University of Southern Queensland

Faculty of Engineering and Surveying

Life Cycle Assessment of a SAW Filter

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ABSTRACT

The environmental implications associated with microelectronic products are significant. Most of the environmental impacts occur during the manufacturing stage which involves intricate and environmentally sensitive processes. This research project was carried out to assess and appreciate the environmental performance of a typical microelectronic product through a Life Cycle Assessment (LCA).

A Surface Acoustic Wave (SAW) filter was chosen as the functional unit of this LCA study. All the processes involved in the manufacturing of a SAW filter were identified and analysed in detail. Process clusters were developed for the ease of data collection. Using these clusters as a basis, life cycle inventory data was quantified and is tabulated in this dissertation.

The quantified inventory data was analysed using a demonstration version of Simapro 7.0 software. Impact assessment method, 'Eco-indicator 99' was chosen for the analysis and the results for some of impact categories are presented. Life cycle interpretation was conducted to establish validity and reliability of the inventory and impact assessment results. Environmentally culpable processes and inventory items have been highlighted and finally, some recommendations have been made based on the results of this LCA.

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GLOSSARY

Allocation	Partitioning of input or output flows of unit process to the product of the study.
Characterisation	Use of characterisation factors (scientific data) to convert the life cycle inventory data of a product into environmental impact category results.
Consistency Check	Part of the Interpretation stage, this check ensures that all relevant information and data needed for the Interpretation phase is available and complete.
Damage category	Grouping of similar impact categories.
EOL	End of Line production processes involved in a SAW filter production. These include assembly, encapsulation, testing and the packing of the finished product for delivery to customers
FOL	Front of Line or the wafer fabrication production processes involved in a SAW filter production. These include photolithography, wafer passivation and wafer preparation for end of line processes.
Functional unit	The reference unit of a LCA.
Goal and Scope	The first stage in a life cycle assessment whereby the goal, audience, functional unit, system boundaries and assumptions used are defined.
Interpretation	The fourth and last stage in a life cycle assessment. The results from life cycle inventory and life cycle impact assessment stages are analysed to ensure credibility and reliability to a LCA study. Conclusion and recommendations are made at the end of interpretation stage.

Impact Category	Represent environmental issues of concerns, such as climate change, respiratory inorganics, eutrophication, fossil fuel depletion etc.
LCA	Life Cycle Assessment. The quantification and evaluation of all inputs, outputs and the possible environmental impacts of a product throughout its life cycle.
LCI	Life Cycle Inventory. The second stage of a LCA in which all inputs and outputs of a product throughout its life cycle are quantified.
LCIA	Life Cycle Impact Assessment. The third stage of a LCA in which life cycle inventory data is translated into environmental impacts scores using scientific (characterisation) factors.
Normalisation	Expression of environmental impact scores relative to an available standard to appreciate the magnitude of the impacts.
Sensitivity check	Part of the life cycle interpretation stage, sensitivity check is the step in which the uncertainties and other expected variations in data are evaluated to determine their sensitivity towards the final results of the LCA.
SAW filter	Surface Acoustic Wave filter. The functional unit of this LCA.
Single score	Aggregation of weighted scores.
System boundary	Defines the length and breath of an LCA. What should and should not be included in a study is determined by its system boundaries.
Weighing	The process of converting category indicator results into a common unit using numerical factors based on value choices. Weighted scores are very subjective and not recommended for comparative studies.

Chapter 1 INTRODUCTION

1.1 Project background

"Nothing last for ever", which is very true in the case of earth's natural resources. Until recent times, the society, motivated by the materialistic gains has chosen to be ignorant about sustainable growth, foolishly assuming that earth natural resources would last forever. Today, these resources are being consumed at an extremely unsustainable rate. Electronic products which are an integral part of a man's daily life, is one of the chief perpetrators.

One of the defining trends of the 20th century has been the growing dependence of man on electronic products. Especially in the past few decades, the explosive growth of electronic, communication and information technology products has spurred economic growth and improved people's lives in countless ways. Microelectronic chips are the building blocks that make up an electronic product. For example, there are hundreds of microelectronic chips in a personal computer. As the electronic industry keeps growing, these chips are just everywhere, in computers, televisions, hand phones and even in automobiles. They play an invaluable role in our daily lives and as such, there is an ever increasing demand for these products. The average growth rate per year of microelectronics industry is about 15%, making it one of the dynamic industries in the world **(**International Technology Roadmap for Semiconductors Executive Summary 2005, p. 1).

Though small in size and weight, the environmental impacts associated with microelectronic products are significant. Most of the environmental implications occur during the manufacturing stage which involves intricate and environmentally sensitive processes. Environmental concerns stems from the use of high purity raw materials, large amounts of water, chemical, energy and the need for extreme cleanliness of the manufacturing environment. Although the industry is well aware of the environmental consequences, there is little consensus in the industry regarding the actual magnitude of these impacts.

Hence, to have a better understanding regarding the actual impacts related to a typical microelectronic product, this research project, “Life Cycle Assessment of a SAW filter” was carried out. Life cycle assessment (LCA) is an organized toolset of procedures for compiling and examining the inputs and outputs of materials along with energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle (ISO standards). LCA is a holistic approach to evaluate the environmental implications of a product through out its life cycle (U.S. Department of Energy 2003)**.** A detailed LCA provides a means of identifying and evaluating the opportunities to minimise environmental impacts at each process stages.

This research project aims to assess and appreciate the environmental performance of a typical microelectronic product through a LCA and then to use the results of the LCA to identify the parts of manufacturing processes that are worst from an environmental point of view. A Surface Acoustic Wave (SAW) filter was chosen for this study. Surface Acoustic Wave (SAW) devices are single-crystal piezo-electric devices that are commonly employed as filters and oscillators. These devices are used extensively in the communication world today, especially in the booming mobile phones and multimedia markets.

A SAW filter was chosen for this research primarily because of the availability of Life cycle Inventory (LCI) data that was required for a LCA. The inventory data was collected from a SAW filter manufacturing company in Singapore. The Life cycle impact assessment (LCIA) and life cycle interpretation stages of the LCA were done using Simapro 7 software.

In addition to the abovementioned objectives, this research project also reviews in detail the past and present literatures published on similar LCA topics to understand the LCA practices and concepts in use today. Many of the literature used as reference material for this project are based on semiconductor products. SAW devices, though not exactly a part of the semiconductor industry, is very similar to a semiconductor device in the manufacturing sense. They are fabricated utilizing common processes used in the manufacture of semiconductors.

1.2 Outline of the Report

This dissertation begins with a brief presentation of the project background in Chapter1. Chapter 2 reviews in detail the available literature on Life Cycle Assessments (LCA). The historical background of LCA, current LCA methodologies and standards are explored. The types, uses, limits and complexities of LCA studies are also discussed. The chapter then moves on to review the available literature on LCA done in Microelectronics industry.

The four stages of the LCA are covered in Chapters 3, 5, 6 and 7. The structuring of the report for these chapters is identical. The first section of each chapter expands on the literature review in Chapter 2 and analyses in detail each of the LCA stage. The current standards and common techniques used are discussed. This information is then used as a basis for the development of methodologies for this particular LCA in the following sections of the chapters. The first stage of the LCA, the Goal and Scope definition is covered in Chapter 3.

Chapter 4 presents the product of this LCA, a SAW filter. It begins with a brief introduction on the functions and characteristics of the product and moves on to study the life cycle of a SAW filter in depth. The processing and manufacturing stage of the SAW filter is documented in section 4.3. The second stage of the LCA, Life Cycle Inventory (LCI) is covered in Chapter 5. All the inventory data collected for this LCA are tabulated in this chapter.

The analysis and findings of the Life Cycle Impact Assessment (LCIA) stage of the LCA are presented in Chapter 6. Chapter documents the life cycle interpretation stage where the results from inventory stage and impact assessment stage are analysed for reliability. Chapter 8 summarises the major results, discusses the limitations and assumptions made during the course of this study and makes conclusions and recommendations based on the results of this LCA.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

This chapter studies in detail the past and present literature available on relevant Life Cycle Assessment (LCA) topics. It begins with a brief look at the historical background of LCA and proceeds on to review the present LCA techniques to identify concepts and ideas being used such as building model of a process, finding specific data, using models of environmental impact based on scientific knowledge and how LCAs are done using software. This chapter further critiques the current international life cycle assessment standards and how Life cycle assessment fits in to the general International situation. The types, uses, limits and complexities of LCAs are also discussed briefly. Concepts developed from this review are used to develop the methodologies for this research project in the subsequent chapters.

2.2 Historical Background of Life Cycle Assessment

The environment has been under constant stress from humans activities over the years. An energy crisis in the late 1960s raised the awareness of environmental impacts. As a result, LCAs were formulated as an approach to understand the impacts of energy consumption, by scientists concerned about the rapid depletion of fossil fuels. As global-modelling studies predicted future depletion of fossil fuels and resulting climatological changes, it sparked an interest in performing more detailed energy calculations on industrial processes **(**Svoboda 1995**)**. In 1969, an environmental study was funded by Coca-Cola Company to determine resource consumption and environmental releases to the environment.

The U.S. Environmental Protection Agency (EPA) refined this methodology and created an approach known as Resource and Environmental Profile Analysis (REPA), which was commonly used in 1970s. REPA as the name suggests, focused only on raw material demands, energy inputs, and waste generation flows.

In Europe a similar methodology was developed and published as *'Handbook of Industrial Energy Analysis'* in 1979 by Ian Boustead.

Life cycle logic was incorporated in to risk assessment methods in the 1980s as main environmental concern was hazardous waste management (Svoboda 1995). As solid waste and pollution became a major concern in the late 1980s and the early 1990s, it brought about a new government and corporate stance on environmental policy and a demand for new LCA approaches.

In 1991, the Society of Environmental Toxicology and Chemistry (SETAC) in conjunction with United States Environmental Protection Agency (USEPA) published a "Code of Practice", the first guidelines for conducting a LCA (Tan & Culaba 2003). The new methodology differed in detail from the earlier versions of the LCA in that, it focused not only on resources and waste flow analysis but also on the more sophisticated topics such as impact and improvement analysis. Likewise, in Scandinavia, a detailed LCA methodology titled "Nordic Guidelines on Life Cycle Assessments" was published in 1995.

International Organization for Standardization (ISO) further refined these guidelines and, a set of standards for carrying out a LCA was developed in 1997 as a part of ISO 14000 Environmental Management Standards. The LCA methodology is defined in the ISO documents ISO14040 to ISO14043 (ISO 14040 Series). This paved the way for making LCA, a comprehensive decision making tool internationally.

Initially the usage of LCA was limited to public sectors, but in recent times, a large number of corporations and non-profit organizations have adopted LCA. With the advent of eco-labelling, LCA is being used increasing as a reporting mechanism. Environmental organizations such as Blue Angel (<http://www.blauer-engel.de>), Green Cross (<http://www.greencross.ch>), and Green Seal (<http://www.greenseal.org >) have adopted LCA. They use and continue to improve LCA for the purpose of product labelling and evaluation (Svoboda 1995).

2.3 LCA Standards and The General International situation

ISO's set of standards and SETAC's 'Code of Practice' is widely accepted as the general framework for LCA today (Potting & Hauschild 2005). Though the two sets of standards differ in some aspects, there is a general consensus on the LCA methodology between SETAC and ISO (Berkel 2000).

SETAC, a scientific and professional society, developed the first set of LCA standards that were published in 1991. Since then SETAC has provided infrastructure, credibility, resources, and technical expertise to the continuous development of life-cycle concepts both in the United States and Internationally. SETAC focuses on the scientific development of LCA methodology through it various workgroups. SETAC's four-part approach to LCA is shown in figure 2.1.

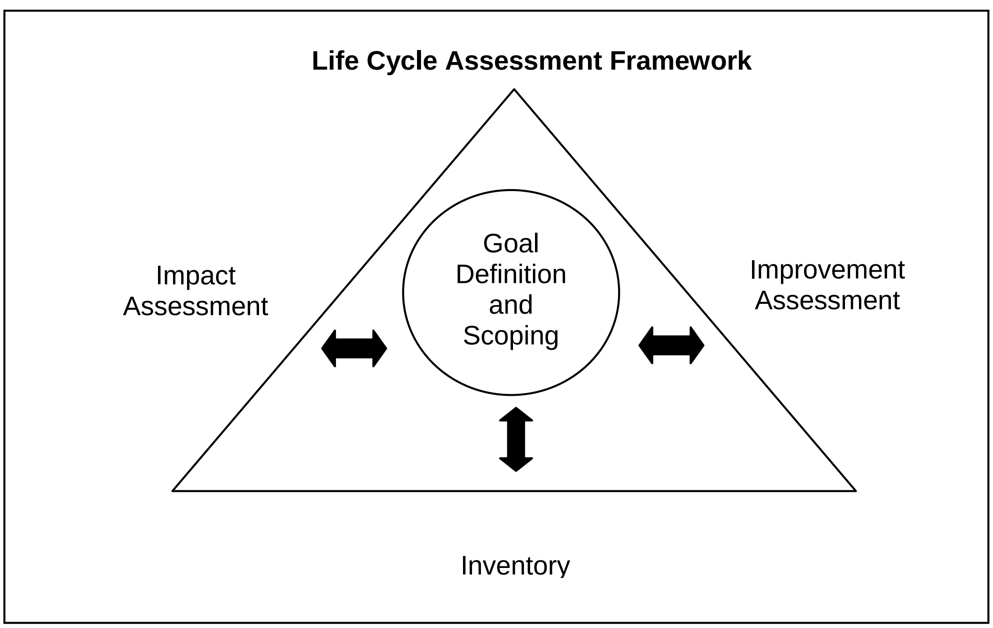


Figure 2.1: Methodological Framework of LCA according SETAC (Curran 2000, p. 1)

SETAC's LCA framework comprises of four interconnected stages; Goal and scope definition, life cycle inventory, life cycle assessment and life cycle improvement analysis.

ISO, which aspires harmonisation and standardisation of practices began its work in 1994, with some involvement from SETAC and published a series of LCA standards in the following years;

- Principles and framework (ISO 14040:1997)
- Goal and scope definition and inventory analysis (ISO 14041:1998)
- Life cycle impact assessment (ISO 14042:2000)
- Life cycle interpretation (ISO 14043:2000)

Currently, these four standards are replaced by two draft standards (which are expected to become standards by end 2006), Principles and Framework (ISO/DIS 14040:2006) and Requirements and Guidelines (ISO/DIS 14044:2006). Requirements and Guidelines standards replace standards ISO 14041, 14042 and 14043 but the Danish Environment agency (2005) reports that there have been no major changes in the content.

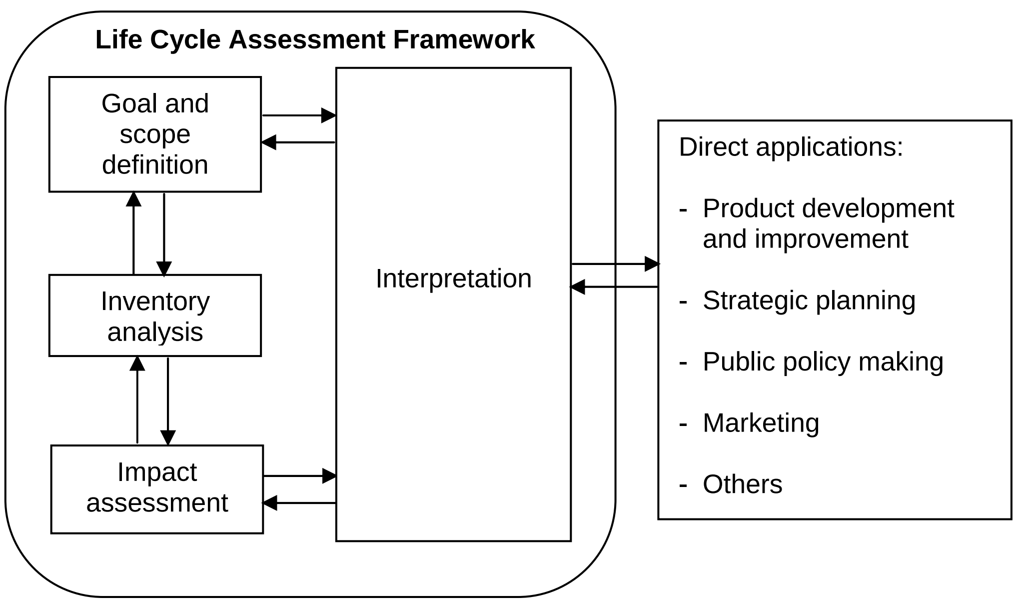


Figure 2.2: Methodological Framework of LCA according to ISO 14040 (LCA101 2001, p. 6)

In comparison to the scientific approach adopted by SETAC, ISO focuses on the procedures to be followed for conducting LCA with a view to assure transparency, independence and accountability of the LCA processes (Berkel 2000)**.** From figures 1 and 2 it is clear that the ISO 14040 series bears a strong resemblance to the SETAC's framework. In ISO's LCA framework, life cycle improvement is not considered as a single stage on it own. It is replaced by another stage, life cycle interpretation.

Today, there are few other regional LCA standards that are being used internationally such as the Danish EDIP methodology documentation, the Nordic guidelines (1995), the Dutch LCA guidelines, and the North American publication with guidelines on inventory and principles **(**Danish Environmental Protection Agency 2005**)**. Though the basic LCA concept remains the same and follows the ISO 14040 series framework, there are some important differences between these standards, mainly because of regional divergences in environmental concerns and control strategies.

The regional LCA standards developed by a government or research organisations can be more suitable for that region than any other standards as it takes in to account the local conditions and concerns. The search for regional LCA standards for Asia, which would have been useful for this project, proved to be futile. Though, a considerable amount of LCAs have been done in Japan, the information was difficult to access (mainly because most the papers published on the web were in Japanese).

In conclusion, ISO standards remain the best code of practice for conducting an LCA, especially in the absence of regional standards. ISO champions the development of international standards and in comparison to other LCA standards; they reflect and document the latest methodological progress in the ISO 14040 series. This research project tries to follow the ISO 14040 series methodically at all times. Any unavoidable deviations from the standards will be highlighted and discussed in detail. From this point onwards, any reference to 'standards' in this report would mean ISO standards unless otherwise stated.

2.4 LCA Methodology

A full LCA is often referred to as the cradle-to-grave approach as it is a systematic assessment of the environmental impacts of a product through all of its life cycle. The LCA framework is made up of four interconnected stages; Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Life Cycle Interpretation (see figure 2.2). It can be seen as an iterative process where by each stage may have to be passed through more than once due to the new demands posed by a later stage. It is important to note that decisions and action that may follow a LCA is outside the framework of LCA according to ISO standards, as shown in figure 2.2.

2.4.1 Goal and Scope Definition

Documented in ISO 14041, the goal definition and scoping phase is a critical part of a LCA study. The conclusions of the SETAC document (Barnthouse et al. 1998, p. 47) reinforces this view: “The study goal and scope are crucial to managing and coordinating a life-cycle study by bringing together the LCA information needed to make an identified decision and an understanding of the reliability and representativeness of the LCA.”.

The goal defines the reasons for conducting the study, the expected product of study, its intended applications, target audience. The scope of the study defines the boundaries, assumptions and limitations and the type of critical review conducted at the end of the study.

2.4.2 Life Cycle Inventory

The Life Cycle Inventory (LCI) analysis is a technical, data-based approach to quantify the energy and raw material consumption, atmospheric and waterborne emissions and other wastes of a product, process material or activity of a product over its life cycle (Vigon et al. 1993, p.7). The LCI standards are defined in ISO14042 document.

Shown below in figure 2.3 is a complete lifecycle (“cradle to grave”) of a product. A full scale LCI involves the quantification of all inputs and outputs that are shown.

