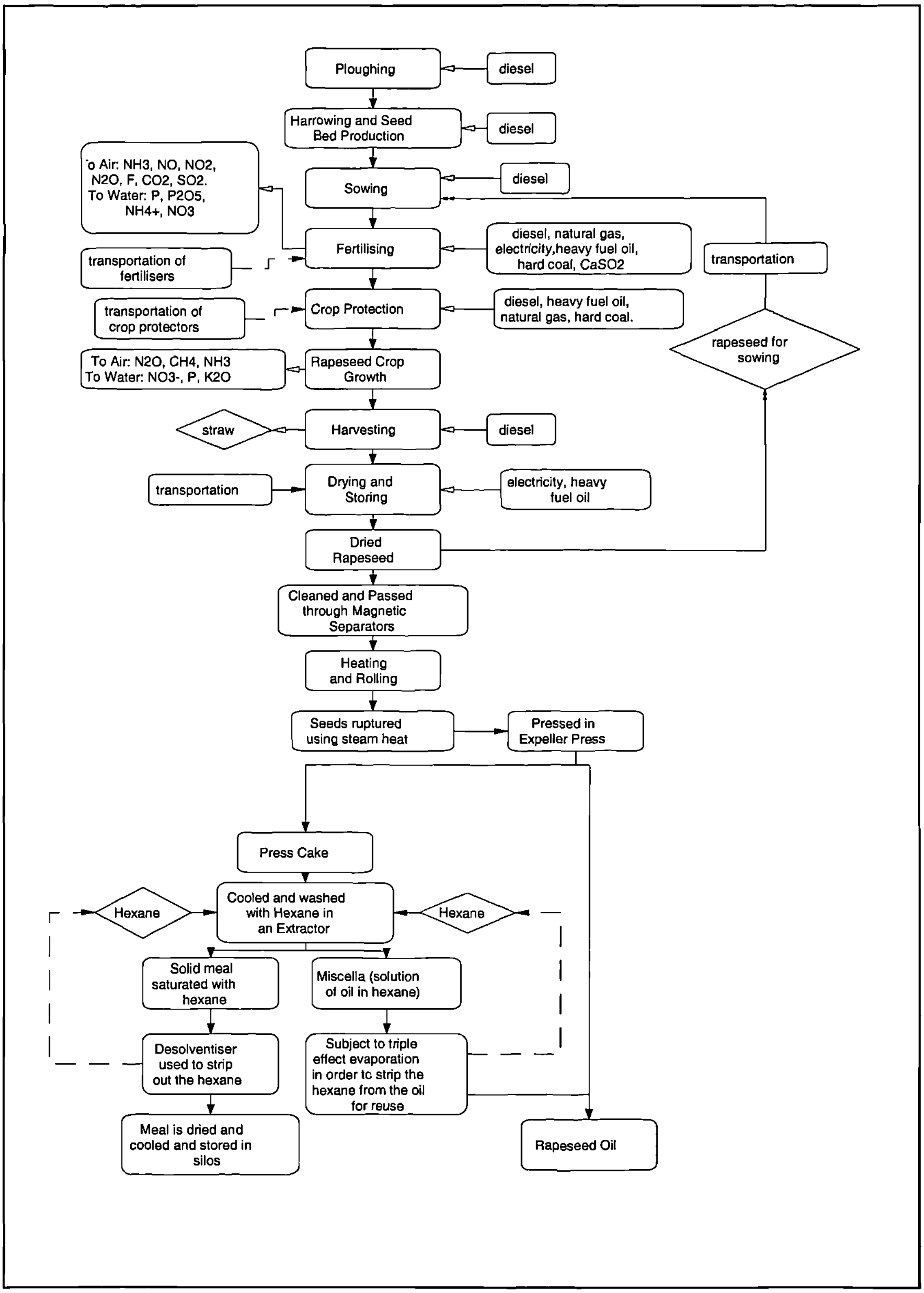

Figure 2. Rapeseed Oil Production.

Figure 4 shows the impact of using both fluids within a forestry machine, in this case, a harvester. It indicates that if the rapeseed oil is replaced three times as frequently as the mineral oil the environmental impact of the rapeseed oil is greater for every environmental effect considered except greenhouse gases. A reduction to one-and-a-half times as much replacement results in a greater impact on acidification, eutrophication and summer smog for systems running on rapeseed oil.

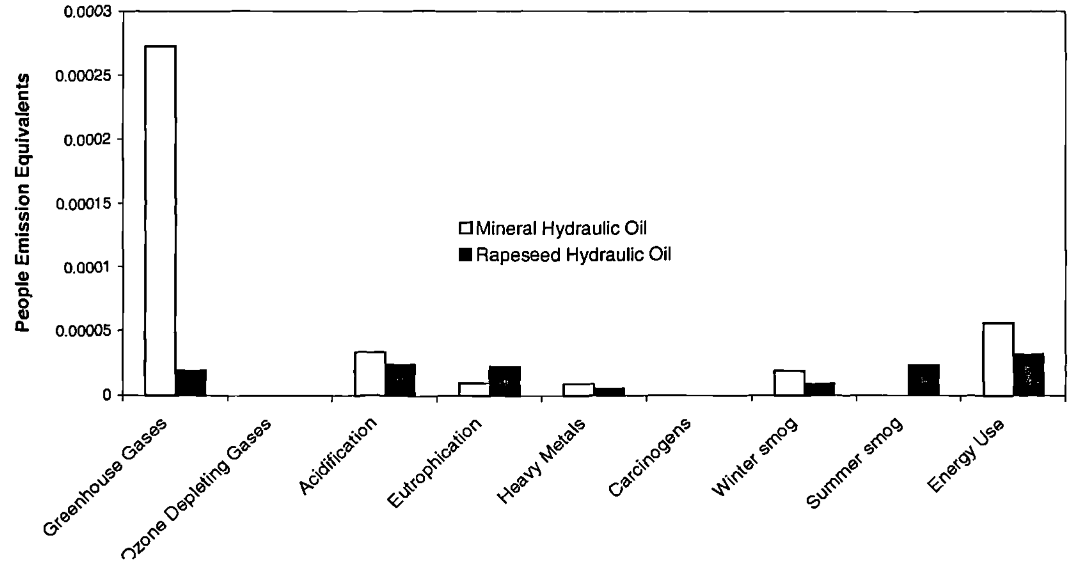

Figure 3. Environmental Impact Associated with the Hydraulic Fluid Production (mineral and rapeseed oil).

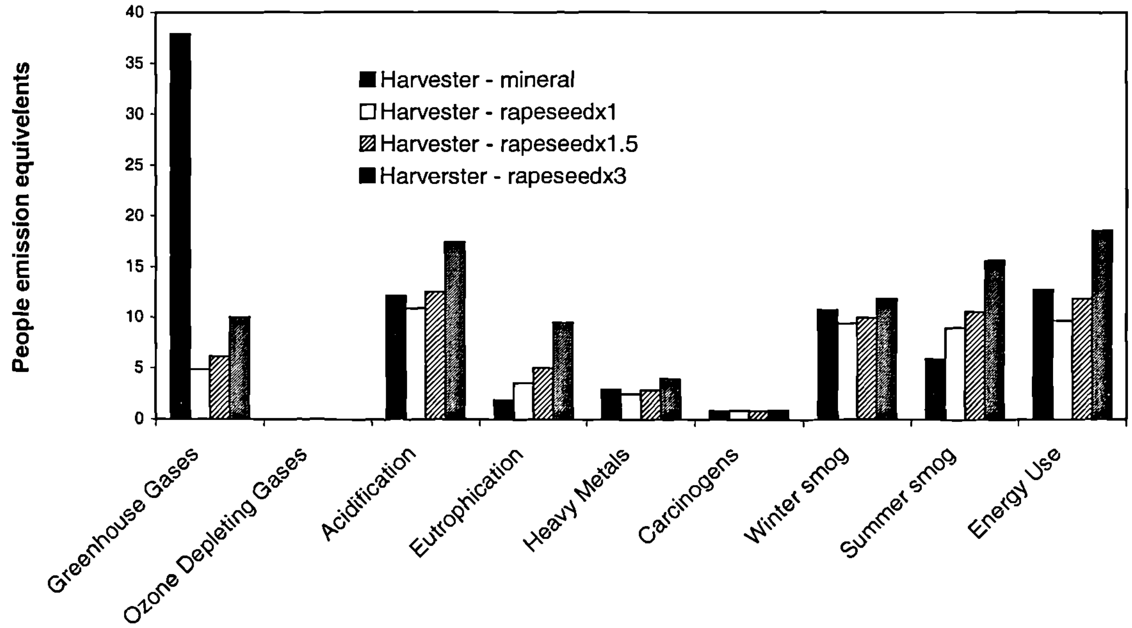

Figure 4. Life Cycle Environmental Impacts Associated with the Use of Rapeseed and Mineral Oil in a Harvester (over a fifteen year lifecycle).

