University of Southern Queensland

Faculty of Engineering & Surveying

Life Cycle Assessment in Electronics

A dissertation submitted by

Adrian Supurmaniam

in fulfilment of the requirements of

Courses ENG4111 and ENG4112 Research Project

towards the degree of

Bachelor of Engineering (Electrical and Electronics)

Submitted: October, 2004

Abstract

Our planets resources are being consumed at an extremely unsustainable rate. Renewable resources are being used up before they can replenish themselves, and non-renewable resources are depleting fast. In our current situation, it is not enough to merely recycle materials. Usually, by the time a product is manufactured, the damage is already done by overuse of materials, the use of non-sustainable materials and processes, and also by materials and processes that pollute the environment.

Life cycle assessment is the 'cradle to grave' analysis of a product, in order to identify the sources of excessive material consumption, and also manufacturing processes that cause pollution. Through the results of an LCA analysis, it is then possible to make decisions and improvements to current designs and processes. In the field of electronics, for example, the manufacture of Printed Circuit Boards can cause water and air pollution if not done properly. However, through Life Cycle equivalent studies, standards have now been developed for the proper and sustainable development of printed circuit boards. The same applies to many other electronic components and devices.

In this research project, all preceding work and studies on the subject matter has been covered. The current methodology for an LCA study has been covered from an International Standards Organization requirement standpoint. Finally, a suitable electronic product, a Calculator has been chosen for this study due to its similarity in terms of main components (Plastic outer casing, printed circuit board, smaller electronic components, rubber keypad, glass screen, and a battery).

From this, the methodology was implemented in the chosen LCA software (SimaPro v5.1), and Impact assessments were performed on the Calculator based on selected Impact assessment methodologies, then thorough sensitivity analysis was performed in order to check the validity and to justify all choices for data (materials and processes as well as disposal procedures). Finally, Improvement assessments have been made, for ease of comparison with other similar products. Any ideas for future work that have occurred during this project have been presented in the final chapter.

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111 & ENG4112 *Research Project*

Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Adrian Supurmaniam
Student Number: 0031034341

____

Signature

____

Date

Acknowledgements

This research was carried out under the supervision of Mr. David Parsons from the Faculty of Engineering at the University of Southern Queensland. I would like to thank him for his continuous assistance and patience during the course of my research.

Special thank must also go to Tim Grant, the Assistant Director at the Centre for Design at The Royal Melbourne Institute of Technology for all his assistance.

Table of Contents

List of Figures

Glossary of Terms

- LCA - Life Cycle Assessment
- Assembly - Collection of materials and processes that make up a product
- Life cycle - The complete useful life of a product, including use-phase products (such as batteries for a calculator)
- ISO - International Standards Organization
- PCB - Printed Circuit Board
- LCD - Liquid Crystal Display
- EEP - Electrical and Electronic Products
- RMIT - Royal Melbourne Institute of Technology

Chapter 1 Introduction

1.1 Authorization, Limitations and Scope of Report

1.1.1 Authorization

The research done for this project was commissioned by the Faculty of Engineering and Surveying, at the University of Southern Queensland as part of the Engineering Research Project ENG 4111 / 4112. The main aim of this study of Life Cycle Assessment (LCA) is to conduct an LCA on a simple piece of electronic hardware, and to develop an efficient method of evaluating and weighting data collected in the data collection stage to be used in the process improvement assessment. Currently, there are many different methods of converting this data into useful information. However, there is much dispute over which method is superior. Therefore, I intend to expand on these methods in an effort to make Life Cycle Assessment more accessible to non-professionals.

1.1.2 Limitations

Some limitations were encountered in the process of my research. One of the main limitations was encountered in the data collection stage. This is due to the fact that since Life Cycle Assessment is still in it's infancy, many corporations and research organizations find little need to publish such data. Some of the major research organizations as well as main software developers publish data lists for specific materials commonly used in production of physical products. The drawback is that such data is limited and information on more uncommon materials are usually not publicly available.

Another limitation is that the data used from SimaPro libraries are correct for European situations, but merely serve as a theoretical purpose for this research project.

1.1.3 Scope of Report and Overview of Project

This report covers a background (Chapter 2) of Life Cycle Assessment, Methodology used in the study, Current ISO standards, LCA development in Australia, the use of Life Cycle Assessment in Electronics, as well as the motivations and limitations of using LCA. It also covers the methodology used (Chapter 3) for the completion of this research project.

The next stage of this report (Chapter 4) covers the breakdown of the product being studied (calculator), as well as a justification for this product selection and the construction of a theoretical scenario in order to make this study as realistic as possible.

A guide is given (in Chapter 5) on the proper usage of the LCA software used in this study, which was SimaPro v5.1 (which was later replaced with SimaPro v6).This guide covers methods on defining an assembly in SimaPro, as well as defining lifecycles and disposal scenarios. It also covers the use of Impact Assessment methods and the use of Sensitivity Analysis.

An Interpretation of the LCA performed is provided according to ISO 14042 standards in Chapter 6. A life Cycle Impact Assessment is performed and analyzed in Chapter 7, and a Sensitivity Analysis is performed on this assessment in Chapter 8.

Finally, (in Chapter 9) the project is summarized, and overall conclusions are drawn about each sub-assembly in the Calculator. This is followed by an Improvement Assessment and recommendations for future work on the subject matter.

Chapter 2 Literature Review

2.1 Introduction and Background of Life Cycle Assessment

This chapter is written with the purpose of reviewing past and current literature which is relevant to the issue of Life Cycle Assessment. The reason for this review is to identify LCA concepts and ideas that have already been developed. This will prove the need for LCA to be incorporated by companies in their products, processes and other activities. In my literature review, I will address a few important points, which are:

- the different stages that a researcher must complete in conducting an LCA,
- different approaches taken in evaluating raw data acquired, and
- how the information can be used in directing company policies and decisions.
- Some of the benefits of using LCA, as well as motivation to use it, and
- The use of LCA in the electrical / electronics field.

In early times, people as a society did not worry about the issue of sustainability. The idea was that raw materials and fuels would last infinitely, and the environment would keep regenerating itself regardless of the amount of pollution and waste released by human processes. In recent times however, we have realized that our precious resources are not going to last forever.

According to Svoboda (1995) at The National Pollution Prevention Center for Higher Education, at the University of Michigan, one of the first efforts in researching sustainability was initiated in the 1960s when scientists were concerned about the rapid depletion of fossil fuel resources. The worlds increasing population and the impact on fossil fuels created an interest in studies regarding the impact energy consumption had on the usage of fuel in an effort to make consumption more efficient.

Later on, the Coca Cola Company conducted some research in 1969 to determine the effects of different soft drink containers on the environment as well as the demand for raw materials for each of the different types of containers. This showed that corporations were starting to get more environmentally conscious.

In the 1970s the U.S Environmental Protection Agency created the Resource and Environmental Profile Analysis (REPA). This methodology of assessing resource and environmental conditions was refined from the Coca Cola Companies efforts and driven by the oil crisis in 1973. Towards the early 1980s the worlds concern shifted towards the management of hazardous wastes. The most logical approach to this problem was to incorporate some sort of study of the life cycle of such products. This early form of life cycle assessment was used by the community as a part of their risk assessment programs, in order to develop environmental protection standards. The major problem with life cycle assessment in the early days was that it was usually carried out by companies *after* their product had been released, and only when it had their best interests at hand. One can see how such organizations may have omitted or purposely ignored negative information simply to boost company standings. As such, these early LCA's were highly undependable.

In the 1990s there has been a tremendous pressure to improve the environmental quality and to ensure that company production processes and activities do not have a significant impact on the environment. It is not only left up to the company to provide this assurance these days, but non-profit environmental organizations have also taken it into their hands to perform life cycle assessments on various products to provide some comparison between them. In this manner, companies are indirectly pressured to improve their processes due to the fear of being eliminated by more eco-friendly competition.

In 1997, the Royal Melbourne Institute of Technology (RMIT) in Victoria, Australia launched a joint project with the CRC for Waste Management and Pollution Control that was sponsored by the Environmental Protection Agencies from Victoria, New South Wales, Queensland, and South Australian Department of Heritage and Environment, as well as Environment Australia. This project was the start of Life Cycle Assessment efforts in Australia. Currently, the Centre for Design team at RMIT launched an Australian Eco-Indicator project in mid-2003. The motivation being to develop a Life Cycle Assessment Methodology for Australian conditions based on the Eco-Indicator '99 project that was completed in the Netherlands. The project is currently in the second stage which is data collection process. This will continue until sometime next year, when the third stage, weighting and data evaluating will take place in mid-2005. Details can be obtained from the Center for Design website http://www.cfd.rmit.edu.au/.

Although the apparent reason to use LCA would be to compare different products for environmental friendliness, such as different kinds of cans for beer, or the difference between nappies and diapers for babies, it is also a powerful tool which can be incorporated into an organization to guide their decision and policy making.

2.2 Life Cycle Assessment Methodology

Different research groups have developed their own methods for conducting LCA's. Each of these methods needs to be taken into consideration. The Society of Environmental Toxicology and Chemistry (SETAC) and The Institute of Environmental Sciences at the University of Leiden describe a complete LCA as comprising of 5 main stages. In sequential order, these are, *Planning, Screening, Data Collection and Treatment, Evaluation and Improvement Assessment*.

One of the largest, oldest LCA companies, based in the UK, Boustead Consulting Ltd. (2004) defines a life cycle assessment as having 3 main stages. First is the *Inventory* stage, where raw data is collected, then comes the *Interpretation* stage, where this data is related to specific environmental situations, and finally comes the *Improvement* stage where the system is modified to eliminate the environmental impacts observed in the analysis.

We can clearly see from this that no matter how different each set of LCA procedures are, they always come down to the same general few steps. For example, in the first approach, the *Planning, Screening, Data Collection and Treatment* stages collectively form the *Inventory* stage in the Boustead model. The Evaluation stage coincides with the *Interpretation* stage as they both involve converting raw data into usable information that relates processes to direct environmental impacts. Finally, the *Improvement Assessment* stage in the first model coincides with the *Improvement* stage in the second.

These similarities can again be seen in the Life Cycle Assessment Research Centers (2002) report on the ISO Committee's LCA model which includes the following steps:

- *Goal and Scope Definition*
- *Inventory Analysis*
- *Impact Assessment*
- *Interpretation*
- *Reporting*
- *Critical Review*

This is quite clearly similar to the previous two models, with slightly different wording. Other than that, we can safely conclude that generally, most life cycle assessments are quite identical, at least as an overview. They all indicate the need to study the system, define goals and scopes of study, the need to gather raw data, to evaluate and categorize this data, as well as the need to report on this data so that important decisions can be made to modify current processes.

2.2.1 Overview of ISO Life Cycle Assessment Methodology

The ISO set of standards for carrying out an LCA is defined in the set of documents ISO 14040 to ISO 14043. 14040 describes a clear overview of LCA practice, applications and limitations of LCA. It is meant to describe the system to potential users and those with a limited knowledge of LCA.

ISO 14041 provides special requirements and guidelines for the preparation, conduct, and critical review of an LCIA, which is the compiling and quantifying of raw data. ISO 14042 provides guidelines on conducting an impact assessment, which relates the data from the inventory to specific environmental impacts. Finally, the ISO 14043 document provides guidance on reviewing the scope of the LCA plus, the nature and quality of data collected.

These standards are very helpful for a researcher like myself who is just starting out in this particular field of research. A few researchers dispute the guidelines set out in these documents , but I cannot see any flaws in them.

2.3 Data Evaluation

Data Evaluation is a much disputed area of Life Cycle Assessment. Although there are many similarities in most areas of evaluation, many researchers dispute the most efficient way to relate raw data to environmental impact. Therefore, this section will examine these different views.

Svoboda (1995) at The National Pollution Prevention Center for Higher Education, at the University of Michigan suggests that a useful impact assessment should address ecological and human impacts as well as social, cultural and economic impacts.
The ISO 14042 standard addresses this stage of LCA. It says that all Life Cycle Inventory data should be categorized into different impact categories. These impact categories will have weightings so that the potential harm of each process can be easily identified. This will enable the more serious problems to be given priority over lesser ones.

This process of data collection, sorting and evaluation is made a lot easier through the proper use of LCA software. I researched a few of the best known software available in the market, keeping in mind that there was a budget involved with their purchase and use. First I wrote in, and requested a copy of the Boustead Model, which is a software used to solve LCAs according the Boustead methodology. This software turned out to be incredibly tedious to use, and was not very user friendly. I then discovered that many research organizations used and published data for SimaPro, an LCA software by the Pre Consultants in the Netherlands. This software was not only easy to use, and very user friendly, with a graphical user interface, but also, plenty of data was available, and is being updated constantly, by many reputed research agencies.

2.4 Improvement Assessment

Improvement Assessment is the process of using the Life Cycle Impact Assessment (LCIA) in stage two of the LCA and using it to make beneficial alterations to the current system. The reason for a review of this topic is to ensure that I have not overlooked any method of using the LCIA data as a decision making tool.

Marano and Rogers (1999) utilized the results of a Life Cycle Impact Analysis combined with linear programming, in order to provide them with the most cost efficient course of Improvement action to be taken. This is a small example of how LCIAs can be combined with other methods to form a decision assisting tool.

There is not much information available on the decisions made after the Life cycle analysis, as most documents simply detail the actual process of LCA but very rarely its post-assessment implications.

2.5 Life Cycle Assessment in Australia

The Australian Eco-Indicator project undertaken by the Center for Design at the Royal Melbourne Institute of Technology in Melbourne is the first large scale LCA project to be initiated in Australia.

This objective of this project is to create an environmental assessment methodology for Australia, based on the Eco-Indicator '99 method developed in the Netherlands. This aims to increase the usability and relevance of LCA for designers, policy makers and non-LCA expert users in Australia. It also aims to expose the environmental impacts of manufacture and processes currently facing Australia.

This project is very much like the Netherlands project, but complete LCAs need to be completed for Australian processes and situations so that a new methodology can be devised

2.6 *Life Cycle Assessment and Electronics*

LCA plays an important role in the field of electrical / electronics products (EEPs). In an Australian context, according to the Center for Designs report on Sustainable Development of Electrical and Electronic products (2001), each year, Australians purchase millions of electrical and electronic products. These products cause vast consumption of energy, water, detergent as well as a large amount of non-renewable resources.

EEPs contribute to such a significant portion of Australia's solid and hazardous wastes that the NSW government has proposed the idea of initiating a product take-back scheme so that companies would have the responsibility of recycling their own products.

The Center for Design outlines several design strategies that would help product designers aim for more sustainable EEPs that do not produce so much waste and by products. The following design guidelines generally apply to most electronic and electrical devices:

- minimise standby power consumption
- minimise warm up time
- power down as far as possible, as fast as possible after use
- minimise operation power requirements
- use efficient power supplies
- for equipment that uses paper, provide double sided copying and printing
- ensure controls for energy saving features are easy to use
- evaluate usage patterns to identify potential to store useful heat, and carry over energy for next task
- minimise heat losses and gains
- incorporate lightweight moving components
- optimise system efficiency under likely range of usage, including standby energy, part load operation

- where water is heated, minimise volume and heat losses and recover waste heat
- where heat must be transferred, optimize the process
- where ducts or pipes are part of the system, optimize insulation and size
- ensure where relevant products comply with the energy efficiency star rating scheme, and that 'point of sale' labels are clearly displayed and promoted.

These design criteria will be taken into consideration when I am making recommendations based on my Life Cycle Assessment of the Calculator being used in this project.

2.7 Motivations and Benefits of using LCA

The ICF Consulting Team (2004) identify one of the reasons for companies to start using LCA is that in today's society, it is becoming increasingly common for an organization to not only be held responsible for financial performance, but also for their impact on society and the environment.

The Center for Design at RMIT (2001) outline some of the motivations for corporations to incorporate LCA into their operations. Firstly, LCA will assist companies in breaking into markets overseas where they will be competing with other companies which use environmental strategies to market their products. It will also provide an edge in the local market where foreign competitors are trying to market their 'green products' which boast environmental efficiency.

Australian manufacturers are recognizing the possibility of LCA becoming a requirement in the near future and are changing to suit this trend. A law in force in Germany requires manufacturers to take back their goods after they have expired their useful lifetime. Obviously, this would promote the need for Life Cycle efficiency, so that materials used in production can be reused later on the in the manufacture of newer products. There is also the awareness that by utilizing materials that are non-renewable, there is a great economic loss, in the sense that the materials are lost forever after their useful lifespan.

The Environmental Management Center (2004) identifies one of the benefits LCA has over a Risk Assessment (RA). While an RA would help identify the risks involved and how to avoid them, what it usually does is to shift the risk to another area. LCA has the benefit of following all processes involved, from ‘cradle to grave’ so all negative elements can be eliminated along the way.

2.8 Limitations of Life Cycle Assessment

Guinee (2001) describes an analysis of the limitations of LCA processes as follows:

- LCA does not provide the capability to carry out a full fledge Risk Assessment study. This is due to the fact that by studying some chain effects, others have to be simplified.

- LCA focuses on the physical aspects of industrial activities instead of on market mechanisms and the secondary effect on technological development.

- LCA focuses mainly on the environmental impacts and fails to address social, cultural and economic impacts.

- Data is currently being compiled in several countries, and standardization efforts are being made, but the fact is that most of the time, this data is obsolete, incomparable or of unknown quality. Data is often available for blocks of processes, such as ‘production of phenolic compound’ instead of the separate processes used to get the compound.

- LCA cannot make decisions, but rather, the data from an LCA should be used to make decisions. LCA can never replace the decision making process. This is an important point, as the Impact Assessment and Sensitivity Analysis stages merely serve to analyze the impact of each sub-assembly, to determine which ones create the most impact. From this, decisions can then be made in the Improvement Assessment.

Chapter 3 Methodology

The following is the methodology I devised to assist me in the completion of my Life Cycle Assessment for this research project. It involves 3 main stages which are Inventory, Interpretation, and Improvement

3.1 Stage 1 - Inventory

In this stage, first, the calculator being studied was dismantled. The components were removed from the circuit board by use of a de-soldering braid and a soldering iron. The parts were then researched, according to commonly used parts in the electronic industry.

These parts were then inventoried by means of building an assembly in SimaPro. By researching commonly used materials for these parts, it was then a process of selecting the correct materials and processes in SimaPro. As there did not exist exact matches, this process had to be completed by means of substituting for the most accurate matches.

The next step in the inventory process was to build a life cycle and disposal scenario for the calculator .To do this, the batteries lifespan was calculated based on the LR1130 button cells data sheet. Based on this data, it was possible to calculate the average lifespan of the calculator (assuming only one battery was used).

To fit a disposal scenario to this project, with European data, based on Australian conditions, the closest match found was the treatment at a modern landfill. This suited the picture as most waste in Australia is treated at a modern landfill. At these landfills, materials that have been separated (glass, plastic, etc.) are treated separately and other waste is buried.

3.2 Stage 2- Interpretation

Once the assembly had been defined and built into SimaPro, it was then possible to carry out Impact Assessment Analysis.

This was done using 3 different Impact Assessment Methods (later detailed in Chapter 5, and 7). The main method was the Eco-Indicator '99 method, which was chosen due to its similarity to the current development of the Australian Eco-Indicator method (which was not yet available for use). The other two methods chosen, the CML 2 baseline 2000 method and the EPS 2000 method were chosen for control reasons. By performing an Impact Assessment using 3 methods, it would then be possible to eliminate any errors and to detect outliers in the results.

The next step in this stage was Sensitivity Analysis. This was the process of modifying the originally defined assembly, in order to determine the correctness and usability of data. In each stage of the modification, additional Impact Assessments were made, and analyzed to determine important changes in impact levels of each sub-assembly.

3.3 Stage 3 - Improvement

In this final stage, all the data from the Impact Assessments and Sensitivity Analysis was analyzed collectively. From here, it was possible to group all the analysis (according to my discretion as the analyst) to make an overall judgment on the sustainability of each sub-assembly in the calculator based on the three Impact Assessment methods chosen. Since 2 of the methods were damage oriented and 1 was product development (monetary and product usefulness) oriented, this created an interesting contrast (which is outlined in Chapter 9).

Based on the summary made on the individual sub-assemblies, it was now possible to analyze each of them according to current manufacture standards (from over the internet) and to make improvement assessments and also judgments about future work that should be done for this project as well as in the field.

Chapter 4 Life Cycle Assessment on a Calculator

4.1 Justification of Product Selection

The scope of my research project was to execute a Life Cycle Assessment on an electronic product using a software program to assist in the analysis. The LCA process is quite complicated, and simply compiling an LCA of a wood shed (which comprises of wooden planks and nails) can prove to be a long and tedious process of data acquisition and inventorying. After this, the data needs to be analyzed and interpreted, which makes the task even more arduous. With such complications arising even for the LCA of a wooden shed, one can imagine how problematical it must be to compile an LCA of an electronic product which has many intricate components.

There are two main reasons I chose a calculator to perform my LCA on. The first being its simplicity, and the second was its similarity (in terms of physical features and material construct) to other electronic products in the market.

The calculator consists of one Printed Circuit Board, which has two capacitors, a battery holder and a battery. This is connected to a Liquid Crystal Display, and operated by a silicon rubber keypad. All these components are housed inside a HDPE casing. This construct of a calculator makes it many times simpler to analyze than an electronic organizer, or a television set which consists of hundreds of (sometimes tiny and complex) electronic and other components. This makes the process of inventorying materials and processes much simpler.

On the other hand, the calculator is similar enough to more complex electronic products to allow for comparison. For example, if we compare mobile phones, televisions and calculators, all of them have a screen of some sort. Due to the complex nature of Liquid Crystal Displays and Cathode Ray Tubes, only the white glass is accounted for. This means that the television screen could be equated in rough terms with a calculator screen (except for the quantity of glass used). All the above mentioned products also comprise of Printed Circuit Boards, minor electronic components and screws (which is accounted for as steel), silicon rubber keypads (on the remote control for a television set), and a hard plastic casing usually made of HDPE.

These products also contain a battery or receive a power supply of some kind. In fact, this may be the only piece of data that may differ greatly between varying electronic products, as mobile phones, etc. would contain more powerful batteries than calculators, and television sets would receive a direct power supply (in this case, electricity consumption would be calculated for an LCA, and copper for the mains wiring would be accounted for in the product assembly).

4.2 *The Calculator Scenario*

Due to the fact that not all information was available for my scope of study, I created a theoretical scenario, by which to explain the rationale behind assigning certain materials and processes to the LCA.

The version of SimaPro that was obtained by the University did not include the Australian data set that had been compiled by the Royal Melbourne Institute of Technology (RMIT) in their Australian Eco-Indicator project. Instead, it included mostly European data. The calculator, on the other hand, was manufactured in China.

Figure 4.1 - ***satellite map of the region with shipping route indicated***

In order to work as accurately as possible with available data, I created the scenario in which I used European data for the materials and processes involved in the manufacture of the calculator in China. From China, the calculator is then transported via a Container Ship to the Port of Brisbane, from where it is transported by truck to Toowoomba, where I purchased it. Once again, the data used for international shipping (China – Australia) and Australian trucking (Brisbane - Toowoomba) are all European. It is therefore imperative to note that the calculations done by myself and those generated in SimaPro are the closest, most educated solutions, but are not valid in a real world scenario. However, it should prove to provide us with a clear picture of what goes on when a product such as this is manufactured in China, and shipped to Australia.

According the China Shipping Lines, there is a direct container ship service that comes from Shanghai, China, and unloads in Brisbane, Sydney and Melbourne Australia. I chose to select the Shanghai – Brisbane route for ease of calculation. From this, we obtain the following distances for cargo transport:

Shipping (Shanghai – Brisbane)

According to the China Shipping Australia Company, a Container ship that leaves Shanghai, China on a direct voyage to Brisbane takes a total of 13 days. According to the SimaPro data for an Average Container ship, it travels at a speed of 43km/hr.

From this, it can be calculated that the ship travels a total of 13416 km.

Truck (Brisbane – Toowoomba)

Toowoomba is located inland about 180 km from Brisbane.

From these figures, it is possible to construct an assembly of the product that is quite complete in a theoretical sense.

4.3 *Breaking Down the Product*

Before a thorough Life Cycle Assessment could be carried out in SimaPro, the Calculator had to be broken down into smaller parts called sub-assemblies. This is done to group the components that make up the Calculator by their materials. The following flowchart (taken from SimaPro) shows the main assembly of the Calculator being broken down into its sub-assemblies and these sub-assemblies being broken down into the separate materials and processes involved in their production.