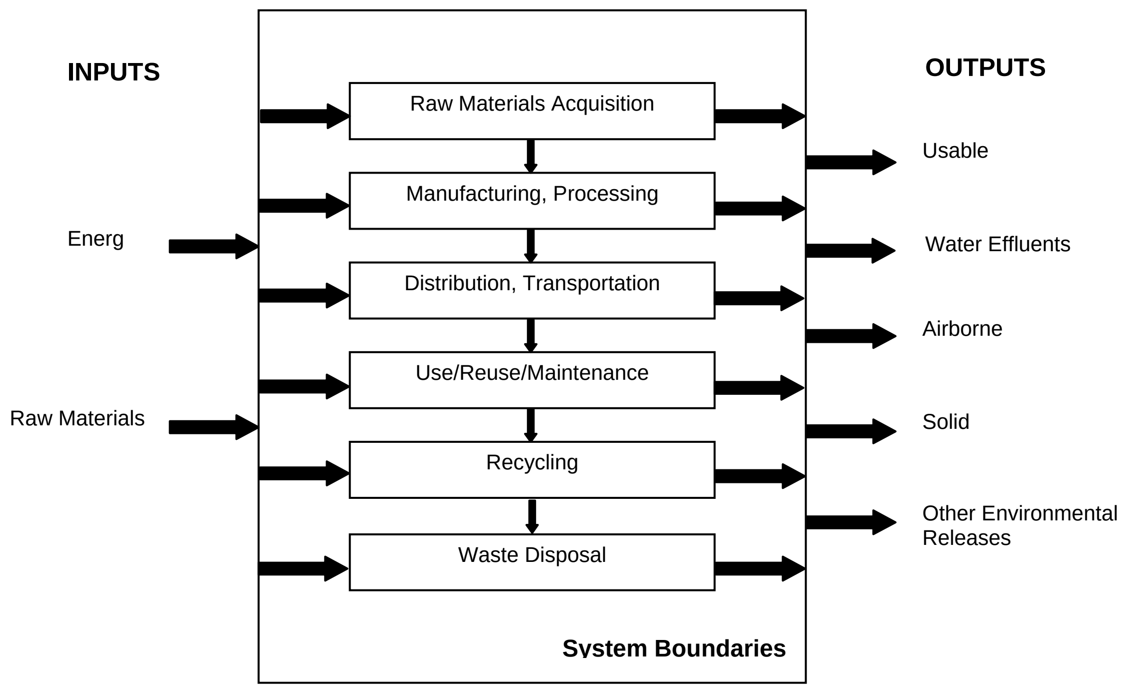


Figure 2.3: Stages in Life Cycle of a product according to SETAC (Tan & Culaba 2002, p. 4)

The scale of the LCI is determined by the system boundaries defined in the scope of the study (the large rectangle that encloses the different life cycle stages in the figure 2.3). In some complex cases, a full scale LCI can be extremely time consuming. The collection of data for LCI is one of the greatest challenges of a LCA as the accuracy and detail of data will significantly influence the final results.

Often in practice, some of the inventory data needed for the LCA of a product might not be available. In such cases, assumptions have to be made regarding this gap in data and general data obtained from other data sources such as text books, periodicals and public databases can and should be used (Vigon et al. 1993, p.7). This data will be less accurate and could be overcome by doing sensitivity analysis in the life cycle interpretation stage, where the effects of data uncertainties can be evaluated

2.4.3 Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) assesses the effects of the resource requirement and environmental loading of a product. According to ISO standards ISO14042, LCIA consists of three main stages which are compulsory; '*Selection*' of impact categories (e.g. climate change), category indicators (e.g. global warming potential), and characterisation models (defining how to calculate the characterisation factors) to be included in the study, '*classification*' of LCI results according to the selected impact categories and lastly, *characterisation* factors to reflect the relative contribution of an LCI result to the impact category indicator result (Goedkoop, Schryver & Oele 2006). Optional steps for LCIA include normalization, grouping and ranking and these are used to simplify interpretation of results. LCIA is commonly done using LCA softwares, which comes with a large number of standard impact assessment methods and databases.

2.4.4 Life Cycle Interpretation

The purpose of life cycle Interpretation is to determine the level of confidence in the final results and present them in a fair, complete and accurate manner (Skone 1998). ISO documents identify three stages to conducting a life cycle Interpretation; *Identification of significant issues*, *Evaluation of the Completeness, Sensitivity, and Consistency of the data* and finally *Conclusions and Recommendations.*

The first stages identifies issues such as inventory elements that had contributed most to the results of the LCIA, the impact of the inventory assumptions made and other anomalies in the inventory data and LCIA results. The evaluation stage which is made up of Completeness, Sensitivity, and Consistency check is done to establish validity and credibility to the results from the previous stages of the LCA. In the last stage of interpretation, conclusions are drawn and recommendations are made using the results of all four stages of the LCA.

2.5 Software Based Life Cycle Assessments

Today, LCAs are commonly done using softwares which comes equipped with extensive inventory databases and large number of standard impact assessment methods. GaBi, TEAM and Simapro are three of the main LCA softwares used in the industry.

GaBi provide simple and quick modelling and analysis of complex, data-intensive problems. It can easily generate ISO-conformable LCAs. GaBi also provides solutions for different problems regarding cost, environment, social and technical criteria and optimization of processes. It is used by many big companies such as Siemens, Nokia and Motorola.

TEAM can evaluate the associated life cycle inventories and potential environmental impacts according to the ISO standards. A comprehensive database, with over 600 modules is included the software. It has a large range of inbuilt mathematical formulas, which simplifies the building of large dynamic databases.

The most popular and widely used LCA software today is "System for Integrated Environmental Assessment of Products" (Simapro). It can easily model and analyse complex lifecycles clearly according to ISO 14040 series of standards. Simapro comes with a large number of databases and standard impact assessment methods such as CML 92, Eco-indicator 95, Eco-indicator 99, and EPS 2000 (Goedkoop, Schryver & Oele 2006). Each method contains a number of impact categories.

2.6 Types of Life Cycle Assessments

A "cradle to grave" approach is essential for evaluating the full environmental impacts of a product but this approach do have some drawbacks. A full LCA is only appropriate for products that are already in the market. For a product that is in its design stage, it is almost impossible to do a full scale LCA because of the uncertainties in the data as final design decisions have not been made. This deters the incorporation of LCA into the design process of a product. Moreover, a full scale LCA can be costly and extremely time consuming for product such as a microelectronic product which involves many complex manufacturing processes. Hence, efforts have been made to simplify the ideal "cradle to grave" concept of LCA. This simplified form of LCAs is known as screened or streamlined LCA. This approach can be implemented in a number of ways as shown below.

- "Cradle-to-gate" – All downstream components are removed. Processes after product manufacturing stage such as consumer use and waste disposal are not taken into account.

- "Gate-to-grave" – All upstream components are removed. Processes before product manufacturing stage are not taken into account.

- "Gate-to-gate" – Both upstream and downstream components are not taken in to consideration for the LCA.

- Applying very loose cut-off rules for the LCA. For example, LCI limitation, where by only raw materials suspected of high impact potential are taken into account. The rest of the inventory items are ignored.

- Others methods include limiting the assessment to a small number of impact categories in the LCIA and completely ignoring LCA interpretation phase.

2.7 The Uses of Life Cycle Assessments

Many organisations, both public and private have incorporated LCA in to their decision making processes. The prime objective of a LCA still remains to identify the potential environmental impacts of a product. At the same time it is also capable of identifying where the greatest reduction in resource requirements and emissions can be achieved. Minimising resource consumptions and emissions often results in profits and this provides an extra motivation to the organisations. Today, LCA applications are most commonly used for internal purposes, such as product design, product improvement, procurement strategies and benchmarking (Frankl & Rubik 2000).

Some of the other ways in which LCA is being utilized are for public sector uses such as eco-labelling (helping consumers to make greener choices), and comparative studies However, the use of LCA for comparison between products for marketing purposes has always been a controversial issue because of the complexities and limitations of LCA, which is covered in detail in section 2.8.

Incorporating into product design, LCA bring a life-cycle approach into Design For Environment (DFE) concept. At the design stage, LCA can be used for process technology selection, optimization, design and development. About 70% of the environmental impacts of a product can be identified at product design stage and it is best that these issues are tackled at design stage itself. Streamlined LCAs are used for this type of analysis.

Product improvement involves identifying and reducing environmental impacts of an existing product. As mentioned earlier, this not only results in profits but also enhances the reputation of manufactures as being environmentally conscious. Some companies conduct internal LCAs for shaping procurement strategies by comparing different products for their environment-friendliness. For example, the United States defence department made use of a LCA to determine policies for purchasing of office supplies (Tan & Culaba 2003, p. 8).

2.8 Life Cycle Assessments and the Microelectronics Industry

Though Industry concur on the significance of the environmental consequences associated with microelectronics, there is little consensus regarding the actual magnitude of these environmental consequences. The main reason for this is a lack of LCAs or other forms of environmental studies done within the industry and in the cases where LCAs have been done; little or no information is released to the public.

Other reasons for this variation in results include the difference in actual production processes of microelectronic products, the way the LCA is structured and the temporal differences. Only three LCAs associated with the microelectronic industry were available for this literature review. These LCAs were reviewed thoroughly and the results are summarised below.

The first case study involved a LCA of an Integrated Circuit Product by Motorola and Fraunhofer IZM (Schischke et al. 2001). The purpose of the study was to identify the environmentally significant areas in Integrated Circuit Product manufacturing by generating a complete mass and energy data set. The consumption of energy, raw water, chemicals, and gases and the origin of water, wastewater, and emissions were considered. For the ease of data collection, the manufacturing processes were divided in to two clusters; facility and fabrication process modules. The functional unit was defined as the product of wafer area and the average number of circuitry layers on a wafer. The method of data collection was through questionnaires. If no data was available, educated assumptions made by experts were used. The Impact assessment was done using ProTox and GaBi 3.2 softwares.

Not much information regarding the actual amount inventory data was available from this study; mostly impact assessment results were documented. The impact of high electricity use was the man contributor to the environmental impacts. About two-thirds of the electricity use was related to facility modules. Nitrogen use was the next highest contributor to the environmental impacts followed by the processes water that was used extensively in the wafer cleaning processes

The second case study was the LCA of an Integrated Circuit Product conducted by ST Microelectronics and Telecom Italia (Taiariol et al. 2001). The device analysed was an EPROM chip in a ceramic dual in line package. A ‘gate-to-gate’ approach rather than a full ‘cradle-to-grave’ was adopted for this LCA. The study was carried out according to the ISO standards. The use clusters were divided in to Front of Line (FOL), where the wafer fabrication was done and End of line (EOL), where the assembly and encapsulation of the chip took place.

LCI was collected from detailed technological analysis, information obtained directly from material suppliers, and a commercial database. Two different functional units were used. “Single silicon wafer processed to obtain the EPROM chip” and a single EPROM device was used for front-end and backend respectively. The functional units were then linked by taking the wafer yield in to account. A subset of more than 400 materials was used in the production. Several databases were used for Impact assessment, namely TEAM, Boustead Model, EIME, and several ad hoc LCA “modules.”

The water consumption was recognised as the most important raw material consumption with a usage of about 29 litres of deionised water for a single EPROM device. The End of line (EOL) production processes were identified as the highest contributor to environmental impacts associated with the material consumption. Some of the inventory data listed for a single EPROM device included the usage of 140 mg of oxygen, 122 mg of nitrogen, 0.03 mg of lead, 6.9mg of arsenic and 1.2 mg of copper. It was reported that about 81% of the total energy usage related to the chip came from the use phase of the EPROM chip followed by EOL production processes (14.2%) and Front of line (FOL) production processes (3.4%).

The third case study reviewed is not a complete LCA but an attempt to raise the awareness in the industry by quantifying the energy and material use in the production of the microelectronic devices (Williams, Ayres & Heller 2002). A 32DRAM chip (made from $1.6\,cm^2$ of silicon wafer) was used as the functional unit for this study. This study analysed the material input and output into the production chain of a DRAM chip to estimate total energy, fossil fuel consumption, and aggregate chemical usage in the manufacture and use phase of typical microelectronic products.

In comparison to the other LCAs reviewed, much more information regarding the actual amount inventory data was available from this study. Listed below are some of the important findings. Though the study used a DRAM chip for data collection, most of the results were reported per cm^2 of input wafer.

- The electricity consumption of the chip throughout its life cycle was estimated to be about 3.3 kWh per cm^2 of input wafer.

- Out of this, about 1.6 kWh was associated with FOL processes while EOL consumption was about 0.32 kWh. This result is in contrast to the LCA study conducted by ST Microelectronics and Telecom Italia which was reviewed earlier. The rest of the electricity consumption came mainly from the use stage and the production of silicon wafers.

- About 20-27 litres of water were consumed per cm^2 of input water.

- The total chemical usage which included, acid/bases, photolithographic chemicals and etchants was estimated to be 45 grams per cm^2 of input wafer.

- 450 grams of elemental gas usage was estimated per cm^2 of input wafer. Almost all of the usage was linked to the heavy usage of nitrogen in manufacturing processes.

Collecting LCI for a microelectronics product which involves many exhaustive and intricate processes can be a real challenge. Fortunately there were a few articles that recommended ways to collect LCI data from the microelectronics industry. Methods for quantifying energy, water, chemical, gas and other raw material requirements at process levels are explained clearly by Meyers et al. (2001) and Dahlgren (2002). For accurately quantifying the energy and material usage, all agreed on the need to take in to account the production time, the idle time and down time and the production yield.

Two approaches are recommended for collection of inventory data for semiconductor manufacturing (Murphy, Allen & Laurent 2003), ‘the top-down’ and ‘bottom-up’ approaches. The top-down approach involves collection of inventory data at a factory level and then disaggregating it into process levels. This major advantage of this approach is that it often results in a manageable database of inventory. However, this method is not suitable if the factory manufactures different products. In such cases it can be extremely difficult to disaggregate the data in to process levels. In contrast, using the bottom-up method, inventory is quantified at equipment-level on a process basis and aggregated at factory or product level. It provides a much more detailed data directly related to the pieces of equipments or processes. Using this approach, it is also easier to implement improvements to mitigate the environmental impact at each process stages.

One of the reasons highlighted for the lack of LCAs being conducted in industry is the short product life-time of microelectronics products. The average life-time of microelectronic product is about 2 years. Generally, conducting an LCA for these products can be time consuming and costly as explained earlier. By the time a LCA is finished, the product may be reaching end of its life-time!

To counter this dilemma, the development of parametric material, energy and emission inventories is recommended by Murphy et al. (2003). It advocates the classification of ‘unit operations’ to create databases for the different unit operations that makes up the manufacturing process. Take for example the manufacturing processes involved in wafer fabrication; unit operations include wafer cleaning, furnace, ion implant and lithography. Lithography consists of sub-processes coating, exposure and development. It’s argued that, though the use of the number of unit operations in products vary, the data regarding each of the unit operations have remained largely unchanged for the last 30 – 45 years.

A major concern that has been highlighted is a lack of data associated with the production of ultra pure chemicals used extensively in the industry. It can be argued that LCA done on Microelectronics products are incomplete (Plepys 2004; Norwood, Boyd & Dornfeld 2004) because of the insufficient knowledge of environmental issues related to ultra-pure chemical manufacturing.

2.9 Complexities and Limitations of Life cycle Assessments

Though the uses of LCAs are many as shown in the previous sections, there are also many limitations that have been identified over the years. As mentioned earlier, LCA is a holistic approach to evaluate the environmental impacts. This holistic nature of the LCA is its greatest strength and limitation.

The broad scope of LCA can only be achieved by simplifying some other aspects of the study (Guinée et al. 2001). In most LCAs conducted spatial and temporal differences are not taken in to account for inventories and impact assessments. Most of time, LCAs are unable to address localised impacts. It does not take in to account localised variables that could affect the final result of a LCA. Another limitation is the fact that LCA regards all processes as linear, which is impractical in a real life scenario. As for the time aspects, LCA can be considered as a steady-state rather than a dynamic approach.

Another cause for concern is the complexities of ISO standard models for a LCA. LCA methodologies according to ISO standards are generic in nature and does not easily relate to any particular industry (Mitchell & Hyde 1999). Often, experts are needed to understand and conduct proper LCAs. Detailed LCAs can be extremely time consuming and costly when done according to ISO standards. An interesting example is the case of critical or peer review of a LCA, as recommended by the ISO. In many cases LCAs conducted today are not peer reviewed because of the cost and time involved (Weidema 1997).

Another complexity of a LCA study is the importance of developing and communicating proper methodological choices and assumption made for an LCA goal and scope stage. The assumptions and choices made could affect the final results significantly. Sometimes LCAs conducted by different practitioners can give two vastly different assessments for the same product. An example is quoted by Allen (n.d., p. 17) on a comparative LCA study conducted between polystyrene and paperboard containers.

Lack of high quality or in some cases a complete lack of data is another very important limitation of a full scale LCA study. Conducting a LCA which may involve hundreds of inventories, it's inevitable that the some of these data are of poor quality or are based on assumption. To overcome these limitations, great care should be placed to check the reliability of the data. LCA studies should discuss and document in detail the data sources, assumptions and quality of the data.

It should also be noted that LCA is one of many environmental managements programs available and may not used as single yardstick to make major industrial decisions. LCA does not take in to account factors such technical performance, cost, risk, political or social acceptance (Skone 1998). Hence, it should be considered as one of the tools and not as "the" tool for making major decisions.

2.10 Summary

If it is managed in the proper way, LCA can be great tool to assess the environmental impacts associated with a product. LCA is a complex tool that is still being developed. The complex nature of the LCA has somewhat been simplified in the recent past by the use of LCA softwares but complexities regarding the data quality, such as geographical and temporal differences remain to a certain extent.

One of major advantage of a LCA is that it is not a rigid tool but a flexible one that can be fashioned to suit the needs of the initiator. Because of its flexibility, LCA are used in a variety of ways in the industry.

Though, LCA studies have generally gained popularity in the last twenty years, there is a serious lack of published data (that is available to public) with regards to the LCAs conducted in the microelectronics industry. Three LCAs carried out in the microelectronics industry were reviewed and it was seen that there is some variance in the LCA results.

Another important aspect of the LCA is that it is purely an environmental assessment tool. This has to be kept in mind when making major decisions based on the results of a LCA.

Chapter 3 GOAL AND SCOPE

3.1 Introduction

The goal and scope definition is a critical phase of a LCA. The main technique used in LCA is modelling (Goedkoop, Schryver & Oele 2006). Usually, scientific models are a simplification of real systems and often, in the case of complex systems, some of the data may be distorted. In the case of a LCA, it is no exception. The challenge of an LCA practitioner is then to develop an LCA model that minimises the effect of these distortions on the final result of the study. An effective counter measure to these problems is to meticulously define the goal and scope as the first step of a LCA.

A detailed review of the methodologies used for goal and scope stage of a LCA was conducted and is documented in the following section. Using knowledge gained from this review the goal and scope of this LCA study was formulated as shown in sections 3.3 and 3.4 respectively.

3.2 Methodology

The goal and scope definition phase is where the initial choices which determine the working plan of the LCA are made. These choices must be flexible and can be changed any time during the course a LCA to suit the needs, limitation and problems faced. This explains the interconnectedness factor in the ISO and SETAC's LCA framework shown in figures 2.1 and 2.2.

In the early days of life cycle assessments, the goal and scope definition stage was widely considered to be a trivial exercise before the start of the actual LCA. Studies over the years have proved that an LCA whose goal and scope definition is poorly conducted often runs in to problems during the other stages of the LCA and final results are often unreliable.