For heavy metals and carcinogens the effects are almost equal, although when the results are examined in quantitative form it is seen that the impact of the systems running on mineral oil is slightly greater in both cases. The difference is so little though that any slight change in the data could change this and it is probably best to consider the impacts as more or less equal. Winter smog, greenhouse gases and energy use show a greater impact for systems using mineral oil. If the rapeseed oil is replaced as often as the mineral oil then most of the environmental impacts considered are greater for systems running on mineral oil, with the exception of eutrophication, carcinogens and summer smog.

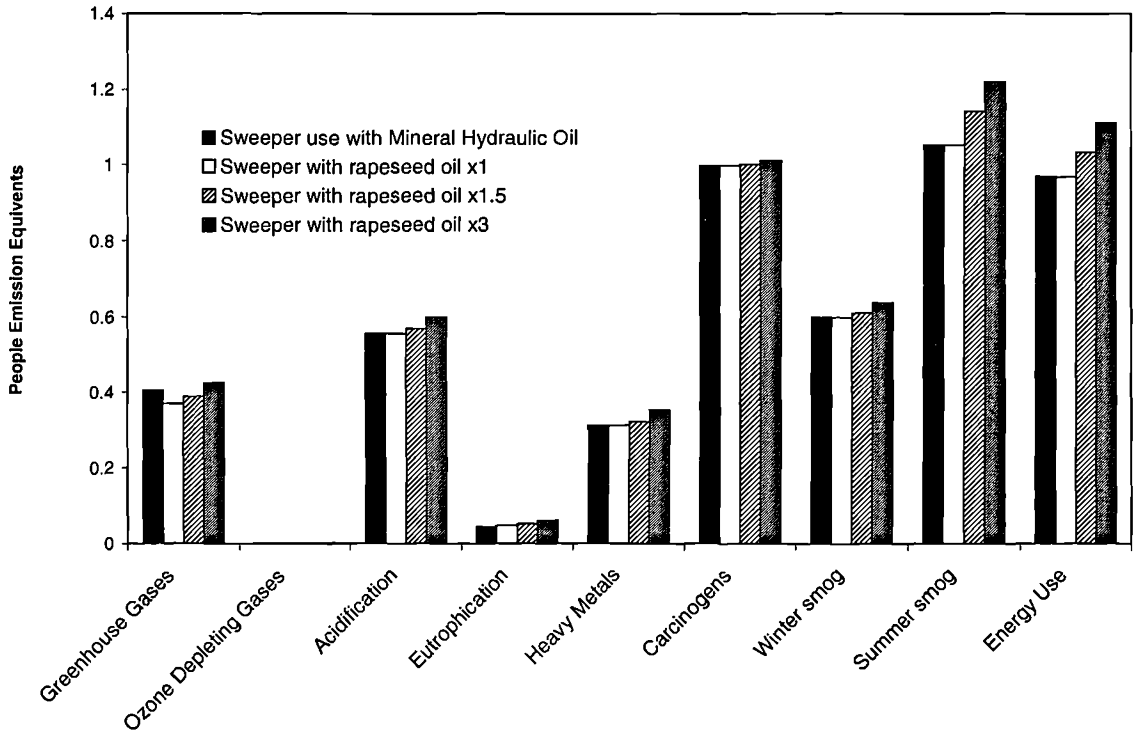

Figure 5. Life Cycle Environmental Impacts Associated with the Use of Rapeseed and Mineral Oil in a Sweeper (over a four year lifecycle).

The impact of the replacement of mineral oil by its rapeseed counterpart is much less sensitive in the case of road sweepers, (Figure 5). This is because a sweeper uses far less oil during its life and so the environmental impact of the production of the machine itself is far more dominant. However, a similar trend to that displayed with the harvester is found. Sweeper use with three times as much rapeseed oil use as mineral oil use shows the largest environmental impact upon all categories.

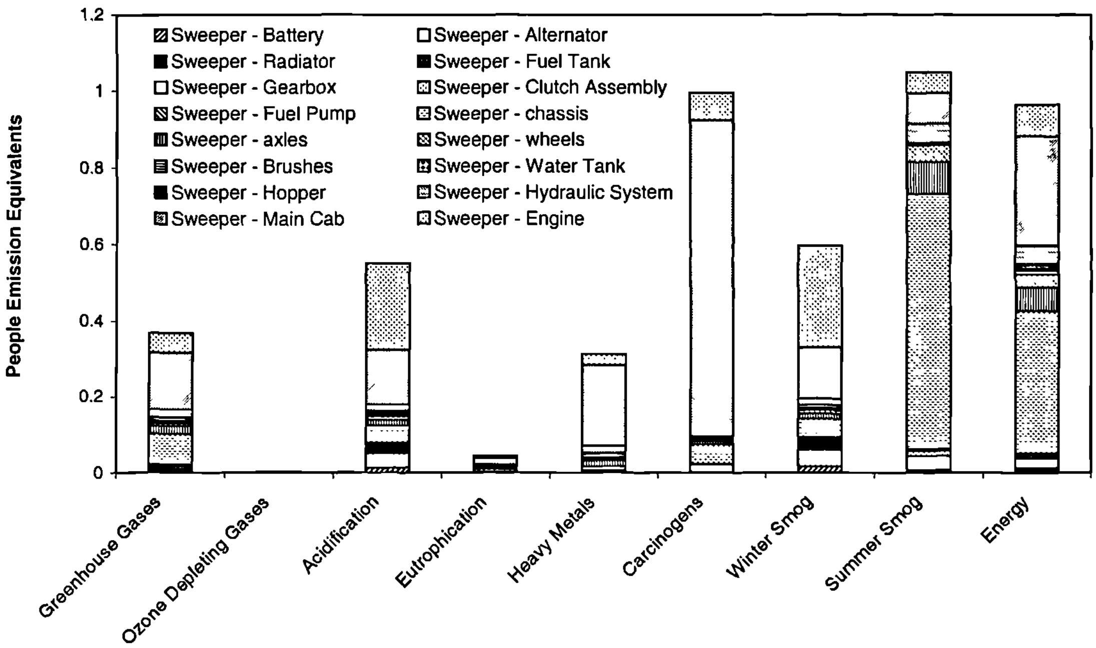

Figure 6. Environmental Impacts Attributable to the Production of the Road Sweeper.

Using one and a half times as much rapeseed than mineral oil gives rise to a larger impact on acidification, eutrophication, heavy metals, carcinogens, winter smog, summer smog and energy use.

The relative difference seen between the impacts of the type and amounts of oils in, for example, the energy use and greenhouse gases in the sweeper and forestry machine is due to the different percentage contribution the hydraulic system makes to the machine production.

The oil use contributes far less to the overall impact of the sweeper than to the harvester, and so changing the hydraulic oil has a less significant impact on the sweeper. This shows that the results of this study cannot easily be transferred between one hydraulic system application and another.

Data Quality and Acquisition

The data employed here was gathered from many sources, including the UK Forestry Commission, (see (Christie, 1996) and (Christie 1997-1999)) the UK Environment Agency, Bath and North East Somerset Unitary Council, previous LCA studies (e.g. (Ceuteric & Spirinckx, 1997) and (Friedrich et al, 1993)), publicly available data sources mainly contained in the software and from individual companies. LCA is an extremely data intensive tool and it has proved very difficult, indeed impossible, to gather sufficient data for a comprehensive assessment. However, it could be argued that in reality this is the case for all LCA studies undertaken to date. In relation to the oil industry it is especially difficult to obtain data since many processes are seen to be commercially sensitive and companies will not release data.

Most of the data used for LCA studies is generic and some of it may well be out of date. Although every effort has been taken to ensure that a comprehensive dataset has been compiled for the study, it would be impossible to say that everything had been considered. There will inevitably be gaps in the data due to ignorance of processes as well as lack of data about known processes. It is the authors' belief that this is the case in all LCA studies and it would be generally helpful for practitioners to acknowledge this fully when studies are published.