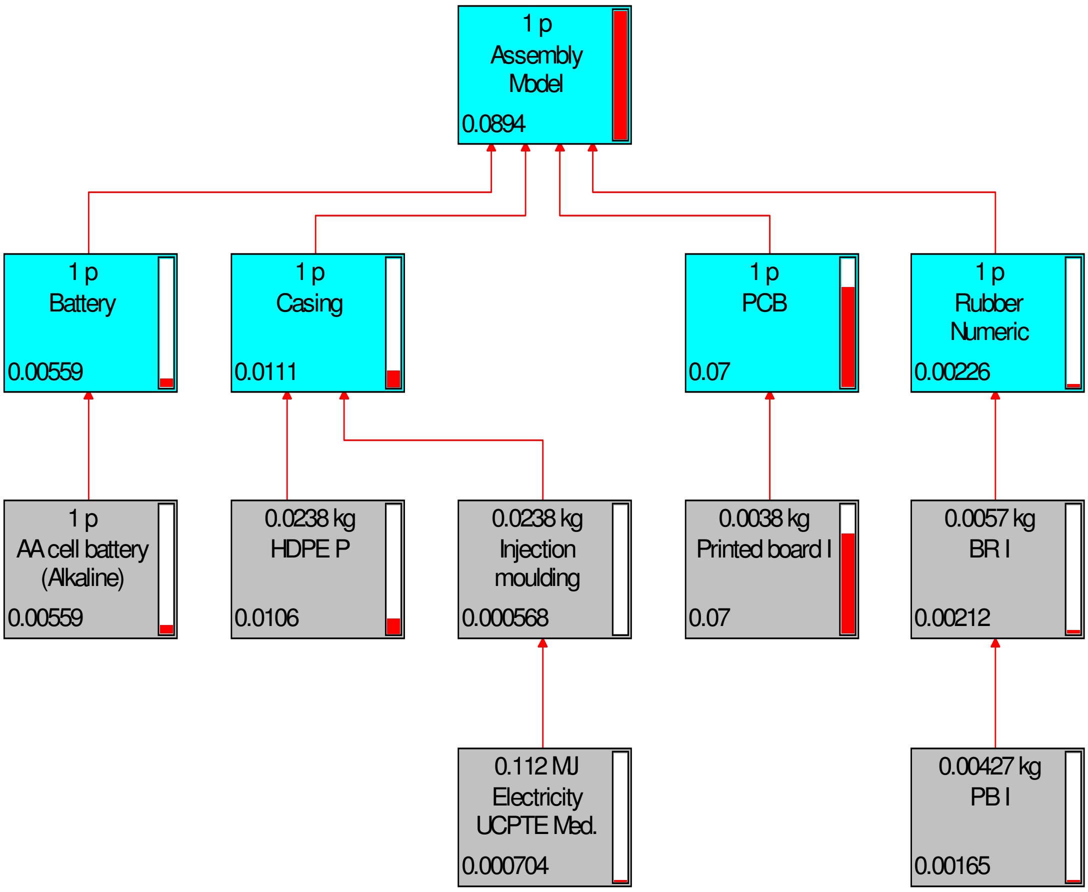

Figure 4.2 - ***Assembly tree showing the sub-assemblies and materials / processes***

From this breakdown, we can see that the Assembly model is broken down into 5 sub-assemblies. It is also apparent from this assembly diagram that the UCPTE Electricity (Electricity supply by the Union for the Co-ordination of Production and Transmissions of Electricity in Western Europe) for the Injection Moulding process is taken into account. Also taken into account is the process used to form the rubber numeric keypad from Butadiene Rubber (reinforced 25%).

It is important to note that the diagram above is simply shown for illustrative purposes only. Not shown in the diagram is the Liquid Crystal Display (LCD) and the Smaller Parts (2 Capacitors, 2 Screws, and the Battery Holder). At first, it was not clear why SimaPro did not display these sub-assemblies. During sensitivity analysis (refer to Chapter 8) however, when the glass was changed from 'White' to 'Virgin', it appeared on the network diagram. This could have been because the 'White' glass did not have a large enough impact contribution to be worth showing on the diagram.

Later on, I confirmed this theory by changing the quantities of the LCD and Smaller Parts to some nonsense high number. All the sub-assemblies were now shown on the diagram. This would mean that if a sub-assembly contains an extremely low impact on the overall system, SimaPro would leave it out of the picture, as this would help place focus on the important sub-assemblies.

(Refer to Appendix B for a list of parts and weights).

Chapter 5 Compiling an LCA in SimaPro 5.1

5.1 Introduction to SimaPro

SimaPro 5.1 is the Life Cycle Assessment software that I chose for this study. Before this selection was made, other possible software choices were first researched. Two of the more prominent software in the market is listed below:

<u>GaBi 4 Software System</u>

(http://www.environmental-expert.com/software/pr_eng/pr_eng.htm)

The GaBi 4 Software system uses environmental impact data collected by the PE Consulting Group at Environmental Expert dot Com. Data compiled and analyzed using this software can only be shared with it's sister software SoFi which is a sustainability analysis software.

Although this software features 650 data sets from industry averages, the use of impact assessment methods such as the Eco-indicator 99, and CML 1996 / 2001, and also a certain ease of functionality, it was not the best choice of software out there since SimaPro 5.1 incorporated all these features, and it had better features in terms of user friendliness, and compatibility with the data set being developed by the Royal Melbourne Institute of Technology (RMIT) in their Australian Eco-Indicator Project.

<u>The Boustead Model</u>

The Boustead model is a computer modeling tool developed for calculating Life Cycle Inventory calculations. This model, if used properly, can be effective. However, it is quite a complicated model, and not very user friendly. Data has to be entered manually, and printouts are complex to decipher.

5.2 Learning to Use SimaPro

As this, or any Life Cycle Assessment software is substantially different from any other software I had used before, there was a learning curve in reaching a thorough level of understanding of SimaPro 5.1s functionality. I could not start work on my particular project immediately, but instead, had to work on several simpler LCA projects in order to determine the proper was to enter data and methods of conducting an extensive interpretation on the analysis performed. There is no easy way to learn how to use SimaPro. I would suggest that anyone keen on learning how to use it start by playing around with the software at every given opportunity, and get acquainted with it by compiling Assemblies of simple products (products that only contain one or two materials / processes). This will also simplify the process of conducting an analysis on these simple assemblies.

There were also a few setbacks, such as a wait period for the university to obtain a full version of the program. In these initial 4 months before obtaining a copy of the software on the faculties servers, I used to demo version available freely over the internet at http://www.pre.nl/simapro/download_simapro.htm.

The demo version offered only limited functionality, with the inability to create a new project. It was still a good tool to learn about the software, but could not be used for any proper research since the demo version could not be saved, copied, imported or exported.

As a start, I worked through the SimaPro 'Guided Tour with Coffee', the 'Tutorial with Wood' and the 'LCA Wizard', each of which gave me valuable insight into the workings of the system.

The guided tour shows the user the various stages of entering data to form an assembly, defining life cycles, disposal scenarios and so on. With this guided tour, the user can only observe pre-programmed data entries and guides a beginner through the main functions of SimaPro as well as the different Impact Assessment Methods that may be utilized in each study.

The Tutorial with Wood leaves the user with the knowledge gained from the guided tour, and lets you look through a Life Cycle Assessment that was compiled on the assembly of a Wooden Shed. Since the guided tour demonstrated the capabilities of SimaPro, this Tutorial allows the user to play around with the template-like structure of the program, as well as allowing them to perform an analysis on the pre-defined assembly using the different Impact Assessment Methods available.

5.3 Applying the LCA Methodology in SimaPro

5.3.1 Description of Project (Goal and Scope Definition)

Before commencing any Life Cycle Assessment project, it is wise to outline certain details to guide the analyst through the study. In SimaPro, an LCA project is set out like a template. There are 5 main categories (each of which contains several sub-categories) in this template. These are:

- Goal and Scope
- Inventory
- Impact Assessment
- Interpretation
- General Data

The layout of the template can be seen in the screenshot below, which shows the Goal and scope definition screen.

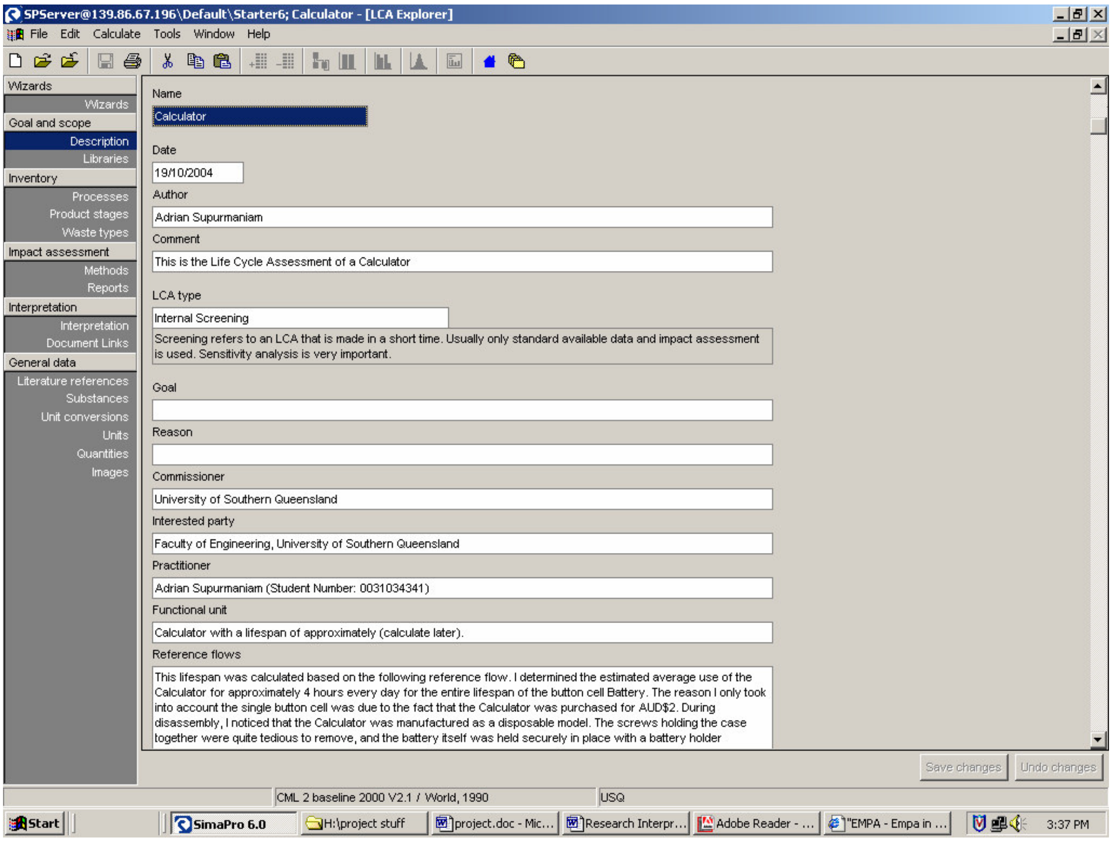

Figure 5.1 – *Goal and Scope Definition Screen*

The first four categories represent the 4 main stages of any LCA study. The last category, General Data contains minor details and information that may be needed in some studies. This includes things like literature references, lists of substances available for use in projects, lists of units and unit conversions, names of quantities and dimensions, and clip art images that can be used to visually describe assemblies within a project.

With my project, as it is with many other projects, systems are constructed for study based on models. These models are often simplifications of real world situations, and often, over-simplification may result in the distortion of reality. With this in mind, the main reason for defining a Goal and Scope before carrying out any study is to ensure the model is constructed in such a way that these simplifications do not affect the outcome of the study too much. Even if they do, the outlier results can be traced back to specific objectives set out for the study.

The description of the project is set out in Goal and Scope. In this section, the user may define any specific comments about the study, the type of LCA, Goal, Reason for conducting the study, as well as provide a description of the Functional Unit, with Reference Flows and Alternative Scenarios.

The type of LCA being carried out is an 'Internal Screening', which refers to an LCA which is carried out in a relatively short time, and uses mainly standard available data. Since I only had the span of approximately 4 months to complete my study, and the data used was mainly from 3 libraries available with SimaPro, this method of LCA was selected.

The concept of the Functional Unit and Reference Flows may be new to many, as they would not have been used except in other Life Cycle type studies. According the SimaPro User Manual, the example of comparing 2 different products (for example a Milk carton and a Milk bottle) is given. 1 Milk Carton cannot be compared to 1 Milk bottle, since the Bottle is reusable (perhaps 10 or more times) and the Carton is disposable. In this manner, it would be more logical to define the individual functional units of the Milk Carton as 1 use, and the Milk Bottle as 10 uses. In this way, a reference flow can be created to compare 1000 Milk Cartons to 100 Bottles.

For my project, I defined the Functional Unit as a Calculator with a lifespan of approximately 1 year. This lifespan was calculated based on the following reference flow. I determined the estimated average use of the Calculator for approximately 4 hours every day for the entire lifespan of the LR110 button cell Battery. The reason I only took into account the single button cell was due to the fact that the Calculator was purchased for AUD$2. During disassembly, I noticed that the Calculator was manufactured as a disposable model. The screws holding the case together were quite tedious to remove, and the battery itself was held securely in place with a battery holder (mounted on the Printed Circuit Board) and this had to be pried open with a screwdriver to remove it. According to this flow of reasoning, I concluded (for the sake of this study) that in the most logical, everyday scenario, an average user would use this Calculator for only as long as the Battery lasted.

The preceding Functional Unit and Reference Flows help to define the project, limiting the study to one Calculators lifespan based on the duration of the battery.

It is also necessary under Goal and Scope definition to select the data libraries being used for each project. Each data library is unique and can be used in collaboration with each other to build assemblies, life cycles and disposal and reuse scenarios. For my LCA, 3 different libraries are used. These are the IDEMAT 2001, BUWAL250 and the SimaPro Data Archive. A short description of each of the different libraries used as well as a listing of sub-assemblies defined from data in these libraries is provided below.

IDEMAT 2001

The Department of Industrial Engineering Design at the Delft University of Technology developed this database. The data contained within this database is original (obtained through research work done by the department), and not derived from other databases.

This is a fine database to use for most international situations since an 'average world situation' is accounted for. However, while suitable for use as a local data substitute, the data is actually only valid in the Netherlands. The IDEMAT 'Manual for Designers' (available through IDEMAT Online) defines the term 'Eco' as the '*Environmental effects that damage ecosystems or human health on a European scale.*' This is due to the fact that the values are calculated based on the impact caused by an 'average European on an average day'. A more thorough understanding of sources of information in this database can be obtained through reading the 'Manual for Designers'.

The inventory includes mining, concentration and processing in case of minerals, and also harvesting and processing of agricultural materials. The way this database was compiled was by compiling 'environmental scores' through emissions recorded through industry averages in Europe. The diagram below (taken from the IDEMAT Online website), shows how these emissions are linked to environmental scores, also known as Eco-indicator values.

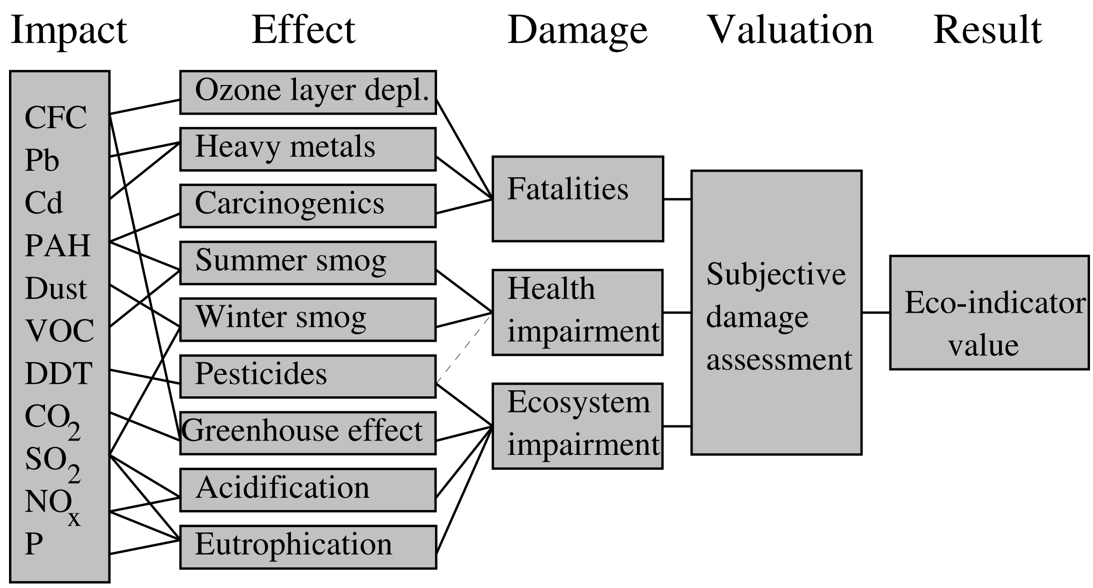

Figure 5.2 – ***Eco-indicator calculation process***

The Eco-indicator values are actually values obtained through a thorough Life Cycle Assessment carried out on common materials and processes. The values are an indicator of how bad the environmental impact is. The higher the value, the worse the impact.

The sub-assemblies for this research project defined using this library are listed below:

- Battery
  Alkaline Battery (Handbook of Batteries, Linden)

- Printed Circuit Board
  Printed Board I (Western Europe)

- Rubber Numeric Keypad
  Butadiene Rubber (BR I, Western Europe)

BUWAL 250

This is the inventory of packaging materials developed by the Swiss Federal Laboratories for Materials Testing and Research (EMPA) for the Swiss Packaging Institute. All data provided in this database is derived from research in a Swiss situation. No more information was freely available about this database except what is presented below.

This databases inventory includes emissions from raw material production, energy production, the production of semi-manufacturers and auxiliary materials, transports and the production processes of materials. It also includes several waste scenarios, one of which has been used for this project.

The sub-assemblies for this research project defined using this library are listed below.

- Liquid Crystal Display
  Glass (white) B250 (Swiss, Western Europe)

- Smaller Parts (2 Screws, 2 Capacitors, Battery holder)
  ECCS steel 20% scrap (Swiss, Western Europe)

SimaPro Data Archive

This is data collected from industries by industry associations, and is usually outdated. However, where little information is available, or if the information contained in the other (more up to date) libraries are not entirely suitable, this Data Archive was used. There is no more information available on this Data Archive, since it was only available with SimaPro 5.1, which was removed prematurely by Information Technology Services at The University of Southern Queensland, before I could finish research on my project. It was later re-installed as SimaPro 6.0 which did not include this Data Archive.

The sub-assemblies defined using the Data Archive are listed below:

- Plastic Casing
  HDPE P (Western Europe)
  Injection Moulding (Western Europe)

- Rubber Numeric Keypad
  Blow Moulding (Western Europe)

5.3.2 Defining an Assembly in SimaPro

The next step in performing an LCA is to define an assembly. With a simple product, such as a plastic bottle, this would be a relatively simple task. All that would need to be defined is the processing of raw materials for the plastic, and the actual manufacture of the bottle from the plastic. With a more complex assembly such as the Calculator, where there are many diverse parts involved, it becomes necessary to define sub-assemblies.

To explain the process simply, the whole Calculator is defined as the main Assembly. Under this, 6 separate sub-assemblies are defined, for the Plastic Casing, Liquid Crystal Display, Rubber Numeric Keypad, Printed Circuit Board, Smaller Parts and the Battery. A breakdown of the Assembly into the separate sub-assemblies can be seen in Chapter 4, under 4.3 Breaking Down the Product. We can see in the screenshot below, how all the sub-assemblies are linked back to the main assembly.

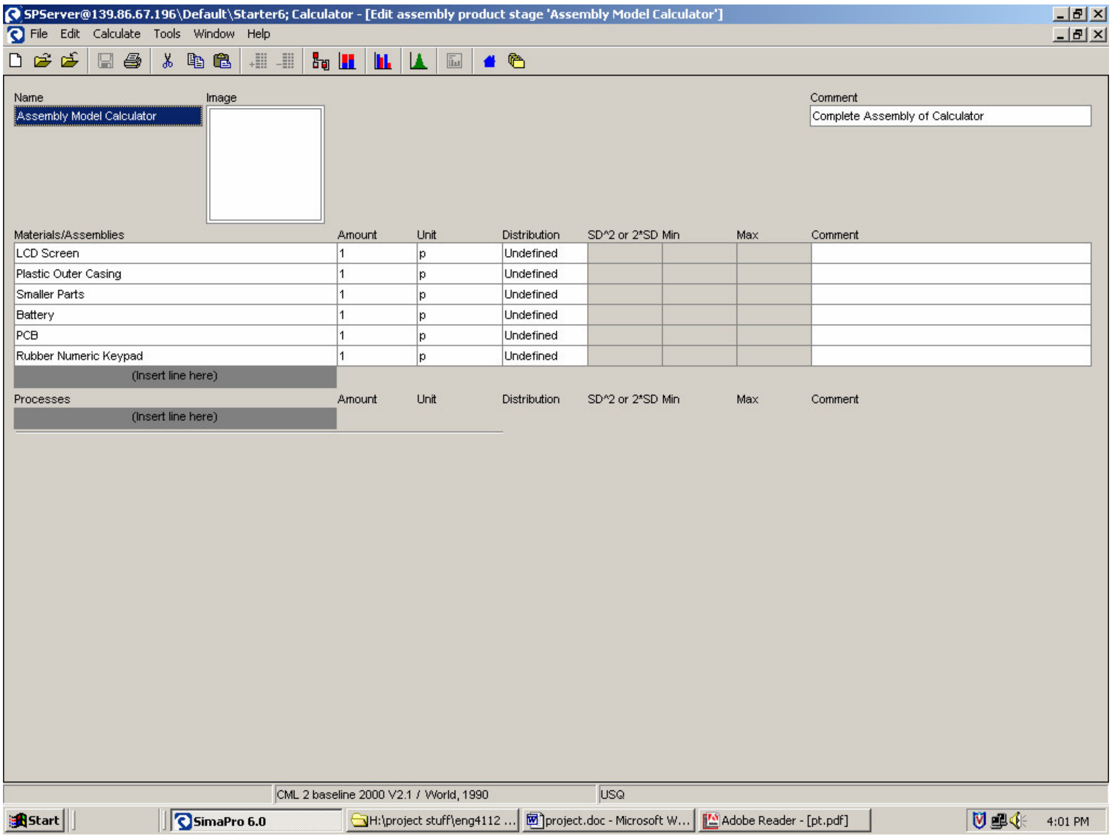

Figure 5.3 – ***Assembly Definition Screen***

Under each sub-assembly, the analyst can define materials and processes involved in its manufacture. Below is a screenshot of the definition of the Plastic Casing. We can see that the material used (HDPE P) and the processes used to form this material (Injection Moulding) into the Calculators Plastic Casing are included.

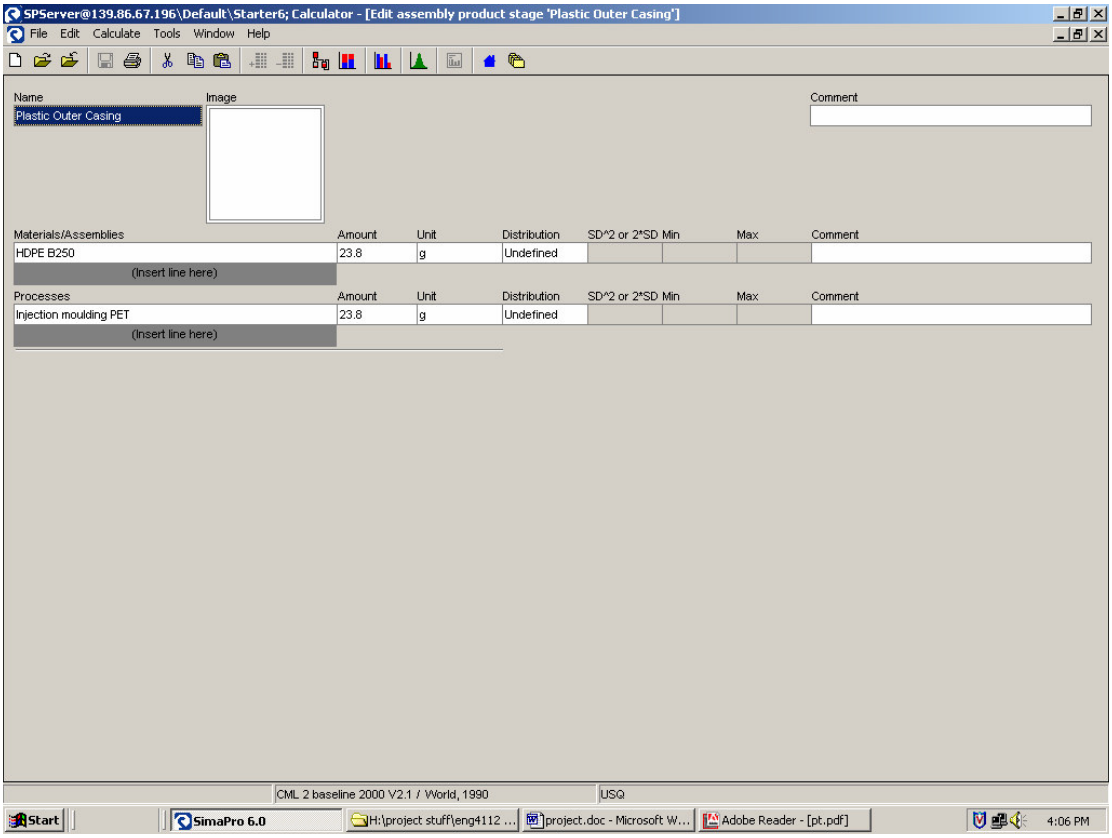

Figure 5.4 – ***Sub-assembly Definition Screen***

5.3.3 Defining Life Cycle and Disposal Scenarios

The Calculator is a relatively simple product, and therefore, its Life Cycle does not involve many components. During its 'use-phase', the only real disposable item is the battery. Since the entire Life Cycle only takes into account one battery, this isn't even a problem anymore. This means that the Calculator being studied is just one entity by itself until disposal.

The following screenshot shows the Life Cycle screen which is used to link the Life Cycle Stage to the main assembly. Also, the disposal of the Calculator in a Modern Landfill is defined.