3.2.1 Goal Definition

The goal definition of an LCA study specifies *the objective for carrying out the LCA, the intended applications, the initiator, the practitioner* and *the target audience*. The methodologies adopted for a LCA is largely determined by its *objective*. Some of the common *objectives* for conducting an LCA include (Vigon et al. 1993):-

- To establish a baseline of information on a system's overall resource use, energy consumption, and environmental loadings.
- To identify stages within the life-cycle of a product or process where a reduction in resource use and emissions might be achieved.
- To compare the system inputs and outputs associated with alternative products, processes, or activities.
- To help guide the development of new products, processes, or activities toward a net reduction of resource requirements and emissions.

Intended applications mean what the LCA can and cannot be used for, what decisions can be made on the basis of the LCA and the possible extent of impacts these decisions could make.

The *target audience* is whom the LCA is conducted for. A LCA could be conducted for private sector, public sector, or academic use. It is important to specify the target audience because studies can be differently structured depending on the need of the target audience.

For example, if an LCA is to be conducted for public sector use then it will most definitely require a critical review before it can be accepted. In comparison, a LCA conducted internally in a company wanting to improve its processes or resource requirements, could readily implement changes based on the LCA without a peer review.

3.2.2 Scope Definition

The scope definition step defines the main characteristics of a LCA. It determines, justify and report the sophistication of the study. The scope of a LCA describes the *system boundaries* and the *functional unit* of the study. *Assumptions* made during the course of the study, *limitations*, *the threshold levels*, *allocations* used and the *type of peer or critical review* conducted is also defined here.

The *functional unit* of the study defines the product or process the study is based on. It should be described in detail so that the any comparisons to alternative products can be made, if necessary in future.

System boundaries determine the length and depth of the study. The sophistication of a LCA is determined by its System boundaries. For a full scale LCA, the system boundaries should include all energy and mass flow related to the functional unit. The 'cradle-to-grave' life cycle of a generic industrial product according to SETAC is shown below again for convenience (see figure 2.3).

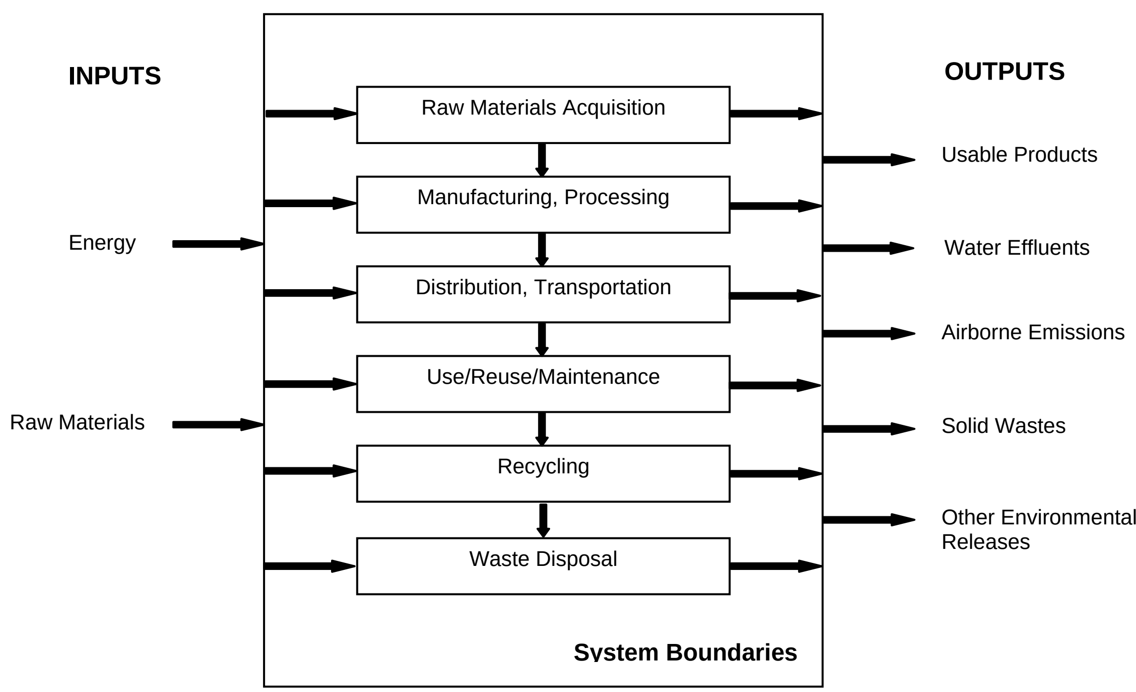


Figure 3.1: The life cycle of a product according to SETAC (Tan & Culaba 2002, p. 4)

It is important to justify the System boundaries established for a LCA. Very often, due to limitations found in the later stages of the LCA, the initial system boundaries cannot be followed. In such cases, it’s imperative to justify and concisely document the changes made to the system boundaries. The same applies to the assumptions used in the course of a LCA.

Threshold levels define the levels below which, the LCA practitioner could consider it meaningless to collect data for inflow or an outflow (Goedkoop, Schryver & Oele 2006). ISO 14040 series recommends three such bases for a threshold levels;

- If the mass of the inflow is less than a certain percentage.
- If the economic value of an inflow is lower than certain percentage of the final product system.
- If the contribution to the environmental impacts from an inflow is below a certain percentage.

Though the latter seems like the most appropriate choice, it should be noted that it is difficult to estimate the actual impact of an inflow before the life cycle impact assessment stage.

ISO 14040 standards require a *critical or peer review* of all LCAs. Often in practice, it is difficult to determine the objective criteria for the quality of a complex scientific work. LCAs, which deals with many assumptions falls into this category of research work. Then, the subjective but professional judgement of peers becomes the ultimate quality assurance (Weidema 1997). The peer review of an LCA could either be a simple peer review of the final results or a 3-step review advocated by SETAC. The three steps involve a review after goal and scope definition, one after data collection stage and lastly one at the conclusion of the study.

Allocations of environmental load are used when a process perform more than one function or output. ISO recommends avoiding the use of allocation in LCAs because of the uncertainties it brings. In unavoidable circumstances, ISO standards suggest the use of mass or energy content of output as a basis for allocation.

3.3 Goal Definition

The goal definition of this particular project is to assess and appreciate the environmental performance of a typical microelectronic product. The results of this LCA are to be used for identifying options for improving the environmental performance of the product at a process level during the course of this research, time permitting or otherwise in future.

This study was conducted by student no: 0031233496 in fulfilment of the requirements of Courses ENG4111 and ENG4112 Research Project' for the University of Southern Queensland. It should be noted that this LCA was done for educational purposes and hence should not be used for any public comparative assertions.

3.4 Scope Definition

3.4.1 The Functional Unit

A Surface Acoustic Wave (SAW) filter, shown below in figure: 3.2 was chosen as the functional unit for this study. The SAW filter measures $13.7 \times 4.8 \times 2.4mm$ and weighs about $415mg$. The filter is manufactured in a production plant in Singapore. This study is to be conducted within the period between of February to October 2006.

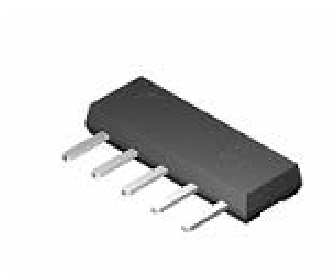


Figure 3.2: Product of the LCA - SAW filter

The chosen SAW filter is a bandpass filter made from Lithium niobate (LiNbO3) wafer and is commonly used in television receivers.

3.4.2 System Boundaries

Making use of the SETAC's Life cycle model (see figure 3.1), the 'cradle to grave' product life cycle of a SAW filter can be broken down in to the stages shown below;

Raw Material Acquisition – All activities necessary to extract raw material and energy inputs from the environment, including the transportation prior to processing.

Processing/Manufacturing - Activities needed to convert the raw material and energy inputs into the desired product. In the case of a SAW filter, this can be broken down further in to two parts;

- The making of semi-products for use in the actual manufacturing stage of the SAW filter.
- The actual manufacturing of SAW filter in a plant in Singapore. (this stage is studied in detail in the next chapter)

Distribution and Transportation - Delivery of the final product to the end users all around the world (delivery of a SAW filter to a television receiver manufacturer).

Use, Reuse, and Maintenance - Utilization of the finished product over its service life. The service life of a SAW product is estimated be 10 years based on the average life span of a television set.

Recycle - Begins after the product has served its initial intended function and is subsequently recycled within the same product system (television).

Waste Management - Begins after the product has served its intended function and is returned to the environment as waste.

The goal of the study states the need to assess and appreciate the environmental performance of a typical microelectronic product. Ideally, to comply with the goal definition, a full scale LCA, using a ‘cradle to grave’ approach had to be conducted. But in this case, a screened or streamlined LCA was conducted because of a number of reasons;

- *Adequacy of data* - almost all literatures reviewed on microelectronic products concur on the fact that the environmental impacts associated with the microelectronic production and use phase are significantly higher in comparison to other stages **(**Williams, Ayres & Heller (2002); Taiariol et al. 2001**)**. The environmental impacts during the use phase occur from the energy usage of the microelectronic products. In the case of a SAW filter, a passive device, this can be negligible.

- *Availability of data* **–** Only the manufacturing data of the SAW filter was available.

- *Time constraints* **–** A detailed LCA for a complex device such as a SAW filter would have taken more than the allocated time of 2 semesters, especially for a first time LCA practitioner.

Hence it was concluded that a streamlined LCA approach was adequate enough to satisfactorily give the results in compliance with the goal definition of the project. This LCA takes to account the raw material acquisition, the making of semi-products, and the actual manufacturing stage of the filter. The use stage, recycle and the waste management stages are omitted from the study.

It can be said that this project took a process based approach rather that a product based approach for the LCA. Hence, in this case the manufacturing processes become the product. This streamlined LCA methodology adopted could be classified as a ‘cradle-to-gate’ LCA.

The system boundaries developed for this LCA is shown in figure 3.3 the next page. At this point, it is recommended to read chapter 4 of this dissertation to understand the processes and applications involved in the manufacturing of a SAW filter, before continuing with this section.

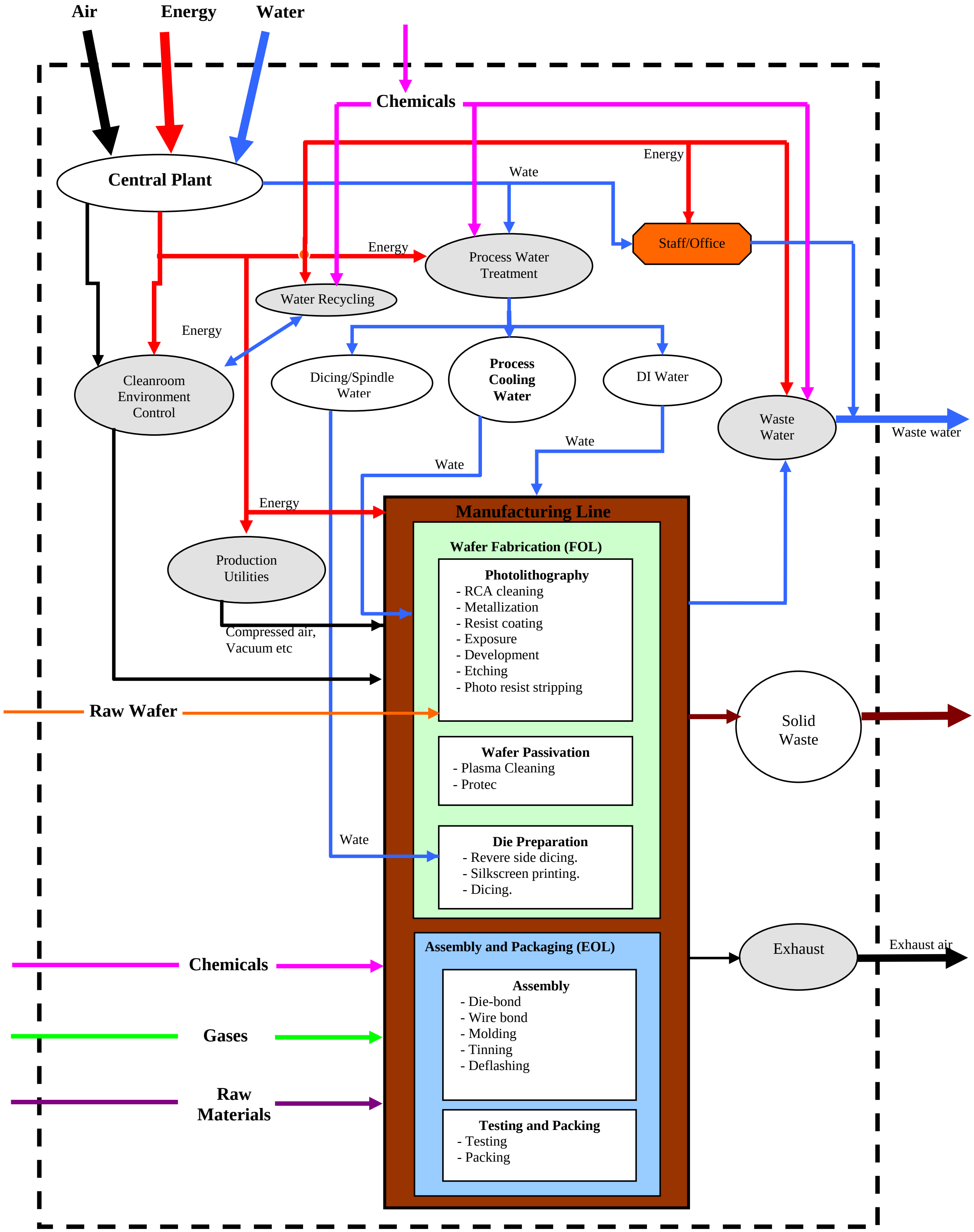


Figure 3.3: The original System Boundaries for the LCA of a SAW filter

From the system boundaries shown in figure 3.3, the three main components of the plant can be seen.

- The manufacturing line (brown rectangular box) is made up two sub-components of Wafer fabrication (light green) and Assembly and packaging (pale blue).

- The facilities modules (grey oval boxes)

- Staff/Office use (orange polygon).

The coloured arrows indicate the flow of energy (red), water (blue) and air (black). The input of gases (green arrows), chemical (pink) and other raw materials (violet) for production processes are also shown. The chemical inputs for facilities modules such as process water plant, water recycling plant and waste water treatment plant are also indicated.

It can be seen clearly that the system boundaries shown indicate a ‘cradle to gate’ approach, except the fact that the waste disposal of solid waste off-site is also taken in to consideration for the assessment. The system boundaries shown in figure 3.3 would have been the ideal choice for this LCA but unfortunately it had to be changed because of the limitations associated with the LCA software that was used for this study. Detailed below are the changes made.

Initially, it was planned to use a full version of Simapro software to do the Life Cycle Impact Assessment (LCIA) stage of this study but some issues with the licensing meant that the only a demonstration version of Simapro was available. The major disadvantage of the demonstration version of Simapro is that it could only be saved up to a total of 16 times which meant that the modelling of a SAW filter in the software was limited. Another major drawback was the database included in the demonstration version; it is nowhere as exhaustive as the full version.

These issues proved to be the main limitations of this LCA. A thorough study would have meant modelling each and every process in Simapro and analysing it to find the origin of most significant impacts. When modelling the life cycle of a product in Simapro, a user has to save each process after entering all the input/outputs flow associated with that process. With only sixteen saves possible, the modelling of the SAW with system boundaries as shown in the figure 3.3 was impossible.

Therefore, modified system boundaries had to be used and the resulting system is shown in the following page in figure 3.4. The following changes were made to the initial system boundary;

- The individual production processes were clustered together to form “large units of operations”.

- The exhaust was clustered together with the cleanroom environment control unit of operation. This was done after it was understood that all the emissions in the factory was under the control limit set by the local government. And hence, only the energy requirements of the exhaust had to be taken into account for this LCA.

An important factor to note here is that both the system boundaries shown here do include the ‘raw material acquisition’ and ‘processing/manufacturing’ of the resources (semi-product) such as chemicals, raw materials and gases that is used in the actual manufacturing of a SAW filter.

At the same time, it has to be kept in mind that no data were collected for the abovementioned stages. The data that will be used for these stages is on the data in the Simapro libraries. Only the immediate manufacturing activity data in the production plant will be collected and modelled for analysis later on.

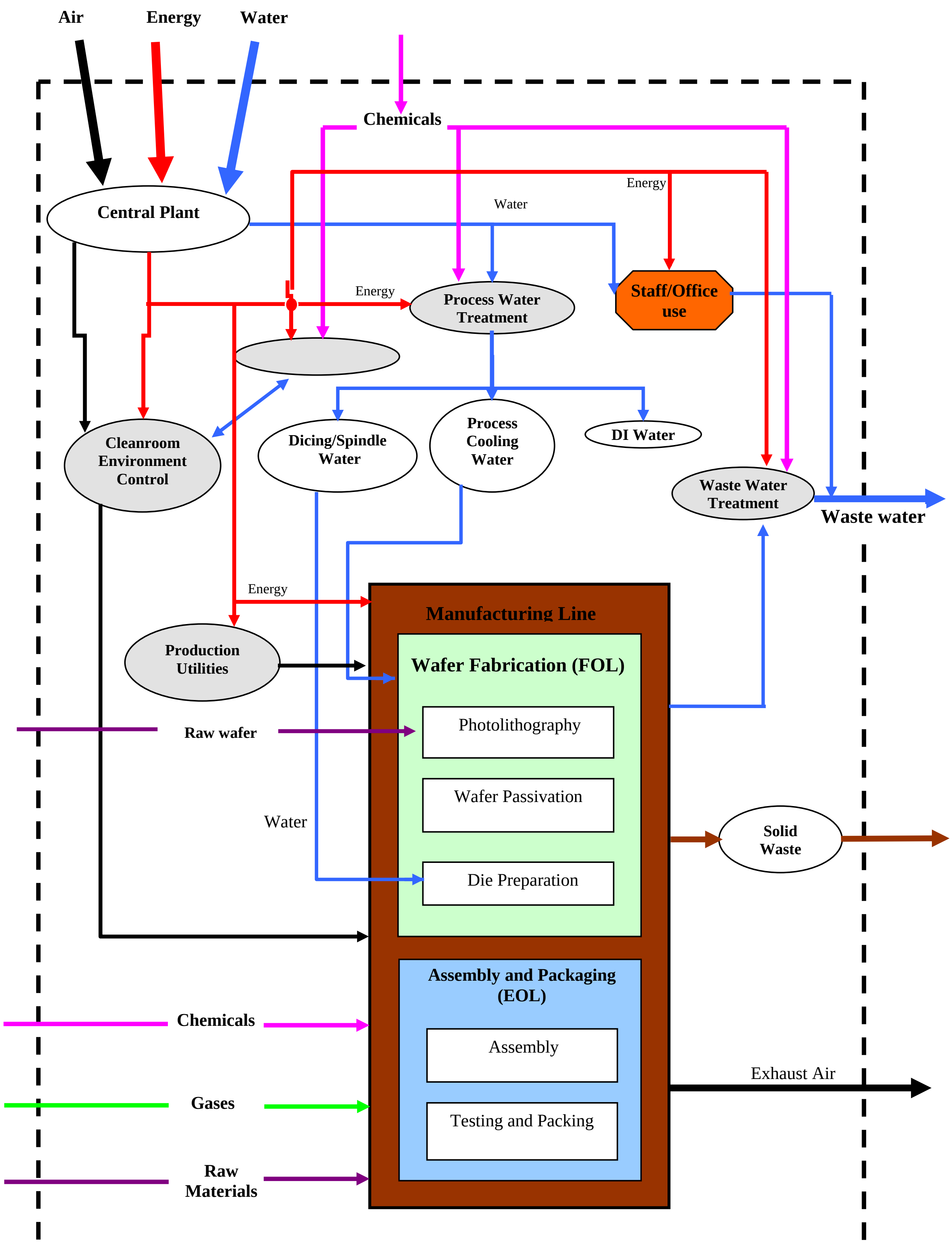


Figure 3.4: Modified System Boundaries for the LCA of a SAW filter

3.4.3 Major Assumptions used

Some assumption had to taken during the inventory collection. During the Life cycle inventory stage, some of the inventory data was not available. In these cases, expert's opinions were sought and estimated values were used. These uncertain data quantities are highlighted and their impact on the final results is analysed in the life cycle interpretation stage. No threshold levels were used for the inventory collection. Because of the modelling constraints, allocation had to be used for modelling the process water treatment. The environmental load was allocated based on the final output mass as recommended by the ISO.