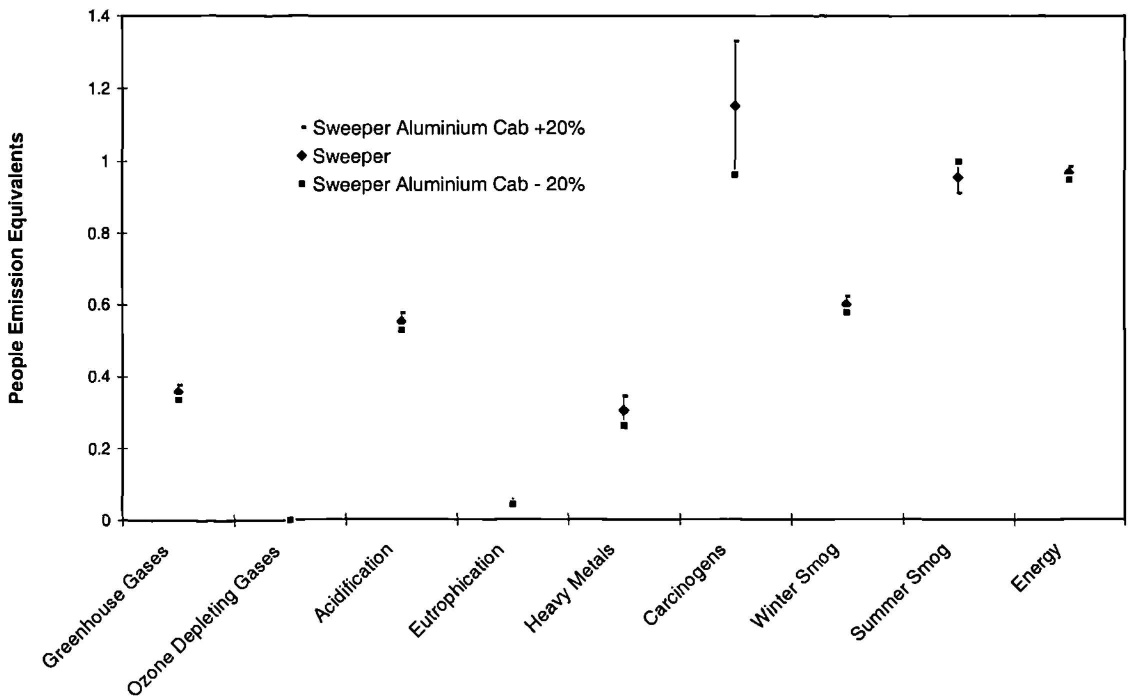

Figure 7. Sensitivity Analysis: Uncertainty Regarding the Weight of the Sweeper's Main Cab.

Sensitivity Analysis

Figures 4 and 5 show the differences in the LCA results when different assumptions were made about the performance of the machines operating with alternative fluids. The final results of a study are often very sensitive to changes in the initial assumptions. It has been illustrated here that the same assumptions employed in different case studies can lead to significant differences in the final results - depending on the assumptions made one could recommend either mineral oil or rapeseed oil on the basis of the LCA.

Most data gathered in the course of an LCA cannot be regarded as precise or absolute. It may be correct to within some error, say 10% or 20%. Obviously it is very time consuming to incorporate such uncertainties into an LCA for all the data used. The software used during this study is not capable of incorporating uncertainty bands for all input data, although it is expected that a version of the software with full sensitivity analysis capability will be available by July 2000.

Sensitivity analysis can also be used to assess which element of the life cycle have the largest impacts, and then to determine how sensitive the LCA is to changes to the values of these elements. It has already been shown that for the forestry machine the amount of fluid consumed is critical to the final results. When the environmental impact of the sweeper production was examined it became apparent that the manufacture of the main cabin made a high contribution to the outcome. This is depicted in Figure 6. The main cabin is predominantly fabricated from aluminium in order to keep the weight down whilst providing a strong structure. However, aluminium production, and in particular aluminium smelting, is very energy-intensive and therefore leads to significant pollutant emissions.

The amount of aluminium in the sweeper cab was estimated using detailed information supplied by the manufacturers. However, it is possible that this could be in error by up to 20%. The effects of a such a change are shown in Figure 7, where the most significant effect is clearly on the impact towards carcinogens. This is unsurprising since Figure 6 illustrates that the main cab production has a large effect on this particular category.

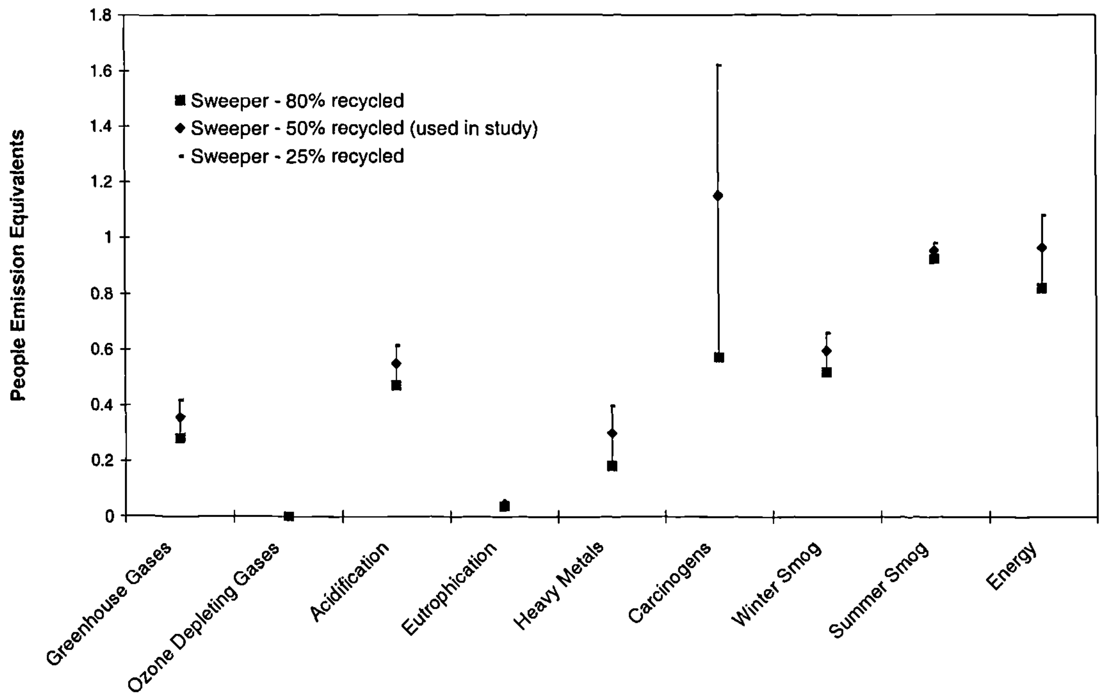

Figure 8. Sensitivity Analysis: Recycled Component of the Aluminium in the Sweeper's Main Cab.

The data for the aluminium production was taken from the database held within SimaPro, and developed in consultation with the European Aluminium Association. An estimate for the type of aluminium used and of the percentage of recycled material it contained was made. However, the true values of these figures remain uncertain. Figure 8 shows the impact on the results if different proportions of recycled aluminium is used. A wider variation in the results is obtained by altering the recycled component of the aluminium than is obtained by varying the weight of the aluminium used in the cabs. This indicates that the LCA is more sensitive to the percentage of recycled material employed in the cab production than to the total amount of aluminium in the machine.

Many LCA studies omit sensitivity analysis and make little effort to illustrate the influence of different assumptions. Of course, there are many assumptions and data uncertainties which could be further explored in the context of the present study, but it is impossible to apply uncertainty bands to every parameter considered in a study. Nevertheless, it has been demonstrated that it is important to assess the consequences of uncertainties within any LCA study. It is also important to identify the parameters examined in sensitivity study. There are many uncertainties within any LCA and it ought to be clear which are examined.

Impact Assessment Methodologies

Changes in assumptions and input data have thus far been considered. However, alterations in the methodology and data handling can also have a large effect on the final results of a study. The software tool adopted for the present study, SimaPro, provides the user with alternative methodologies. The data presented by the authors here and in earlier papers employed the Eco-Indicator 95 (EI95) methodology. However, Eco-indicator '99 (EI99), the new methodology from Pre Consultants, has been incorporated in the latest version of SimaPro. EI99 uses a damage assessment approach, moving away from the simple "less is better" ideology in EI95 towards a more accurate assessment of damage to ecosystems, health or resources. However, although EI99 is good in principle, there are problems in practice. For example, the damage to ecosystem quality caused by acidification or eutrophication via airborne emissions is based on a Dutch model. This is clearly a limitation as the Netherlands cannot be regarded as representative of other parts of Europe. There are few rocky areas and no hills or mountains in the Netherlands and much of the natural ecosystem is based on sand dune-like features. Therefore, emissions which produce a certain change in plant life in the Netherlands may not have the same effect in other countries and geographic areas. As with all LCA products, though, it is a new tool and will obviously be improved over time.

One problem with analysing and comparing Life Cycle Assessments is the inability to determine how the LCIA has been carried out. The traditional classification, characterisation and valuation stages may well not be carried out in an LCA and it may be unclear what is used in their stead. The environmental impact categories included in a study are easy to determine as they are always shown in the results. The reasons why they have been chosen may be less clear and the actual emissions and raw materials that have been included in the LCIA may be very difficult to ascertain. Are all emissions that could possibly affect, for example, the greenhouse effect included in the category for greenhouse gases or are only the gases which are "scientifically proven" to have an effect included? EI99 may make this process simpler by trying to include the three major "mind sets" related to emission impacts and their importance. The EI99 methodology employs three categories based on what is termed "cultural theory". These sub-groups arise from the different approaches to the complex choices about which emissions should be included in an LCIA. Pre Consultants argue that there are three main methods for determining impacts:

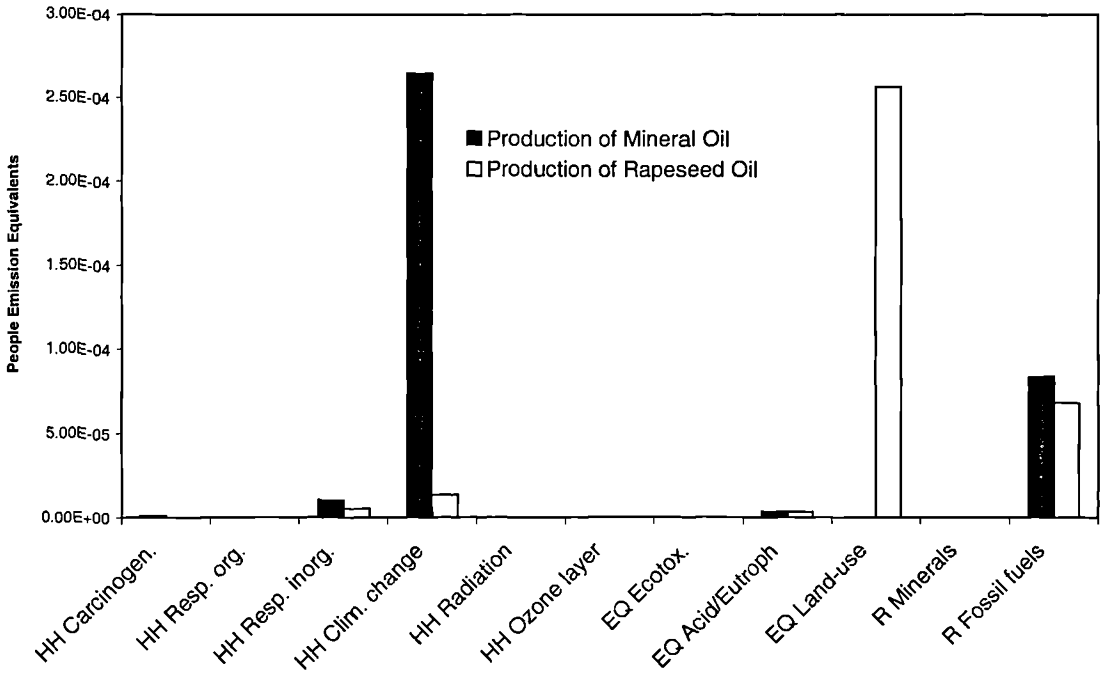

Figure 9. Eco-Indicator '99: Environmental Impacts Associated with Oil Production.

- **Individualist (I)**

  In this socio-cultural model only proven cause and effect data is included. A short term perspective is taken and age weighting for humans is incorporated. The most important years in the human life are taken to be between 20 and 40. This model does not consider the use of fossil fuels as that is a long term issue.

- **Hierarchical (H)**

  This model includes data for which there is scientific evidence. If an emission is likely to have an effect on a well-defined environmental problem and this is backed up by scientific evidence, then it will be considered. This model is generally used as a default within EI99.

- **Egalitarian (E)**

  The egalitarian model uses the "precautionary principle". All potential effects are considered. It has a long term perspective and is the most comprehensive of the three socio-cultural models. However, there is significant uncertainty associated with its application in practice.

The inclusion of these three alternatives highlights the main options in data analysis. The choice of one or other approach serves to act as a sensitivity analysis. This is because decisions are constantly being made within the LCA process as to which emissions should be allocated to which impact category. Decisions are made, perhaps unconsciously, due to a practitioner's understanding of a particular issue and also due to his or her belief of how important the issue is. Knowledge of how significant a contribution the emission or use of the raw material will make will also play a part in the decision-making process. The use of the three alternatives enables the practitioner to be more aware of the decisions made within the LCIA. It ensures that LCA practitioners are aware of the different perspectives upon the impacts of certain emissions and allows them to see the impact on the final results when these alternatives are employed.

Figure 9 presents the same data as displayed in the earlier Figure 3, but EI99 is used instead of EI95. The use of EI99

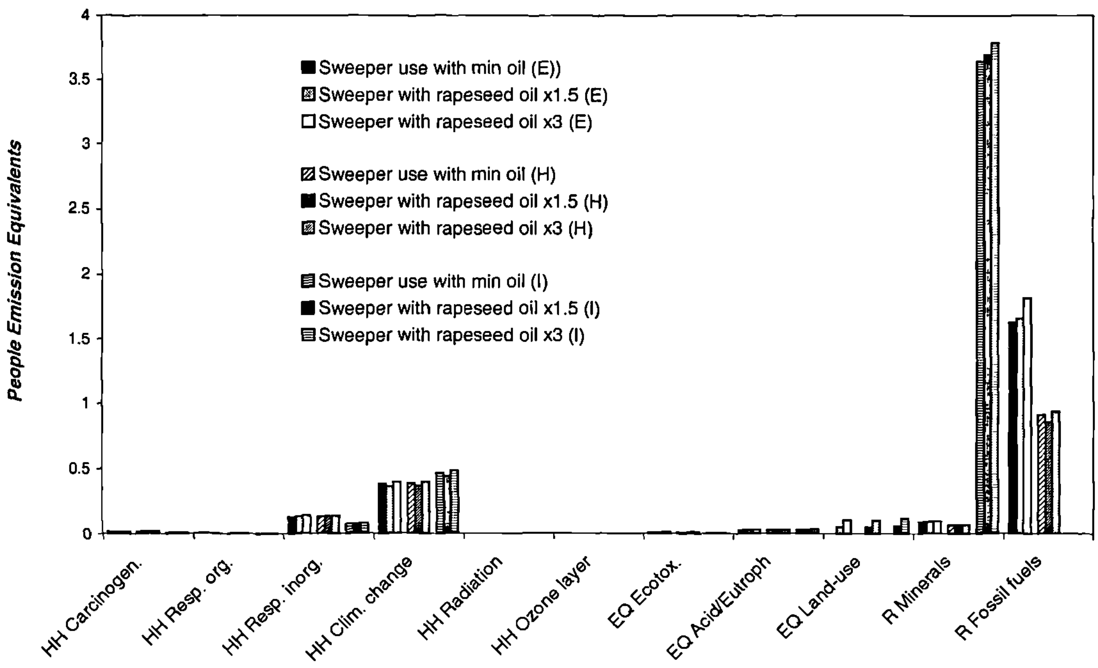

Figure 10. Examination of Cultural Theory in Eco-Indicator '99.

yields very different results than does the use of the EI95. The production of mineral oil does not look "worse" overall in terms of environmental impact when using EI99, yet it does with EI95. It is clearly worse in terms of climate change, but there is a "new" impact category, land use, which obviously shows a high impact for rapeseed. Other impacts are more equal with mineral oil having a slightly greater impact in most categories. The labels HH, EQ and R on this graph refer to the damage categories examined: human health, ecosystem quality and resource extraction. Figure 10 shows the comparison of the life cycle of a sweeper employing different hydraulic fluids using the different impact methodologies adopted by EI99. The different methodologies within EI99 do not change the pattern of the overall comparative outcome for the use of the different oil types. While the results here do not show that one oil type is better with one methodology and worse with the other methodology, nevertheless the different socio-cultural methodologies do have an effect on the results. Comparison of Figure 10 and the earlier Figure 5 show that with either of these methodologies, the environmental impact of the systems using 3 times as much rapeseed is worse than for those using mineral oil. However, although the same conclusion is reached using both methodologies, the results differ significantly and indicate that care must be taken when selecting an impact assessment methodology. It is probable that if different case studies were chosen the two methodologies might not give rise to the same overall conclusions. This assumption is backed up by the differences shown in the results for the oil production.

Weighting

The impact data reported in this study have not been weighted. Normalisation has been applied, comparing the emissions and raw material use in each case study with total European values. The valuation stage is presently a very subjective one and it was not thought beneficial to attempt it here.

Concluding Remarks

LCA is potentially a very useful environmental management tool. However, there are many ways of interpreting the same data and this may give rise to different results. Uncertainties associated with the input data for specific cases or the methodology selected for the Impact Assessment stage influence the outcome. It is therefore desirable for assessment studies to incorporate sensitivity analysis and to be clear about the assumptions made and the methodology adopted. LCA cannot be employed like a "black box" tool. However, it is very difficult to prevent this occurring, especially when results are presented in short papers or reports.

Data quality in LCA is generally poor due to uncertainties in public datasets and the unwillingness of industry to make case-specific data freely available. There must be a determined effort made amongst the LCA community to encourage the full publication of results so that there is more data available.

This study has illustrated the significance of the assumptions made in a LCA. Where possible, all the important assumptions should be outlined at the time the results are reported. The consequence of altering these assumptions should be shown. In the case studies used it is illustrated that differing the impact categories studies alone can have an impact on the final results. If it were assumed that a system could run equally well on mineral oil as rapeseed oil then the conclusions of the study would be that for the categories studied the rapeseed is probably the "better" fluid. However, if the assumption were made that three times the amount of rapeseed was needed, then the conclusion would be that the mineral oil was better. If no mention of these assumptions were made in the report then subsequent decisions could be taken on the basis of incomplete data.

The environmental impact categories chosen also have a large effect on the final results. A case study relying on large amounts of land use will come off well in a study where land use is not considered, as is shown in the mineral vs. rapeseed oil case study in this paper. The two different methodologies also yield different results for the rapeseed and mineral oil production comparison. This is not only due to the damage methodology employed within EI99, but also to the different categories studied. It is important that environmental effects are not masked by the categories chosen and that the readers are aware that an LCA can only describe contributions to defined categories.