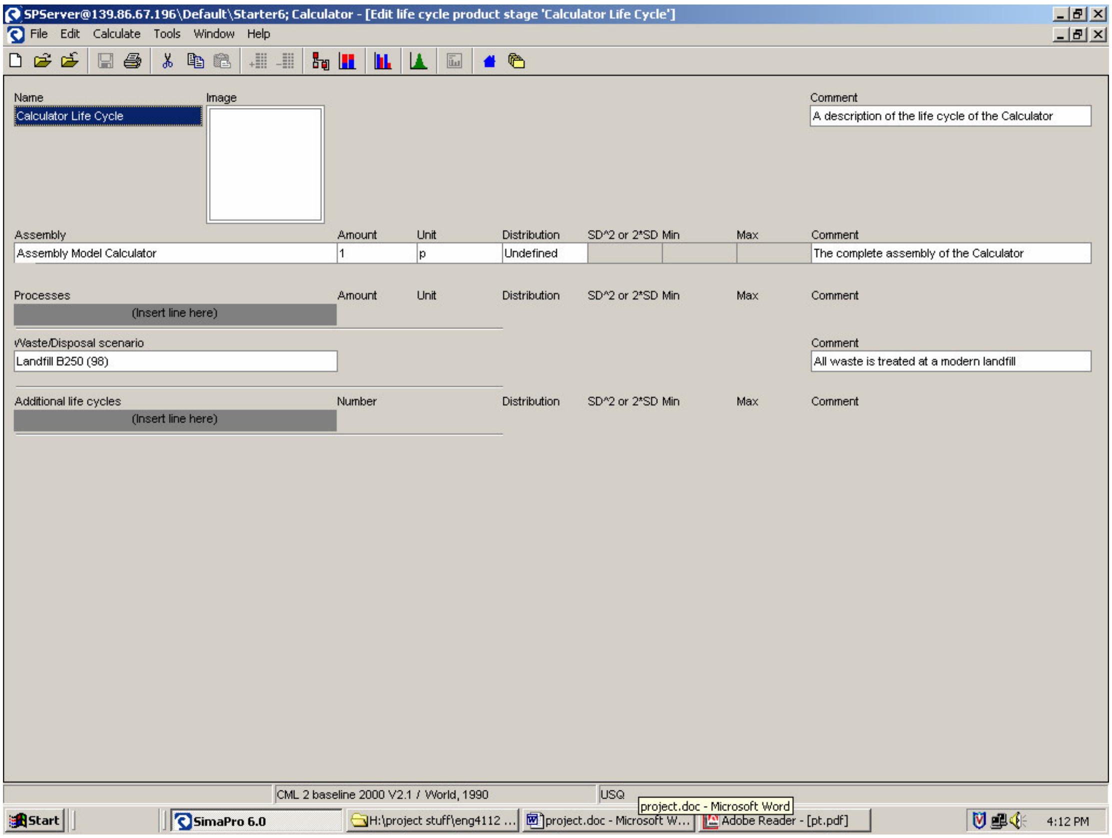

Figure 5.5 – ***Life Cycle and Disposal Definition Screen***

To define a disposal scenario, I used the following sequence of reasoning. In an ideal world, the user would dismantle and recycle each individual part of the assembly. This would involve separating the Metal (battery holder, screws, and capacitor parts) and Glass (from the Liquid Crystal Display), from the HDPE Plastic Casing. Each part would be treated appropriately, and this would result in a more sustainable situation. However, in a more logical scenario, the average household will not bother to separate the assembly in this way. Since the Calculator only costs a minimal amount (refer to the Functional Unit and Reference Flows in the Description of Project in the beginning of this chapter), it is assumed that once the battery expires, the Calculator goes into the trash, and is then treated at a modern landfill. The data for the landfill comes from the BUWAL 250 library.

5.4 Impact Assessment Methods and the use of Sensitivity Analysis

The process of Impact Assessment involves the linking of each specific process to specific environmental impacts. Often, one manufacturing or transporting process will lead to many smaller emissions and impacts on the environment. An Impact Assessment Method is a compilation from research done by a certain organization. This organization conducts a study on different processes present in their particular area, and produces a methodology for linking these processes to environmental impacts.

SimaPro 5.1 offers a range of Impact Assessment Methods that can be selected after the initial process of constructing an assembly and life cycle and disposal / reuse scenarios. The main method I selected for my research was the Eco-Indicator '99 Method developed in the Netherlands. This is a damage oriented method and has been designed for user friendliness. It has also become the basis for the Australian Eco-Indicator Project being currently executed by the Royal Melbourne Institute of Technology (RMIT). Another 2 methods were also selected for comparison. These were the CML 2 baseline 2000 method and the EPS 2000 (product development) method, all of which are detailed in *Chapter 7*.

Once the Calculator assembly had been defined, an Impact Assessment was performed using the 3 selected methods from SimaPro. Since the assembly was built using standard data from Databases in SimaPro, it was important to use Sensitivity Analysis to re-evaluate these data choices (for materials and processes) to make sure that the most sustainable solutions were chosen. In order to do this, materials and processes were substituted for other values, and separate Impact Assessments were carried out as a sensitivity analysis (detailed in Chapter 8).

Sensitivity analysis was extremely important in this study, not only to determine the validity of data choices, but also to verify the validity and appropriateness of Impact Assessment Method Choices.

Chapter 6 LCA Interpretation

6.1 Interpretation

The interpretation of the Life Cycle Assessment is the important step of converting raw data, and SimaPro impact assessment output into a summary of observable impacts against expected output. This should be documented in such a way that it is possible to use it as a basis for comparison with the LCA's of other similar products. The International Standards Organisations standard ISO14043 provides guidance for the interpretation of results from an LCA study. The interpretation of my research project LCA follows these guidelines as closely as possible.

The use of sensitivity analysis is very important in this section as it assists in determining the relevance of results. A sensitivity analysis is the process of varying the inputs to a sub-assembly, in this case, the materials and processes that go into that sub-assembly, in order to determine the effects of this change to the measured output (environmental impact in each category or overall).

The purpose of this project was to perform a Life Cycle Assessment on a basic electronic product to see how the common components that form the construct of these products may impact the environment. I also explore options for improvement through the use of sensitivity analysis.

6.2 Consistency Check

The inventory data of the calculator assembly utilizes data from BUWAL250 and IDEMAT 2001 as well as SimaPros Data Archive. The Data Archive has data that is, in principal, outdated (1990s) but is still valuable. This data is used when it is the best apparent selection among the others available. This section looks at the important similarities and discrepancies between these data sets in order to determine the extent to which they affect the outcome of the study.

6.2.1 System Boundaries and Capital Goods

The use of system boundaries was important in this study to outline the actual goals of the study. Without these cut-off criteria, it would be difficult to obtain proper usable results from the study as the data would be far too vast. System boundaries set for this study were:

Time Period:	2000 to 2004 (time of manufacture / time of data periods)
Geography:	Asia, China and Australia (manufacture of calculator and use geography)
Type of Technology:	Average / Outdated Technology
Representativity:	Mixed Data / Average from processes with similar outputs / Average of all suppliers / Theoretical Calculation
Cut-off rules:	Less than 1% physical criteria / Less than 1% socio economic criteria / Less than 5% environmental relevance (These percentages are chosen based on requirements of individual studies. For example, here I have chosen to not pay so much importance on the physical and socio-economic criteria, and more importance on the environmental criteria.)
System Boundary:	Second and Third order (material / energy flows including operations and capital goods)
Boundary w nature:	Agriculture is part of production system

The definition of capital goods according the Wikipedia (The Free Encyclopedia) is any goods that can be used to make other goods and services, is man made (not naturally occurring), and is not used up immediately in the production process (unlike raw materials and intermediate goods).

The use of capital goods in my analysis was extremely limited. The only actual capital good taken into account was the UCPTE Electricity used in the Injection Moulding and the molding of the rubber numeric keypad.

6.2.2 Regional Aspects

This project uses data from 2 main libraries, which are the BUWAL 250 and IDEMAT 2001 (both detailed in *Chapter 5*). These libraries contain data from Switzerland and from Europe. This data is being used in collaboration with an Impact Assessment method from the Netherlands (Eco-Indicator '99) and also a method from Sweden (EPS 2000).

Together, this information and methods are used to analyze an electronic product (calculator) manufactured in China, and the data for transport and any assumptions made are for an Australian condition.

6.2.3 Representativity

Representativity is split into two main categories. The type of technology used in the study and the main sources of data. The reason for identifying these portions of information is to ensure that the correct type of information is obtained.

Since the Calculator was manufactured in China, and then shipped and consumed in Australia, the region selected was both China and Australia.

The calculator is quite a simple model, and only contains basic components. By comparison to other products in the market, we can see that today's calculators have many modern features which are not incorporated in the model in focus. This shows us that the Calculator has outdated, or at best, average technology.

As for the sources of data used in this project, the exact company which manufactured the Calculator was not identified. Nor was manufacturing information for China readily available. The only information on manufacturing materials and processes available was from the data Libraries in SimaPro. Therefore, the types of information identified to be used in this project was mixed data (data from old archives), average data from processes with similar outputs, average data from all suppliers, and theoretical calculation (calculation of transport from China to Australia and transport within Australia, as well as the calculation of weight of smaller parts in Calculator).

It should also be noted that the Average date from all suppliers and Average data from processes with similar outputs are averages from processes and suppliers in Western Europe.

6.3 Contribution Analysis

In this section, the processes from the calculator assembly that contribute considerably towards the Life Cycle Impact Assessment results are examined. In the SimaPro Life Cycle Impact Assessment (LCIA) screen, there is a separate tab for Process Contribution. In this section, the user is shown a table with the contribution of each process used.

These process contributions can be viewed from many different information perspectives. An analyst can view the actual amount of contribution or a standardized 'single score' contribution, in which processes contribution can be compared to other processes. One can also view the Damage Indicator, Normalized Indicator, and the Weighted Indicator, in which impacts on Human Health, Ecosystem Quality and Resources can be analyzed. There is also an Impact Indicator, in which specific impacts on the environment from these processes is shown. The 'cut-off' option can be used to eliminate processes that contribute an insignificant amount of impact to the study.

There are 13 main processes that occur in the calculator assembly. Out of this, only 8 processes contribute to more than 0.1% of the total environmental load if the Eco-Indicator 99 is used.

If a 1% cut-off is used, only 4 processes remain significant. These are the manufacture of the Printed Circuit Board (PCB), High Density Polyethylene (HDPE P), alkaline battery, and Poly-butadiene.

At 5%, only the PCB, the HDPE P, and the alkaline battery remain significant processes. The PCB has the highest impact, as it remains significant right up to a cut-off point of 78%.

These process contributions can also be viewed as a bar chart or a pie chart.

6.4 Anomality Assessment

This section is reserved for unexpected or unusual results. Outliers in project outcomes usually indicate errors. Up to this point, none have been discovered.

6.5 Mismatch between Inventory and Impact Assessment

This project utilized a number of Impact Assessment Methods. These are discussed in terms of compatibility with the projects Life Cycle Inventory. Specifically, the methods used are the CML 2 baseline 2000, and the Eco-Indicator 99.

There are 3 different versions of Eco-Indicator 99. These are the versions from the egalitarian perspective, the hierarchist perspective, and the individualist perspective. In the egalitarian perspective, impacts are viewed in a very long time frame. All substances are included as long as there is any indication of an impact. From this perspective, damage is unavoidable, and leads to catastrophe. From the hierarchist perspective, impacts are also viewed from a long-term viewpoint. Substances are included if its impact is agreed to be significant. According to this perspective, damages can be avoided through good management. The final version is the individualist perspective, which is viewed from a short-term perception (100 years or less). From this perspective, substances are included only if there is irrefutable proof of significant environmental impact. It is the notion that it is possible to recuperate from damages caused by these substances through technological and economic development. This perspective also assumes that fossil fuels cannot be depleted.

From this analysis of the different versions of Eco-Indicator 99, I have chosen to use the hierarchist perspective since this includes a long-term consideration of effects, and only moderately significant substances are included in the Impact Assessment. Also, it would be possible to consider techniques of reducing or eliminating these impacts through good management.

When using the Eco-Indicator 99 (H) to analyse the assembly, SimaPro generates a list of substance results that were not covered in the method. This is found in the LCIA screen, under the ‘checks’ tab. In this project, 255 substances were listed. Using the CML 2 baseline 2000 method, 238 substances were listed, meaning these substances were not covered by this method. From this list of unlisted substances, an analyst can determine how extensive the mismatch is between the Impact Assessment Method used, and the Life Cycle Inventory of the product.

For this project, the mismatched substances were frequently similar between the 2 main Impact Assessment Methods used. Almost all of these substances existed only in very small quantities, and I believe that there are not significant to the outcome of my LCA.

Chapter 7 Life Cycle Impact Assessment

7.1 Introduction to Life Cycle Impact Assessment

In the stage of Life Cycle Impact Assessment, or LCIA, Impact Assessment methods are used to link each of the materials and processes in the Calculators lifespan to a specific environmental impact. Each of the Impact Assessment methods used for this research project have been outlined and detailed. These are the Eco-Indicator '99 Method, the CML 2 baseline 2000 Method, the Ecopoints '97 method. They were selected based on the suitability of the Impact Assessment categories, and also since they were the most up to date methods being used today.

In this section, the methodologies that make up these Impact Assessment Methods will be explained in some detail, and also the range of impact assessment categories that they feature. A description of each impact category is adapted from the SimaPro 6 Database Manual (provided with SimaPro v6). Then, each of these methods will be applied to the calculator assembly in order to perform a Life Cycle Assessment. A Sensitivity Analysis is also performed on each of the sub-assemblies to determine if the impact contribution of each can be reduced through the use of different materials or processes.

It should be noted that where percentages are used to indicate the impact contribution of sub-assemblies to impact categories, they represent the percentage of impact caused by the sub-assembly against the total assembly. This means that the assembly as a whole would cause 100% impact in all categories affected.

Next, each of the sub-assemblies involved in the assembly of the Calculator are discussed according to the results obtained from the analysis obtained from each Method.

7.2 *Eco-Indicator '99 (Netherlands Impact Assessment Method)*

This Impact Assessment method was initially developed under a Dutch program in 1995. It was part of an environmental initiative by several companies including Philips Consumer Electronics and Volvo / Mitsubishi. The method was continuously updated up to the year 2000 and is highly compatible with ISO 14042 requirements.

This method was mainly designed to be user friendly and to allow for environmental impact scores to be turned into a design improvement tool for designers and product managers. The methodology presented by this method is currently one of the most widely used in the world. It features more than 200 predefined eco-indicator scores for commonly used materials and processes, and updates are constantly available (depending on service agreements of software used).

Although this method features many different impact categories including Carcinogens, Respiratory organics / inorganics, Radiation, Acidification / Eutrophication, Climate Change, Ozone Layer and Minerals, each of which is discussed below.

- *Carcinogens* (Measures emissions of carcinogenic substances to air, water and soil).

- *Respiratory inorganics* (Measures respiratory effects of emissions of dust, sulphur, and nitrogen oxides to air resulting from winter smog).

- *Respiratory organics* (Measures respiratory effects of emissions of organic substances to air resulting from summer smog).

- *Climate change* (Measures damage (diseases and death) caused by climate change).

- *Radiation (*Measures damage from radioactive radiation).

- *Ozone layer (*Measures damage due to increased UV radiation resulting from emissions of ozone depleting substances to the air).

- *Ecotoxicity* (Measures emissions of ecotoxic substances to the air, water and soil and the damage caused to the ecosystem quality).

- *Acidification / Eutrophication* (Measures acidifying substances to the air, and the resulting damage on ecosystem quality).

- *Land use* (Measures the damage resulting from the conversion or occupation of land).

- *Minerals* (Measures decreasing mineral grades and the resulting surplus energy used to mine each extra kg of mineral).

- *Fossil fuels* (Measures lowered quality of resources and the surplus energy used to extract each MJ, kg or m3 of fossil fuel).

It only has 3 main endpoints in its damage assessment stage. These are Human Health, Environment and Resources. This means that SimaPro will output a single bar graph (a Damage Assessment graph was unable to be reproduced) that shows the proportion of damage caused by each of the sub-assemblies being analyzed. Some Damage Assessment has been made in Chapter 8.

There are 3 versions of the method available for use, which are briefly outlined below for further understanding.

- *Hierarchist perspective* (long term perspective, and substances are included if there is consensus regarding their effect)

- *Egalitarian perspective* (extremely long term perspective, and substances are included if there is any indication regarding their effect).

- *Individualist perspective* (short time perspective of 100 years or less, and substances are included only if there is complete proof regarding their effect).

For this research project, the Hierarchist perspective version of Eco-indicator ’99 was chosen since it took into account a moderately long term perspective (as opposed to the other two extremes), and from this perspective, damage is said to be avoidable through good management.

7.2.1 Impact Assessment (Eco-Indicator '99 Graphs)

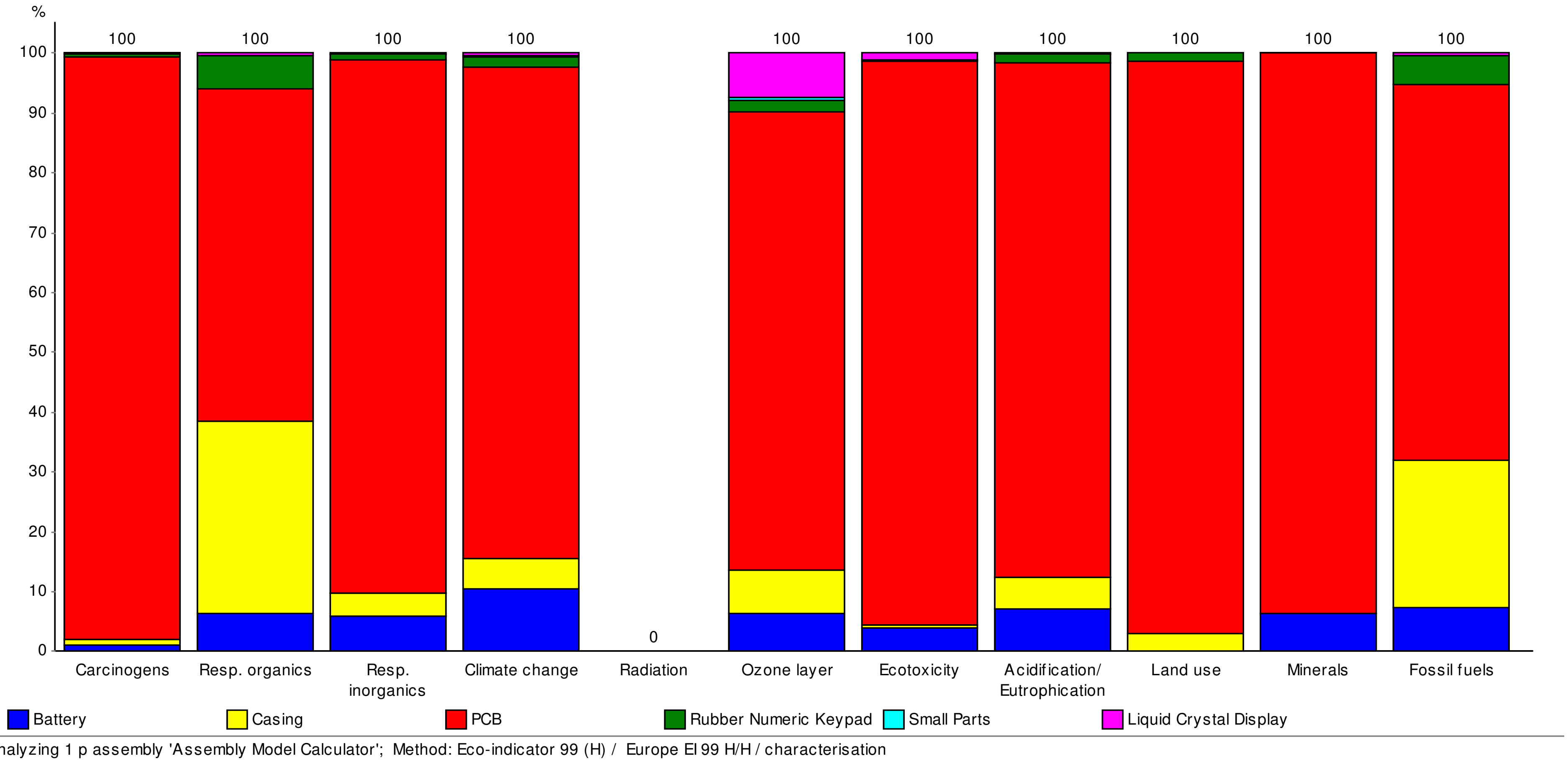

Figure 7.1 - All original weights and materials (original assembly) without transport

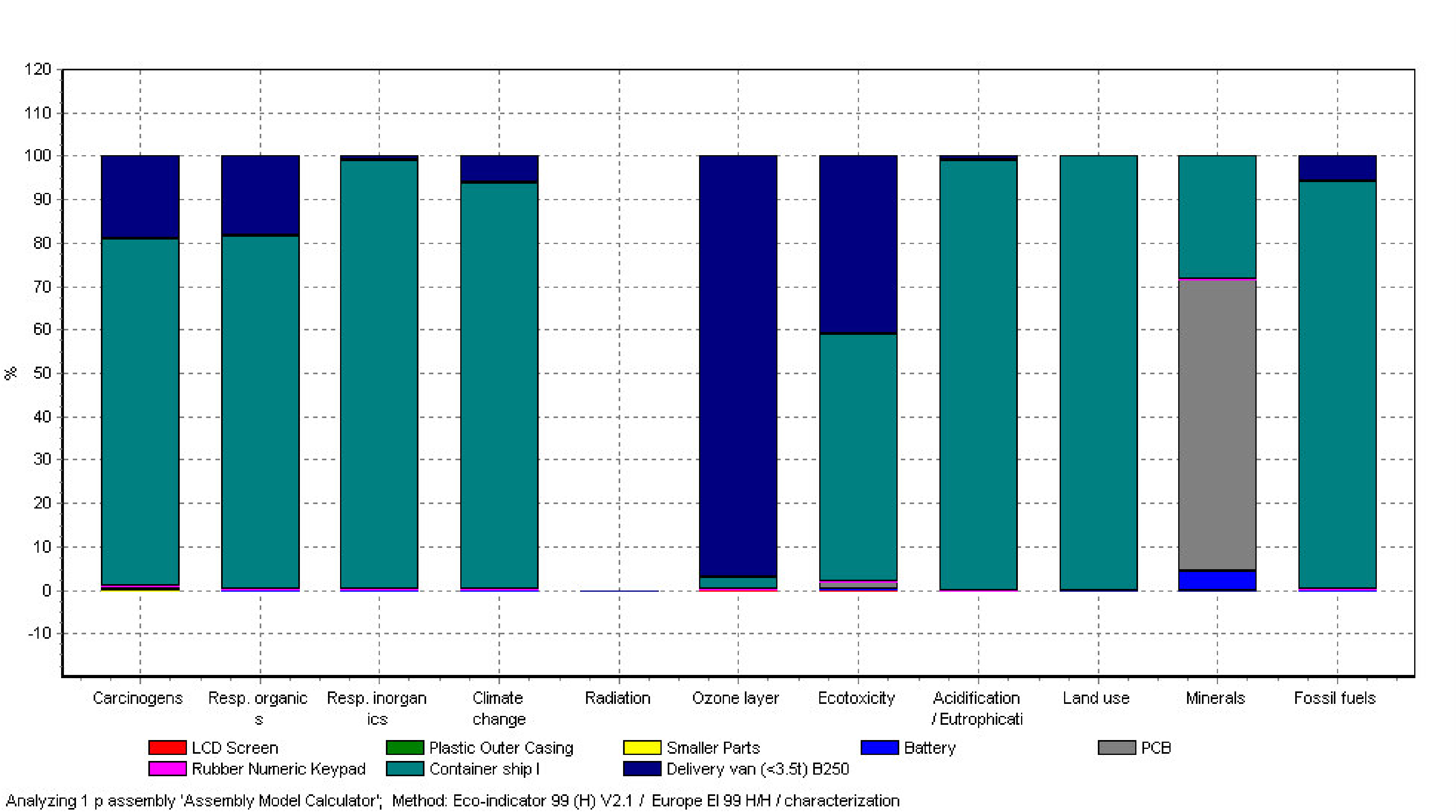

Figure 7.2 - All original weights and materials (original assembly) with transport

7.2.1 Impact Assessment (Eco-Indicator '99)

The bar graphs shown on the previous pages are the results from an Impact Assessment done with the Eco-Indicator '99. We can see from this that the different Impact categories are individually assessed in terms of each of the separate sub-assemblies. Each sub-assembly is shown as a proportion of its contribution to the impact in that particular category.

One clear observation from the graph is that the Printed Circuit Board (PCB) contributes towards most of the impact across the chart. For Carcinogens, Eco-toxicity and Land Use, the PCB contributes to nearly all the impact. The smallest impact categories are Respiratory Organics and Fossil Fuels.

The plastic casing is the sub-assembly that has the second largest impact. The main impact is in Respiratory Organics for which it contributes nearly a quarter of the impact, and in Fossil Fuels. The casing also has minor impact in Respiratory In-organics, Climate Change, Ozone Layer, Acidification / Eutrophication, and Land Use. It also has a slight (but negligible) impact on Eco-toxicity. The casing has absolutely no impact on Minerals.

The battery does not have a major impact, but does contribute slightly (approximately 5 to 10 %) to the impact on Respiratory Organics and In-Organics, Climate Change, Ozone Layer, Eco-toxicity, Acidification / Eutrophication, Minerals and Fossil Fuels. It has a negligible impact on Carcinogens and no impact on Land Use.

The Rubber Numeric Keypad has about an 8% impact on Respiratory Organics and Fossil Fuels. It also has a minor impact (about 2%) on Respiratory In-organics, Ozone Layer, Acidification / Eutrophication, and Land Use. It has negligible impacts on Carcinogens and Eco-toxicity, and no impact on Minerals.

The Liquid Crystal display has a 10% impact on the Ozone Layer, and approximately 2% impact on Eco-toxicity. The Small parts in the Calculator have a negligible impact in all affected categories. None of the sub-assemblies that make up the Calculator causes any Radiation, as this is one category that is not affected at all.

All these results were obtained from the analysis for an assembly for a Calculator that was manufactured and not transported anywhere. Adding transportation into the equation was possible by defining it in the main assembly as a process. From this, some judgments could be made about the effect of transporting a product over such a long distance (refer to *4.2 The Calculator Scenario* in *Chapter 4* for distance calculations).