Another major limitation was the lack of inventories in the Simapro database. Many of the specialized chemicals used in the manufacturing line, especially in the wafer fabrication were not found in the Simapro database. Even if some of the chemicals were available, there was no information regarding their grade. Chemicals used in microelectronic production are usually high grade chemicals whose production is many times more energy intensive than the ordinary chemicals. Because of these limitations, all chemicals used (except acids) in the production of a SAW filter were classified either as organic or inorganic chemicals.

For the wafer used, electronic grade silicon was used as a substitute for lithium niobate wafer that is used in SAW filters, due to the unavailability of data in Simapro database. Even then, only a dataset regarding metallurgical silicon was available in the Simapro data. The production yield of producing electronic grade silicon from metallurgical silicon is quoted at around 20% (factor of >5) by (Tsuo et al. 1998). Williams, Ayres and Heller (2002) reports that about 9.4 kilograms (factor of 9.4) of metallurgical silicon wafer is needed per kilogram electronic grade wafer. As such, a factor of 8.5 was taken for this LCA. Hence, to represent the 50 grams of lithium niobate wafer, 425 grams of metallurgical silicon from the Simapro database was used (an estimation based purely on mass).

It should be noted that no peer review was conducted for this LCA during any stage of the study. The main reasons were lack of time and cost.

Chapter 4 SAW FLTER

4.1 Introduction

This chapter introduces the product or the functional unit of this LCA, a Surface Acoustic Filter (SAW) filter. The full manufacturing of this product is done in a factory in Singapore. Considerable amount of time was spent in the factory to understand the manufacturing processes involved and the overall factory setup.

All the details that have been collected are presented in this chapter. In the first section, the characteristics and applications of the SAW filter are briefly presented. The following sections document the life cycle stage, ‘production\manufacturing’ of a SAW filter.

4.2 What is a SAW filter

The SAW chip shown in figure 4.1 is a piezo-electric single crystal device (e.g. quartz, lithium tantalate, lithium niobate), polished on the surface and coated with one or more comb-like, interlocking electrode fingers, called interdigital transducers (IDT). These usually consist of aluminium and are deposited by common photolithographic means.

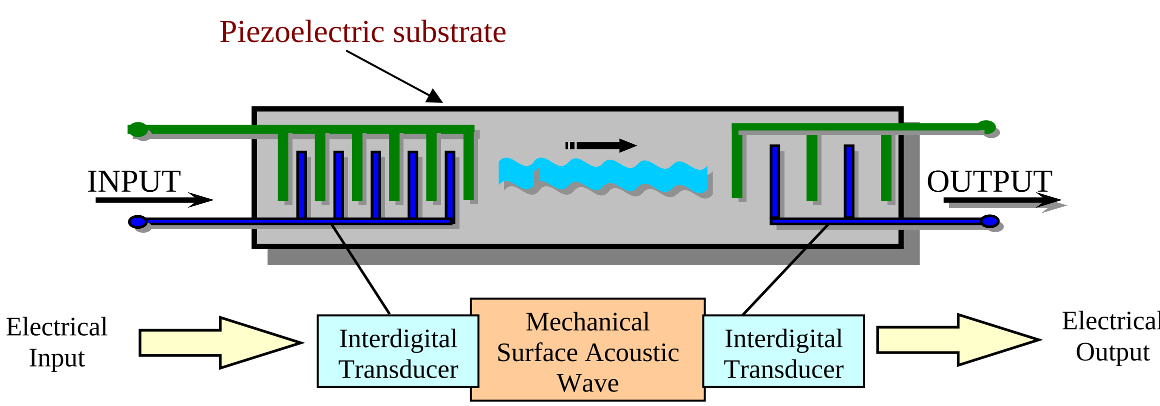


Figure 4.1: A SAW substrate

In a SAW filter, when an electric signal is applied, an electrical field is produced between the differently polarized transducer fingers. Because of the piezoelectric effect, the chip surface is deformed mechanically and a surface acoustic wave spreads out from both sides of the transducer. The reflectors on both sides of the transducer reflect these acoustic waves and thus create a standing wave, which is converted back into an electrical signal at an output transducer.

The wave is efficiently excited at the frequency, $f = V_{saw} / \lambda$ where wavelength, $\lambda = 4d$ ($d =$ spacing between IDT). Hence, SAW filters are very flexible concerning design; the center frequency and bandwidth can be determined by the spacing of the transducer fingers, their number, and the crystal type used. Bandwidth of emitted frequencies is inversely proportional to the number of IDT fingers. SAW devices can also be used as delay devices as the velocity of the acoustic mechanical waves is a fraction of the electromagnetic waves.

SAW devices are very widely used in modern in multimedia devices, automotive electronics, wireless communication terminals and base stations due to their stability, reliability and compactness. They come in metallic, plastic or ceramic forms in Single-In-Line (SIP), Dual-In-line (DIP), Surface Mounted (SMD) and more recently, the Chip Size Saw Package (CSSP). The SIP5 SAW filter selected for this study is shown in figure 3.2. This Lithium niobate (LiNbO3) filter is commonly used in television receivers.

The production process of the filter begins with the raw substrate (LiNb03 wafer) being processed using fabrication techniques similar to wafer fabrication in the semiconductor industry. The processed wafer is then singulated and mounted on to a metal leadframe. The chip and the leadframe are electrically connected by wire-bonding and finally, the chip is encapsulated with a thermoplastic (epoxy resin) material. The completed filters are then tested electronically and are packed before delivery to the customers.

4.3 The Processing/Manufacturing stage of a SAW filter

The life cycle model of SAW filter according to SETAC was briefly discussed in the previous chapter. This section takes a detailed look at the of a SAW filter.

As stated earlier, processing/manufacturing stage can be divided in to raw materials processing and the actual SAW filter manufacturing. The raw materials processing involves the making of ‘semi-products’ for use in the actual manufacturing stage of a SAW filter. It includes the processing of specialised chemicals, gases, lithium niobate wafers, leadframes and other raw materials. Almost all of these semi-products are processed offsite and then delivered to the SAW manufacturing plant.

There are many components that make up this manufacturing plant. For the ease of understanding and structuring of life cycle inventory analysis later on, the following clusters were defined;

- Manufacturing line - where the actual production processes occur. It involves many long and complex processes

- Facilities modules – Cleanrooms where the production occurs are maintained by the facilities operations. The facilities also support the production processes by producing and delivering some of the necessary materials for the production. Further more it collects and treats the wastes from production.

- Staff/Office use - Staff and office use in the company. It includes general staff use, lightings, building infrastructure, office and work equipments.

4.3.1 The Manufacturing Line

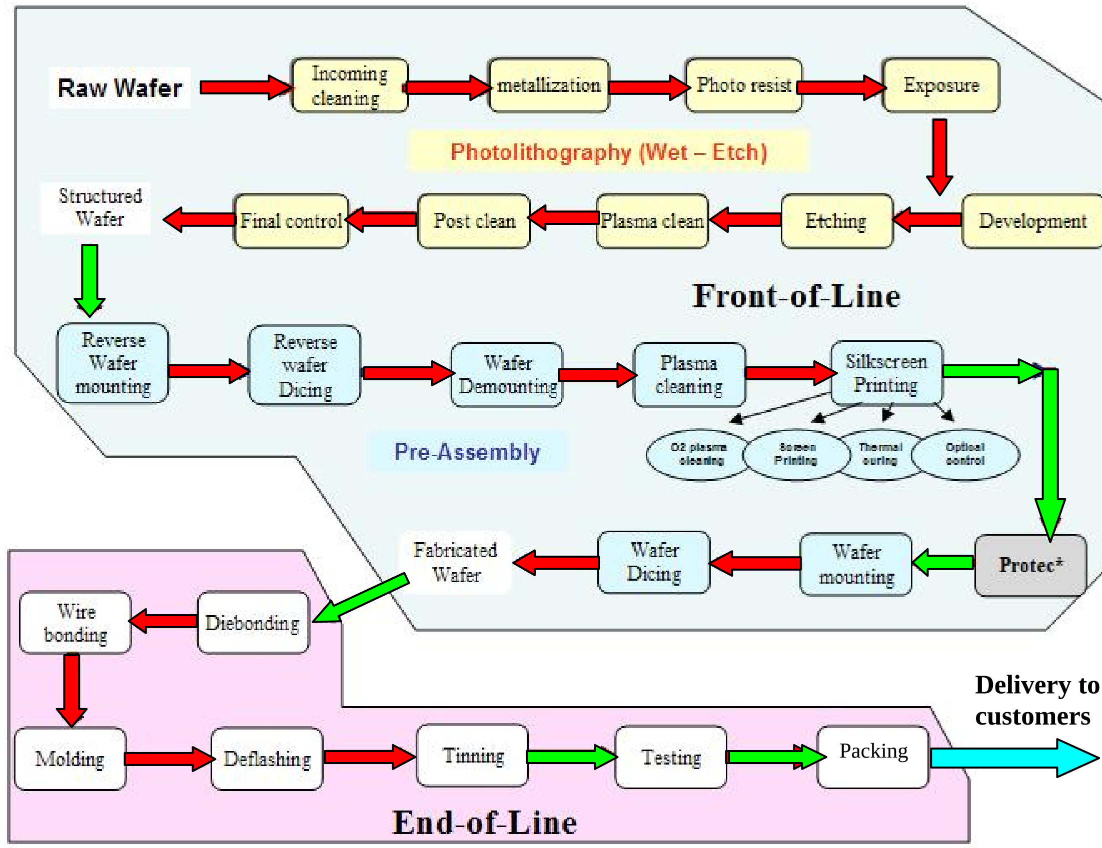


Figure 4.2: Process flow in the manufacturing line of a SAW filter

Figure 4.2 above details the processes involved in the manufacturing of a SAW filter. The boxes represent each manufacturing process while the arrows indicate the process flow. The manufacturing line is separated mainly into two sectors; the Front of Line (FOL) and the End of Line (EOL). The FOL processes deals with wafer fabrication, while the assembly, encapsulation, testing and packing are done in EOL.

The FOL sector is further divided in to three sections; Photolithography processes (shown in figure 4.2 using by yellow boxes), Pre-assembly processes (light blue boxes) and a Protec process (shown by grey box). The EOL sector is divided in to two sections; Assembly processes and Testing/ packing processes. The red coloured arrows indicate the process flow between processes in a section while the flow from each section to another is represented by green coloured arrows.

4.3.1.1 Front Of Line (FOL)

As explained in the previous page, the company divides the wafer fabrication process into three stages, namely photolithography, pre-assembly and Protec. Photolithography and Protec are both done in class 10 cleanrooms while pre-assembly stage is done in a class 100 cleanroom.

Cleanrooms are controlled environments used for manufacturing of products where there is a need for extreme cleanliness. They are classified according to their level of contamination that is specified by the number of particles per meter-cubed and by maximum particle size (1, 10,100, 1000 and so on). To give a better perspective of things, a non-cleanroom environment outside would be considered about a 5,000,000 class clean room (*Cleanroom* 2006)

The wafer fabrication of the raw wafers begins with the **Photolithography** stage which is shown below in figure 4.3. Summarised below are the processes involved.

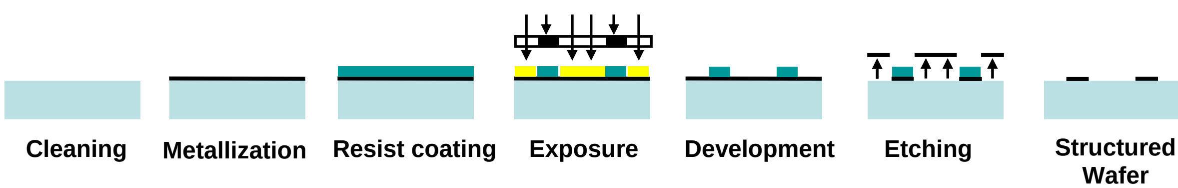


Figure 4.3: Major photolithography processes

Incoming cleaning - Raw wafers are cleaned using Hydrogen peroxide and ammonium hydroxide. This is to ensure a clean wafer surface for good adhesion.

Metallization- The front surface of wafers is coated with a layer of aluminium inside a controlled process chamber.

Photo resist coating – After metallization, the front surface is again coated with a homogeneous photo active layer of photo resist which is structured by the subsequent processes of exposure and development.

Exposure - The coated wafers are exposed to UV light through a retiled with SAW filter pattern.

Developing - The exposed resist on the wafers is dissolved away by the developer solution.

Etching and photo resist removal – Top layer of the wafers is removed through the opening in resist layer. The remaining photo resist is then stripped off leaving behind the structured wafer.

The last stage in the photolithography stage is the post cleaning process after which the structured wafers are inspected thoroughly for etching irregularities and other defects. The wafers which are within specifications are then sent to the pre-assembly area while the failed ones are either scrapped or sent for rework.

Pre-assembly is where the wafers are prepared for singulation and assembly. It is done in two parts, in between which the wafers are sent for wafer passivation in **Protec**. *Pre-assembly and Protec* processes are summarised below.

Reverse wafer mounting and *dicing* – As shown below, wafers are mounted with the structured surface facing down on to an adhesive foil to provide support during dicing. The reverse surface of the wafer is diced shallowly for the suppression of bulk waves.

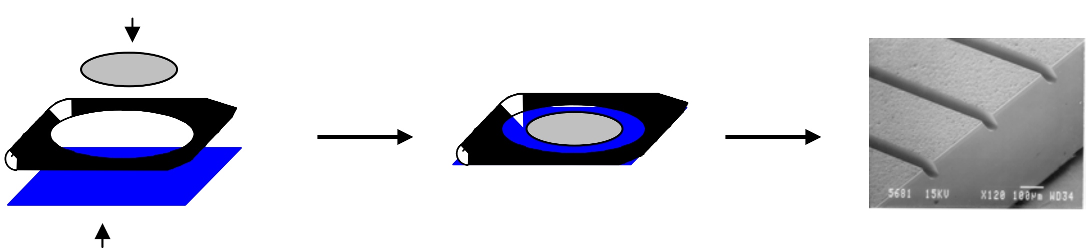


Figure 4.4: Wafer mounting and dicing

Wafer demounting and Plasma cleaning – After dicing, the wafer are dismounted from the adhesive foil and under goes cleaning by means of oxygen plasma to ensure good adhesive surface before the next process.

Silkscreen printing – A mass screen is printed on each end of the die using epoxy as a dampener for suppression of the surface wave in certain regions of the chip.

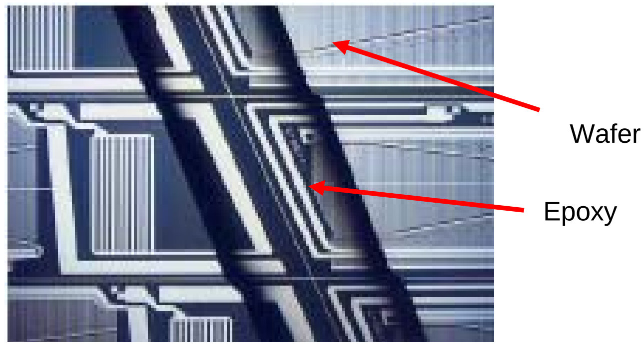


Figure 4.5: Silkscreen printing

The wafers are then sent back in to the class 10 cleanroom to undergo wafer passivation process known as Protec. Passivation is necessary because of the encapsulation technique adopted for the filter. The passivation is a two-fold (wall and roof) process, patented by the company, known as Proximate Roof Technology (Protec) where by a high-tech polymer component is structured via photolithographic means to cover the active substrate, the inter-digital transducers of the SAW die.

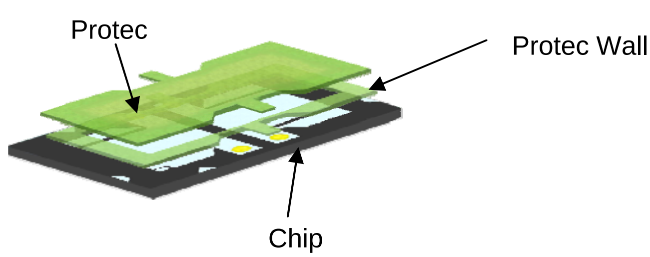


Figure 4.6: Chip Passivation

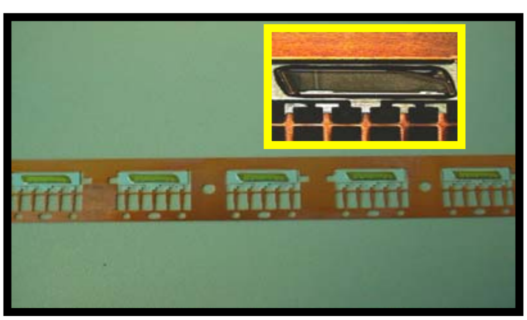
Wafer mounting and *dicing* – After Protec, passivated wafers are transferred back to the Pre-Assembly area. Wafers are again mounted on to the frame as shown in figure 4.4, but this time with the structured surface facing upward. The mounted wafers are then singulated at the dicing process and wait for transfer to the FOL.

The wafer fabrication stage involves many other sub-processes which are occur between the processes shown, such as thermal curing, general cleaning, plasma cleaning, inspection and testing procedures. For example, wafers are thermally cured after photoresist coating, silkscreen printing, Protec and dicing processes. The cleaning processes involved are a series of steps designed to remove both large and small particles from the wafer surface. General cleaning involves common high pressure cleaning or scrubber cleaning techniques. For plasma cleaning, the surfaces of the wafers are cleaned by means of oxygen plasma generated in the cleaning machine.

4.3.1.2 End Of Line (EOL)

After wafer fabrication process, the singulated wafers are transferred to the **assembly** area. The assembly area is also divided in to two sections on the basis of cleanroom environment control measures. The so-called front-end processes of the assembly area, *Diebonding* and *Wirebond* are done in a class 1000 cleanroom, while the back-end processes beginning with molding to tinning are done in a non-cleanroom environment.

The assembly process begins with *diebonding* where singulated dies are picked from the mounted wafers and are placed on a leadframe as shown below in figure 4.8. A thermoset epoxonic material is used as an adhesive. A single leadframe consists of 10 separate units. The bonded units are then placed in curing oven to solidify the epoxy to maintain chip position.



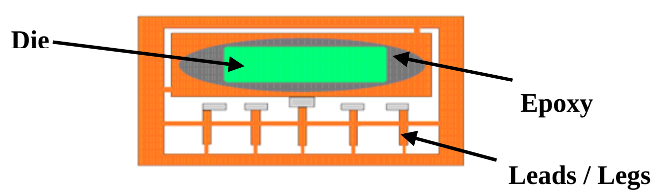


Figure 4.7: Diebonding

The cured units are then *wirebonded* using $30\,\mu m$ gold wires, to provide electrical connection between the die and lead frame.