LCA is a simple and elegant idea, but in practice it is nothing of the sort. However, it is still relatively early in the evolution of the methodology. Improved data availability, greater transparency of assumptions made, and a better understanding of the methodology should allow LCA become a very important environmental management tool.

Acknowledgements

The work reported here was carried out by a multidisciplinary team, with expertise/interests in fluid power system design and control (CRB), energy and the environment (GPH), and natural environmental science (MCM). It forms part of a major research programme funded by the UK Engineering and Physical Sciences Research Council to support the Engineering Design Centre for Fluid Power Systems at Bath (grant GR/L26858). This study has been greatly assisted by the provision of operational data by the Bath and North East Somerset Council, Jack Allen, the Forestry Commission and the Environment Agency.

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Select Committee on Science and Technology Sub-Committee 1

Non-Food Crops

Call for Evidence

Submission to the Select Committee on Science and Technology Sub-Committee.

M.C.M^cManus+, G.P. Hammond# and C.R. Burrows*

May 1999

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# Professor of Mechanical Engineering
* Professor of Systems Engineering and Hebron and Medlock Dean of Engineering and Design

1. Introduction

The University of Bath has been using Life Cycle Assessment (LCA) for the comparison of alternative fluid power systems for the past eighteen months. The project is sponsored by the Engineering and Physical Science Research Council (EPSRC) and is being carried out Marcelle M^cManus, under the supervision of Professors Clifford Burrows and Geoffrey Hammond. The research has analysed the use of mineral oils and rapeseed oils employed for fluid power purposes in forestry machinery. The findings of the study enable the research team to respond to the call for evidence regarding the use of LCA to compare the use of non-food crops with conventional materials. Consequently this evidence relates to Question 3 of the Sub-Committee's enquiry only.

This evidence provides a brief overview of LCA, its reliability as an assessment technique, the problems associated with such studies and the benefits in its use. One of the case studies used in the research at the University of Bath is discussed briefly and its suitability for use as a tool for comparing the environmental impact of non-food and conventional materials is assessed.

2. An Introduction to LCA

Life Cycle Assessment is an environmental management tool which has become increasingly popular in recent years. It is a technique that may be used in conjunction with other environmental management tools such as Environmental Impact Assessment and Environmental Risk Assessment. However, LCA considers impacts and effects of a product or system over its entire life cycle. It is the only environmental management tool that avoids positive ratings for measurements which result from shifting the environmental consequences i.e. a product which has better performance in one part of its lifecycle than another will be considered over both parts. LCA assesses the energy input, materials input, emissions to air, emissions to water and solid waste over the entire life cycle. This means that the environmental impact of the product or system is assessed from the "cradle to the grave". Figure 1 shows the inputs and outputs to a product or system over the entire life cycle.

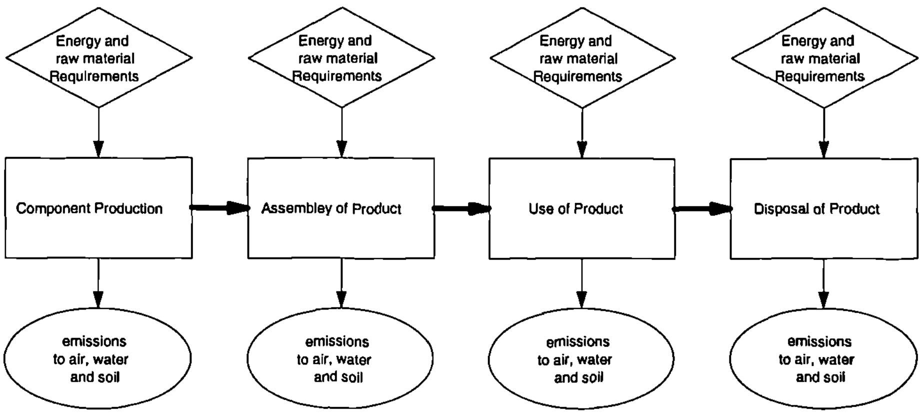

Figure 1 Inputs and Outputs considered in an LCA study

Until the early 1990's there was no common methodology for LCA. This meant that LCA studies were often incomplete, or their procedures varied so widely that they were not comparable. In the 1990's the Society of Environmental Toxicology and Chemistry (SETAC) devised a methodology which was been generally accepted by leading practitioners. The main framework of this methodology has now been incorporated into the ISO 14040 series of international standards on LCA. The SETAC and ISO guidelines provide a framework for LCA. There are four main stages: Goal Definition, Inventory, Impact Assessment and Improvement Assessment. These stages have also been incorporated into a number of the commercial software packages available.

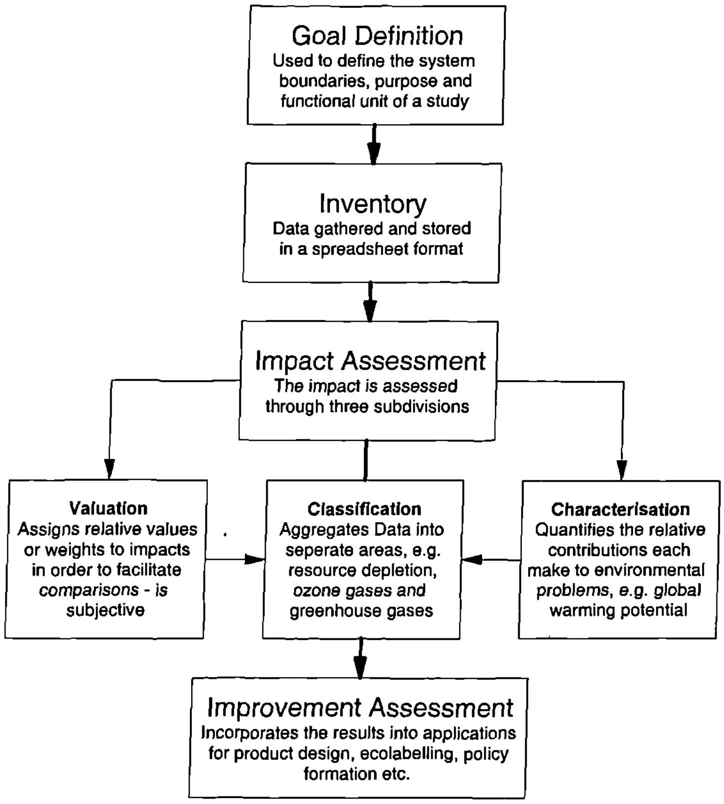

Figure 2. Stages in LCA as defined by SETAC

2.1 Goal Definition

This first stage shown in Figure 2 is used to identify the issues to be examined within a given study. The environmental impact of a whole system or product cannot realistically be presented as a single parameter and so LCA therefore examines environmental impacts with respect to known environmental "problems" such as global warming, ozone depletion or acidification. The task of this initial scoping phase is to carefully outline the potential environmental problems involved and to present clear reasoning behind the choices. It is important that the process of LCA is transparent in order to avoid the possibility of an unscrupulous practitioner being able to "bend" the results so that one particular product is favoured over another. For example, if a certain result was wanted it might be possible to carry out the LCA without examining the contribution to a particular environmental issue which could yield a negative environmental impact. LCA can result in vast amounts of data gathering and it is at this initial stage that the boundaries of the study are established. If the study is to be comparative then the boundaries around the products or systems to be examined must be very similar.

2.2 Inventory

This stage involves data gathering as shown Figure 1. It is a very time consuming stage and it can typically take over a year to gather enough data for a thorough LCA. However, the increasing availability of commercial and other databases should reduce this as LCA becomes more commonplace. The information is stored in a data base and analysed in the subsequent stage, that of the impact assessment. Care must be taken when using purchased or general access data that the data is accurate and specific enough for that particular study. Ideally a test of verified validity needs to be applied.

2.3 Impact Assessment

In this stage data is examined with respect to known environmental issues or problems such as acidification, ozone depletion, energy use, global warming and so on. The stage is sub-divided into three elements: classification, characterisation and valuation. Often there is a fourth stage, normalisation, which can either occur before the valuation or often instead of the final valuation stage.

2.3.1 Classification

The classification stage allows all the data from the inventory to be grouped together into predetermined environmental issues or "problems" (classifications) as previously outlined Section 2.1. When the data has been classified there will be several inputs and a variety of emissions resulting from each environmental "problem" considered. The data can therefore be very complex and difficult to comprehend. Consequently a weighting is given to each, and all the contributions to each issue are added together to enable easier comparison.

2.3.2 Characterisation

The weighing and addition of the inventory data forms the characterisation stage. This allows different inputs to each of the classifications to be amalgamated. The various greenhouse gases (for example, CO_2, CFC's and HCFC's) are believed to contribute to global warming with differing degrees of severity. In order to weight these different impacts CO_2 is given a value of 1 and the other greenhouse gases are given a value which corresponds to their relative effect. Once the characterisation stage has been completed there will be one 'equivalent' emission under each of the classifications. However, this data can still be difficult to interpret. For example, a graph displaying 1000kg of CO_2 equivalent for greenhouse gases, 900kg of CFC11 equivalent ozone depleting gases and 800kg of SO_4 equivalent acidification products would not necessarily mean that the impact to global warming is any greater than that for acidification. Neither the contributions or the environmental issues can be compared directly.