It was apparent from the bar graph presented on the previous pages, that the impact from transport is so great that it practically overshadows the impact from the rest of the assembly. In the damage assessment step, the Container Ship was found to have a 90% impact on Human Health and Eco-system Quality and a 65% impact on Resources. The remainder of the impact on these 3 damage categories was accounted for by the Delivery Van.

The Delivery Van is responsible for 100% of the impact on Carcinogens, Ozone Layer and Eco-toxicity, and approximately 60% of Respiratory Organics, and 40% of Climate Change and Fossil Fuels. It also causes about 10% impact on Respiratory In-organics and Acidification / Eutrophication.

The Container Ship causes about 90% of the impact on Respiratory In-organics and Acidification / Eutrophication. It also causes about 60% impact on Climate Change and Fossil Fuels and approximately 40% impact on Respiratory Organics.

7.2.2 Damage Assessment (Eco-Indicator '99)

When the versions of SimaPro were changed from 5.1 to v6.0, the new version did not display damage assessment characteristics. Therefore, it was not possible to reproduce some of the graphs used in the initial Damage Assessment. There are, however, some comments on Damage Assessment in the section on Sensitivity Analysis (refer to *section 8.1* in *Chapter 8* for the actual Damage Assessment).

7.3 CML 2 baseline 2000 Method

This method is an improvement on the Dutch Guide to LCA in 1992 by the Center of Environmental Sciences (CML). This method is also known as the NOH method or Heijungs 1992.

This method is slightly similar to the Eco-Indicator '99, but varies in terms of Impact Categories featured. Impact Categories are:

- *Depletion of abiotic resources* (Determined based on the extraction of minerals and fossil fuels and is concerned with the protection of human welfare, human health, and ecosystem health).

- *Climate Change* (Records the global warming potential in the next 100 years from carbon dioxide emissions to the air. Climate Change will affect ecosystem health, human health, and material welfare).

- *Stratospheric Ozone Depletion (*Measures CFC-11 emissions to the ozone on an infinity timescale. Effects of this ozone depletion is a larger fraction of UV-B radiation reaching earths surface with adverse effects on Human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials).

- *Human Toxicity (*Human Toxicity Potentials are calculated based on an LCA on 1,4-dicholorobenzene equivalent emissions on an infinite timescale and measure fate, exposure and effects of these toxic substances).

- *Fresh-water aquatic eco-toxicity (*This category also measures 1,4-dichlorobenzene equivalent emissions on an infinite timescale and measures the fate, exposure and effects to air, water and soil).

- *Marine Eco-toxicity* (Measures impact of toxic substances to marine ecosystems – refer to fresh water toxicity).

- *Terrestrial Eco-toxicity (*Measures impact of toxic substances on terrestrial ecosystems – refer to fresh water toxicity).

- *Photo-oxidant formation (*Measures the formation of reactive substances from ethylene equivalent emissions over a timescale of 5 days and its impact on human health and ecosystems which damage crops).

- *Acidification (*Measures Acidification potential of emissions of SO2 equivalent emissions on an eternal timescale to air on soil, groundwater, surface water, organisms, and materials).

- *Eutrophication (*Measures PO4 equivalent emissions over an eternal timescale and its impact on excessive levels of macro-nutrients to water, air and soil).

Following is an impact assessment on the Calculator based on this method.

7.3.1 Impact Assessment (CML 2 baseline 2000)

The bar graphs shown on the following pages are the impact assessments done with the CML 2 baseline 2000 method. This impact assessment is done with the original assembly including transport and without transport. Each sub-assembly is shown according to its proportion of impact in each particular impact category.

As in the Eco-Indicator method, the Printed Circuit Board has the highest impact contribution, and affects all categories. The highest impact is on Fresh Water Aquatic Ecotoxicity for which it accounts for 100%. It has a slightly less impact (approximately 90%) on Human Toxicity, Marine Aquatic Ecotoxicity, Photochemical Oxidation, and Acidification. It impacts Abiotic Depletion, Global Warming, Terrestrial Ecotoxicity, and Eutrophication by 65% to 85%. The PCBs smallest impact is on the Ozone Layer Depletion for which it only accounts for 50% of the impact.

7.3.1 Impact Assessment (CML 2 baseline 2000 Graphs)

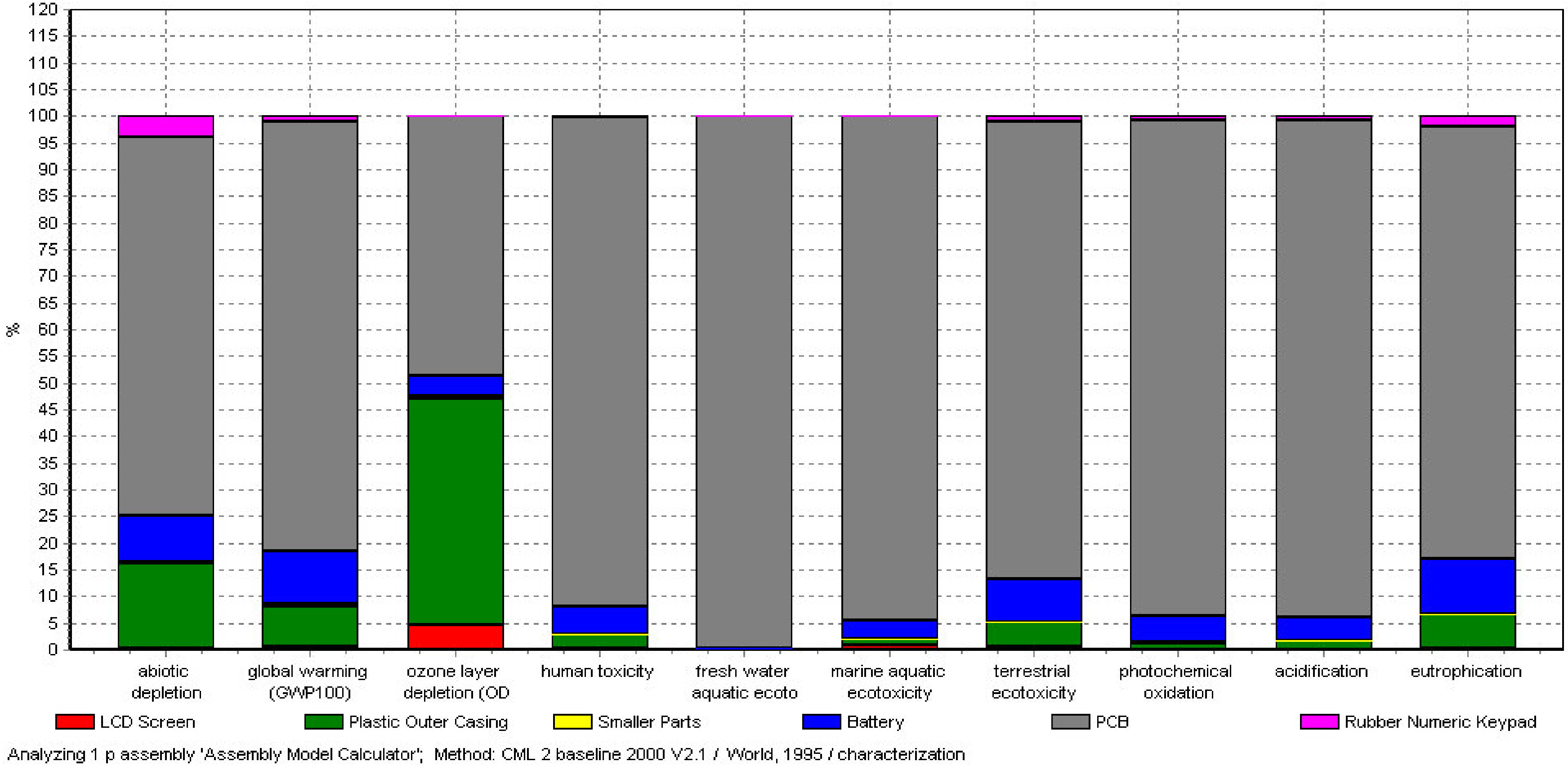

Figure 7.3 – CML 2 - All original weights and materials (original assembly) without transport

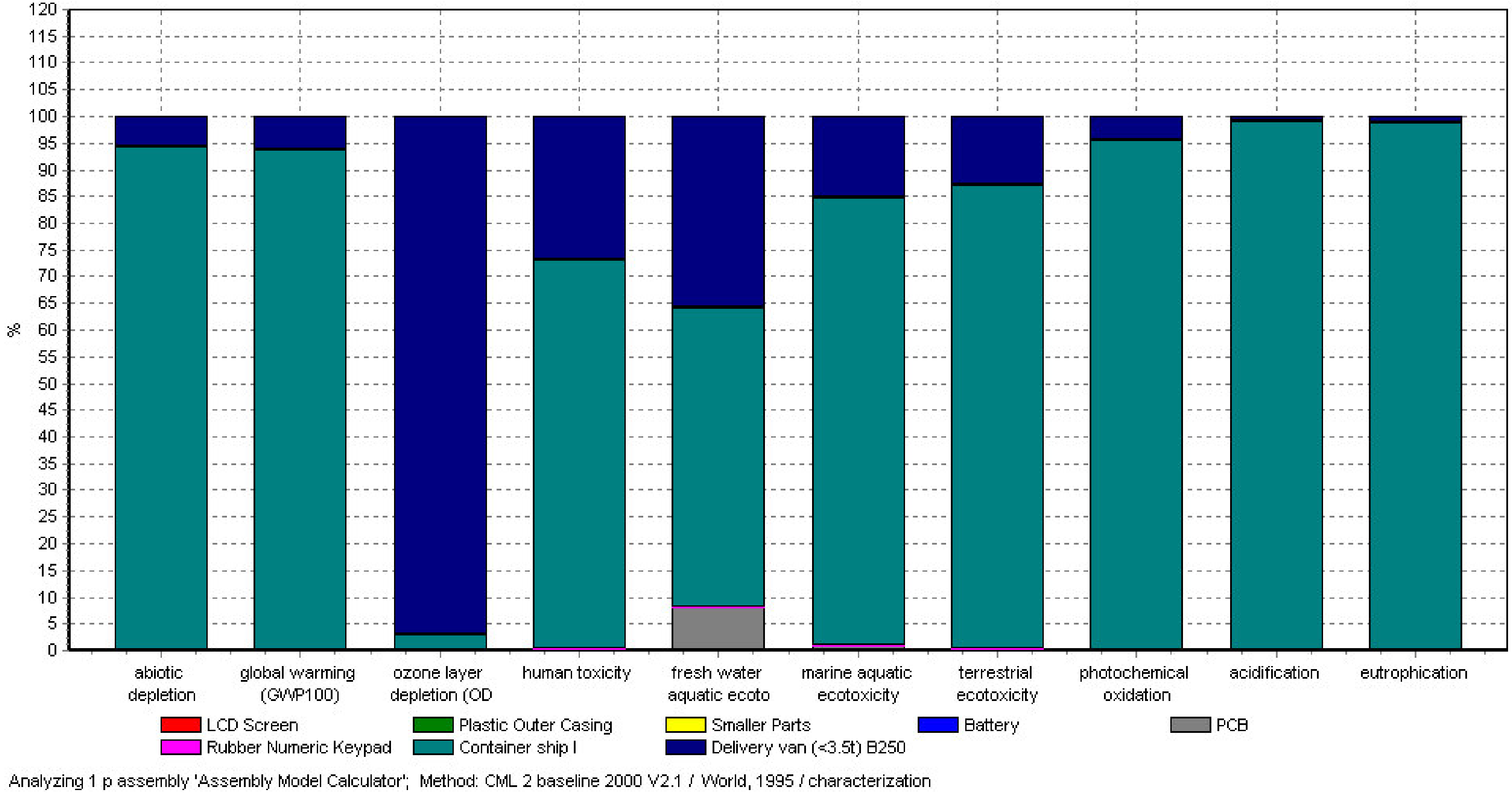

Figure 7.4 – CML 2 - All original weights and materials (original assembly) with transport

7.4.1 Impact Assessment (CML baseline 2000 continued)

The second highest impact sub-assembly is the Plastic Outer Casing. Although it does not have as high an impact or impact as many categories as the PCB, it does contribute a 45% impact on Ozone Layer Depletion. It has a 15% impact on Abiotic Depletion, and 10% on Global Warming and Eutrophication. The plastic casing also contributes 5% of the impact on Terrestrial Ecotoxicity, and 2.5% impact on Human Toxicity.

The next sub-assembly worth noting is the Battery. The Alkaline Battery has an impact on all impact categories except for Fresh Water Aquatic Ecotoxicity. The largest impact of the Battery would be 10% on Abiotic Depletion, Global Warming, Terrestrial Ecotoxicity and Eutrophication. Its remaining impact is approximately 5% on Ozone Layer Depletion, Human Toxicity, Marine Aquatic Toxicity, Photochemical Oxidization, and Acidification.

The glass from the Liquid Crystal Display only has a 5% impact on Ozone Layer Depletion.

The Rubber Numeric Keypad only has a 5% impact on Abiotic Depletion and approximately 5% impact on Eutrophication. The remaining impact on the other categories are negligible.

Smaller Parts might show up as a line (maybe 1% or less in some categories) but this is quite negligible, and focus should be placed on the more important sub-assemblies such as the PCB and the Plastic Casing.

7.4 EPS 2000 (Swedish Impact Assessment Method)

This method was developed by The Chalmers University of Technology in 1999 and is used to assist designers and product developers in companies interested in comparing 2 or more products to see which one has the least impact on the environment. The top-down assessment technique places some importance on product usefulness and monetary benefit than merely on environmental impact.

In this research project, only one product is studied but the usefulness of the system to compare two products are noted. There are five impact categories used in this method, which are outlined below:

- *Human health* (Measures damage in terms of years of life lost, severe morbidity and suffering, and severe nuisance)

- *Ecosystem production capacity* (Measures impact on crop, wood, fish and meat, base cat-ion, irrigation water and drinking water production capacity).

- *Abiotic stock resources* (Measures the depletion of elemental or mineral reserves and the depletion of fossil reserves).

- *Biodiversity* (measures the extinction of species).

- *Cultural and recreational values* (this category is difficult to define as a standard indicator and therefore, is not included in most studies unless individually defined by the analyst).

On the following pages are the graphs of impact assessments performed on the original assembly with and without transport included with the EPS 2000 Impact Assessment method. Following the graphs is an impact assessment discussion.

7.4.1 Impact Assessment (EPS 2000 Graphs)

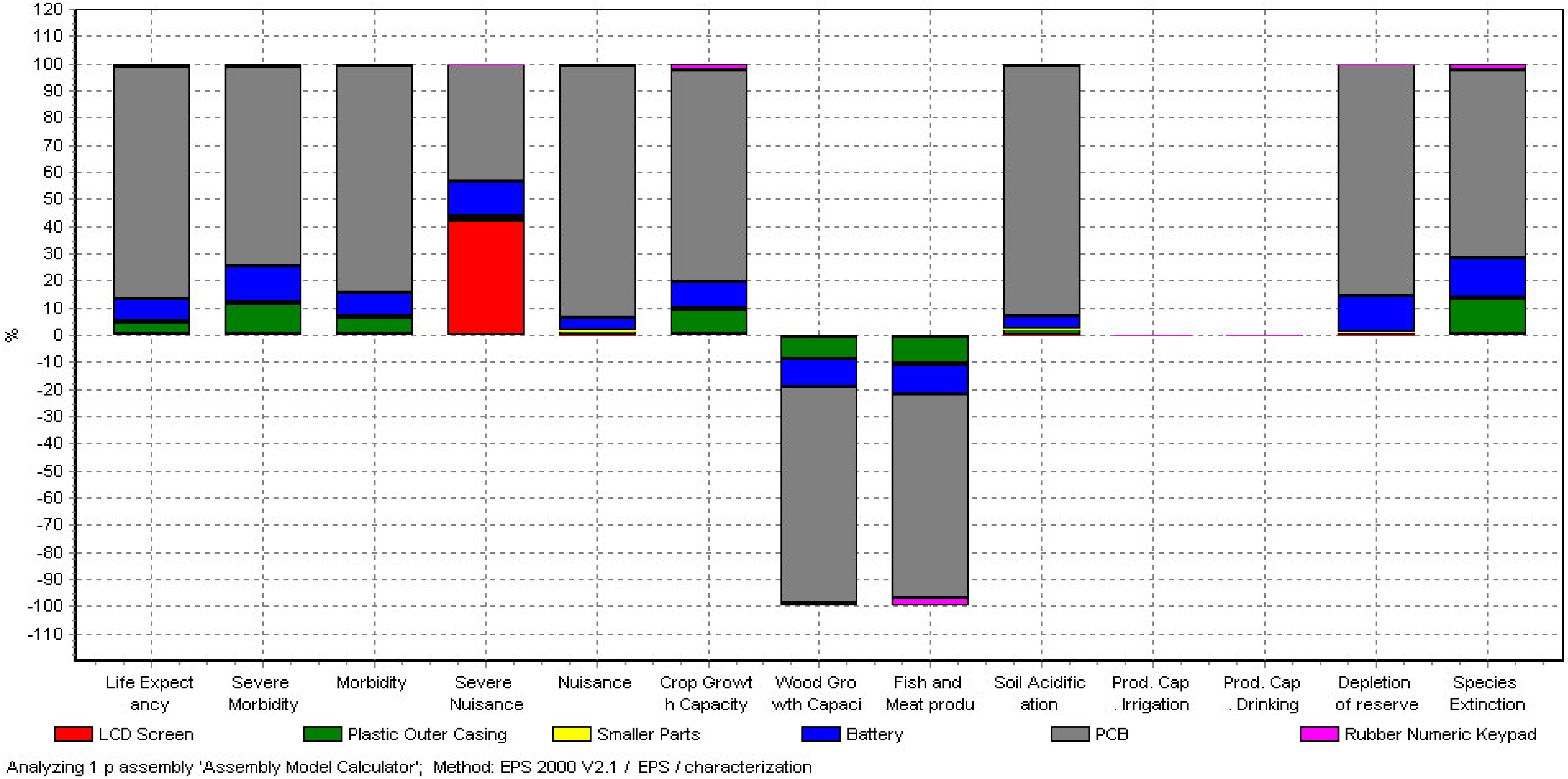

Figure 7.5 – EPS 2000 - All original weights and materials (original assembly) without transport

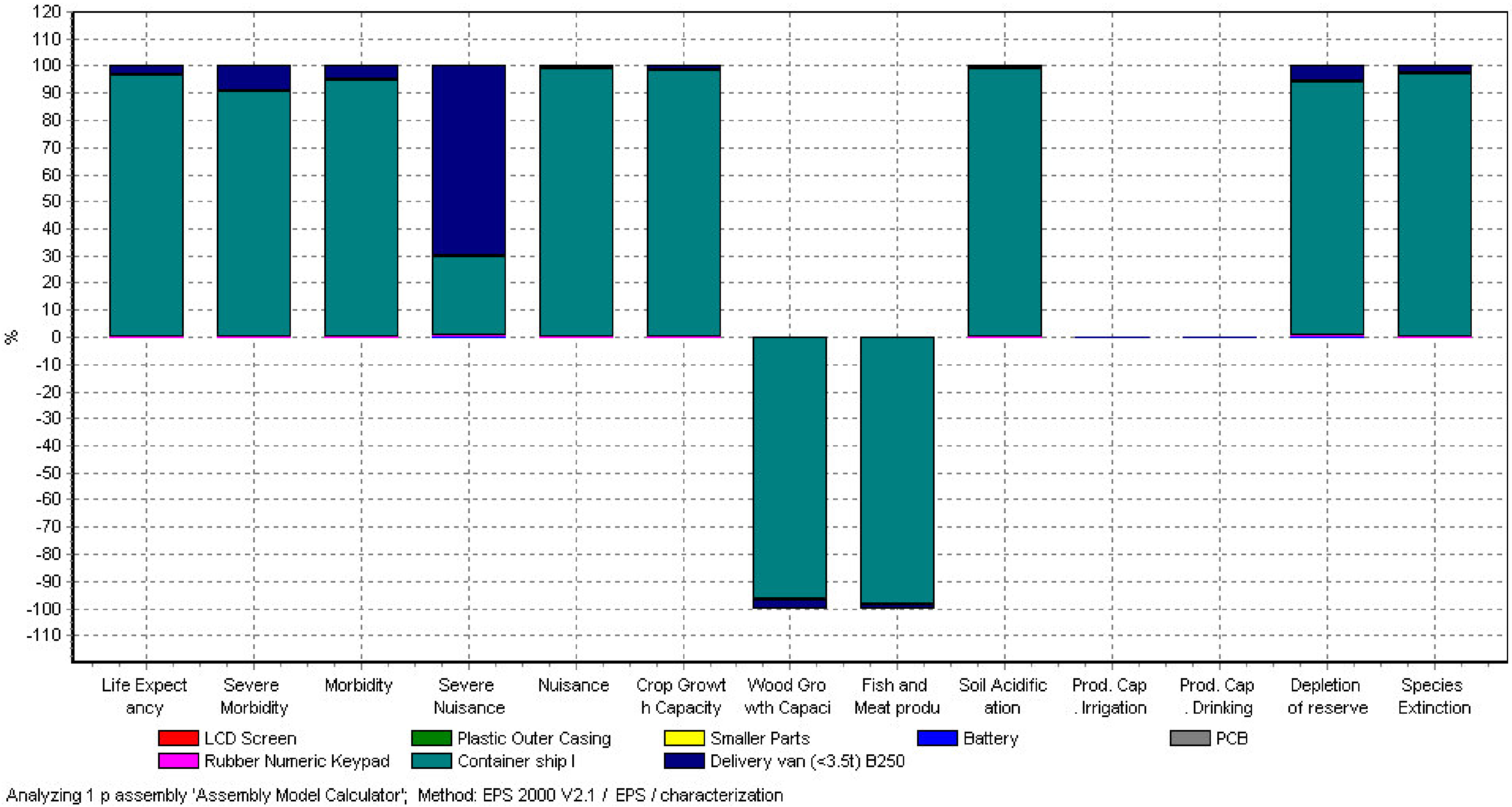

Figure 7.6 – EPS 2000 - All original weights and materials (original assembly) with transport

7.4.1 Impact Assessment (EPS 2000 continued)

The graphs on the previous two pages show the impact assessment on the original Calculator assembly with and without transport performed with the EPS 2000 impact assessment method.

It can clearly be seen that even in this method, the PCB creates a large impact in all categories. The largest categories are Nuisance and Soil Acidification. Only two categories are not affected by this assembly, which are the Production Capacities of Irrigation and Drinking water.

The second largest impact is caused by the LCD screen. However, this impact only exists in Severe Nuisance (40% contribution) and does not impact any of the other categories.

Besides the PCB, the battery is the only other sub-assembly that affects every impact category. The impact is not large, and fluctuates between 10 to 20%. Its largest impacts are on Species Extinction, Severe Nuisance and Severe Morbidity. Like the PCB, this sub-assembly does not affect the Production Capacity of Irrigation and Drinking water.

The Plastic Casing creates a relatively small impact in 7 out of 13 impact categories. These categories (from largest to smallest) are Severe Morbidity, Species Extinction, Wood Growth Capacity, Fish and Meat Production and Crop Growth Capacity, and the smallest impacts are in Morbidity and Life Expectancy.

The Rubber Numeric Keypad hardly impacts any of the categories at all, but some impact does exist on Severe Nuisance, Crop Growth Capacity, Fish and Meat Production, Production Capacity of Irrigation and Drinking Water, Depletion of Reserves and Species Extinction. Impacts on these categories are so small that they are difficult to measure. However, the impact is estimated to vary from 1 to 3 or 4%.

Smaller parts has an even smaller impact (approximately 1%) on Nuisance, Soil Acidification and the Depletion of Reserves.

Taking a look at the modified assembly (to include transport), once again, as in the two previous Impact Assessment methods, we can see that the impact of transport overshadows the impact of the actual sub-assemblies of the Calculator, hence the reason for leaving it out of the initial Impact Assessment.

The Container Ship has an enormous impact (approximately 95 to 100%) on all categories except Severe Nuisance, and the Production of Irrigation and Drinking water. In Severe Nuisance, it has only a 30% impact, and 0% impact on the remaining 2 categories.

The largest impact of the delivery van is on Severe Nuisance (70%), and the second largest impact is on Severe Morbidity (10%). The remaining impact for the delivery van is (approximately 1 to 5%) on all remaining impact categories, except the Production of Irrigation and Drinking water.

Chapter 8 Sensitivity Analysis

8.1 Introduction to Sensitivity Analysis

Sensitivity Analysis involved modifying materials, processes and the quantities in which these things were used in order to record important changes in impact categories. Each modification is reverted to its original value before another one is made. This is true for all 3 impact assessment methods used. As the bar graphs were too large to reproduce on the same page with text and needed a separate page for each one, the graphs for each modification are included immediately after each Sensitivity Analysis section.

8.2 Sensitivity Analysis with Eco-Indicator '99

The data for the Printed Circuit Board (PCB) used in this study is from SimaPro's IDEMAT 2001 library. It is the average of all suppliers in Western Europe between 1995 and 1999. Since no other data was available for use, no sensitivity analysis was done on this sub-assembly in any of the methods used. Instead, it is discussed in the individual impact assessment of the sub-assemblies later on. Since the impact in all categories is so great by the PCB, removing it from the assembly for the sensitivity analysis actually helped bring out the impact behavior of the other sub-assemblies.