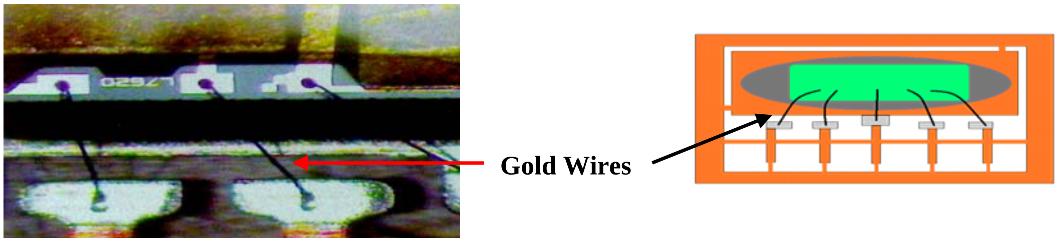


Figure 4.8: Wirebonding

The wirebonded units are then transferred out of the cleanroom and to the back-end of the assembly area. The units are then encapsulated in a plastic package (thermoset epoxy resin) by compression *molding*.

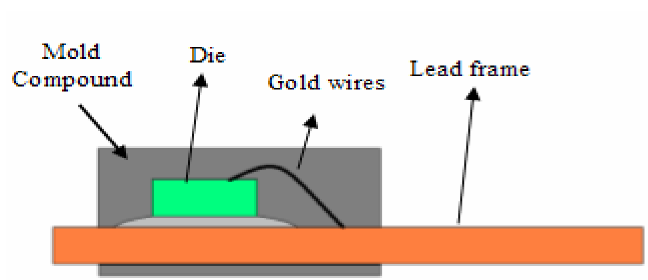


Figure 4.9: Molding

The mold bleeds and flashes are removed by the next process, *deflashing*, whereby a plastic media is used for blasting and cleaning of the leads for better soldering of leads. It also performs dam-bar cutting.

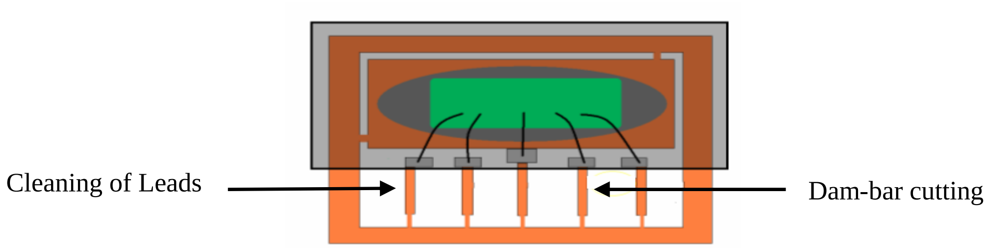


Figure 4.10: Deflashing

Next process is *tinning* where units are trimmed and punched out (singulation) from the leadframe. The singulated unit's leads/legs are then applied with flux and tin soldered.

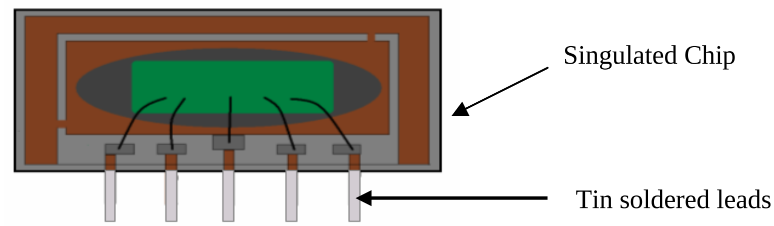


Figure 4.11: Tinning

The units are then transferred to the *testing and packing* area where they are electronically tested and laser marked for product identification. The finished SAW filters are then packed in to plastic tubes as shown below. After a final visual inspection for mechanical defects, the tubes each containing twenty-five SAW filters, are packed into carton boxes for transportation to customers as below (figure 4.13).

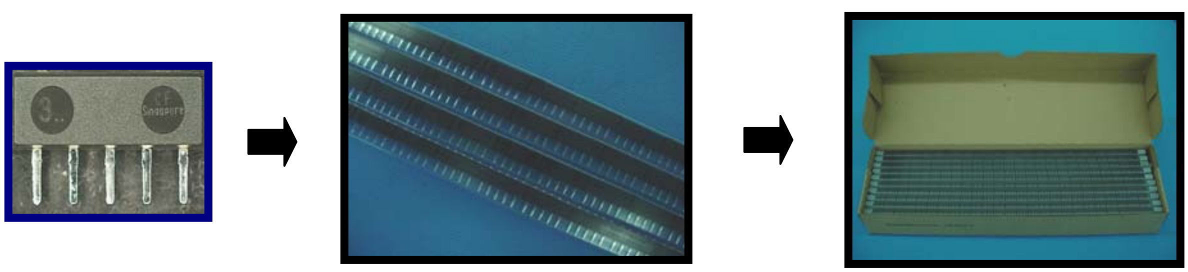


Figure 4.12: Testing and Packing

4.3.2 Facilities Modules

The major facilities operations in the factory are summarised in figure 4.14 below. The flow of water and air in the factory is shown using blue and black coloured arrows respectively. The major operations include,

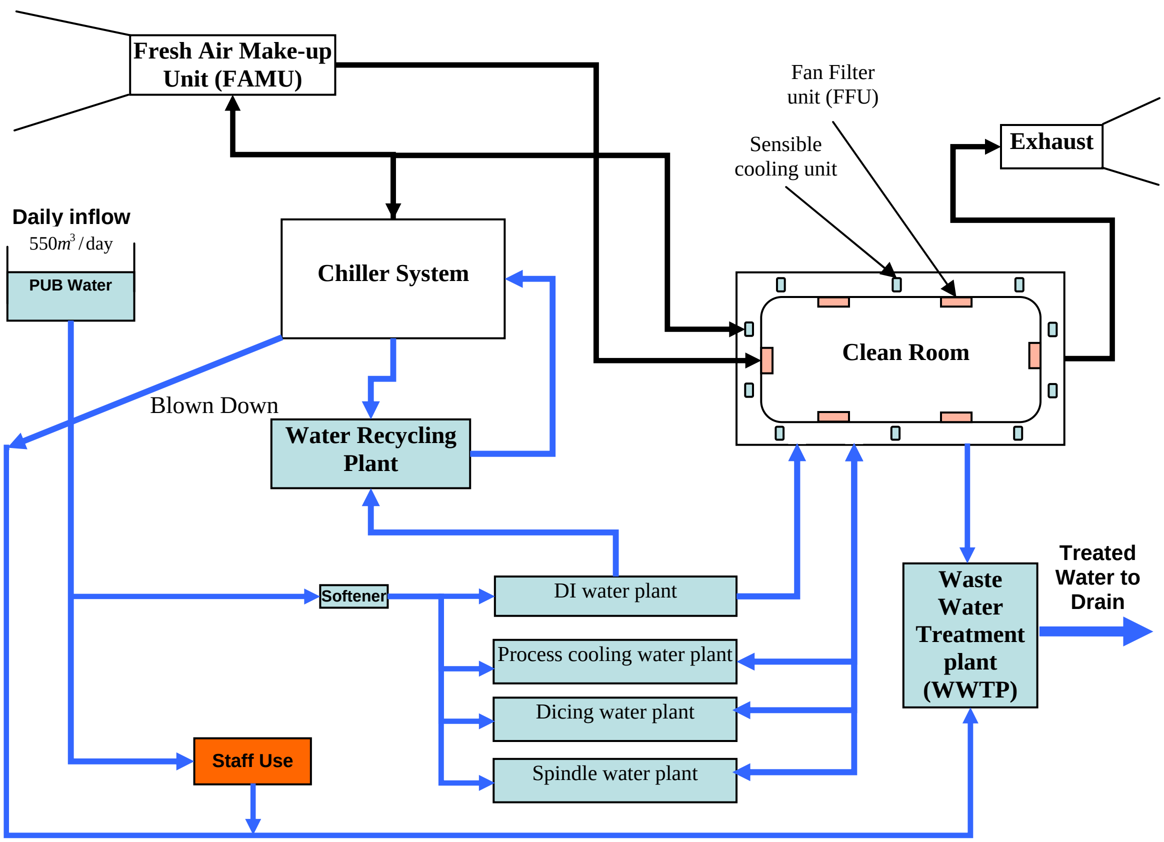


Figure 4.13: Major facilities operation

- Factory environment control (HVAC system) – Control and maintenance of both cleanroom and non-cleanroom area. Major modules include fresh air make up units (FAMU), chillers, cooling towers, fan filter units (FFU), sensible cooling units and exhausts.

- Water processing plant (blue boxes) – The production and delivery of process water needed for manufacturing processes such as deionised water, process cooling water and cutting water.

- Water recycling plant (blue box) - Recycles reject reverse osmosis (RO reject) water from deionised water plant and condensed water from HVAC system, to be used for cooling towers.

- Waste water treatment plant (blue box) – Waste water from manufacturing and facilities operations are treated before releasing to the drain.

- Utilities for production (not shown in the diagram) – The production and delivery of utilities such compressed air and vacuum to the manufacturing processes. All the chemicals and gases needed for the production of a SAW filter are manufactured offsite and then delivered to the facilities in the factory. Facilities then deliver these chemicals and gases to the manufacturing processes.

4.3.3 Staff and Office Use

Usually, a small portion of a company's resources are used up by its office use and staff. Hence, it was important to include them as a cluster in the production/manufacturing stage of a SAW filter. In this case staff/office cluster includes all the activities in the factory that are not included either in manufacturing or facilities clusters. These include general staff use, lightings, building infrastructure, office and work equipments.

Chapter 5 LIFE CYCLE INVENTORY

5.1 Introduction

The next stage of this LCA study was to collect and quantify the Life Cycle Inventory (LCI) of a SAW filter. This proved to be the most time consuming and challenging part of this LCA. Nevertheless, this stage had to meticulously executed, for its accuracy and clarity is bound have a profound impact on the final results of this study.

In the following section, the methodologies used commonly for LCI analysis are reviewed. Using these methods are a guideline, the LCI analysis for this research project was carried out. The techniques adopted and the subsequent results obtained for this LCA are documented in section 5.3 onwards.

5.2 Methodology

The most demanding task of a LCA is the Life Cycle Inventory (LCI) analysis, which is the quantification of material and energy (resources and wastes) flows associated with a product system under study (Goedkoop, Schryver & Oele 2006). To put it bluntly, it is the accounting of a product's inputs and outputs throughout it life cycle.

The quality of LCI provides the basis not only to evaluate the environmental impacts but also to provide potential improvements (LCA101 2001). The quality of the LCI data is reflected through out LCA process, hence the accuracy and detail of the LCI is of utmost importance. Taking Environmental Protection Agency's (EPA) LCI framework as reference, the LCI could be separated in to four steps;

- Development of a flow diagram of the processes being evaluated.
- Development of a data collection plan.
- Collection of data.
- Evaluation and reporting of data.

Development of a flow diagram deals with the setting up of a systems boundary for each of the individual processes that are in the main system boundaries of an LCA, such as the one that was defined in chapter three (see figure 3.3). The flow diagrams provide an outline of the major processes to be modelled, including their interrelationships (Guinée et al. 2001). This stage could make the whole LCA process less complicated and provide a methodological approach to data collection. The accuracy and detail of the LCI largely depends on the complexity of these process flow diagrams.

The data collection plan ensures that the quality and the accuracy of the LCI meet the requirements specified in goal and scope definition stage. As stated earlier, there are two types of data collection methods that are recommended for use in Microelectronics industry. The 'top-down' approach consists of collecting data at a factory level and then disaggregating it to process levels. This approach often results in manageable databases. However, it is not suitable if the factory manufactures different products. In such cases, it can be extremely difficult to disaggregate the data in to process levels (Murphy, Allen & Laurent 2003).

In contrast, using the 'bottom-up' method, inventory is quantified at equipment-level on a process basis and aggregated at factory or product level. It provides a much more detailed data directly related to the pieces of equipments or processes. Using this approach, it is also easier to implement improvements to mitigate the environmental impact at each process stages. The main drawback of this approach is the amount of time and resources needed.

The data collection plan consists of four different tasks; defining the data quality goal, identifying data sources and types, identifying data quality indicators and developing a data collection worksheet and checklist. Data quality goals provide a guide for the quality of the data that needs to be collected. In keeping with the goal and scope of the study this helps ensure that the time and resources spent on LCI stage is kept to a minimum. Data quality indicators are the benchmarks against which the collected data can be measured to determine if the data quality requirements have been met.

It is good to identify the sources of LCI data or at least most the data before the actual data collection, as this will reduce cost and time. Examples of sources of data include, directly measured, databases, journals, reference books, internet and best engineering judgement.

Data for an LCI can be classified into two types; Foreground data and Background data. Foreground data is the very specific data that is needed for modelling of the system for the next LCA stage, life cycle impact assessment (Goedkoop, Schryver & Oele 2006). Background data refers to data for generic materials, most often the semi-products that were discussed in chapter three, transport, waste management, all of which can be found in databases and literature.

Once the data sources and types have been identified, the next task in data collection plan is to develop a data collection Inventory checklist that covers the most decision areas in the performance of an inventory (LCA101 2001). The purpose of this checklist is to guide the foreground inventory collection and to enable construction of a database to store the collected data. Checklists are extremely important in a large LCA project, as many people might be tasked for data collection. Having checklists helps to ensure completeness, accuracy and consistency.

The next step of the LCI analysis is *data collection* which generally involves site visits, research and direct contact with technical experts who are familiar the product of the study. Often in case of complex LCAs, data collection can be tricky. It can be extremely difficult to get accurate LCI data for some of processes. In such circumstances, educated guesses by experts are the highly recommended option. In other cases, though data may be available, it might be difficult to quantify in to a functional unit level. This may cause the system boundaries of the product to be altered.

The last step in the LCI is to evaluate and document the collected LCI data that is to be used for the next stage of the LCA, life cycle impact assessment. The methodologies and strategies adopted for data collection and the final LCI results should be reported clearly and concisely.

5.3 Life Cycle Inventory of a SAW filter

Following closely to the methods described in the preceding paragraphs, a detailed LCI analysis was conducted for the SAW filter. The first step was to identify the foreground and background data. All the data associated with the immediate production/manufacturing of a SAW filter in the plant were considered to be the foreground data. This included all the activities and processes that are highlighted in chapter three (System boundaries) and four (processes in the manufacturing of a SAW filter). Raw material extraction, manufacturing of the semi-products and their transportation details were considered to be background data.

In order to structure the data collection three main clusters were defined as stated in chapter three. The three clusters are Infrastructure modules (facilities), the manufacturing line and staff and office use. They were defined on the basis of ease of data collection, types and availability of data. For instance, manufacturing line data was available for each individual processes that were easily broken down in to the functional unit level, where as for facilities modules, the only data available was quantified at the factory level and had to allocated to unit level accordingly. In such a scenario, both the 'bottom-up' and 'top-down' approach had to be used.

The next task of this LCI was to identify the complete process flow involved in the manufacturing of a SAW filter. It was important to understand each and every process in some detail to know what data needed to be collected and the reason it had to be collected. Each and every process including those from the facilities and staff/office use were studied for short period of time. This involved several line tours to the factory and countless interviews conducted with the process engineers and production staff.

Equipped with the information gathered, flow diagrams for each and every process in factory were created to aid the inventory collection. An example of such a flow diagram, the diebonding process flow diagram is shown in figure 5.1 on the next page. Using the created flow diagrams as a basis, checklists were then prepared for data collection.

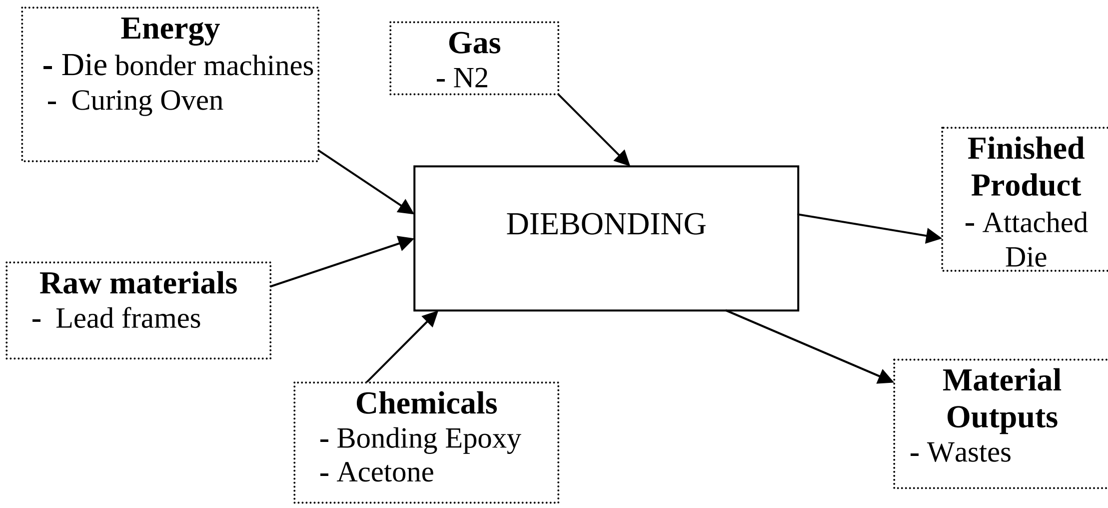


Figure 5.1: Flow diagram of the Diebonding process

In order to accurately quantify the LCI of each individual manufacturing process in the factory accurately, it was important to note some of the production terminologies, namely the machine utilization and yield. Production machines are not operated continuously, but rather in *lots*. A *lot* in Front of Line (FOL – Wafer fabrication) in the factory means a batch of 25 wafers, while in End of Line (EOL – Assembly/Testing) it means 1600 SAW filters.

The time in between lots, where the machines are turned on and are waiting for lots to be processed is classified as idle or standby time. Material and energy consumption during this period is a fraction of what is consumed during the actual production time. Another important aspect of time to consider is the down or shutdown time when the machine is under repair or undergoing periodic maintenance. Most of the time, negligible material and energy consumption occur during this period.

Yield refers to portion of each lot that is usable after each process. Production yield varies for each process. Typically, yield values are higher than 95% for most of the processes. Yield losses occur due to specification failures, quality issues and operator mishandling.

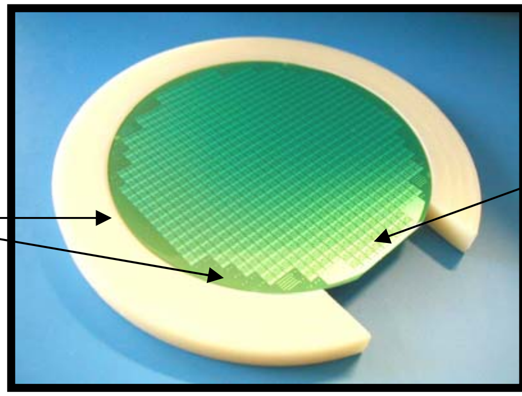


Figure 5.2: A SAW Wafer

An important aspect regarding the data calculation in FOL other than the production yield and utilisation is the area of the SAW filter that is actually used for fabrication (see figure 5.3). Though the unused areas are not fabricated, they still go through almost all the same processing steps as the used area and hence, this unused area had to be taken in to consideration when calculating the LCI. The fact that the SAW wafer is not a full circle (one side of the circle is cut) was also taken in to account.

Another major task before the start of the actual inventory collection was to identify a suitable reference unit which could be calculable for all sources (Williams, Ayres & Heller 2002). At different stages of the manufacturing process, the available data in the factory was quantified in different units of measurement. For instance, all the available data for wafer fabrication (FOL) was in terms of a single wafer, while for assembly/packaging stage it was in terms of a single SAW filter.

To overcome this complexity it was decided to use the frontal surface area (area of the patterned surface) of the die as a reference unit for data collection. As mentioned earlier in goal and scope definition, the SAW filter (functional unit) used for this study measures $13.7 \times 4.8 \times 2.4mm$ and weighs about $415mg$. The actual size of die (lithium niobate wafer) that is that is embedded in the filter measures $10.3 \times 2.1 \times 0.5mm$ and weighs around 50 mg. Then, frontal surface area of the SAW chip is equal to,

$$= 10.3 \times 2.1 = 0.2163cm^2$$

This data was used as the ***reference unit*** for the LCI collection which documented in the following sections. It should be noted that the all the data quantified here were based solely on the consumption and at no instance, recyclability of this materials in the factory or off-site were considered.