2.3.3 Valuation

One potential option to overcome this problem is to give a value to each of the categories of emission outlining which is most important to a given study. This is a subjective process and it has not often been carried out in LCA. Another option is to normalise the data so that it is more easily understood. This is not a well defined process either and can also be perceived as subjective. Normalisation cannot be considered a direct alternative to valuation, but does allow some comparison without the same degree of subjectivity.

2.3.4 Normalisation

One method of normalisation, and perhaps the most common, is to compare the data with average European emissions, or with European legislative limits. This is done in the hope that such limits are set at a level where each effect will have a broadly comparable impact in the environment. Although this is not strictly the case it does enable easier comparison. However, there are inevitably problems associated with obtaining the necessary data for normalisation. Some countries in the world do not have regulatory limits or emission level data. Data collection and accuracy can also present difficulties. All types of normalisation have drawbacks which need to be fully examined in the context of any given study. Within the research at the University of Bath the concept of "people emission equivalents" has been used. Data for the average European emissions for each category was obtained. This obviously results in a very large number and the emissions for the study were fairly small. Therefore, for ease of comprehension the emissions were divided by the number of people in Europe. This gives an average "person emission". This was then compared with the emissions in the study to give "people emission equivalents".

2.4 Improvement Assessment

In the Impact Assessment stage has been reached graphs which show the areas of significant impact occur will have be produced. These should be examined both as a for means of determining ways of improving the process and also to double check the data in the most important areas. Obviously, the aim of the improvement assessment stage is to identify areas where improvement can be made. These need not be areas with the largest impacts but may be areas where small improvements can be made easily. This stage enables the whole process to work to help improve the environmental performance throughout production, use and disposal of the product or system.

3. Limitations of LCA

LCA a very useful tool but it has many limitations in the present state of development. The method employed only allows for the examination of global and regional impacts and not local impacts. This can obviously bias results. However, as long as there are other studies carried out which do take into consideration local impacts then LCA can still be used to good effect. One of the major limitations to LCA is time and data. To undertake a full LCA study requires a vast amount of data, much of which is not within the public domain. Companies are often unwilling to part with the sort of sensitive data required for a full study. The use of more generalised public domain data or estimates obviously decreases the accuracy of the study. Credible databases are increasing with the rise in popularity of LCA and these can either be purchased as a commercial database or as part of a software package. There is a call for all LCA databases to be in the same format by the Society of Promotion of Life Cycle Development (SPOLD) so that data transfer can be more easily facilitated. This is now taking place to some extent, but the use of LCA is still too limited to mean that a practitioner will be able to find all the information needed from a public database. Consequently much time is still invested in gathering fundamental information.

4. LCA Case Study

The research at the University of Bath has examined case studies related to fluid power systems. In one case the use of conventional mineral oil has been compared with rapeseed oil in the hydraulic systems of forestry machinery. This is obviously a particularly sensitive application from an ecological perspective. A full account of this case study has been reported by Burrows et al (1 & 2). The production and use of mineral and rapeseed oil was obviously examined. However, the disposal process for both oils is currently the same and so will have no differential impact for the purposes of the study. Data availability was a significant problem in this study and although every effort has been made to obtain realistic the degree of uncertainty is quite high. The results will be refined as more and better data is obtained. A full sensitivity analysis is currently being carried out. Once this has been completed areas of potentially high sensitivity can be re-examined.

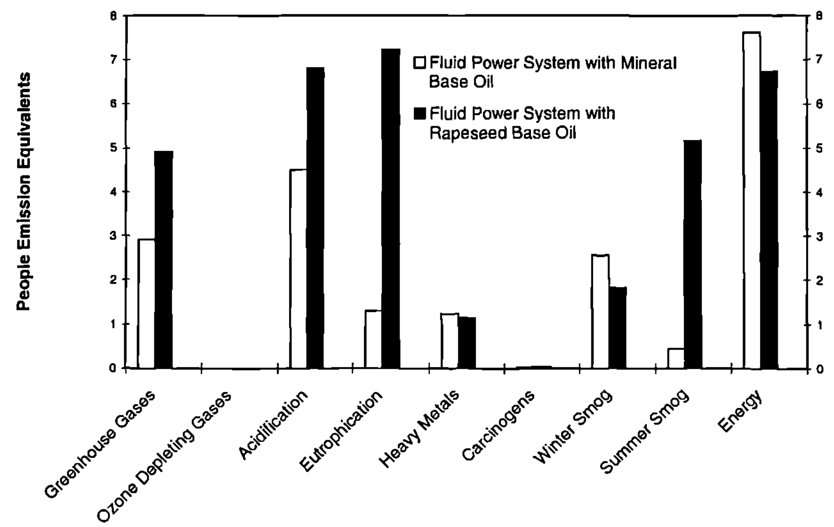

Figure 3. Normalised comparison of a fluid power system over a fifteen year life cycle using mineral and rapeseed base oils.

The baseline study results shown in Figure 3 show that over all the rapeseed oil has a greater impact on the environment than that of the mineral oil. These results are a modification of those shown in Burrows et all [2]. The modification has arisen as a result of the incorporation of additional data. The impact of the rapeseed is greater than that of the mineral oil in all areas examined other than energy use and winter smog. However, if the impact to fossil fuel use and sustainable development had been chosen as categories the over all results may look slightly different.

One of the benefits of LCA is that data can be presented in different formats. For example, it is possible to refine the data used for the rapeseed base oil and illustrated in Figure 3. It can be broken down into separate components, different stages of production and use, and used to determine where the largest effects are. This is shown in Figure 4. If all the stages in the production and use of the rapeseed are analysed then it is seen that the main contributory stages within the production of the rapeseed are the crushing of the seeds, the fertiliser production, the drying of the rapeseed and the natural process of the rapeseed growth itself.

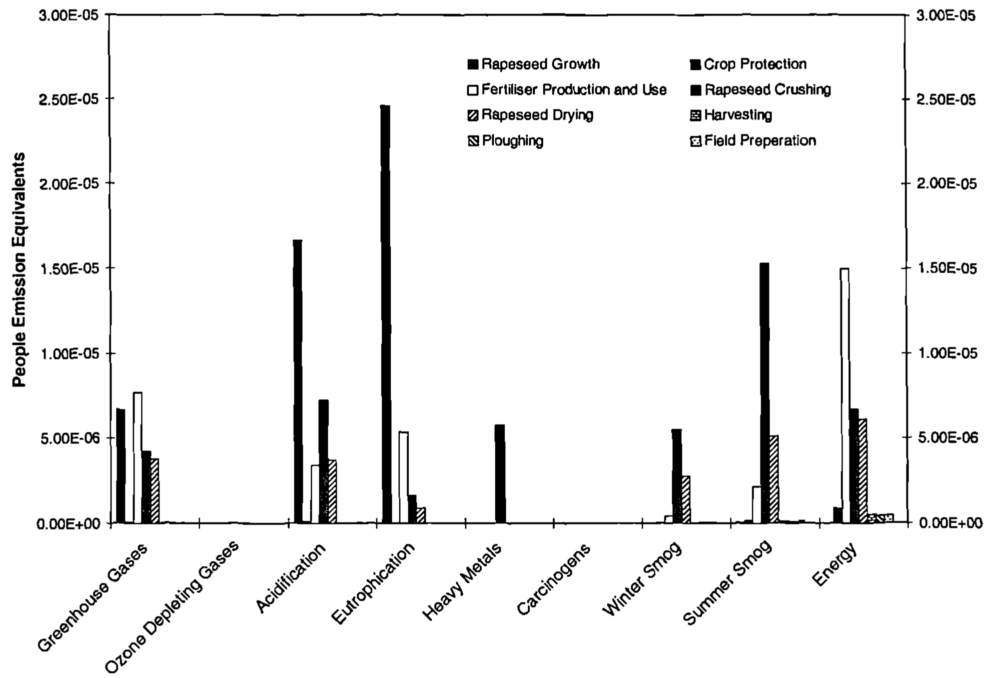

Figure 4. Detailed Normalised Data for the Base Rapeseed Oil Production.

Rapeseed fluids do not have the same properties as mineral fluids and therefore the way in which they perform within a hydraulic system is very different. At present, with current specifications for hydraulic systems, this means that hydraulic fluids based on rapeseed have to be replaced more frequently than those based on mineral fluids. This exacerbates the negative impacts within the production process.

With this information of this it is possible to determine whether it is possible to improve any of these stages. Areas with large environmental impacts can be examined further to see if there is any possibility for improvement. For example, examination of fertiliser production or the rapeseed crushing stage may show that there are ways to improve these processes easily. However, as the growth of the rapeseed is a natural process it will be very difficult to improve that part of the rapeseed production. Once the stages with the larger impacts have been analysed then it is important to look at the stages with smaller impacts as there may be improvements that can be made within these stages which, examined altogether, could have a significant effect on the over all performance. The ease with which LCA can find such contributions and stages is invaluable and helps to make it a comprehensive environmental management tool.