The material used for the Plastic Casing was HDPE P (High Density Polyethylene) and is from the SimaPro Data Archive. Data from this archive is usually outdated but was selected as it was the most suitable data for this project. It is better to have some data than no data at all. The data was obtained from averaging processes with similar outputs in Western Europe between 1985 and 1989. The process used to make the plastic case is Injection Moulding and this is an estimate of processes in Western Europe from 1990 to 1994.

For the sensitivity analysis, first the quantity of HDPE used was changed from 23.8 grams to 100 grams (approximately 4 times more) and this revealed no change in impact levels. This tells us that the amount of HDPE used in the manufacture has no effect on the levels of emissions produced. For example, the emissions probably come from the transport of some material or fuel from one point to another, and small increments of HDPE production would not show a difference. If this were so, then large increments would probably show a small difference since each truckload / shipload would probably be carrying enough material / fuel for each ton production of HDPE.

Next, the HDPE B250 material was changed to Polypropylene (PP P) which is a similar material to HDPE, but is in fact harder and stiffer. It turned out that the new material still impacted all the same categories as the HDPE, but now, the impact contributions were much larger (almost twice the impact).

The battery did not provide many options. Instead, there were only options for Alkaline, Nickel-Cadmium and Lithium-Ion batteries. The Alkaline battery had approximately half the impact of the other two batteries. Multiple batteries were not tested for the purpose of this research project for several reasons. The logic behind this is that the Calculator was only purchased for 2 dollars. The screws behind the calculator were quite tedious to remove, and after this, the user has to pry open the battery holder (it was not made for changing batteries, probably due to it being a low cost unit), and replace the button cell. In a realistic situation, this would not normally happen. Therefore, it was safe to make the assumption that the life-span of the Calculator was only as long as the life of its battery.

For the Liquid Crystal Display (LCD), only the glass was accounted for, since this is the material that accounts for most of this sub-assembly. The data used was for White Glass from the BUWAL250 library. This glass is manufactured in Switzerland from 55% recycled glass and 45% virgin glass. In an effort to try to reduce the impact in all categories, this White Glass was changed to 100% recycled Glass from the BUWAL132 library. From approximately 10% impact on the Ozone Layer and 2% on Eco-toxicity (assumed from the process of blowing sheet glass), the impact contribution of the LCD disappeared from the charts. It can therefore be summarized here that no matter what the individual application is, it is much better to recycle glass than to manufacture new sheets.

Measuring the sensitivity of the smaller parts used was quite simple. 20% Electrolytic Chrome Coated Steel was chosen for the production of Capacitor parts, screws and the battery holder. This steel is made from 20% scrap and 80% virgin materials. By increasing the proportion of recycled material used in this sub-assembly, the impact contribution reduced proportionately.

The transport of the Calculator from China to Brisbane, Australia was defined as transport by a Container Ship over 13416 kilometers. The data for the ship was from the SimaPro Data Archive. It is the Western European data average of a container ship (47000 tons) sailing at relatively high speeds (43 km/hr). It was chosen because this data was tailored to suit products and not mass transport. The data for transport from Brisbane to Toowoomba (180km) was for a delivery van (<3.5 ton) from the BUWAL250 library which averages specific such transports from between 1990 to 1994. This data was chosen because it was the most likely form of transport from Brisbane for such a product compared to the other transport modes available.

For road transport, the delivery van seemed like the most suitable mode of transportation for the goods in question (a load of Calculators). To determining how much better it was than other forms of transport, it was changed to the average data for road transport by a 16 ton diesel truck with an average load of 50%. Surprisingly, this 16 ton truck reduced the impact on Carcinogens and Eco-toxicity by 65%, and the impact on Respiratory Organics and Climate change by about 30%. The impact on the 3 damage categories had now reduced to less than 10% each. This means that the 16 ton truck was actually a much better selection for road transport.

For a sensitivity analysis on the Container Ship I, the only other suitable mode of oceanic transport available, which was a Bulk Carrier I from the IDEMAT 2001 library, was chosen. This consisted of mixed data of an average of all suppliers. It counted fuel consumption, assumed most return trips were made empty, and did not account for harbor operations. The graph on the next page shows that the impact on Respiratory In-organics and Acidification / Eutrophication actually increased by 5% to 95%, Impact on Climate Change and Fossil Fuels also increased to 75% and impact on Respiratory Organics also increased by 10%. Now, there was also 100% impact on Land Use, and major impacts on all other categories except for the Ozone Layer. The impact contribution in all 3 damage categories has also increased. This results in the conclusion that the Container Ship is a more sustainable transport solution.

8.2 Sensitivity Analysis with Eco-Indicator '99 (Graphs)

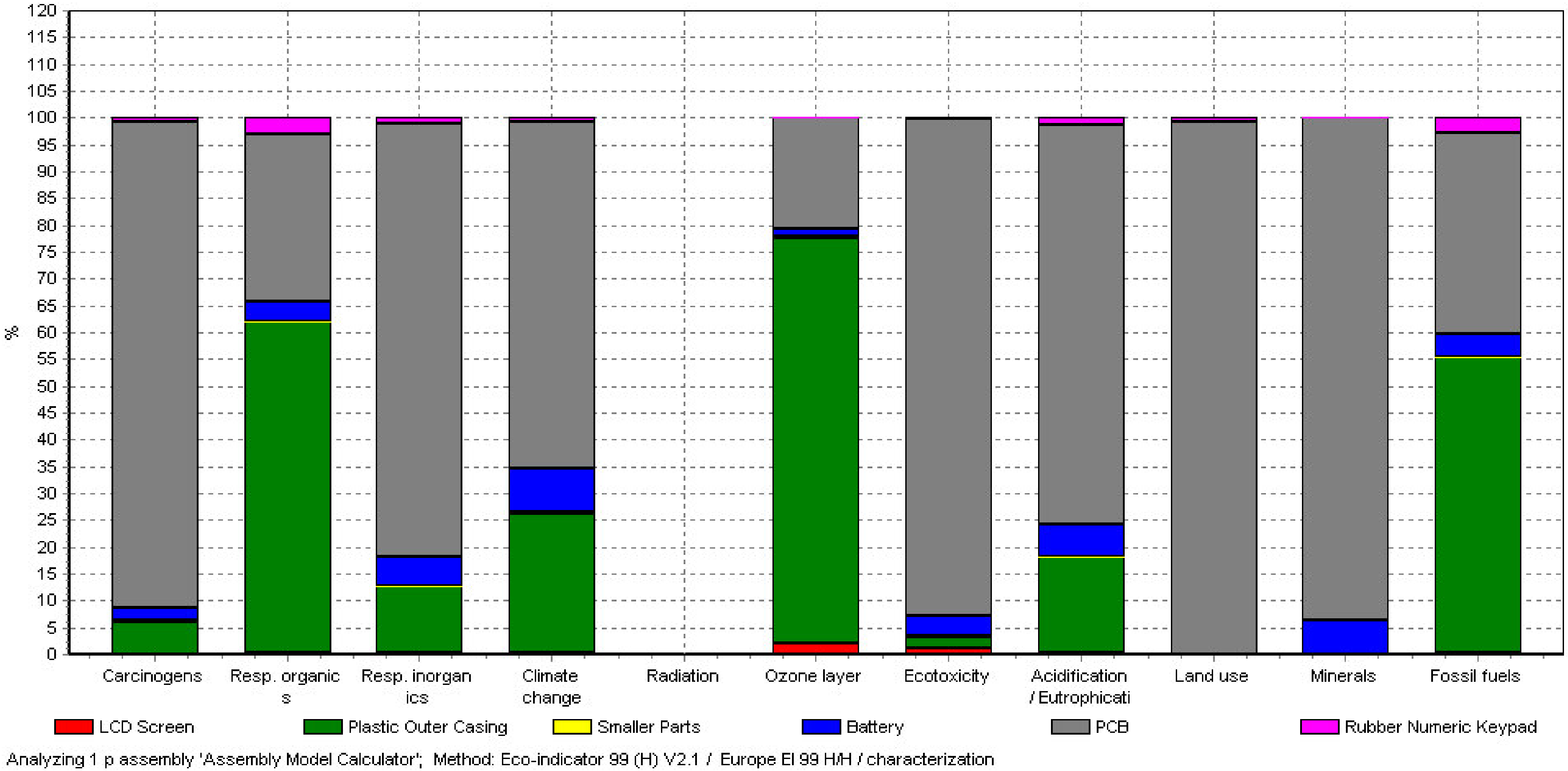

Figure 8.1 – Eco - Changed quantity of HDPE B250 to 100g

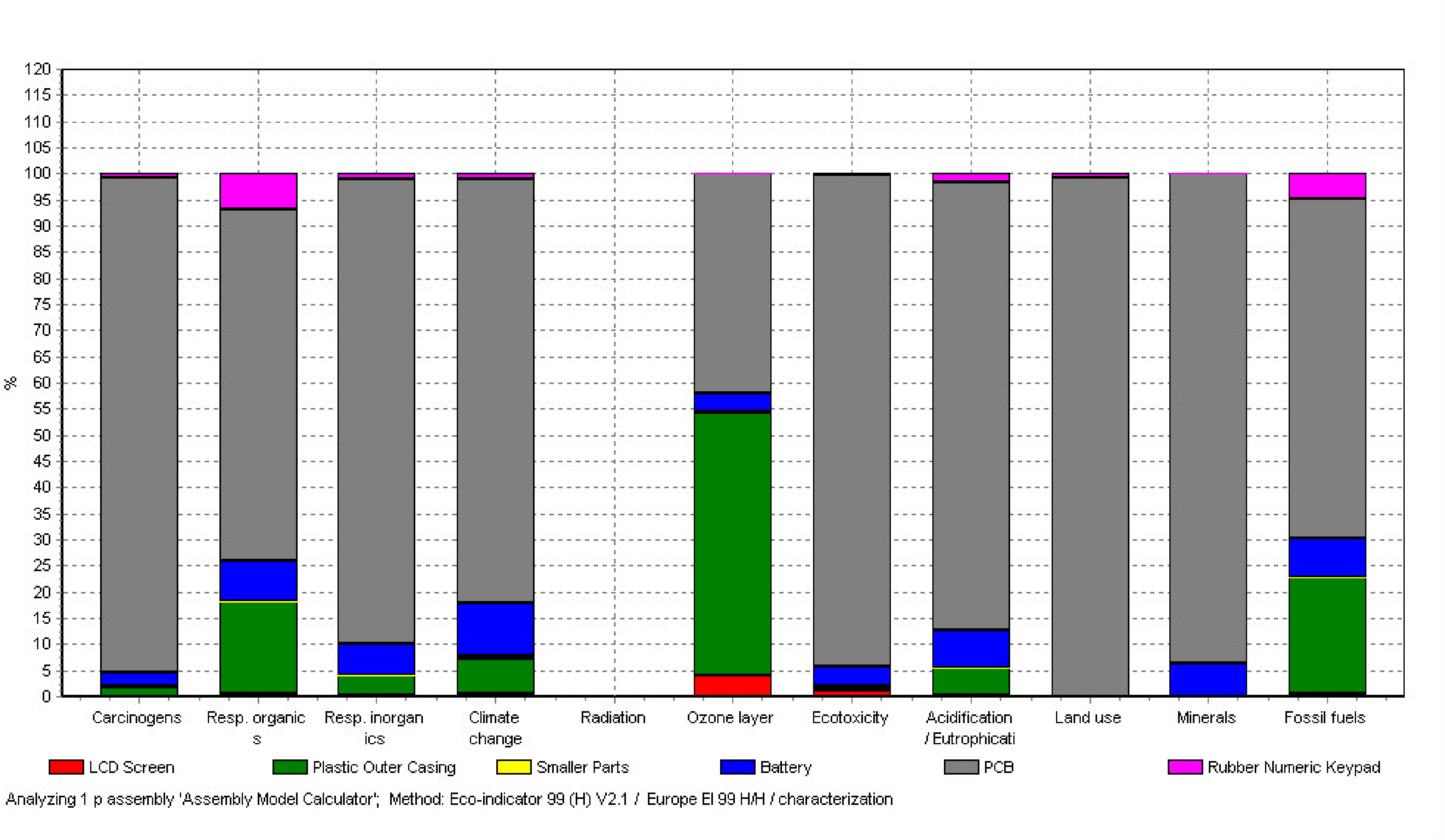

Figure 8.2 – Eco - Changed HDPE B250 Material to PP granulate average B250

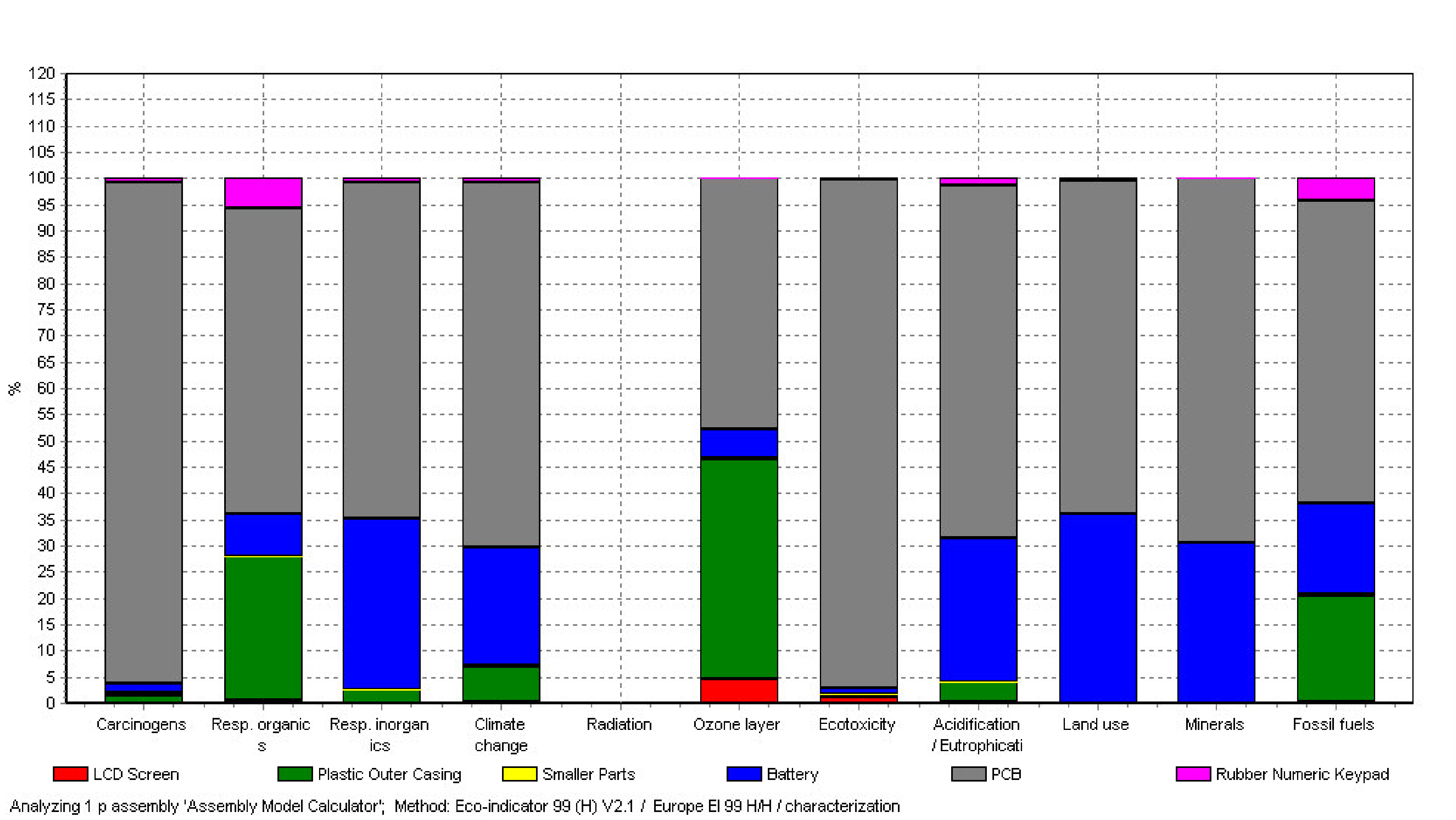

Figure 8.3 – Eco - Changed Battery from Alkaline to Li Ion

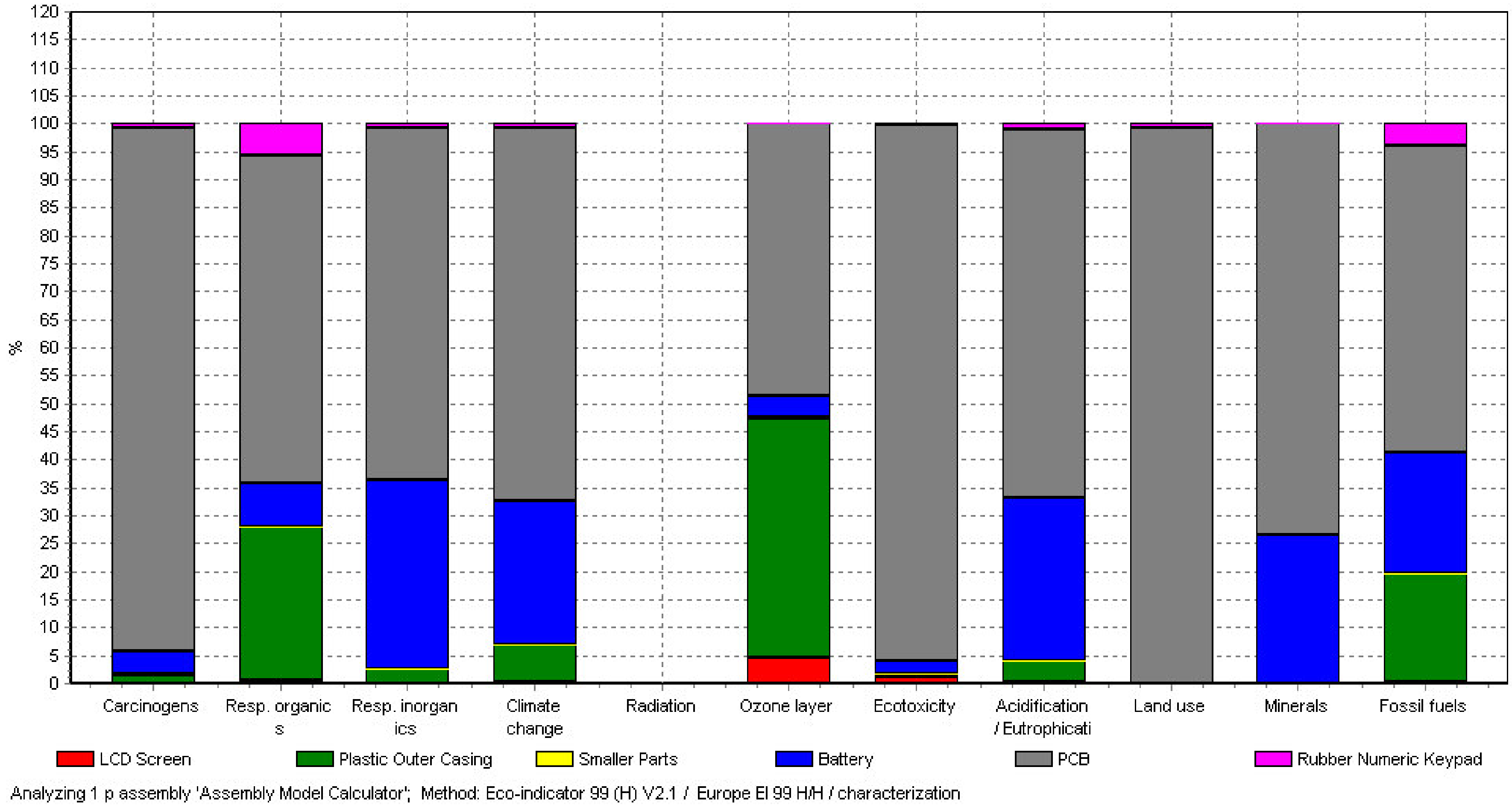

Figure 8.4 – Eco - Changed Battery from Alkaline to Ni Cad

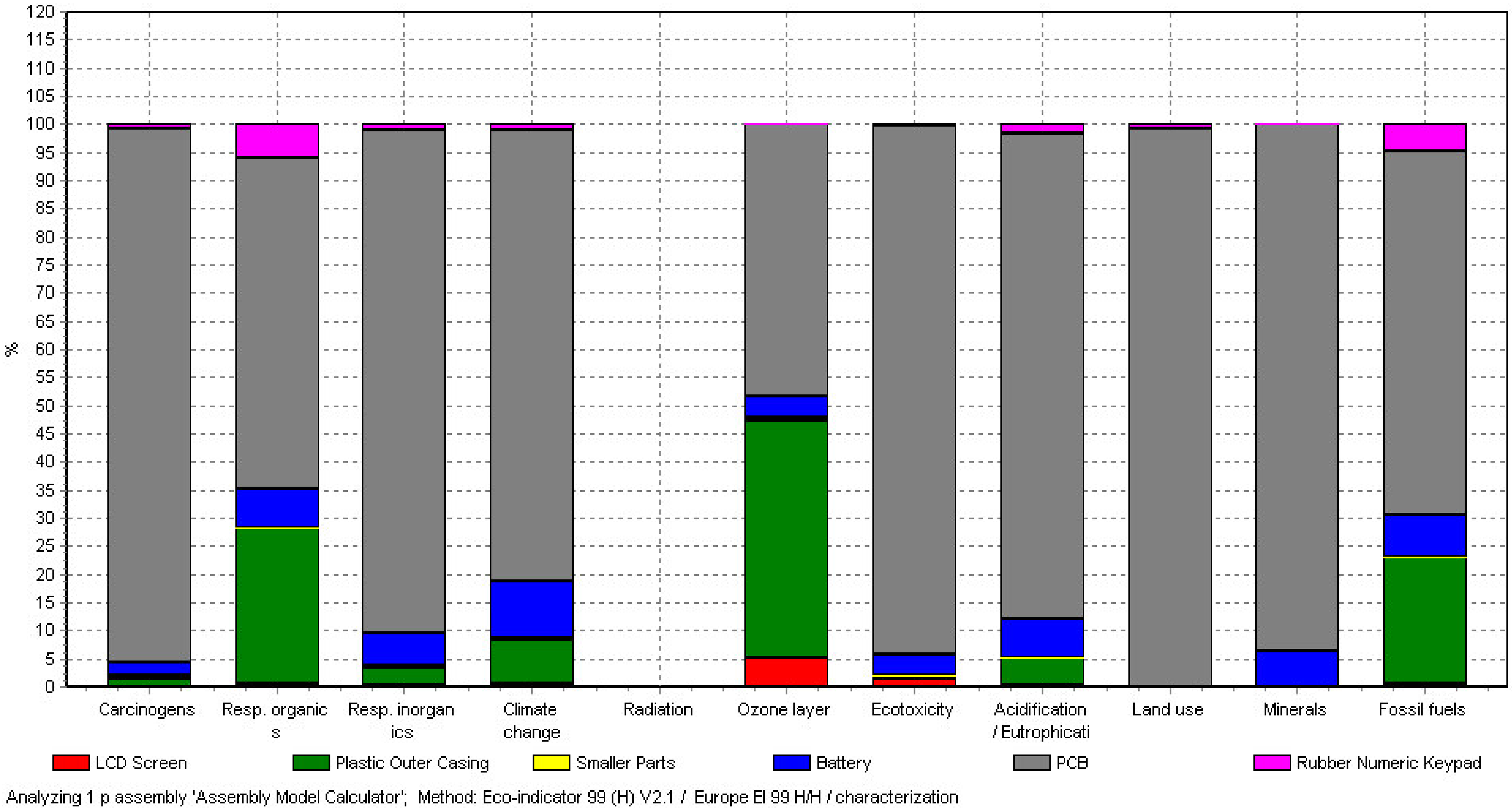

Figure 8.5 – Eco - Changed Glass from White to Virgin

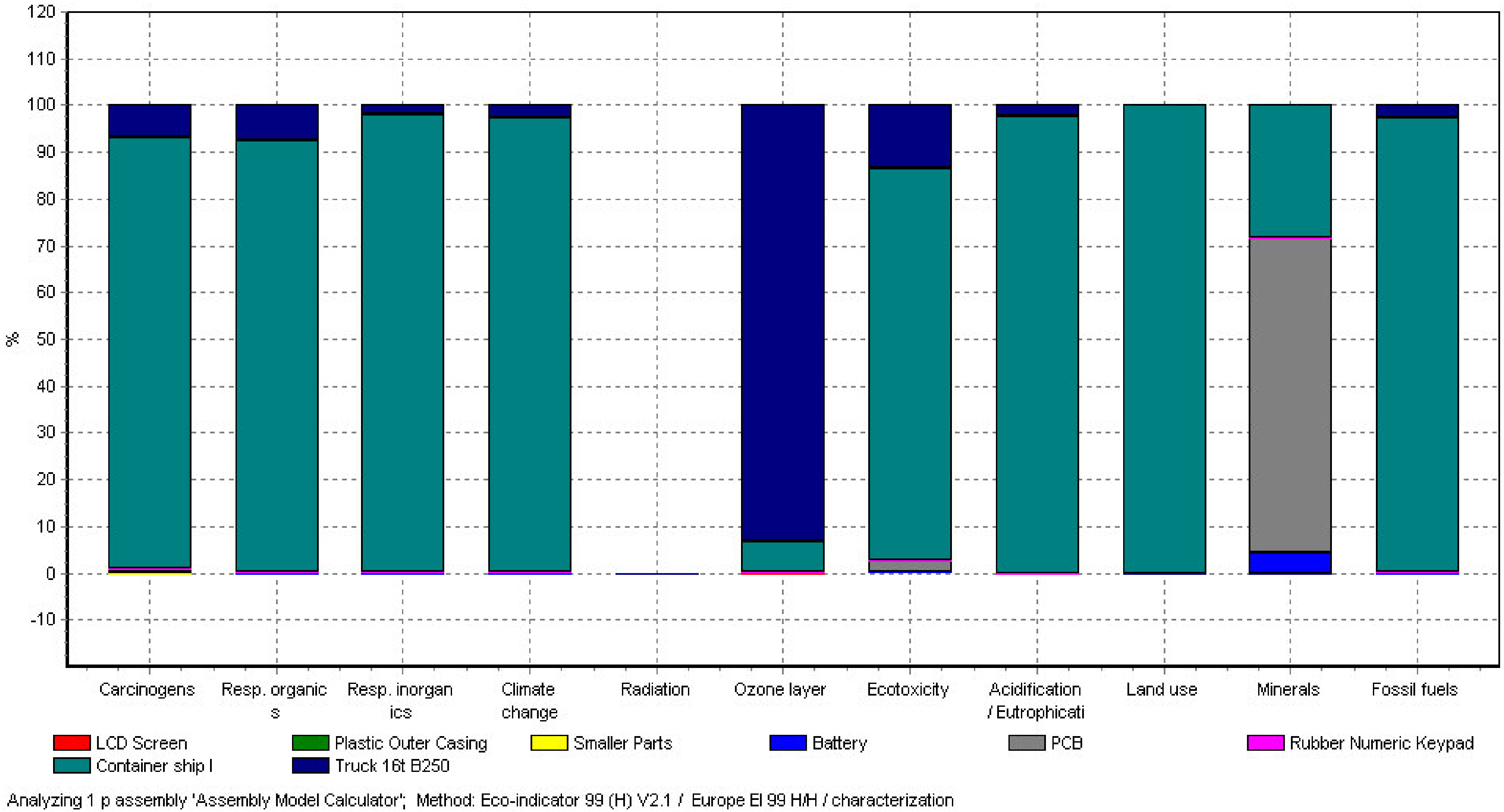

Figure 8.6 – Eco - Changed Delivery Van (<3.5t) B250 to 16 t truck B250 with 50% load average