5.3.1 Manufacturing Line

A ‘bottom-up’ approach was used for quantifying of life cycle inventory of each process of the manufacturing line. On studying the flow diagrams created for individual process it was noted that all manufacturing line processes should further be separated in to the wafer fabrication (FOL) group and the assembly/Testing/packaging (EOL) group. This separation was based on the product output from each area; the product output from the wafer fabrication area was in wafers, while the product output from the manufacturing area was in chips or SAW filters.

Based on this arrangement, two checklist formats, one each for FOL and EOL were created. The sample checklists are shown in Appendix B. The checklists included the energy consumptions, the gas and water consumption and the production details of each process (over a period of four weeks).

The next step was to collect the inventory data regarding chemical, gas and other raw material consumption. To accurately quantify these items, raw material consumption, chemical consumption, production output, production yield for each individual process was studied over a period of four weeks. The data collected was then averaged out to a daily basis. Most of the information was readily available in company’s production database. When ever there was gap in the data collected, process engineer’s opinion was sought and estimations based on average values were used.

Using this information in conjunctions with the details from the checklist, LCI data quantified for the functional unit of the study (a single SAW filter). The calculation techniques that were used are documented in the next few pages.

Manufacturing line - Energy consumption

The first task was to use the information from checklists to quantify the energy requirements of the machine/s and other utilities associated with individual process. The peak current during production and idle mode for all machines (shown in checklists) were obtained from the facilities department and in some cases from the machine manual. The Energy consumption for all machines in production and idle mode was calculated using a power factor of 0.85. The results for FOL and EOL are summarised in table 5.2 and 5.3 respectively.

For each process, once the total number of machines involved in the production, their rated voltage, active and idle load, the machine utilization data, and the process yield were known, energy consumption was easily calculated. To demonstrate the method used, shown below is a sample calculation for the incoming cleaning process, which involves 2 machines. The average output for incoming cleaning process is 3790 wafers/day with a yield factor of 99.3%. The data collected for the incoming cleaning process is given in the table 5.1.

Machines	No of machines	Rated Voltage (V)	Load Active (A)	Load Idle (A)	Uptime (hrs)	Idle time (hrs)	Down time (hrs)
Wet bench	1	400	30	25	21.36	0.96	1.68
Spin rinse dryer	1	230	15	10	22.8	1.2	0

Table 5.1: Incoming cleaning process data

Using the data from the table, the $Energy\ Consumption_{Active}$, is given by,

$$= \left[\frac{\left(\sqrt{3} VI_{active} \cos\phi \times time_{active} + VI_{active} \cos\phi \times time_{active} \right)}{1000} \right] \times \frac{1}{Average\ no\ of\ wafers}$$

$$= \left[\frac{\left(\left(\sqrt{3} \times 400 \times 30 \times 0.85 \times 21.36\right) + (230 \times 15 \times 0.85 \times 22.8)\right)}{1000}\right] \times \frac{1}{3790}$$

$$= 0.1172 KWh / wafer$$

Similarly, $Energy\ Consumption_{Idle}$ is given by,

$$= \left[\frac{\left(\sqrt{3} VI_{Idle} \cos\phi \times time_{Idle} + VI_{Idle} \cos\phi \times time_{Idle}\right)}{1000}\right] \times \frac{1}{Average\ no\ of\ wafers}$$

$$= \left[\frac{\left(\left(\sqrt{3} \times 400 \times 30 \times 0.85 \times 0.96\right) + (230 \times 15 \times 0.85 \times 1.2)\right)}{1000}\right] \times \frac{1}{3790}$$

$$= 0.00434 KWh / wafer$$

And hence, the total energy consumption of the process per wafer is,

$$Energy\ Consumption\ per\ wafer\ (KWh) = Energy\ Consumption_{Active} + Energy\ Consumption_{Idle}$$

$$= 0.122 KWh / Wafer$$

The above shown value is energy consumption per wafer if all processed wafers are usable (100% yield). But in this case the process yield is given as 99.3%. Taking this yield into consideration, the total energy consumption of the process per wafer is,

$$Energy\ Consumption\ per\ wafer\ (KWh) = \frac{0.122}{0.993} = 0.123 KWh / wafer$$

To convert the calculated energy consumption per wafer into a single chip level (reference unit), firstly the frontal surface area of the SAW wafer (with the cut-out area) must be calculated. The cut-out area is estimated to be 5% for SAW wafers. And hence, then the surface area of a 4inch (5.08cm) wafer is given by,

$$= \pi r^2 \times 0.95 \;\; = \pi \times (5.08)^2 \times 0.95 = 81.08 \times 0.95$$

$$= 77.0295 cm^2$$

Then the energy consumption per chip is,

$$Energy\,Consumption\;\; per\; chip\,(KWh) = \frac{Energy\,Consumption\;\; per\; wafer}{Surface\;\; area\, of\;\; wafer} \times reference\;\; unit$$

$$= \frac{0.123KWh}{77.0295} \times 0.2163$$

$$= 3.453 \times 10^{-4}\, KWh / Chip$$

The energy calculation for EOL adopts a similar strategy and is shown below. The calculation is simpler because the average daily output per process is in number of chips and not wafers.

$$EOL\; Energy\, Consumption = \left(\frac{Energy\, Consumption_{Active} + Energy\, Consumption_{Idle}}{Daily\; average\, Output\; (Chips)} \right) \times\, yield$$

$$= KWh/chip$$

Using methodologies described here, the energy consumption of all manufacturing processes was calculated and is shown in table 5.2 (FOL) and 5.3 (EOL). The main processes are shown in bold letters.

Energy Consumption - FOL (Wafer Fabrication)							
	Process	**KWh / Wafer (active)**	**KWh / Wafer (Idle)**	**KWh / Wafer (Total)**	**Process Yield**	**KWh / Wafer fiter**	**KWh / SAW fiter**
PHOTOLITHO	**Incoming cleaning** -Wet bench	0.09983	0.00374	0.12217	98.6%	0.1239	0.00035
	Spin Rinse Dyer	0.0186	0				
	Metallization	0.50345	0.0275	0.53095	97.2%	0.54653	0.00153
	Resist Coating	0.49289	0.05193	0.54482	96.6%	0.56429	0.00158
	Exposure	0.1679	0.00459	0.17249	98.5%	0.17521	0.00049
	Developing	0.1961	0.024	0.2201	97.5%	0.22574	0.00063
	Etcing	0.10901	0.00088	0.1264	97.6%	0.1296	0.00036
	Spin Rinse Dyer	0.01651	0				
	Plasma cleaning	0.07038	0.00407	0.07445	99.8%	0.0746	0.00021
	Post Cleaning	0.11384	0.00116	0.13171	99.6%	0.13224	0.00037
	Spin Rinse Dyer	0.01671	0				
	Total						**0.00554**
PRE ASSEMBLY	**Wafer Mounting**	0.057	0.003	0.093	98.8%	0.09	0.00026
	Oven curing	0.025	0.008				
	Reverse side Dicing	0.425	0.000	0.425	96.2%	0.44	0.00124
	Demounting	0.006	0.000	0.006	99.6%	0.01	0.00002
	Plasma cleaning	0.060	0.007	0.067	98.2%	0.07	0.00019
	Silk screen printing	0.136	0.041	0.177	95.8%	0.19	0.00052
	Oven curing	0.055	0.011				
	Wafer Mounting	0.049	0.003	0.080	98.5%	0.08	0.00023
	Oven curing	0.021	0.007				
	Wafer Dicing	0.578	0.002	0.580	95.0%	0.61	0.00171
	Total						**0.00417**
PROTEC	**Protec (Total)**	1.392	0.271	1.663	98.7%	1.6849	**0.00473**

Table 5.2: Energy consumption data for Front of Line

	Energy consumption - EOL (Assembly / Testing)					
	Process	**KWh / SAW Filter (active)**	**KWh / SAW Filter (Idle)**	**KWh / SAW Filter (Total)**	**Process Yield**	**KWh / SAW Filter**
ASSEMBLY	**Die Bonding**	0.000996	0.0000429	0.0010389	99.20%	0.00105
	Oven Curing	0.000677	0.0001246			
	Wire Bonding	0.000285	0.0000061	0.0002911	99.70%	0.00029
	Molding	0.006788	0	0.0075099	98.00%	0.00693
	Oven Curing	0.000654	0.0000679			0.00072
	Deflashing	0.002741	0.000144	0.002885	97.65%	0.00295
	Tinning	0.002072	0.000526	0.002598	96.50%	0.00269
	Total					**0.01544**
TESTING / MARKING / PACKING	**Testing/ Marking**	0.0019	0.000685	0.002585	93.78%	0.00276
	Final Inspection	0.000621	0.000288	0.000909	96.55%	0.00094
	Total					**0.0037**

Table 5.3: Energy consumption data for End of Line

Manufacturing line - Water and Gas consumption

The quantifying of water and gas consumption proved to be more challenging than energy consumption because there were two types of flows involved; *continuous* and *discontinuous* flow. *Discontinuous* flow means that a machine does not consume any water or gas when in idle mode. Some of the machines however consume water and gases when in idle mode and this is classified as *continuous* flow.

With the information gathered from the checklists (sample checklists shown in Appendix B) LCI data was calculated depending on the flow of water/gas using the following formulas shown below. The first step in calculation was to find the daily water and gas usage.

For FOL, the daily usage of *Continuous* flow is given by (ignoring the negligible down time),

$$Daily\ usage\ in\ liters = Flow\ rate\ (Lit/\min) \times 24hrs \times 60\min$$

For FOL, the daily usage of *Discontinuous* flow is given by,

$$Daily\ usage\ in\ liters = Flow\ rate\ (Lit/\min) \times No\ of\ machines \times No\ of\ runs\ per\ day$$

For EOL, the daily usage of *Discontinuous* flow (All processes in the **EOL** uses follow *discontinuous* flow) is given by,

$$Daily\ usage\ in\ liters = Flow\ rate\ (Lit/\min) \times Cycle\ time\ per\ chip\ in\ minutes$$

Whereby cycle time is calculated as,

$$Cycle\ time\ in\ min = \frac{Average\ production\ time\ per\ day}{Average\ chips\ produced\ per\ day}$$

$$Average\ production\ time = 1440min - Idle\ time(min) - down\ time(min)$$

Once the daily usage was calculated, the next step was to quantify the data in to chip level.

For FOL,

$$Consumption\ per\ wafer = \left(\frac{Daily\ usage\ in\ liters}{Average\ Number\ of\ Wafers\ produced\ daily}\right) \times \frac{1}{yield}$$

Then, the usage per SAW filter is given by,

$$Consumption\ per\ SAW\ \ filter\ (Lit) = \frac{Consumption\ per\ wafer}{area\ of\ \ the\ wafer} \times area\ of\ \ the\ chip$$

For EOL the consumption rate is given by,

$$Consumption\ per\ SAW\ \ filter\ (Lit) = \left(\frac{Daily\ usage\ in\ liters}{Average\ No\ of\ \ chip\ \ produced\ daily} \right) \times \frac{1}{yield}$$

Once all the values have been calculated they were converted to mass. The resulting LCI list for water and gas consumption is shown in table 5.4 and 5.5 for EOL and FOL respectively.

Water and Gas consumption - EOL (Assembly / Testing)							
	Process	**N2 (mg)**	**O2 (mg)**	**Helium (mg)**	**DI Water (grams)**	**Process Cooling Water (grams)**	**Dicing water (grams)**
ASSEMBLY	**Die Bonding**	153.305	-	-	-	-	-
	Oven Curing	-	-	-	-	-	-
	Wire Bonding	589.188	-	-	-	-	-
	Molding	-	-	-	-	-	-
	Oven Curing	-	-	-	-	-	-
	Deflashing	-	-	-	139.691	-	-
	Tinning	-	-	-	-	-	-
	Total	**742.493**	**0**	**0**	**139.691**	**0**	**0**
TESTING / MARKING / PACKING	**Testing/ Marking**	-	-	-	-	-	-
	Final Inspection	-	-	-	-	-	-
	Total	**0**	**0**	**0**	**0**	**0**	**0**

Table 5.4: Water and Gas consumption data for End of Line

Water and Gas Consumption - FOL (Wafer Fabrication)							
	Process	**N2 (mg)**	**O2 (mg)**	**Helium (mg)**	**DI Water (grams)**	**Process Cooling Water (grams)**	**Dicing water (grams)**
PHOTOLITHO	**Wet bench**	0.393	-	-	6.05182	-	-
	Spin Rinse Dyer	23.569	-	-	9.077733	-	-
	Metallization	1337.700	-	-	-	1.52095	-
	Resist Coating	185.174	-	-	-	-	-
	Exposure	1.616	-	0.1077	-	-	-
	Developing	188.601	-	-	0.02568	-	-
	Etcing betch	0.014	-	-	9.2856	-	-
	Spin Rinse Dyer	106.040	-	-	2.786	-	-
	Plasma cleaning	0.932	2.642	-	-	-	-
	Post Cleaning - Wet Bench	0.407	-	-	6.2674	-	-
	Spin Rinse Dyer	24.427	-	-	9.401	-	-
	N2 Wafer storage Cabinet	1.325	-	-	-	-	-
	Total	**1870.20**	**2.64**	**0.11**	**42.90**	**1.52**	**0.00**
PRE ASSEMBLY	**Wafer Mounting**	63.330	-	-	-	-	-
	Oven curing	-	-	-	-	-	-
	Reverse side Dicing	94.350	-	-	-	1.962	1.635
	Demounting	31.423	-	-	-	-	-
	Plasma cleaning	48.975	3.623	-	-	-	-
	Silk screen printing	10.286	-	-	-	-	-
	Oven curing	-	-	-	-	-	-
	Wafer Mounting	-	-	-	-	-	-
	Oven curing	-	-	-	-	-	-
	Wafer Dicing	182.909	-	-	26.482	4.573	3.811
	Total	**431.27**	**3.62**	**-**	**26.48**	**6.54**	**5.45**
PROTEC	**Protec (Total)**	**798.69**	**13.60**	**-**	**118.95**	**0.52**	**-**

Table 5.5: Water and Gas consumption data for Front of Line

Manufacturing line - Chemical and Raw materials consumption

The chemicals and other consumable materials usages were calculated adopting the same methodologies used for calculating water and gas consumption data. The results are shown below in table 5.6 and 5.7 for EOL and FOL respectively.

Chemical and Raw material Consumption Per SAW Filter (EOL)				
	PROCESS	**CHEMICAL / RAW MATERIALS**	**Material type**	**Mass (mgram)**
ASSEMBLY	Die Bonding	Epoxonic 94. Biphenol-A .	Epoxy resin	4.05
		Acetone. C_3H_6O	Organic Solvent	6.40
		LeadFrame (0.6g / Chip) - Final product only contains ~ 0.15g	Metal	
		i. LeadFrame - Copper, Cu (97%)		435.40
		ii. LeadFrame - Iron, Fe (2.35%)		11.20
		iii. LeadFrame - Phosphorus, P (0.08%)		0.90
		iv. LeadFrame - Zinc, Zn (0.13%)		0.63
		v. LeadFrame - Silver, Ag (0.3%)		1.80
	Wire Bonding	Gold wire (>99%) Wire bonding	Metal	0.75
		Ethanol	Organic Solvent	1.64
	Molding	Mould compound	Thermoset Plastic (Epoxy resin)	447.30
		Mold cleaning and conditioning sheet	Rubber	2.75
	Deflashing	Deflashing Media blast. [Granulated Melamine Formaldehyde]		281.66
	Tinning	Solder. Tin (96%) and silver(4%)	(Pb Free solder S-Sn96 Ag4)	20.26
		Flux. 2-aminoethanol + DL-malic + glycolic acid + oxalic acid	Flux 2164	28.98
	Common	IPA	Organic Solvent	85.50
Testing / Marking / Packing	Testing / Marking / Packing	Container stick (1 stick - 7.8g)	PVC	185.00
		End Cap (2g) 2 for 1 stick	SEBS compound	9..3
		Carton Box	Paper	20.00
	Common	IPA	Organic Solvent	20.29

Table 5.6: Chemical and Raw material consumption data for Front of Line

Chemical and Raw material Consumption Per SAW Filter (FOL)				
	PROCESS	**CHEMICAL / RAW MATERIALS**	**Material Type**	**Mass (mgram)**
PHOTOLITHO	Incoming cleaning	Ammonia 28% VLSI		16.08
		Hydrogen Peroxide solution 31% (H2O2) SLSI		23.19
	Metallization	Aluminium 99.999%	Metal	4.60
	Resist Coating	AZ1505 Photoresist	Photoresist	11.25
		AZ EBR Solvent 70:30.	organic solvent	15.34
	Developing	Developer AZ826 .	aqueous solution	28.52
	Etcing bench	Etchant Acid Nitric acid >70%, Hyfrofloric acid >7%	Acid	13.50
		NMD-W	Organic solvent	87.48
	Common	IPA	organic solvent	24.35
PRE ASSEMBLY	Silkscreen Printing	Epoxonic 217 Component A.	Epoxy resin	0.61
		Epoxonic 217 Component B.	Epoxy resin	0.52
		Epoxonic 217 Component C3-propylimethoxysilan	Epoxy resin	0.005
		EPA (EthoxyPropylAcetate)	Organic solvent	10.85
		Ethanol	Organic solvent	0.23
	Common	IPA	Organic solvent	18.76
PROTEC	PROTEC	3-TPA Adhesion Primer.3-C9H23NO3Si, 3-TPA	Polymer material	0.07
		Ammonia Solution (NH4OH) 25 % VLSI		2.19
		Hydrogen Peroxide 31 % SLSI		4.03
		Sulfuric acid 96% (H2SO4)	Acid	14.92
		Sodium Carbonate anhydrous (Na2CO3)		3.42
		Sodium Silicate solution extra pure		0.82
		Magnesium Sulphate heptahydrate MgSO4 x 7H2O		1.82
		Anti-Foam Pluronic. (Ethylene Oxide Block polymer)		0.92
	Common	IPA	Organic solvent	14.35

Table 5.7: Chemical and Raw material consumption data for End of Line

5.3.2 Facilities and Staff / Office use

To begin with the LCI, a considerable amount of time was spent with facilities group to understand the facilities operations (figure 4.14) and staff / office use. On the advice of the facilities engineer, facilities modules were separated in to five different processes for the ease of data collection. They are,

- Factory environment control (HVAC system)
- Water processing plant
- Water recycling plant
- Waste water treatment plant
- Utilities for production

Checklists were created based on the flow diagrams for each process of facilities. A single check list was also created for staff/office use. Unfortunately, all the data available for both these clusters were quantified at factory level and hence a ‘top-down’ approach had to be used. The task was then to disaggregate and assign this factory level data to a single SAW filter level (reference unit). This was a tricky as the factory produces three different types of SAW filters as mentioned in chapter 4. And so, it was not advisable to disaggregate using the number of SAW filters produced daily. A common factor had to be used to disaggregate the data accurately.

Disaggregating factors such as cost and weight were considered but in the end, it was decided to use the number of wafer produced daily as the common factor for disaggregating the factory level data. All the three types of SAW filters produced in the factory are different in terms of size, weight and packaging (encapsulation). The only common thing about the three types of products is that they all go through the same wafer fabrication (FOL) process. All three products are fabricated on a 4-inch wafer and they undergo the same wafer fabrication techniques which are detailed in chapter 4. The only difference between these products is that they undergo different assembly and encapsulation processes (EOL) depending on the packaging used (Plastic, ceramic or metallic).