With any LCA it is possible that much of the data will be very sensitive to small changes. Therefore a sensitivity analysis should be undertaken. A sensitivity analysis is currently being carried out for this study and therefore the results shown should not be used as evidence against the use of non food crops in industry. Much of the negative impact shown for the rapeseed are due to its poor qualities within a hydraulic system meaning that more rapeseed oil is used within a system than mineral oil. This elevates any impacts which are seen in the production phase. This may not be the case with other uses.

Again, limitations to the study can be seen as only global and regional impacts were examined within the LCA part of the study. This means that the choice of forestry machinery as a case study in this respect was irrelevant as the impact of spills on the local ecology was not considered. However, also shown is the surprising results that the overall, global impact for the rapeseed oil was greater than those for the mineral oil. But, it must be remembered that these are preliminary results, no sensitivity analysis has yet been carried out and the reliability of some of the data is still in question, indeed, some of the data is absent.

5. Conclusions and Recommendations

In conclusion, it is suggested that LCA is a very important tool which can be used to determine global and regional impacts of a product or system from the "cradle to the grave". Currently it is unable to include local impacts, but it is possible that some means to achieve this will be forthcoming in the future. With continued use with other environmental management tools it forms a very comprehensive impact assessment package. Its use negates the examination of products on a snapshot image, one which examines only one part of a life-cycle, which may well give incorrect impressions.

Even with the help of any of the commercial software or databases on offer it is not a simple task and deference to the time taken to perform an LCA must be given. With time, and increased public domain database access then the amount of time taken for each individual LCA will be reduced, but that will probably not be in the immediate future.

The initial stages of LCA can be described as scientific and objective. However, the latter stages, including the normalisation and valuation stages are subjective. This leads to problems as at least one of these stages has to be undertaken in order for the study to be interpreted. This should not discourage the use of LCA however as it is still one of the more scientific environmental management tools. Once more research has been carried out on the latter stages it has the potential to become more scientific with a more complete standard methodology. Although many reservations have been outlined about LCA's use it is believed that overall it is an important tool which could be used more frequently.

6. References

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[2] **Burrows, C. R., Hammond, G.P. and McManus, M.C.** (1999) Life Cycle Assessment of Some Mobile Hydraulic Systems, *The Sixth Scandinavian International Conference on Fluid Power, SICFP '99*, Tampere, Finland.

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12 Appendix 2 - Steering Committee Members

Steering Committee Members 1997-2000

C.R. Burrows	University of Bath
P.M. Hopkins	Sterling Hydraulics Ltd.
K. Milnes	EPSRC
G. Muscat	Hydac-Flupac Ltd
I Patterson	Sauer-Sundstrand Ltd
N. Brenchly	Forward Industries Ltd
K. Cleasby	Eaton Corporation
P. Cooke	Mannesman Rexroth Ltd
J. Shepherd	JCB
P. Read	EPSRC
D. Spall	Mannesman Rexroth Ltd
D. Tilley	University of Bath
J. Hudson	Sauer-Sundstrans Ltd.

13 Appendix 4 - Characterised Data

Class	Unit	Total	Hydraulic system	Engine	Chassis	Axles	Brakes	Electrical system	Main Body	Production of Cutting Head	Steering	Drive Shaft
Greenhouse Gases	kg CO2	2.98E+04	357	2.31E+03	1.47E+04	1.92E+03	112	195	2.68E+03	1.56E+03	52.2	418
Ozone Depleting Gases	kg CFC11	0.000509	3.76E-06	0.00024	0	1.81E-05	1.06E-06	1.87E-06	0.00015	7.62E-05	6.28E-07	5.02E-06
Acidification	kg SO4	857	2.09	68.7	639	9.07	0.529	7.83	18.4	9.63	0.254	2.03
Eutrophication	kg PO4	21.8	0.138	0.783	7.99	0.568	0.0331	0.0601	1.12	0.618	0.0155	0.124
Heavy Metals	kg Pb	0.0921	0.000161	0.00427	0.0778	0.000839	4.92E-05	4.80E-05	0.005	0.00301	2.68E-05	0.000214
Carcinogens	kg B(a)P	0.00921	0.000174	0.00245	0.00295	0.00109	6.36E-05	1.88E-05	0.00104	0.000592	2.82E-05	0.000225
Winter smog	kg SPM	777	1.77	67.1	618	8.07	0.471	7.71	14.9	7.88	0.229	1.83
Summer smog	kg C2H4	102	3.86	9.53	3.37	22.9	1.34	0.124	21.6	12.8	0.598	4.78
Energy Use	MJ LHV	8.32E+05	2.06E+04	6.84E+04	2.30E+05	1.14E+05	6.63E+03	2.88E+03	1.22E+05	7.60E+04	2.97E+03	2.38E+04
Solid	kg	7.86E+03	211	1.08E+03	1.57E+03	1.31E+03	76	541	1.30E+03	733	34.1	273

Characterised Data for the Production of the Harvester

Class	Unit	Total	Hydraulic system	Engine	Steering	Axles	Brakes	Electrical system	Main body	Chassis	Drive Shaft	Wheels	Container ship
Greenhouse Gases	kg CO2	2.64E+04	470	1.19E+03	52.2	614	74.7	261	2.84E+03	1.53E+04	418	2.34E+03	1.43E+03
Ozone Depleting Gases	kg CFC11	0.000379	1.20E-06	0.000169	6.28E-07	2.07E-06	7.09E-07	3.64E-06	0.000181	0	5.02E-06	1.54E-05	0
Acidification	kg SO4	835	3.25	41.8	0.254	3.49	0.353	11	19.6	666	2.03	26.7	39.5
Eutrophication	kg PO4	19.5	0.24	0.414	0.0155	0.246	0.0221	0.084	1.19	8.32	0.124	1.79	3.41
Heavy Metals	kg Pb	0.0945	0.00186	0.00274	2.68E-05	0.00162	3.28E-05	0.000133	0.00601	0.0811	0.000214	0.000656	0
Carcinogens	kg B(a)P	0.00706	0.000117	0.00155	2.82E-05	0.000248	4.24E-05	3.48E-05	0.00104	0.00307	0.000225	0.000691	0
Winter smog	kg SPM	765	2.62	40.8	0.229	2.9	0.314	10.8	15.8	644	1.83	20.5	21.3
Summer smog	kg C2H4	63.4	1.41	2.76	0.598	4.18	0.89	0.118	21.7	3.51	4.78	19.8	1.2
Energy Use	MJ LHV	6.42E+05	1.30E+04	2.74E+04	2.97E+03	2.49E+04	4.42E+03	3.72E+03	1.25E+05	2.40E+05	2.38E+04	1.38E+05	2.12E+04
Solid	kg	6.00E+03	97.3	648	34.1	257	50.7	809	1.32E+03	1.64E+03	273	862	8.14

Characterised Data for the Production of the Forwarder

Class	Unit	Total	Battery	Alternator	Radiator	Fuel Tank	Gear Box	Clutch Assembly	Fuel Pump	Chassis	Axles	Wheels	Brushes	Water Tank	Hopper
Greenhouse Gases	kg CO2	4.81E+03	69.8	42.2	15.1	5.22	92.3	20.9	28.9	1.04E+03	272	90.6	36.8	56.7	128
Ozone Depleting Gases	kg CFC11	0.00131	0	1.75E-06	0	6.28E-08	2.24E-05	2.51E-07	9.09E-08	1.26E-05	7.45E-07	6.03E-07	2.94E-05	0	0
Acidification	kg SO4	62	1.55	4.24	2.16	0.0254	0.576	0.101	0.348	5.07	1.61	1.03	0.361	0.397	0.894
Eutrophication	kg PO4	1.71	0.0198	0.0184	0.00662	0.00155	0.0272	0.0062	0.0137	0.31	0.116	0.0688	0.0264	0.0299	0.0673
Heavy Metals	kg Pb	0.0169	1.17E-05	5.93E-05	2.83E-07	2.68E-06	0.000254	1.07E-05	9.77E-06	0.000535	0.000854	2.57E-05	7.19E-05	0.000301	0.000677
Carcinogens	kg B(a)P	0.0108	4.97E-08	1.75E-05	8.80E-10	2.82E-06	0.000211	1.13E-05	4.41E-06	0.000564	9.82E-05	2.70E-05	4.37E-07	9.91E-06	2.23E-05
Winter smog	kg SPM	56.3	1.53	4.16	2.13	0.0229	0.495	0.0917	0.363	4.58	1.33	0.788	0.22	0.319	0.718
Summer smog	kg C2H4	18.8	0.0198	0.0409	0.00067	0.0598	0.667	0.239	0.102	12	1.52	0.769	0.0805	0.0125	0.0282
Energy Use	MJ LHV	1.53E+05	923	730	191	297	4.01E+03	1.19E+03	803	5.94E+04	9.78E+03	5.32E+03	1.46E+03	903	2.03E+03
Solid	kg	2.16E+03	0.0295	518	268	3.41	42.6	13.7	6.21	683	96.5	33.7	0.624	4.58	10.3