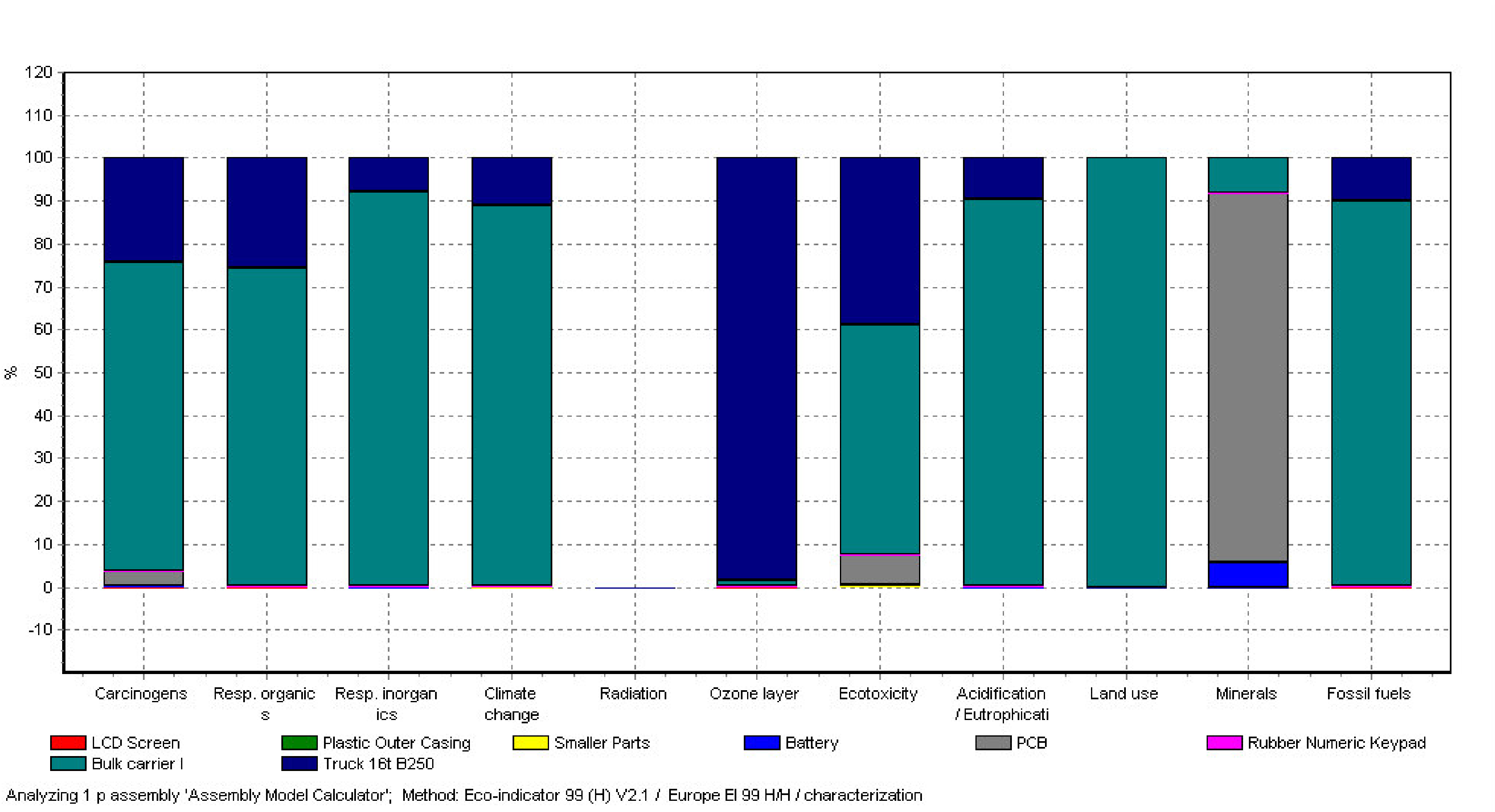

Figure 8.7 – Eco - Changed Container Ship I to Bulk Carrier I

8.2 *Sensitivity Analysis with CML 2 baseline 2000*

The first step in the sensitivity analysis, changing the amount of HDPE from 23.8g to 100g proved to increase the impact levels in all categories by almost double. The main increase was in Ozone Layer Depletion, from 40% to 75%. The second highest jump was in Abiotic Depletion (15% to 45%). Global Warming and Eutrophication increased from 10% to approximately 25% impact, and the impact on Terrestrial Ecotoxicity went from 5% to 15%. The impact on Human Toxicity went from 2.5% to 10%. The smallest increases, but probably quite important, was the impact on Marine Aquatic Ecotoxicity and Photochemical Oxidization. In the original assembly, there was almost no impact on these categories. After the change in HDPE quantity, both these categories had a 5% impact contribution from the plastic casing.

The next step, changing the HDPE B250 to a PP granulate average B250 proved to have very little effect on the system. The only change was that the impact contribution of the plastic case on Ozone Layer Depletion changed from 40 to 50%.

Changing the battery from Alkaline to Lithium Ion only affected 4 impact categories. For Photochemical Oxidization and Acidification, the impact increased from 5% to approximately 37.5%. The remaining two affected categories were Abiotic Depletion and Global Warming, in which the impact caused by the Li-Ion battery doubled from 10% to 20%.

By changing the Alkaline battery to Nickel Cadmium, the impact categories once more increased in the same proportions as for the Lithium Ion. The only difference was that the impact on Abiotic Depletion and Global Warming increased by a further 25% to 35% impact in these categories.

For the Liquid Crystal Display, modifying the glass used from White B250 to Virgin B250 proved only a minor modification. The only increase recorded was the impact on Abiotic Depletion, which was only a 2.5% increase from an initial 2.5%.

For a sensitivity analysis on transportation used, when the 3.5ton delivery van was replaced with a 16 ton truck, impact levels actually reduced. The main change was in Human Toxicity to Fresh Water Aquatic Ecotoxicity with a reduction from 25% and 35% impact respectively, to 15% and 20% impact respectively. The other changes from the replacement of road transportation was a 15% impact on Marine Aquatic Ecotoxicity and Terrestrial Ecotoxicity to less than 5% impact on both categories. There was also a small change (from 5% to 2.5% impact) on Abiotic Depletion and Global Warming. When the Container Ship was replaced with a Bulk Carrier, the results were synonymous with the Eco-Indicator '99, with reduced impact in all categories. Impact reduced by as much as 4 times. In fact, with the Bulk Carrier, there was now 0% impact on the Ozone Layer.