Hence it was appropriate to use the average number of wafers produced daily (3700 wafers) to disaggregate the factory level data to a wafer level, from which it was easily be quantified in to reference unit level. To disaggregate from wafer level to a reference unit level, the same methodologies used for manufacturing line were used.

Facilities – Energy Consumption

To disaggregate from wafer level to reference unit level, the same methodologies used for manufacturing line were used. The LCI data for facilities energy consumption is shown below.

Energy Consumption - Facilities modules				
	Description	Total (KWh)	Per Wafer (KWh)	Per SAW filter (KWh)
HVAC	Chiller	23184	6.266	0.01759
	Chiller Peripherals i.cooling tower ii.chilled water pump iii.condenser water pump iv.Sensible cooling water pump	7800	2.108	0.00592
	FAMU	9240	2.497	0.00701
	Exhaust	900	0.243	0.00068
	FFU	2505.45	0.677	0.00190
	Total			**0.03311**
Utilities For Production	Air compressor	11520	0.584	0.00164
	Dryer	799.2	0.182	0.00051
	Vacuum	1476	0.292	0.00082
	Total			**0.01047**
Process Water	DI Water System	1392	0.376	0.00106
	Wafer dicing water	408	0.110	0.00031
	Process cooling water	720	0.195	0.00055
	Spindle water System	204	0.055	0.00015
	Total			**0.00207**
Water Recyling	Water Recycling Plant	537.6	0.145	0.00041
	Total			**0.00041**
WWTP	Waste Water Treatment Plant	408	0.110	0.00031
	Total			**0.00031**

Table 5.8: Energy consumption data for Facilities

Facilities – Water consumption

Facilities modules consume about $250m^3$ of water daily, mostly for factory environment control (HVAC system). Out of $250m^3$ of water consumed, about $145m^3$ of water is recycled from reverse osmosis (RO) reject and other chiller condenser wastes. Table below shows the calculation details of facility's water consumption. Highlighted in yellow is the consumption rate per SAW filter.

Water Consumption - Facilities Modules		
Estimated wafers per Day	3700.00	pcs
Water Consumption for Facilities Modules	250.00	m3
Recycled water (145 m3/day)	145.00	m3
	Per Wafer (m3)	**Per SAW filter (cm3)**
Factory Use (HVAC System)	0.07	189.73
Recycled water (145 m3/day)	-0.04	-110.04
Total Actual use	0.03	**79.69**

Table 5.9: Water consumption data for Facilities

Facilities – Chemical consumption

Shown on the next page in table 5.10 is the chemical consumption of the five facilities process identified. Once again, the method used to disaggregate the daily consumption to wafer level was by dividing the average number of wafers produced in the factory.

Chemical Consumption - Facilities Modules				
Process	**Chemical**	**Daily Usage (KG)**	**Per Wafer (KG)**	**Per SAW Filter (m gram)**
HVAC	Corrosion inhibitor	2.63	0.00071	1.9961
	Biocide(Glutaraldehyde)	2.68	0.00073	2.0360
	Lubrincant oil			0.0007
Process Water	Glycerin (C3H8O3)	1.23	0.00033	0.9357
	Chemical Inorganic	1.55	0.00042	1.1763
Utilities for Prod	Lubrincant oil			0.0007
WWTP	Sodium Hydoxide	33.67	0.00910	25.5497
	Sodium Chloride	5.91	0.00160	4.4852
	Hydrochloric Acid	7.89	0.00213	5.9882
	Ammonium Hydroxide	2.75	0.00074	2.0870
WRP	Chemical organic	1.51	0.00041	1.1460

Table 5.10: Chemical consumption data for Facilities

Staff / Office Use

Staff and office use include all the activities in the company that are not included either in manufacturing or facilities clusters. These include general staff use, lightings, building infrastructure, office and work equipments. Table 5.11 and 5.12 (next page) shows the energy consumption and water consumption for staff / office use respectively.

Energy consumption - Staff / Office Use			
Description	**KWh**	**Per Wafer (KWh)**	**Per SAW filter (KWh)**
Bulding Infrastucture	4963	1.3414	0.0038
Lighting (production & office)	961	0.2597	0.0007
General staff use, office and work equipments	1636	0.4422	0.0012
Total	7560	2.0432	**0.0057**

Table 5.11: Energy consumption data for Staff and Office use

Water consumption - Staff / Office Use			
Description	**Vol (m3)**	**Per Wafer (m3)**	**Per SAW filter (cm3)**
Total Staff/office Use	50	0.0135	**37.95**

Table 5.12: Water consumption data for Staff and Office use

Waste

Unfortunately there was no data available for waste produced at process level. The only data available regarding wastes was quantified at cluster level. The company disposes the waste through licensed vendors who collect the waste weekly from each unit process. The wastes collected by vendors are classified as either inert or hazardous waste. Inert waste includes waste rags, wipes and absorbent material contaminated with solvents and Isopropyl alcohol. Waste lamp, fluorescent tubes with traces of mercury and used photoresist are some of the items that make up hazardous waste. The inventory list of waste that was quantified for a SAW filter is shown below in table 5.13.

	Wafer Fab (FOL) (m gram)	Assembly (EOL) (m gram)	Facilities (m gram)	Office / Staff Use (m gram)
Solid (Inert)	122.69	93.24	22.42	6.85
Solid (Hazardous)	0.72	0.27	1.23	0.22
Liquid (Inert)	60.34	46.29	3.4	-
Liquid (Hazardous)	136.68	45.8	7.08	-

Table 5.13: Factory waste disposal data

Chapter 6 LIFE CYCLE IMPACT ASSESSMENT

6.1 Introduction

Life cycle impact assessment (LCIA) is the third stage of a LCA in which life cycle inventory is processed and evaluated to understand the extent of the impacts on environment. This chapter begins with a general look at the LCIA methodology. LCIA for this study was done using Simapro software, which is covered in section 6.3. The following sections document the modelling of the SAW filter life cycle in Simapro and explore the selected impact assessment method for this study, the Eco-indicator 99. The results of the LCIA are presented in section 6.5. Some conclusions based on the LCIA results are made in the final section of this chapter.

6.2 Methodology

LCIA provide a linkage between the product of the study and the environmental impacts. The results of LCIA are usually interpreted in terms of environmental impacts and social preferences (Guinée et al. 2001). Overall contribution and risks to environment and public health, social, cultural and economic impacts are some of the factors considered in LCIA. In short, an LCIA result forms the environmental profile of the product of study (Svoboda 1995). According to internationals standards, a LCIA comprise of the following elements. The first three are obligatory, while the rest are optional.

Selection and definition of impact categories and damage indicators – The goal and scope of a LCA should provide the guidance for selection of impact categories to be studied. Shown in figure 6.1 is an example of an impact assessment method structure. ISO recommends identification of end-points or damage indicators prior to selection of impact categories (mid–points). The term mid-points indicate that impact categories are located somewhere intermediate between LCI results and the damage on the impact pathway. End-points are where the actual environments impacts actually occur.

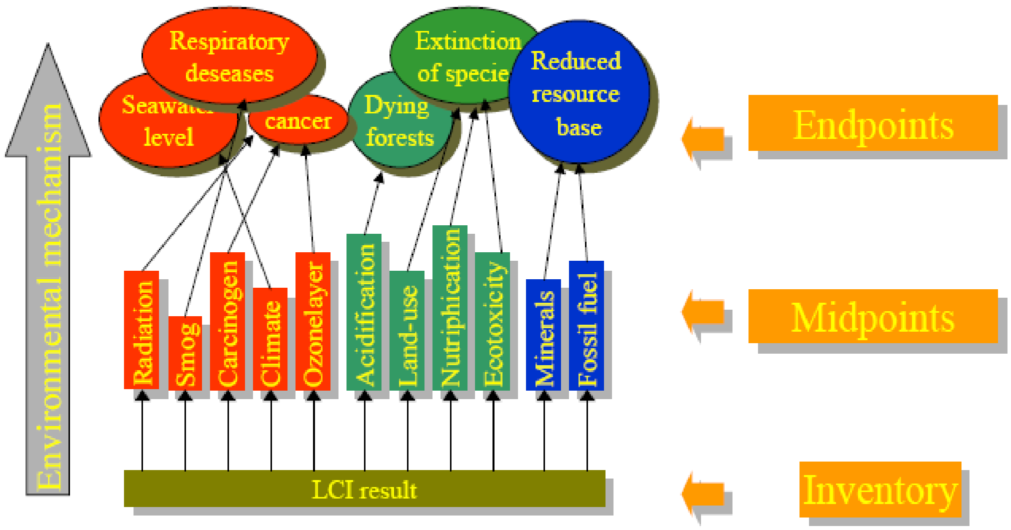


Figure 6.1: General overview of the structure of an impact assessment method (Goedkoop, Schryver & Oele 2006, p.21).

Classification - At this stage the results of the LCI are organized and assigned to the selected impact categories. For an LCI item that contribute only to one impact category, this is a simple exercise, but if an LCI item contribute to two or more impact categories, certain allocations rules have to be used.

Characterization – Scientific characterization factors that are derived using characterisation models are used to calculate the category indicators results. Characterization factors, also known as equivalency factors are multiplied to the applicable LCI result to obtain the impact category indicator result. This enables the aggregation of results between the contributors to each impact category.

Normalisation – As the name suggests, normalisation is the process whereby category indicators can be expressed relative to an available standard. This can be achieved by dividing the impact category indicators by a 'normal' value (LCA101 2001). Normalisation serves two purposes. Through normalisation impact categories that are insignificant in comparison to other impact categories can be ignored in a LCA. Normalisation also shows the order of magnitude of environmental impacts associated with a product.

Grouping – Similar category end-points can be grouped into structured set of damage categories to better facilitate the results of a LCIA into specific area of environmental concern. Since end-points can be grouped, this in turn groups the mid-point indicators. To enable this grouping, the results for each impact indicator in a group have to be expressed in term of same unit during characterisation.

Ranking – Impact categories can be ranked according to the magnitude of their contribution to environmental impacts. This stage is usually done by a panel of LCA experts who are familiar with the goal and scope of the study.

Weighing – Weighing is described by the ISO as "the process of converting indicator results by using numerical factors based on value choices (Bengtsson & Steen 2000). The most controversial and difficult aspect of the LCIA, weighing assigns relative values or weights to different impact categories based on their importance. It is a procedure that is very much subjective as it is difficult to prove that one impact category is more important than the other one. Other factors such as time or the region of study could also influence the results. 'Single score' results are the aggregation of weighted impact category scores.

The abovementioned factors make the LCIA a complex exercise. However in recent times, with the advances made in computers, the LCIA phase has been simplified to a great extend. Today, vast majorities of LCIAs are done using software tools (previously touched on in chapter two). The obvious advantages of using computer technology include (Unger, Wassermann & Beigl 2004),

- The ease of calculating of environmental parameters such as classification, characterisation, etc that is often complicated and convoluted. Most LCA practitioners, who are from the industry, are only interested in the actual results of the study for product and process improvements. For LCA softwares used today, the practitioner only has to key in the appropriate inventory data and the computer does the rest. At the click of a button, results such as characterisation, normalisation and weighing are calculated and displayed instantaneously.

- Softwares enable practitioners to store, manage and edit the large amount of data associated with a LCA.

- Softwares include extensive databases that contain processes, flows and process chains which can be used for the actual modelling of the product of the study.

- Structuring of the modelled scenario, display of the process chains and presentation and analysis of the results can be further improved by using software.

- Most of LCA softwares come equipped with a number of international and regional impact assessment methods. This gives practitioners flexibility regarding the results of their LCA.

With the use software tools, the choice of impact categories is often determined with the choice of software used for the analysis. Though majority of the impact categories remain the same in different LCA impact assessment methods, a few of them are modelled in slightly different manner. Using the ISO's life cycle impact assessment (ISO 14042:2000) methodologies as a guide, a number of Impact assessment methods have been developed by LCA experts, both internationally and regionally.

Impact assessment methods can be generally classified into either problem-orientated or damage-oriented. In problem-orientated methods such as CML 92 and EDIP the quantitative results are grouped at mid-point categories (see Figure 6.1) to reduce the uncertainties involved. Usually the mid-point categories have rather abstract units and are thus difficult to group together.

Damage-orientated methods calculate the impact assessment results at the end-points categories. Usually they are calculated in common units for impact categories within a group. This makes the calculation difficult compared to the problem-orientated methods but are easier to understand and evaluate. Examples of Damage-orientated methods include Eco-indicator 99, Eco-indicator 95 and EPS (Environmental Priority Strategy).

One of the most commonly used LCA softwares, Simapro was chosen as the platform to perform the analysis for this LCA. The following sections explore the software, the modelling methodologies adopted for this LCA and the chosen impact assessment method. It should be noted that all description of the software is based on the demonstration version of Simapro software that was used for this project.

6.3 Introduction to Simapro

System for Integrated Environmental Assessment Products" or otherwise known as Simapro is developed by Pre consultants, a Netherlands based company. The software is reliable and has a proven track record among LCA enthusiasts all over the world. The main appeal of Simapro is its flexibility in modelling and its user friendliness. Though costly, a single user license for a period of six month costs about 800euros, a demonstration version of the software is available freely over the internet.

So far, no LCA softwares in the market today are officially accredited with ISO standards and Simapro is no exception (Goedkoop, Schryver & Oele 2006). However, Simapro has been developed in accordance to the existing ISO set of LCA standards. This is the evident in the way the program is structured. The five main components of modelling a LCA in Simapro are made up the four stages of a LCA and an optional component, 'general data', which contain minor details such literature references, images and information that will not actually influence the results of a LCA.

Every LCA conducted is treated as a project in Simapro. Once a project has been created, the goal and scope section of the software begins with the documentation of goal and scope of the study. The second subsection, 'libraries', allow the choices of databases that are available in Simapro. The databases available are all unique and have been developed by various research organisations. The selected databases can be used in conjunction to build assemblies, life cycle and waste scenarios for a project. Overall there are ten such assemblies available in the demonstration version of Simapro. The last subsection, gives the practitioner a choice of data quality indicators. Time, geography, type and allocation issues that are may influence the accuracy of the final results can be set here.

The process subsection of the life cycle inventory stage shows the selected databases. They include a wide variety of details on raw materials, processes, energy usage, transportation, waste scenarios and waste treatments. If the data is insufficient or inappropriate for an inventory item, the user can either edit the item from the database or create a new item. All the data altered will be local to the selected project and will not affect the default databases in the software.

Using the data from the libraries the sub-assemblies, assemblies, disposal scenarios and finally the full life cycle of a product can all be modelled in the product subsection. The rest of the subsections show a description of the systems used and creation of waste types, both of which are not available in the demonstration version of the software.

After the life cycle of a product has been build in Simapro, the impact assessment can be carried out according to the chosen assessment methods. The assessment method can be selected in the method subsection in Simapro. The demonstration version of Simapro includes sixteen such methods. The full version of Simapro offers the LCA experts an option to create their own impact assessment methods (Goedkoop, Schryver & Oele 2006). Usually LCA assessments are done using just one method, or at the most two methods for comparative reasons. However, it can be very difficult to compare the results obtained using different methods because of the different characterisation factors, mid-points and end-points categories used (explained in section 6.2).

Once the impact assessment method has been chosen, the LCIA results can be calculated almost instantaneously in Simapro. The user has the choice of selecting between the characterisation, grouping, normalisation, weighing or single score results to be displayed on the screen. A complete view of the life cycle of a product can be obtained by selecting a ‘tree’ or ‘network’ display. These displays are particularly useful in pinpointing a hot spot in entire product assembly.

According to Simapro, the life cycle interpretation stage in Simapro is designed as a checklist that covers the relevant issues that are measured in the ISO standards (Goedkoop, Schryver & Oele 2006). Interpretation stages such as contribution and sensitivity analyses can be done easily in Simapro by making using use of network and tree displays and process contribution graphs.

6.4 Modelling a SAW filter Life cycle in Simapro

Though user-friendly and easy to use, the modelling of a product can be quite tricky in Simapro for a first time user. Simapro recommends first time users to spend some time learning to use the software. This was accomplished by doing the two tutorials, 'Guide tour with coffee' and 'Tutorial with wood', which are offered with the software. A considerable time was wasted doing the tutorials because the number of saves easily ran out (as mentioned earlier in the goal and scope section of this report, only a demonstration version with sixteen possible saves was available) and the only way to reuse the software was to reformat the entire operating system and reinstall the software again.

With the knowledge gained from using the tutorials, the SAW filter life cycle was modelled in Simapro following closely the methodologies explained in sections 6.1 and 6.2. The challenge here was to create an accurate the life cycle model of a SAW filter within allowed number of sixteen saves. The demonstration version did not allow the creation of a new project and hence, an existing tutorial project, had to be modified for this LCA.

Under the goal and scope section of Simapro, the first step was to select the libraries to be used for the project followed by data quality indicator requirements such as geography and time. The following three libraries were chosen;

- **BUWAL 250** - focuses mainly on packaging materials, energy, transport and waste treatments. Developed by EMPA St.Gallen in Switzerland for a study commissioned by the Swiss Ministry of the Environment.

- **ETH–ESU 96** - includes about 1200 processes such as energy, electricity generation, waste treatment, transport etc. The database covers mainly Swiss and Western Europe situations.

- **IDEMAT 2001** - developed at the Delft University of technology, Netherlands, the main focus of this database is very much on production of materials. The data is original and not taken from other LCA databases.

The next task was to create the full life cycle model of a SAW filter. Before the actual modelling of the life cycle, the entire LCI items were checked against the similar items in the libraries in Simapro for compatibility.

Other than the issues regarding the inventory data that was highlighted in goal and scope of the study in chapter 3, two major issues were found. Firstly, the Simapro databases did not have any data on deionised water, which is used extensively in the production of the SAW filters. To overcome this shortcoming, a process model of factory water system was developed as shown below. The model of 1 kg of process water is shown here for the ease of explanation and does not indicate any environmental impacts scores or results.

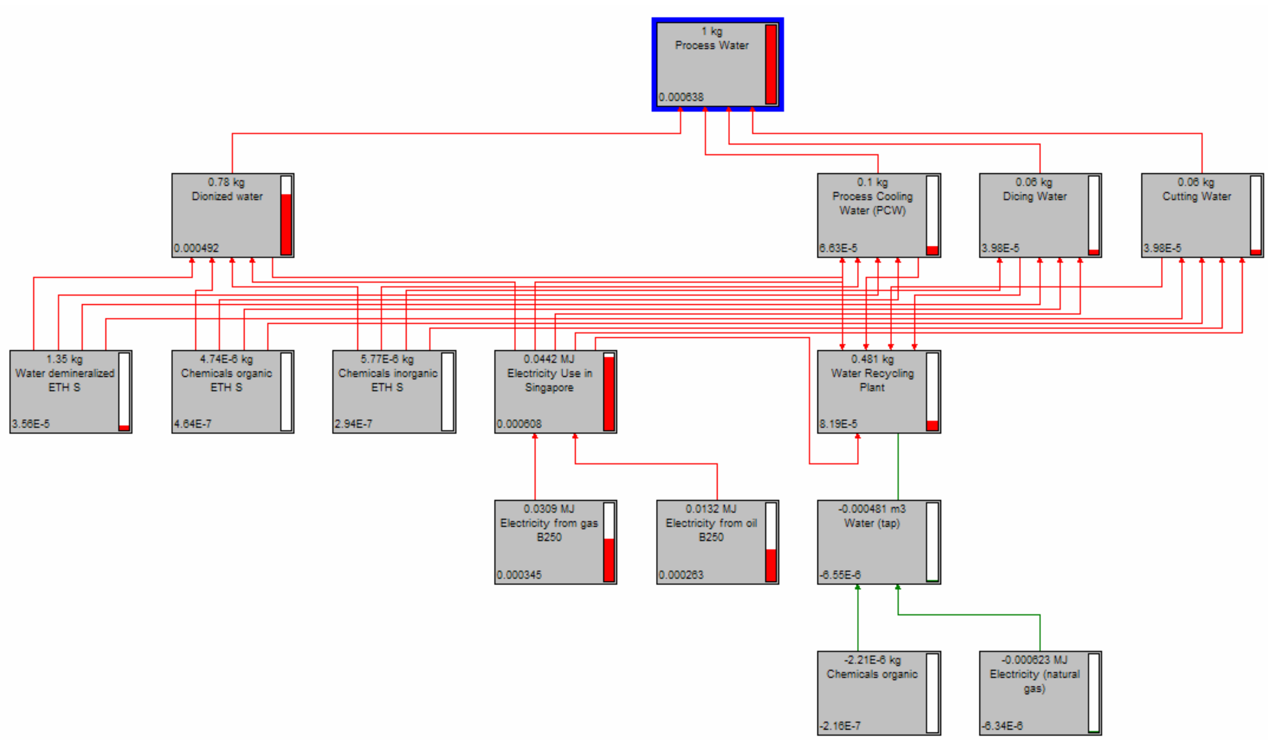


Figure 6.2: Model of factory water system

The output of this process water system included deionised water, process cooling water, dicing water, cutting water. An allocation method based on the total weight of the process water produced (DI water - 78%, PCW water - 10%, cutting water - 6%, and dicing water - 6%) daily in the factory was used for this model. From the figure, it can also be seen that the water recycling plant have also been modelled (of negligible importance in the final picture).