Characterised Data for the Production of the Sweeper

Class	Unit	Sweeper Production	Mineral Hydraulic Oil
Greenhouse Gases	kg CO2	4.81E+03	478
Ozone Depleting Gases	kg CFC11	0.00131	1.19E-09
Acidification	kg SO4	62	0.514
Eutrophication	kg PO4	1.71	0.0506
Heavy Metals	kg Pb	0.0169	6.72E-05
Carcinogens	kg B(a)P	0.0108	2.16E-10
Winter smog	kg SPM	56.3	0.241
Summer smog	kg C2H4	18.8	2.15E-06
Energy Use	MJ LHV	1.53E+05	6.69E+03
Solid	kg	2.16E+03	0.696

Class	Unit	Production of Harvester	Diesel Use	Hydraulic Oil use
Greenhouse Gases	kg CO2	3.00E+04	8.84E+06	4.24E+04
Ozone Depleting Gases	kg CFC11	0.000509	0	0
Acidification	kg SO4	860	1.09E+05	683
Eutrophication	kg PO4	21.9	1.67E+04	33.2
Heavy Metals	kg Pb	0.0921	0	0
Carcinogens	kg B(a)P	0.00921	0	0
Winter smog	kg SPM	780	3.00E+04	533
Summer smog	kg C2H4	104	1.67E+04	358
Energy Use	MJ LHV	8.88E+05	1.15E+08	2.42E+07
Solid	kg	7.86E+03	3.87E+03	204

Characterised Data for the Production Versus Mineral Oil and Diesel Use in the Harvester

Class	Unit	Production of the Forwarder	Diesel Use	Mineral Hydraulic Oil use
Greenhouse Gases	kg CO2	2.64E+04	8.84E+06	4.24E+04
Ozone Depleting Gases	kg CFC11	0.000379	0	0
Acidification	kg SO4	836	1.09E+05	683
Eutrophication	kg PO4	19.5	1.67E+04	33.2
Heavy Metals	kg Pb	0.0945	0	0
Carcinogens	kg B(a)P	0.00706	0	0
Winter smog	kg SPM	766	3.00E+04	533
Summer smog	kg C2H4	64	1.67E+04	358
Energy Use	MJ LHV	6.65E+05	1.15E+08	2.42E+07
Solid	kg	6.00E+03	3.87E+03	204

Characterised Data for the Production Versus Mineral Oil and Diesel Use in the Forwarder

Class	Unit	Harvester - mineral	Harvester - rapeseedx1	Harvester - rapeseedx1.5	Harverster - rapeseedx3
Greenhouse Gases	kg CO2	4.95E+05	6.34E+04	8.02E+04	1.31E+05
Ozone Depleting Gases	kg CFC11	0.000513	0.000512	0.000514	0.00052
Acidification	kg SO4	1.36E+03	1.22E+03	1.41E+03	1.96E+03
Eutrophication	kg PO4	71.3	136	192	363
Heavy Metals	kg Pb	0.158	0.133	0.154	0.216
Carcinogens	kg B(a)P	0.0094	0.0094	0.00949	0.00977
Winter smog	kg SPM	1.01E+03	890	946	1.12E+03
Summer smog	kg C2H4	106	161	191	279
Energy Use	MJ LHV	7.37E+06	1.53E+06	1.88E+06	2.93E+06
solid	kg	8.75E+03	9.21E+03	9.89E+03	1.19E+04

Characterised Data for the comparison of the Harvester using different hydraulic fluids

Class	Unit	Forwarder - mineral	Forwarder - rapeseedx1	Forwarder - rapeseedx1.5	Forwarder - rapeseedx3
Greenhouse Gases	kg CO2	4.92E+05	6.00E+04	7.69E+04	1.27E+05
Ozone Depleting Gases	kg CFC11	0.000381	0.00038	0.000381	0.000383
Acidification	kg SO4	1.34E+03	1.20E+03	1.39E+03	1.94E+03
Eutrophication	kg PO4	69	133	190	361
Heavy Metals	kg Pb	0.162	0.137	0.158	0.222
Carcinogens	kg B(a)P	0.00718	0.00718	0.00724	0.00741
Winter smog	kg SPM	1.00E+03	878	934	1.10E+03
Summer smog	kg C2H4	64.9	120	148	232
Energy Use	MJ LHV	7.17E+06	1.33E+06	1.68E+06	2.71E+06
Solid	kg	6.77E+03	7.23E+03	7.84E+03	9.69E+03

Characterised Data for the comparison of the Forwarder using different hydraulic fluids

Class	Unit	Sweeper use with Mineral Hydraulic Oil	Sweeper with rapeseed oil x1	Sweeper with rapeseed oil x1.5	Sweeper with rapeseed oil x3
Greenhouse Gases	kg CO2	5.28E+03	4.84E+03	5.08E+03	5.53E+03
Ozone Depleting Gases	kg CFC11	0.00131	0.00131	0.00131	0.00131
Acidification	kg SO4	62.5	62.4	63.9	67.3
Eutrophication	kg PO4	1.76	1.83	1.98	2.36
Heavy Metals	kg Pb	0.017	0.017	0.0175	0.0191
Carcinogens	kg B(a)P	0.0108	0.0108	0.0109	0.011
Winter smog	kg SPM	56.5	56.4	57.6	60
Summer smog	kg C2H4	18.8	18.9	20.4	21.8
Energy Use	MJ LHV	1.60E+05	1.54E+05	1.63E+05	1.76E+05
Solid	kg	2.16E+03	2.16E+03	2.25E+03	2.34E+03

Characterised Data for the comparison of the Sweeper using different hydraulic fluids

14 Appendix 5 - Sensitivity Analysis Maths

Sensitivity Analysis maths

There are N numbers x_1, $x_2, \ldots x_N$ with $\sum_{i=1}^{N} x_i = T$

A given number of the series x_I has a percentage error E_I. X_I is to be perturbed by E_I but the total of the series must remain at T. This is achieved by perturbing all the other numbers of the series by some percentage λ. The following equation must therefore be satisfied:

$$\left[\sum_{i=1}^{I-1}\left(1+\frac{\lambda}{100}\right)x_i\right]+\left[x_I\left(1+\frac{E_I}{100}\right)\right]+\left[\sum_{i=I+1}^{N}\left(1+\frac{\lambda}{100}\right)x_i\right]=T.$$

We can solve for λ:

$$\left(1+\frac{\lambda}{100}\right)\left[\sum_{i=1}^{I-1}x_i+\sum_{i=I+1}^{N}x_i\right]=T-x_I\left(1+\frac{E_I}{100}\right)$$

$$1+\frac{\lambda}{100}=\frac{T-x_I\left(1+\frac{E_I}{100}\right)}{\sum_{1=1}^{I-1}x_i+\sum_{i=I+1}^{N}x_i}$$

$$\lambda=100\left[\frac{T-x_I\left(1+\frac{E_I}{100}\right)}{\sum_{i=1}^{I-1}x_i+\sum_{i=I+1}^{N}x_i}-1\right]$$

$$\lambda = 100\left[\frac{T - x_I\left(1+\frac{E_I}{100}\right)}{x_1 + x_2 + x_3 + \ldots + x_{I-1} + x_{I+1} + \ldots + x_N} - 1\right]$$

$$\lambda = 100\left[\frac{T - x_I\left(1+\frac{E_I}{100}\right)}{T - x_I} - 1\right].$$

Now we introduce the new constraint that x_J can't change more than plus or minus λ_o where $|\lambda_o|$ is less than or equal to $|E_I|$. Then

$$\left[\sum_{i=1}^{N}\left(1+\frac{\lambda}{100}\right)x_i\right] - \left(1+\frac{\lambda}{100}\right)(x_I + x_J) + x_I\left(1+\frac{E_I}{100}\right) + x_J\left(1\pm\frac{\lambda_0}{100}\right) = T$$

$$1+\frac{\lambda}{100} = \frac{T - x_I\left(1+\frac{E_I}{100}\right) - x_J\left(1\pm\frac{\lambda_0}{100}\right)}{\left(\sum_{i=1}^{N} x_i\right) - x_I - x_J}.$$

If $E_I < 0$, then:

$$\lambda = 100\left[\frac{T - x_I\left(1+\frac{E_I}{100}\right) - x_J\left(1+\frac{\lambda_0}{100}\right)}{\left(\sum_{i=1}^{N} x_i\right) - x_I - x_J} - 1\right];$$

if $E_I > 0$, then:

$$\lambda = 100\left[\frac{T - x_I\left(1+\frac{E_I}{100}\right) - x_J\left(1-\frac{\lambda_0}{100}\right)}{\left(\sum_{i=1}^{N} x_i\right) - x_I - x_J} - 1\right].$$

when:

E_I	= known percentage error
λ	= percentage correction for all other data
T	= total value of everything
$x_1,\ldots, x_n$	= members of the series
x_I	= value applying error to
x_J	= limiting change value
λ_0	= maximum percentage change for X_J