8.2 Sensitivity Analysis with CML 2 baseline 2000

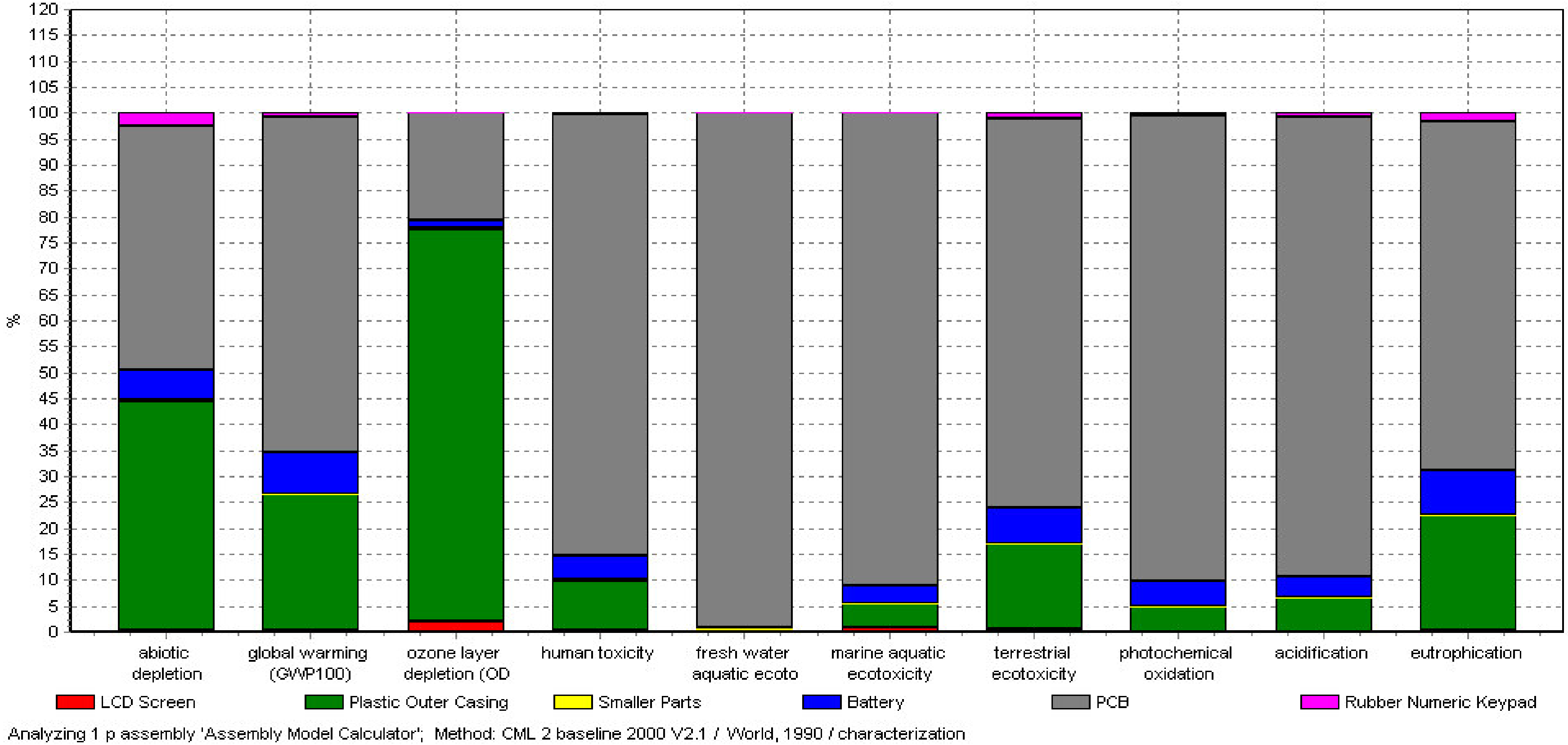

Figure 8.8 – CML 2 - Changed quantity of HDPE B250 to 100g

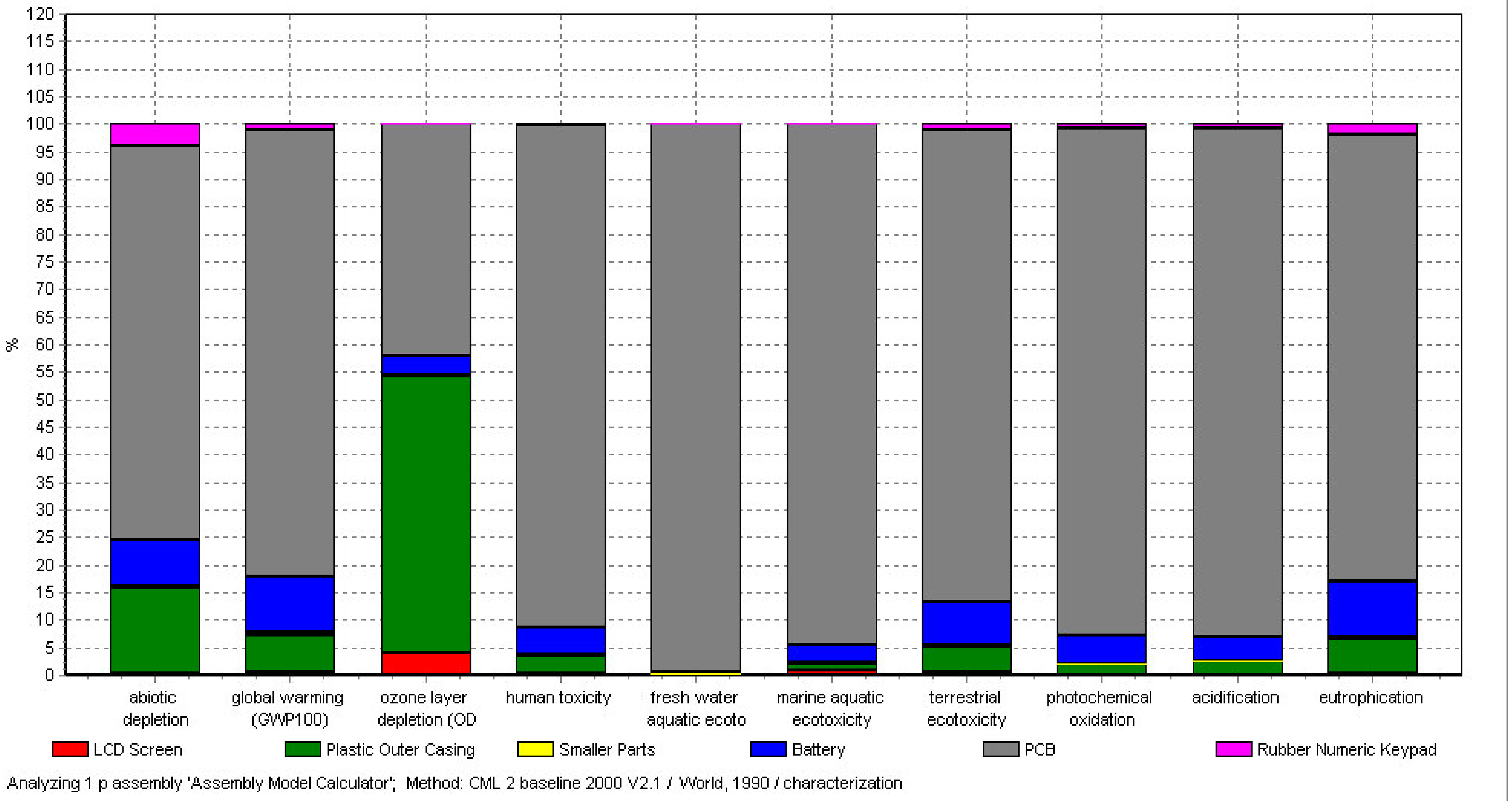

Figure 8.9 – CML 2 - Changed HDPE B250 Material to PP granulate average B250

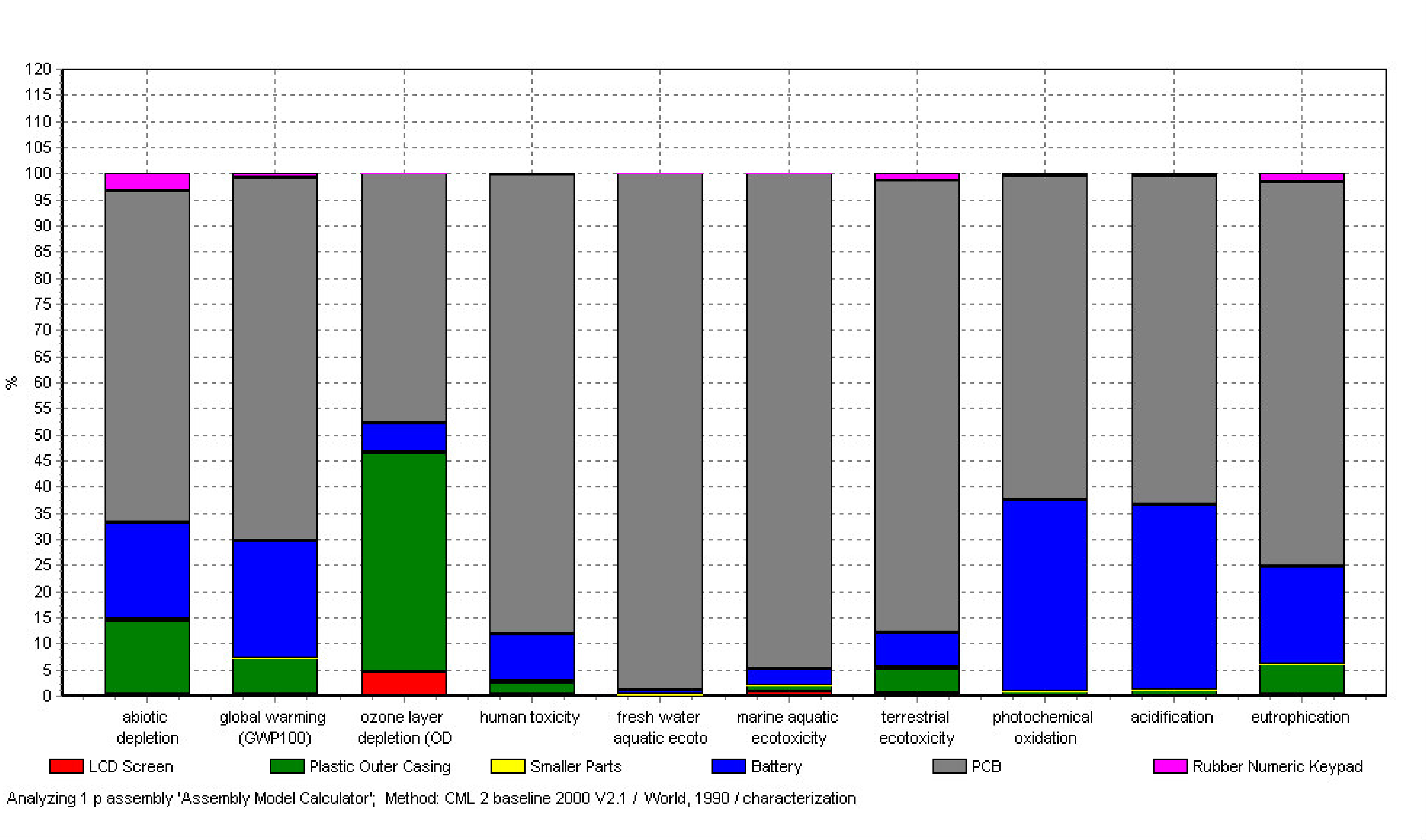

Figure 8.10 – CML 2 - Changed Battery from Alkaline to Li Ion

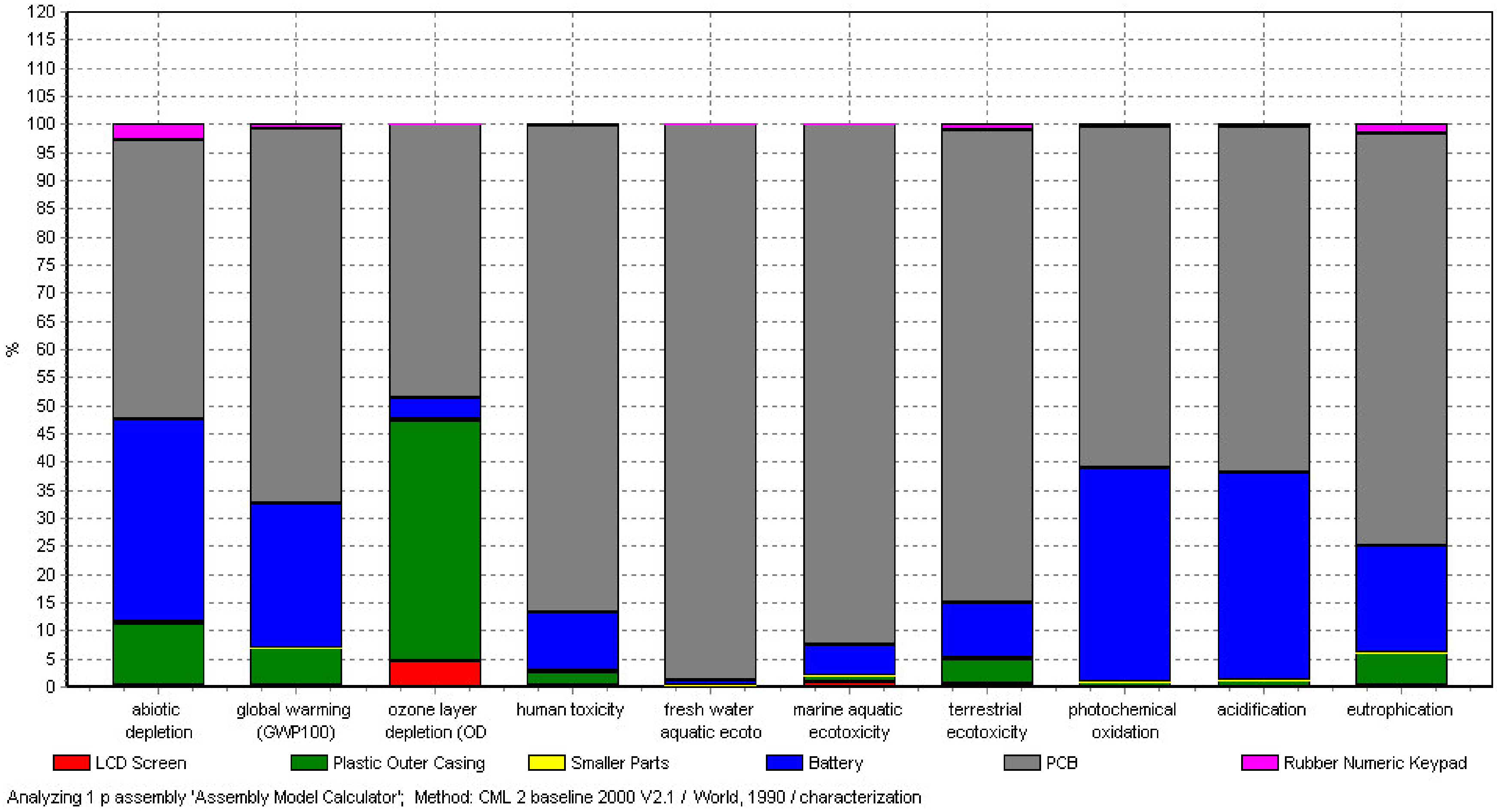

Figure 8.11 – CML 2 - Changed Battery from Alkaline to Ni Cad

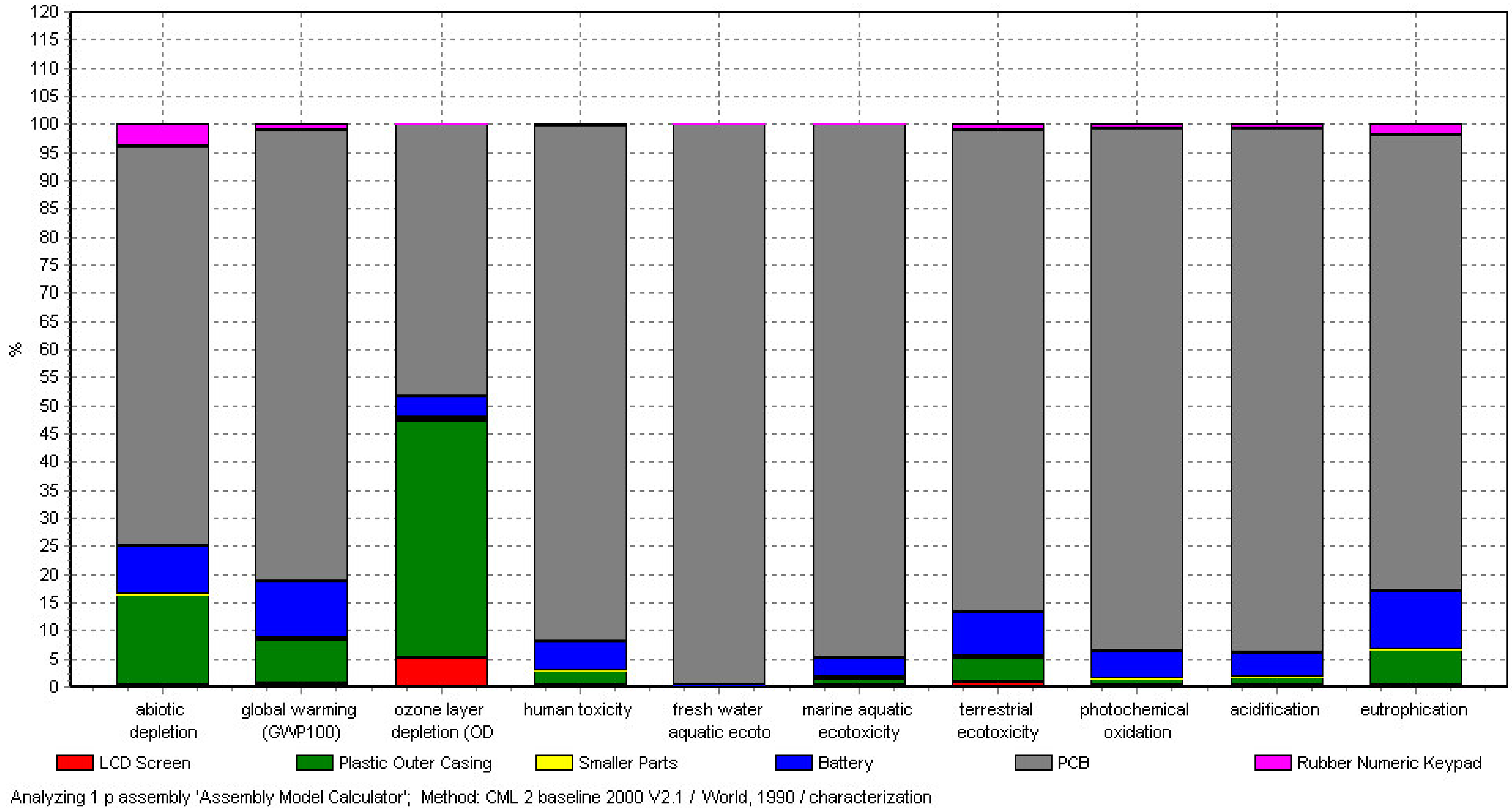

Figure 8.12 – CML 2 - Changed Glass from White to Virgin

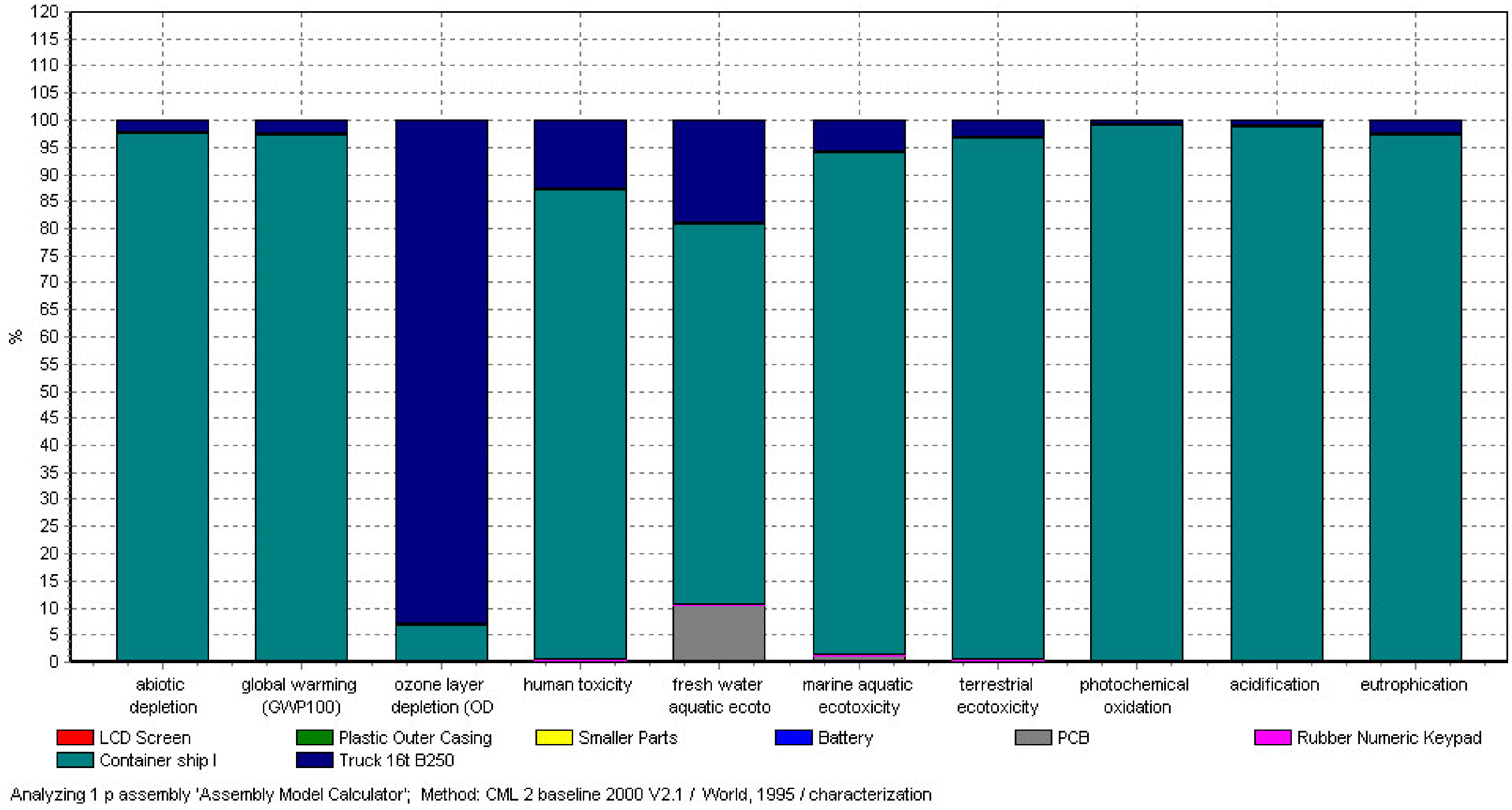

Figure 8.13 – CML 2 - Changed Delivery Van (<3.5t) B250 to 16 t truck B250 with 50% load average

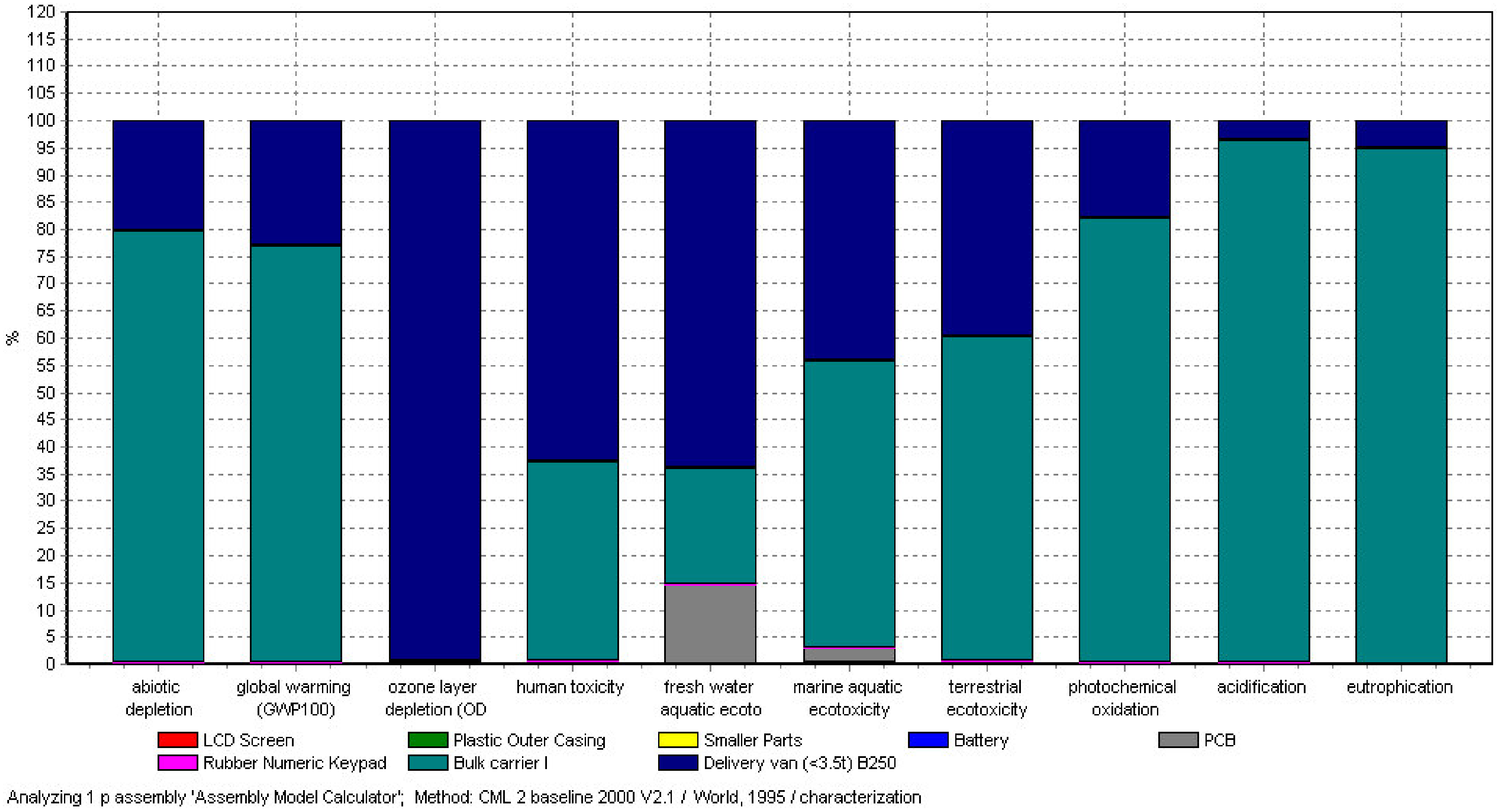

Figure 8.14 – CML 2 - Changed Container Ship I to Bulk Carrier I

8.3 Sensitivity Analysis with EPS 2000

When the quantity of HDPE B250 used was changed from 23.8g to 100g (approximately 4 times), it turned out that the impact levels affected quadrupled as well (x4). This is not the same effect as the analysis with Eco-Indicator '99, where the impact levels did not change. However, this makes sense since this method features a monetary benefit assessment characteristic, where more material used would mean more cost to product development.

When the material used was changed from HDPE B250 to PP granulate average B250, this new material still impacted all the same categories in the same proportions. Quite simply, the PP granulate average had the same impact as the HDPE.

Changing the Alkaline battery to a Lithium Ion battery had some interesting effects. Firstly, impacts on Wood Growth Capacity and Depletion of Reserves doubled (x2). The impact on Life Expectancy, Morbidity and Nuisance tripled (x3). On the positive side, impacts on Severe Morbidity, Fish and Meat Production, and Species Extinction reduced slightly. However, even with these reductions, the increase in the other impact categories shows us that the Alkaline battery is still more preferable.

The change from Alkaline to Nickel Cadmium had almost the same impact levels as the Lithium Ion battery. The only main difference was that now, instead of a 15% impact on Depletion of Reserves, the Ni Cad battery had a 100% impact.

Changing the glass used in the Liquid Crystal Display from White B250 to Virgin B250 does not reveal any changes whatsoever in the only category impacted, which is Severe Nuisance.

As a sensitivity analysis on transportation, when the delivery van is replaced with a 16 ton truck, with an average load of 50%, the impact on Severe Nuisance reduces from 70% to approximately 10%. This is also the category impacted when the Container Ship is changed to a Bulk Carrier. The impact for the Ship changes from 30% to about 90%.

8.3 *Sensitivity Analysis with EPS 2000 (Graphs)*

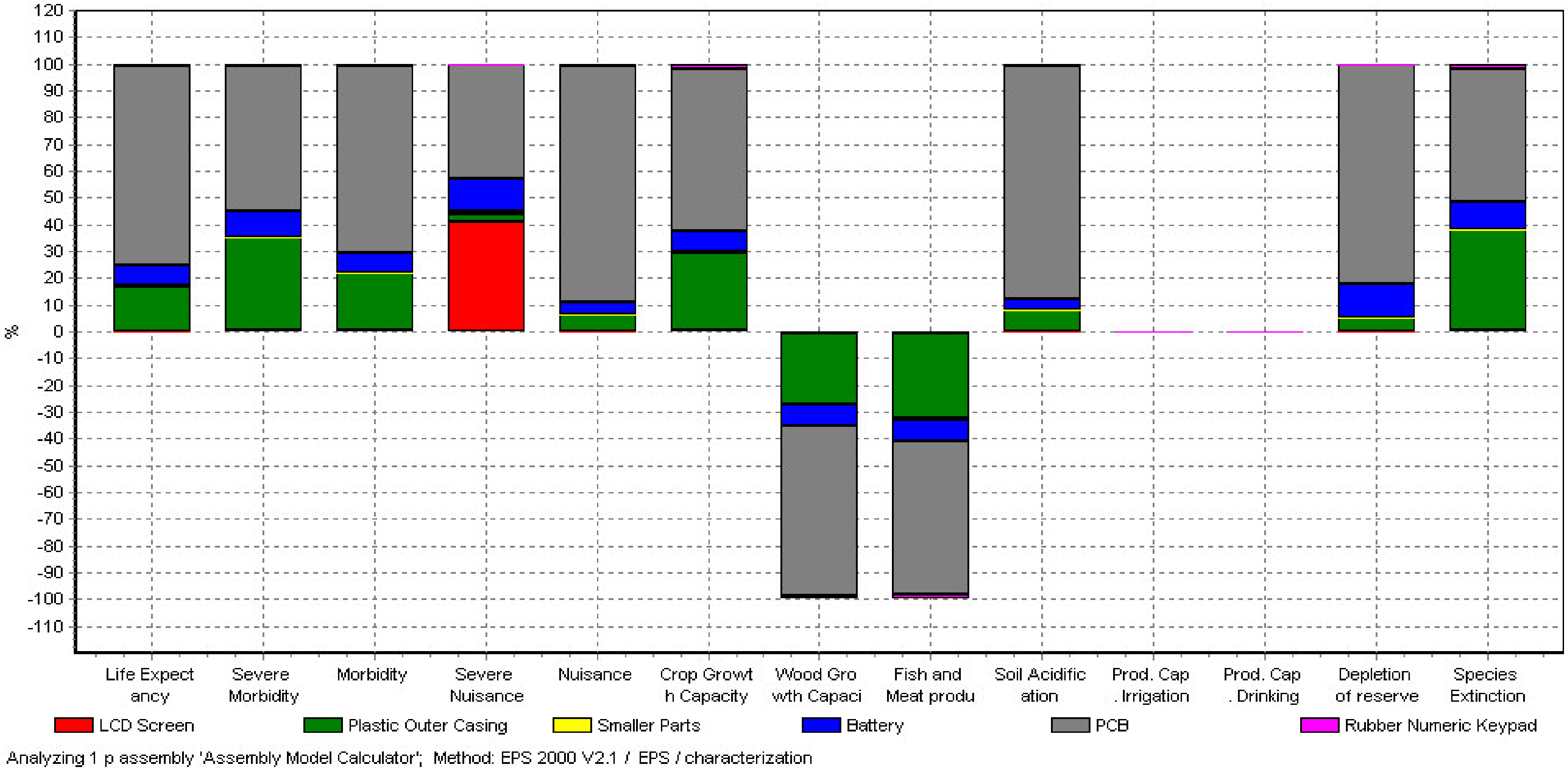

Figure 8.15 – EPS - Changed quantity of HDPE B250 to 100g

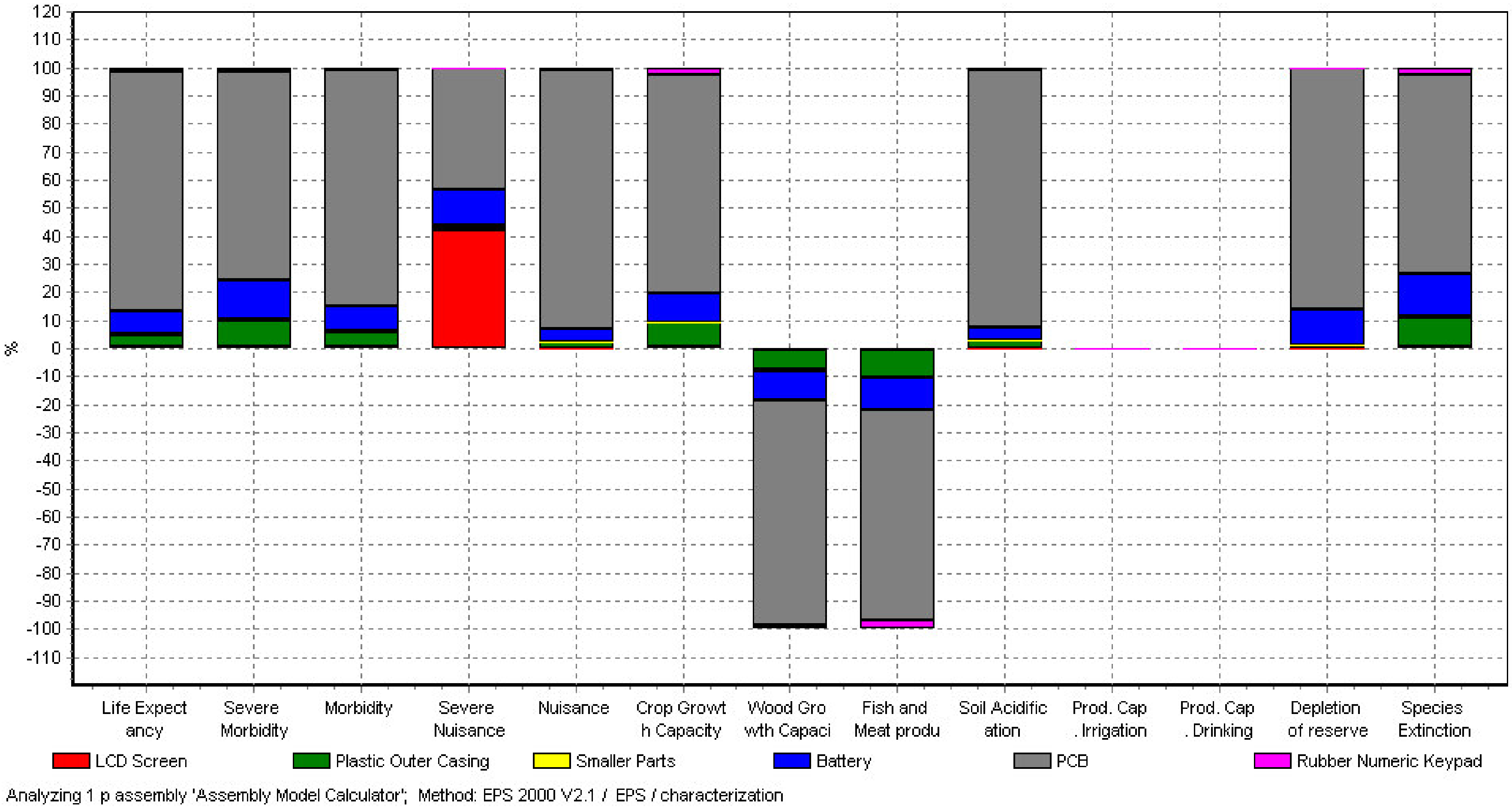

Figure 8.16 – EPS - Changed HDPE B250 Material to PP granulate average B250

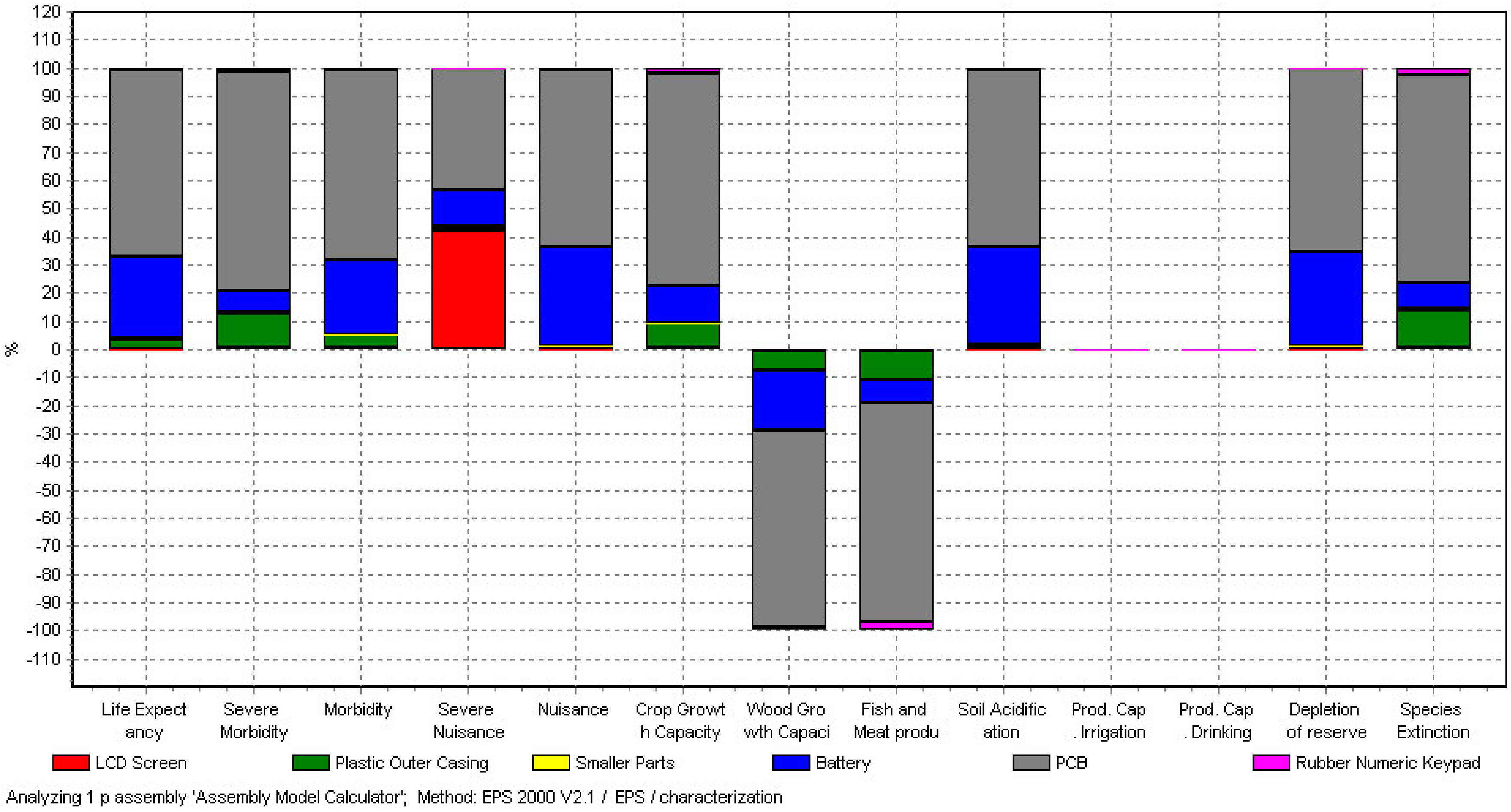

Figure 8.17 – EPS - Changed Battery from Alkaline to Li Ion

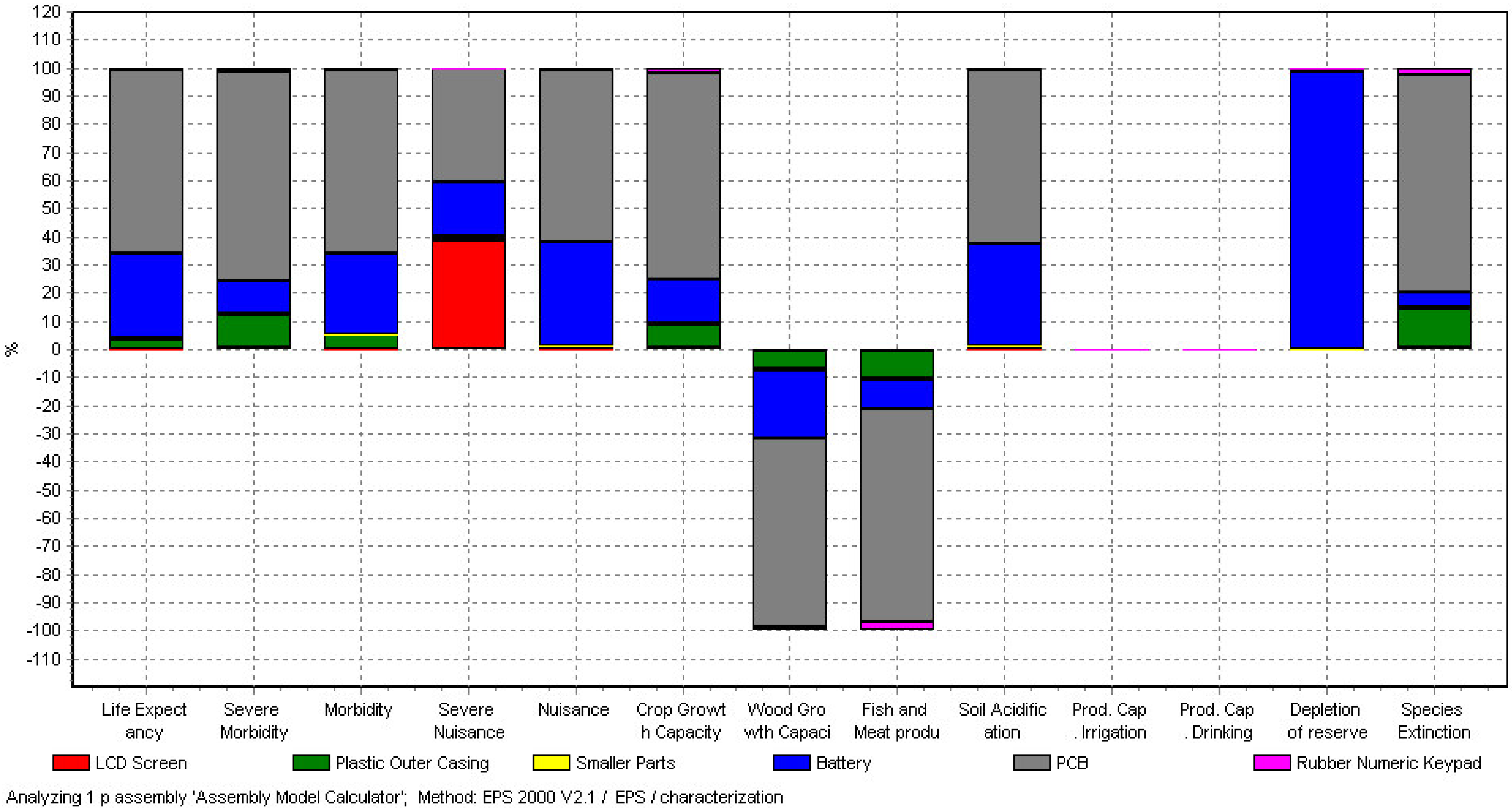

Figure 8.18 – EPS - Changed Battery from Alkaline to Ni Cad

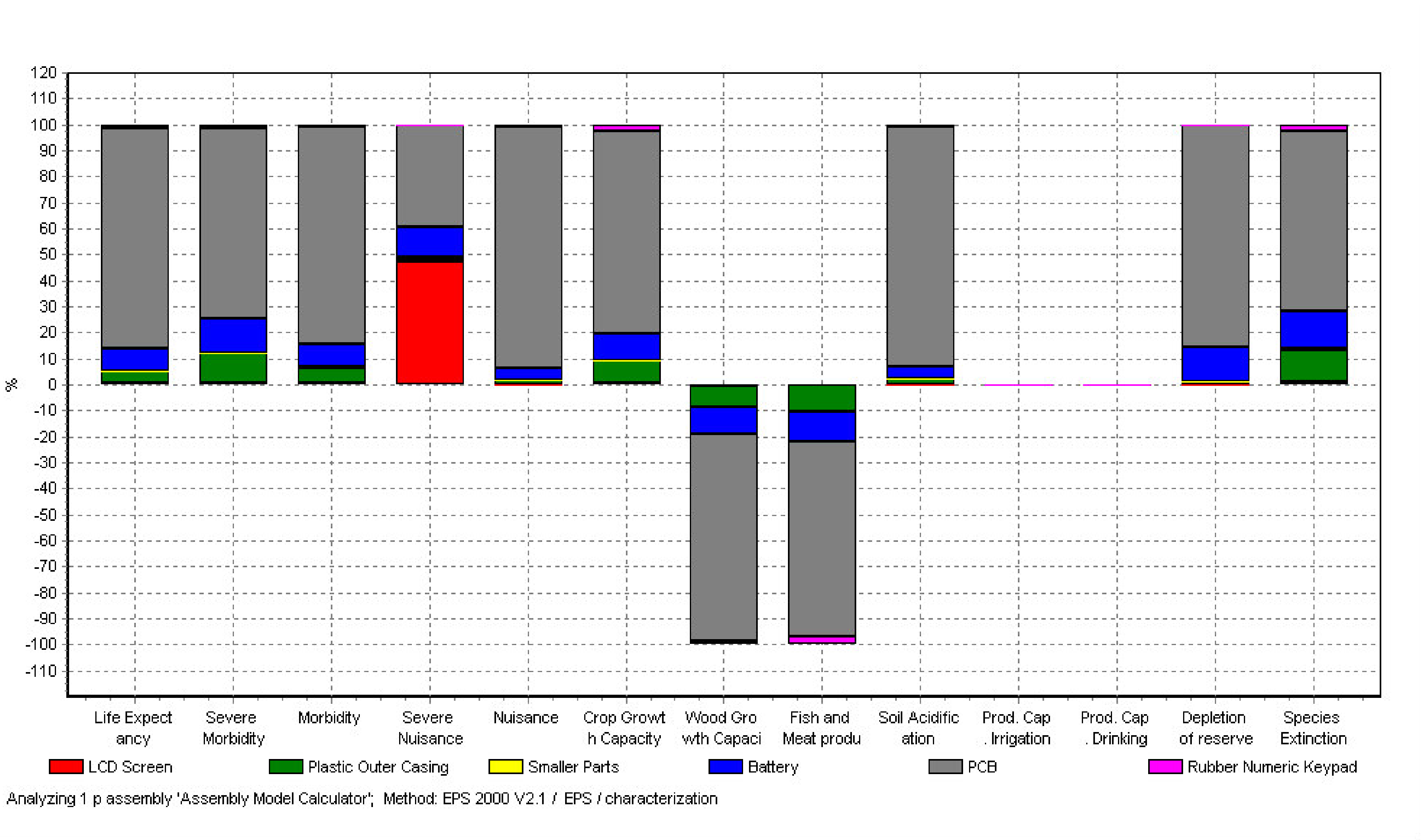

Figure 8.19 – EPS - Changed Glass from White to Virgin

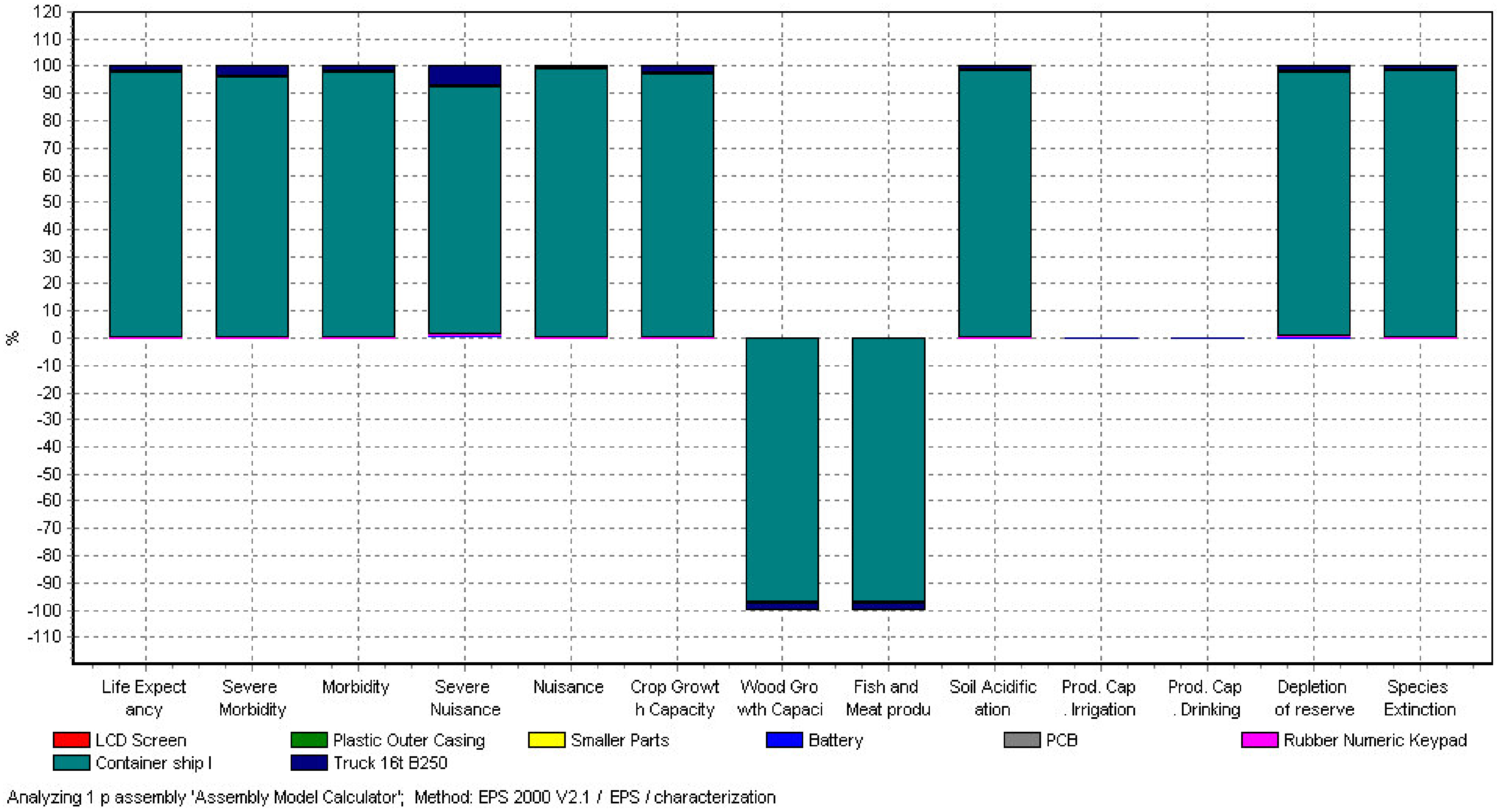

Figure 8.20 – EPS - Changed Delivery Van (<3.5t) B250 to 16 t truck B250 with 50% load average

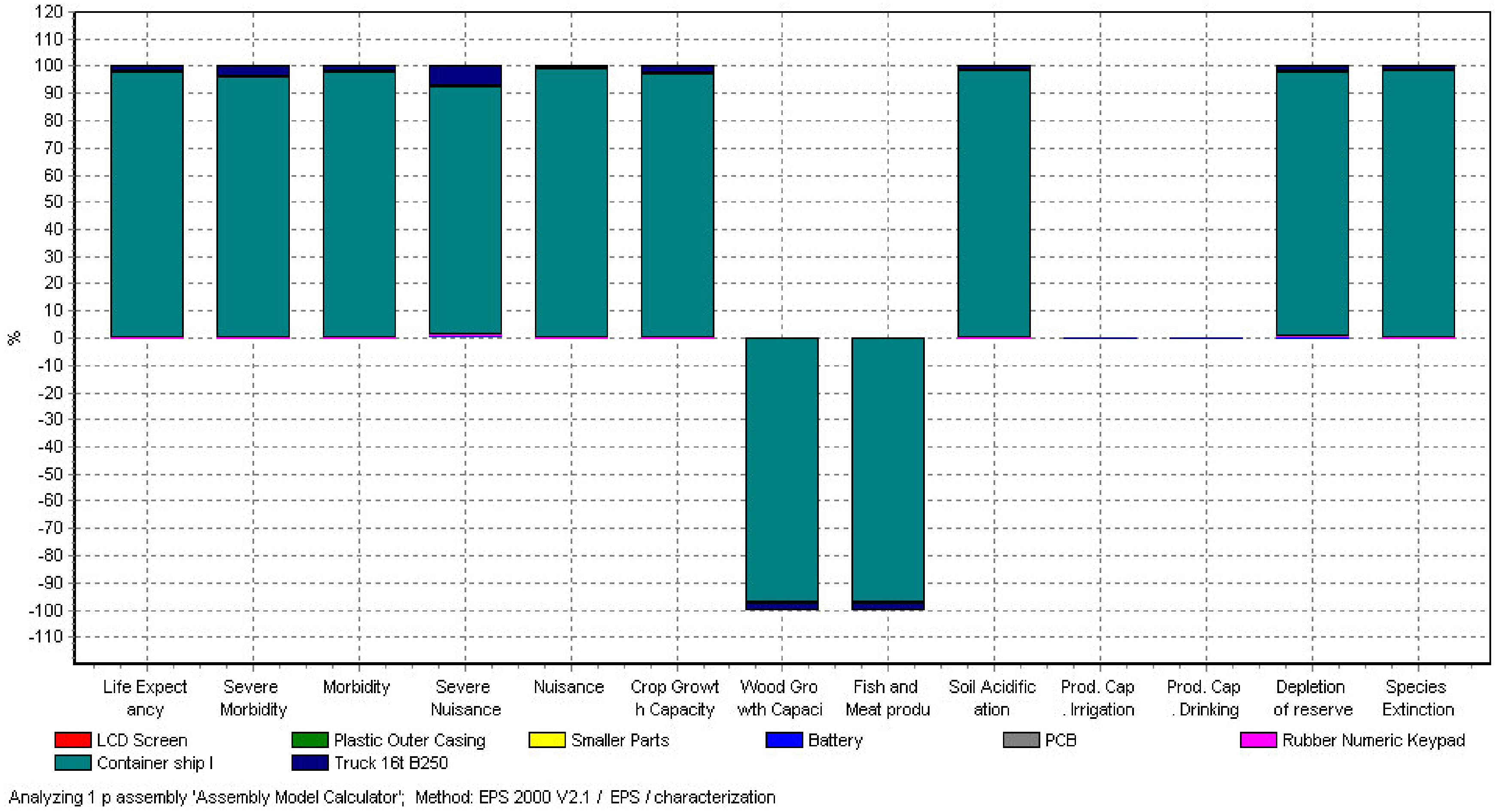

Figure 8.21 – EPS - Changed Container Ship I to Bulk Carrier I

Chapter 9 Conclusions and Summary

9.1 Achievement of Objectives

In conclusion, all of the objectives set out for this research project have been fulfilled in the previous chapters.

The background of Life Cycle Assessment and all previous assessment methods that have led up to it have been researched and understood (*Chapter 2*). In addition to this, the current methodology for LCA has been researched, and applied successfully to this Life Cycle Assessment on a Calculator (*Chapter 3*).

Current International Standards Organization standards for an LCA study have been summarized (*Chapter 2*) and many sources of data have been analyzed in the process of compiling the assembly of the calculator (*Chapters 4,5 and 8*). LCA study in Australia has also been looked at, by analyzing the research done by the Royal Melbourne Institute of Technology, Melbourne in their Australian Eco-Indicator '99 project (*Chapter 2*).

Finally, the objective of this project to select, fully understand, and to apply the LCA methodology in suitable software available in the market (SimaPro v5.1 and v6) has been accomplished. The Inventory, Interpretation, Life Cycle Impact Assessment and Sensitivity Analysis have been effectively completed, and detailed in this report.

The following sections (*9.2 and 9.3*) of this chapter summarize the Impact Analysis and Sensitivity Analysis of all the sub-assemblies involved, and provide a useful basis for comparison with other similar products in the market.

9.2 Impact Assessment of Sub-Assemblies

In this section, each of the sub-assemblies is analyzed in terms of environmental impact as the observed average of results obtained from each of the different Impact Assessment Methods and the sensitivity analysis performed. Suggestions for a more sustainable product assembly based on new manufacturing methods and materials are discussed.

Printed Circuit Board

The only available information for the Printed Circuit Board (PCB) was from the SimaPro IDEMAT 2001 library. From the Impact Analysis performed (Sensitivity Analysis was not performed due to lack of data choices), it was apparent that this was a non-sustainable manufacture of PCB. No matter which Impact Assessment method that was used, the PCB always accounted for most of the impact (approximately more than 70% every time) in almost every category. Methods for sustainable PCB development and manufacture are discussed in section 9.3.

Liquid Crystal Display

The Liquid Crystal Display (LCD) was accounted for as glass. The reason for this was that the other components of the display were negligible.

Through sensitivity analysis (initially performed with SimaPro v5.1), it was determined that recycled glass was definitely more sustainable than newly manufactured glass. The higher percentage of recycled glass used, the lower the impact of the LCD on all categories. Although this same sensitivity analysis could not be performed with EPS 2000 method, it is assumed that the recycled glass would cause more costs associated with the system, and therefore be disagreeable to the impact categories in this method.

In SimaPro v6, the only sensitivity analysis that was done was to change the glass from White B250 to Virgin B250 from the BUWAL 250 library. This showed little to no changes in impact categories.

Battery

Besides the Alkaline battery (which was used since it was the type of battery supplied with the Calculator), there were only 2 other options which were the Lithium Ion and the Nickel Cadmium batteries.

The Lithium Ion battery showed up to be worse than the Alkaline, and caused more impact, though still in the same categories (as with the Nickel Cadmium). Although it caused less impact than the Ni Cad battery, this was still not a sustainable product to use.

At a glance, the Nickel Cadmium (Ni Cad) batteries may seem like a friendlier alternative to the disposable dry cell, due to their rechargeable nature. However, from this Life Cycle Analysis, it is apparent that even though the impact on Ecotoxicity (referring to *Chapter 8, 8.2 Sensitivity Analysis with Eco-Indicator '99*) reduces (only slightly by approximately 5%), impacts on other categories double and triple. This means that the benefits of using these rechargeable Nickel Cadmium batteries are not justified due to the large impact on the environment.

Plastic Casing

The plastic casing had the second largest impact in every Impact Assessment method after the PCB. The material used was HDPE and even though this material breaks down to biodegradable components when incinerated, it still created a large impact in most categories. This may mean that the actual manufacture of raw HDPE and the manufacture of HDPE products create wastes that impact the environment.

In this case, it does not matter how well a substance biodegrades or goes back to nature, because the damage has already been done.

Smaller Parts (Capacitors, Screws and Battery Holder)

The smaller parts in this system caused practically no impact whatsoever. When it did, it was usually insignificant. This could be because the material used for this sub-assembly was steel. In capacitors, only the metal parts were accounted for. The ECCS 100% recycled steel used in this study proved to be extremely sustainable.

Rubber Keypad

The data used for the Rubber Keypad was for Butadiene Rubber. This is not the correct type of rubber to be used for this particular application, but was the closest option that was available. Therefore, it was decided that this data would be used, together with Extrusion for molding the rubber into a keypad.

This proved to have very little impact on the overall system. Therefore, it is concluded that the rubber keypad does not cause large problems in terms of environmental impact. The rubber can be broken down to form new products after disposal.

9.3 Recommendations for Improvement

The only sub-assemblies that need improvement are the Printed Circuit Board and the Plastic Casing.

Printed circuit board manufacture produces sludge through the use of non-sustainable materials. This can be remedied through the use of easily recycled materials, the use of de-ionized water in process baths, use of mild chelators, and through the use of alkaline cleansers instead of solvents for degreasing operations. The following website provides good information on the sustainable manufacture of PCBs through reduction of waste and pollution from the source (http://www.calgold.ca.gov/P2/3672.htm).

The Plastic Casing is not very sustainable. In general, any kind of plastic is not good, in terms of manufacture, and also in terms of biodegradability. It may be advisable to replace the plastic used in this assembly, and also in most similar assemblies with a metal of some sort. This would eliminate most of the waste created by this process.

For the Rubber Numeric Keypad, the more sustainable solution would be to use Silicon Rubber. This is the rubber that is being used by mobile phone and television manufacturers in the industry these days for rubber keypads. They are resistant to many substances, last long, and is extremely sustainable.

9.3 Proposal for Future Work

The university has a multi-user license for SimaPro version 6.0 which includes the Australian database from the Australian Eco-Indicator Project compiled by RMIT. This database includes materials and processes gathered from the Australian industry, and features an Australian Impact Assessment Method that was derived from the original Eco-Indicator ’99 project. Perhaps another LCA on the same product could be done, to provide for comparison between a more accurate analysis with the current one.

A new Impact Assessment method provided with SimaPro v6 is the IPCC 2001 method, which calculates the environmental impact of a defined assembly on Global warming, based on the emissions to air. Perhaps another study could be done to determine the effects of an electronic product (e.g. – a calculator) on global warming.

The call for standards is important to make any Life Cycle Assessment accessible and usable by those in engineering, product development, and also to the consumers. Perhaps in the future, some sort of standardized method of grouping data from different Impact Assessment methods could be developed, so that some sort of rating system could be developed. This rating system would help engineers and product developers select appropriate materials for newly designed products, and would assist consumers in making more sustainable choices when purchasing electronic products.

List of References

- Susan Svoboda, (Manager of the University of Michigan Corporate Environmental Management Program), *Notes on Life Cycle Analysis*, National Pollution Prevention Center for Higher Education at The University of Michigan, viewed 20th October 2004, http://www.umich.edu/~nppcpub/resources/compendia/CORPpdfs/CORPlca.pdf

- PRé Consultants Website, *What is Life Cycle Assessment?*, viewed 20th October 2004, http://www.pre.nl/life_cycle_assessment/life_cycle_assessment.htm

- Boustead Consulting Ltd. Website, 'The Boustead Model', viewed 20th October 2004, http://www.boustead-consulting.co.uk

- The LCA Research Center, 'What is LCA?', viewed 20th October 2004, http://www.lcarc.re.kr/English/index.htm

- ICF Consulting Website, 'Sustainable Development and Life Cycle Programs', viewed 20th October 2004, http://www.icfconsulting.com/Markets/Environment/envmgmt06.asp

- The Centre for Design, 'ERD Guidelines: EEPs', RMIT website, viewed 20th October 20044, http://www.cfd.rmit.edu.au/services/publications_web_tools/articles/erd_guidelines_eeps

- Ryding, '*ISO 14042 – Environmental Management, Life Cycle Assessment, Life Cycle Impact Assessment*', the Swedish Environmental Management Council Website, viewed 20th October 2004, http://corbu.aq.upm.es/~cbedoya/webacv/articulo/lca4_307.pdf

- Guinee, 'An Operational Guide to the ISO Standards – Part 1', University of Leiden Website, viewed 20th October 2004, http://www.leidenuniv.nl/interfac/cml/ssp/projects/lca2/part1.pdf

- Marano and Rogers, 'Process System Optimization for Life Cycle Improvement', Energy Citations Database, Environmental Progress ; VOL. 18 ; ISSUE: 4 ; PBD: Win 1999, viewed 20th October 2004, http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=20015099

- Environmental Management Center, 'Life Cycle Assessment', EMC Website, viewed 20th October 2004, http://www.emcentre.com/textile/lca.htm

- International Standards Organisation, 'ISO 14040 outlines', ISO Website, viewed 20th October 2004, http://www.iso-14001.org.uk

- Wikipedia (the free encyclopedia), ‘Capital (economics)’, Wikipedia Website, viewed 20th October 2004, http://en.wikipedia.org/wiki/Capital_%28economics%29

- IDEMAT Online, ‘Manual for Designers’, IDEMAT Online – Delft University of Technology Website, viewed 20th October 2004, http://www.io.tudelft.nl/research/dfs/idemat/Backgr/bi_frame.htm

- Goedkoop, Oele, Effting (Pré Consultants), ‘SimaPro 6 Database Manual Methods Library’, June 2004, Pré Consultants, The Netherlands

- Goedkoop, Oele, (Pré Consultants), ‘Introduction into LCA with SimaPro’, June 2004, Pré Consultants, The Netherlands

- Goedkoop, (Pré Consultants), ‘SimaPro Tutorial – The Wood Example’, November 2002, Pré Consultants, The Netherlands

- China Shipping Australia , ‘Schedule Timetable’, China Shipping Australia Website, viewed 16th September 2004, http://www.cnshipping.com.au/schedule/

- NationalGeographic.com, ‘China-Australia Map – The Map Machine’, National Geographic Society Website, viewed 10th August 2004, http://plasma.nationalgeographic.com/mapmachine/index.html?&themeId=100&ext=73.794019,-45.382725,163.073422,46.219934&size=s&maplayers=Roads%20and%20Railroads%3A%3AT%7E%7EPlaces%3A%3AT%7E%7EPolitical%20Boundaries%3A%3AT

- Australian Life Cycle Assessment Network, ‘Links’ Australian Life Cycle Assessment Network Website, viewed 20th October 2004, http://auslcanet.rmit.edu.au/

- Bawei Group, ‘AG10 (LR1130) button cell characteristics’ Sunturn / Everturn Battery Productions Co. Website, ‘viewed 28th October 2004, http://www.sunturnbattery.com/cgi-bin/sunturnbattery/AG10%28LR1130%29.html

- Envirosense, ‘Common Sense Solutions to Environmental Problems’, Envirosense Website – Environmental Protection Agency , 28th October 2004, http://es.epa.gov/program/p2dept/energy/nice3/nice3-7.html

- Environmental Expert.com, ‘Gabi 4 Software’, Environmental Expert S.L Website, viewed 28th October 2004, http://www.environmental-expert.com/software/pr_eng/pr_eng.htm

- Pré Consultants, ‘SimaPro Download’ Pré Consultants Website, viewed 28th October 2004, http://www.pre.nl/simapro/download_simapro.htm

- California Environmental Protection Agency, 'Pollution Prevention (P2) for Printed Circuit Board Manufacturing 3672' California Environmental Protection Agency Website, viewed 28th October 2004, http://www.calgold.ca.gov/P2/3672.htm

Appendix A Project Specification

University of Southern Queensland
FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **Adrian Supurmaniam**

TOPIC: Life Cycle Assessment

SUPERVISOR: Mr. David Parsons

ENROLMENT: ENG 4111 – S1, ONC, 2004
ENG 4112 – S2, ONC, 2004

SPONSORSHIP: Faculty of Engineering, USQ

PROGRAMME: **Issue A, 23rd March 2004**

1. Research background information on the origins and uses of Life Cycle Assessment over a period of time.

2. To understand the current Methodology of Life Cycle Assessment as well, as to investigate its current limitations, including standards, the need for data, and its sources, as well as how the methodology is used.

3. To summarize on the current state of the technique. This involves reporting on papers published by professionals and research institutions.

4. Researching the level of research and development in Life Cycle Assessment in Australia.

5. Apply the LCA methodology to a specific product in the Electrical / Electronics area using an LCA software (Sima Pro).

6. Produce a detailed report on the research by interpreting the final Life Cycle Inventory and producing relevant data that can be utilized as a useful basis for comparison to other products.

Appendix B Calculator Parts and Weights

- Calculator (Before disassembly) - 39.5 grams
- Circuit Board (with solder, 2 Capacitors and Battery Holder) – 4.6 grams
- Circuit Board (empty) - 3.8 grams
- Battery Holder - 0.3 grams
- LCD screen - 4.2 grams
- Battery - 1.2 grams
- Plastic Outer Casing - 23.8 grams
- Rubber Numeric Keypad - 5.7 grams