The second issue involved the electricity generation models available in Simapro. The electricity generation models available were suitable only for use in Europe and North America. As electricity consumption was expected be one of the major contributors to the environmental impacts associated with the product of this study, it was important that an appropriate model was used. Hence an electricity generation model for Singapore was created. Electricity generation in Singapore is from oil (30%) and natural gas (70%). The model can also be seen in the figure 6.2.

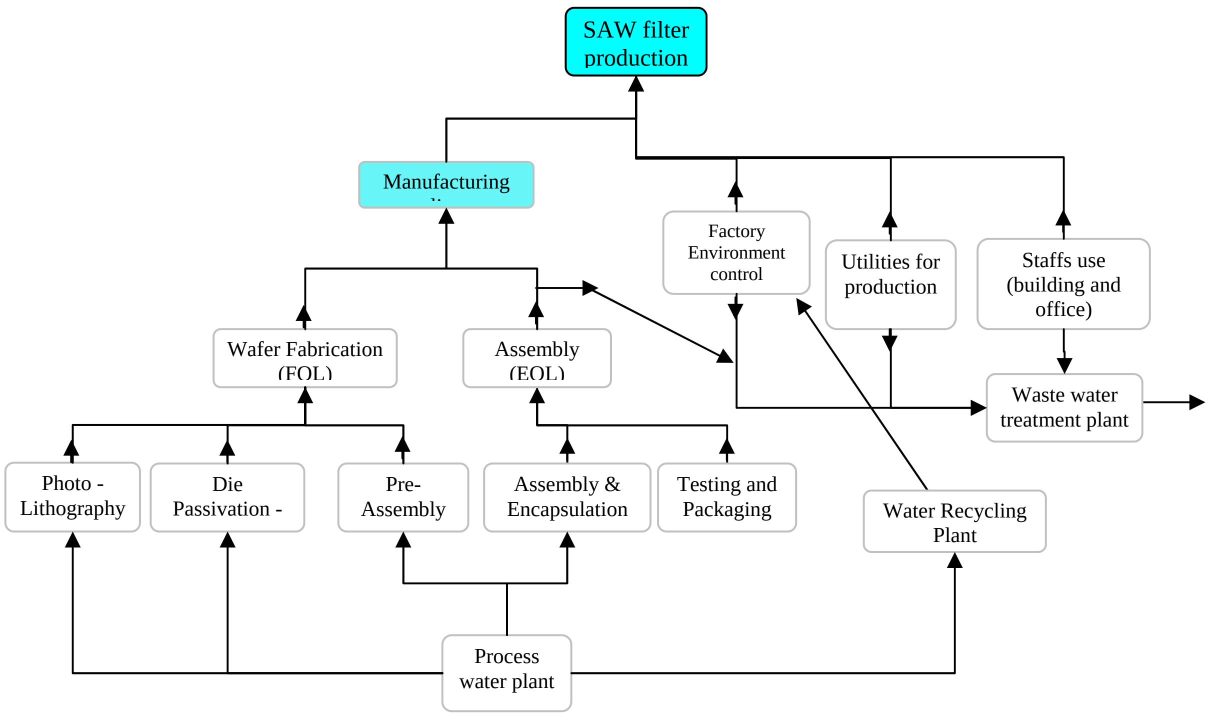


Figure 6.3: Model of SAW filter in Simapro

The rest of the processes, sub-assemblies and assemblies were then modelled using data from the selected libraries as shown in the figure above. The modelling of the full life cycle was carried out by closely following the system boundary diagram and the limitations detailed in Chapter 3.

A point to note from the diagram shown above, the arrow shown pointing upwards from the water recycling plant indicate the use of recycled water that is later used for factory environment control.

Waste disposal was modelled at cluster level as explained in LCI chapter (see Chapter 5) employing the disposal scenarios for both hazardous and inert waste in Singapore. In Singapore, 70% of the waste is incinerated, while the rest is land filled. The data for waste disposal came from ETH-ESU 96 libraries.

Once the model was build, the next step was to do the actual impact assessment. Eco-indicator 99 was chosen as the impact assessment method for this LCA. The following section takes a detailed look at this method.

6.4.1 Impact Assessment Method - Eco Indicator 99

Eco-indicator 99 was chosen as the impact assessment method for a number of reasons. It is described as 'the state of the art' LCIA methodology that is one of the most widely used by practitioners all around the world (Simapro 2006). It follows the ISO 14042 standards very closely. Moreover, the results using this impact assessment method are easy to comprehend mainly because of the number of damage categories (end-point) it uses.

Eco-indicator 99 is a damage-oriented impact assessment that was initiated by Dutch authorities to replace the previously popular LCIA method, Eco-indicator 95. Though it was popular among LCA practitioners Eco-indicator 95 was limited by its inability to accurately weigh different environmental aspects (Goedkoop & Spriensma 2001).

Developed in a top-down fashion, Eco-indicator 99 simplifies the weighing problem by, using just three end points, as shown in figure 6.4 on the next page. The three damage categories can be compared to grouping of different end-points. The three endpoints are then linked to the inventory results (shown on the extreme left of the figure 6.4) using the damage models (shown in white boxes). The three damage categories (groupings) used are damages to human health, damages to ecosystem quality and damages to fossil and minerals resources.

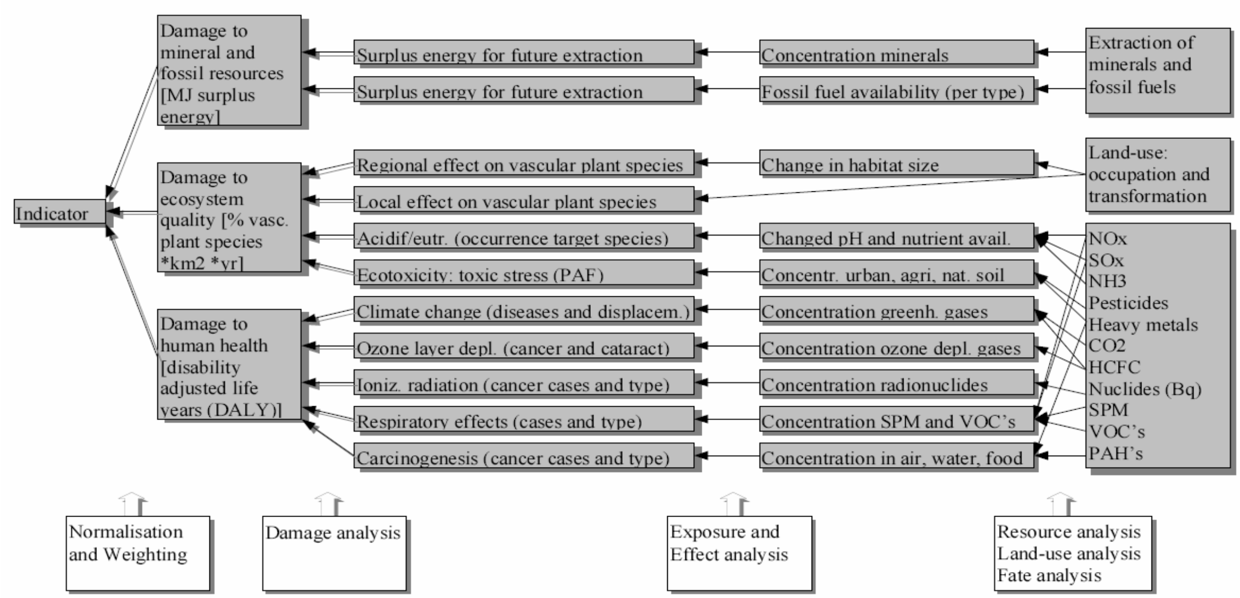


Figure 6.4: General representation Eco-indicator 99 methodology (Goedkoop & Spriensma 2001, p.1).

Damages to Human health **–** is linked to the impact categories shown below. These impact categories could affect the health of human beings in a number of ways both in long and short term. To aggregate these damages to human health, Disability Adjusted Life Years (DALY) is used as tool for comparative weighing. The DALY scale is a disability weighing scale ('O' meaning perfectly healthy and '1' meaning death) that is used by organisations such as World Health Organisation and World Bank. (Potting & Hauschild 2003)

- *Carcinogens* – emissions of carcinogenic substances to air, water and soil

- *Respiratory organics* – respiratory effects of emissions of dust, sulphur, and nitrogen oxides to air resulting from winter smog.

- *Respiratory Inorganics* - respiratory effects of emissions of organic substances to air resulting from summer smog

- *Climate change* – diseases and death caused by climate change.

- *Ozone layer depletion* – refers to the reduction of protective ozone layer caused by the emission of ozone depleting substances such as chlorofluorocarbons and halons.

- *Radiation* – damages caused by radioactive radiation.

***Damages to Ecosystem quality* –** is linked to the three impact categories shown below. It is expressed in percentage of the species that are threatened or have disappeared in a certain area due to the environmental load. This damage indicator is more complex to define than the damage to human health as models used for the three impact categories are not homogeneous. A compromise had to be made and the actual units used is Potentially Disappeared Fraction (PDF) times area times year (PDF*m^2*yr) (Goedkoop & Spriensma 2001).

- *Ecotoxicity* – includes all substances that are toxic to the environment. Ecotoxicity substances released to air, water and soil effect the quality of ecosystem.

- *Acidification / Eutrophication* – acidification is caused by the release of proton in the terrestrial or aquatic system. It causes inefficient forest growth and acid lakes without any wildlife. The impacts are mainly seen in Europe. Eutrophication is described as the enrichment in nutrients that lead to increased production of the flora and fauna that causes deterioration in water quality and an unbalance in the aquatic ecosystem.

- *Land use* - the amount of land used for a given activity and the decrease in aesthetic value that is caused by the activity.

Damages to minerals and fossil resources – models only minerals and fossil fuels, other resources such as biotic resources are ignored. Resource damage category is expressed in MJ surplus energy per extracted materials.

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

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

In order to deal with the uncertainties in the models used for LCA of a product, Simapro offers three different choices of the ECO-indicator 99 methodology (Simapro 2006) using the concept of cultural perspectives, as shown below. Hierarchist perspective was chosen for this LCA as this perspective takes a balanced distinction between long and short term effects and generally facts are included if they are backed up by scientific evidence.

Prespective	**Time view**	**Manageablity**	**Level of eveidence**
Hierarchist	*Balance between short and log term*	*Proper policy can avoid many problems*	*Inclusion based on consensus*
Individualist	*Short time*	*Technology can avoid many problems*	*Only proven effects*
Egalitarian	*Very long term*	*Problems can lead to catastrophe*	*All proven effects*

Table 6.1: Choices of ECO –indictor 99 methodology

A drawback of Eco-indicator 99 is that, it is basically modelled for use in Europe. All emissions and land use impact categories and all subsequent impacts are modelled using European data (Goedkoop & Spriensma 2001). Exceptions to this are the damages to resources, damages created by climate changes, ozone layer depletion, air emissions of persistent carcinogenic substances and radiation.

6.5 LCIA Results

To understand the relative magnitude of the environmental concerns caused by the production of a SAW filter, normalised results of the damage and impacts categories were calculated and the results are shown in figure 6.5 and 6.6 respectively. By default, Eco-indicator 99 normalizes the impact results with the environmental effects caused by an average European during a year.

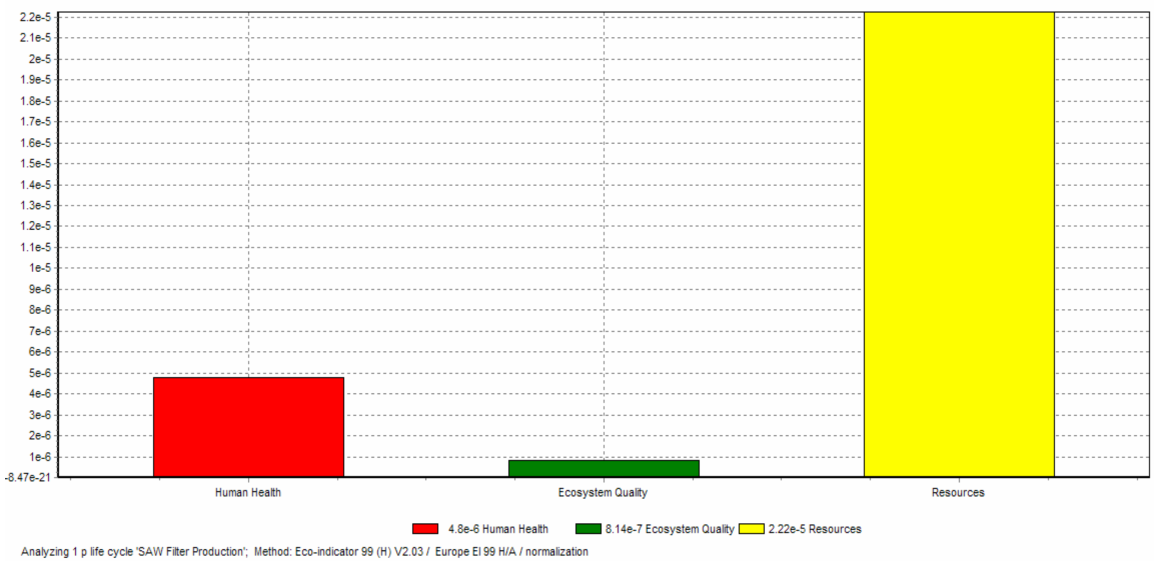


Figure 6.5: Normalization of the environmental damage assessment categories

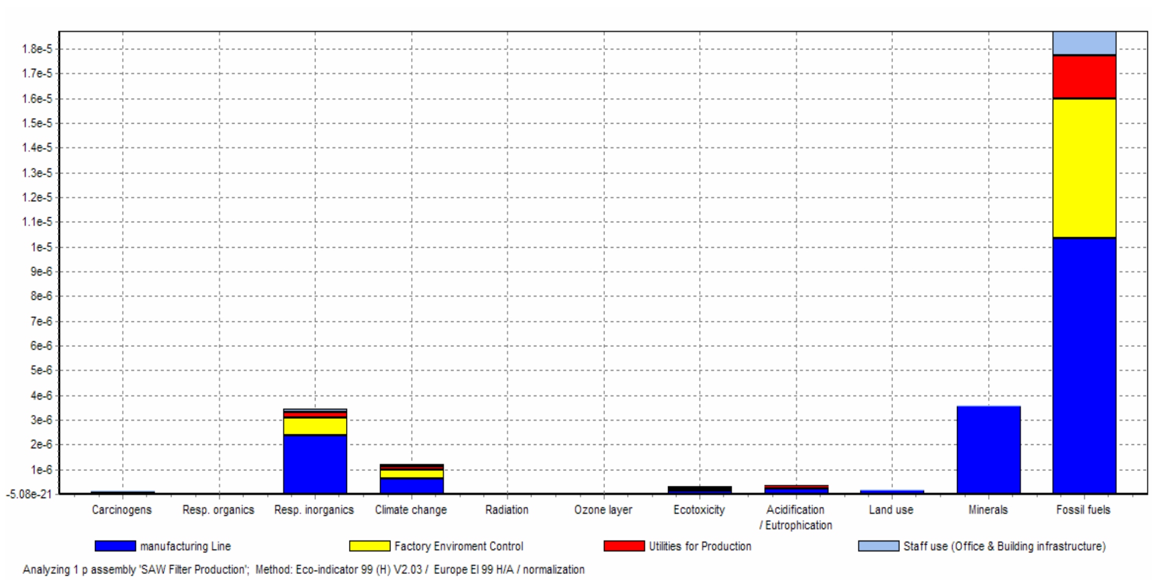


Figure 6.6: Normalization of the environmental impact assessment categories

From figures 6.5 and 6.6 on the previous page, the following conclusions can be reached.

- Damage to resources (fossil fuels and minerals) is the worst affected damage category. This is possibly because of the high energy consumption of SAW filter production process.

- Respiratory inorganics and climate change are the main contributors to human health category, while carcinogens make up a very small percentage. Contributions from other impact categories; respiratory organics, radiation and ozone layer are insignificant.

- In comparison to other damage categories, ecosystem quality is the least affected damage category, with acidification/eutrophication and ecotoxicity, the main contributors.

- Most of the environmental loads associated with each impact category can be linked to the manufacturing line (in blue), while the least contribution comes from staff/office use (shown in light blue).

- The second highest contributor is the facilities support modules (factory environment control and utilities for production, shown in yellow and red respectively)

- Only eight of the impact categories contribute notably to the final environmental result, so the rest of the impact categories can be ignored.

To analyse the specific stages of the production and their impact on the final LCIA results, a detailed analysis was then carried out, firstly at damage categories levels, and then subsequently on at impact category level. The next three subsections documents this analysis, only the impact categories (resp.inorganics, climate change, minerals depletion, fossil fuels depletion, acidification/eutrophication, ecotoxicity and land use) that contribute significantly to the overall results are discussed.

One of the main objectives of this research project was to find the 'environmental hotspots' in production process of a SAW filter. Preliminary analysis showed that it was rather difficult to pinpoint the culpable processes because of a number of reasons.

- Inability to model the whole process system in the Simapro demonstration software.

- A small number of the processes contributed to environmental load in magnitudes many times higher than the majority of the inventory, thus masking some of the other impacts.

To overcome the shortcoming of the second point above, the following methodology was adopted for this impact assessment. Firstly, LCIA analysis was carried out on a full model of the production system (see figure 6.3). Further analysis was then carried out on the actual production processes (End of Line (EOL) and Front of Line (FOL) of the manufacturing line) of a SAW filter except for minerals and land use impact categories (because results obtained are quite easily understood and can easily be linked to the production processes involved).

It should be noted that mostly network and tree diagrams, rather than characterisation and damage assessment bar charts, are used for means of investigation. This was necessary because of the restricted way the model was built in Simapro demonstration version. The cut-off values for each network shown were set accordingly, so that important information can be documented. The thicknesses of lines that link different processes display the contribution to the total environmental loads. All results are shown in cumulative mode. The thermometer indicators shown on the right edge of each box (processes), shows their significance relative to the final result.

The major limitation of presenting the results this way was the poor quality of the network diagrams that had to be used for the documentation in the next few pages (this is especially true if a hardcopy of the report is read, whereas for a softcopy the diagrams can be zoomed-in to see the details). Network and Tree diagrams of better resolution are shown in Appendix C.

6.5.1 Damage to Resources

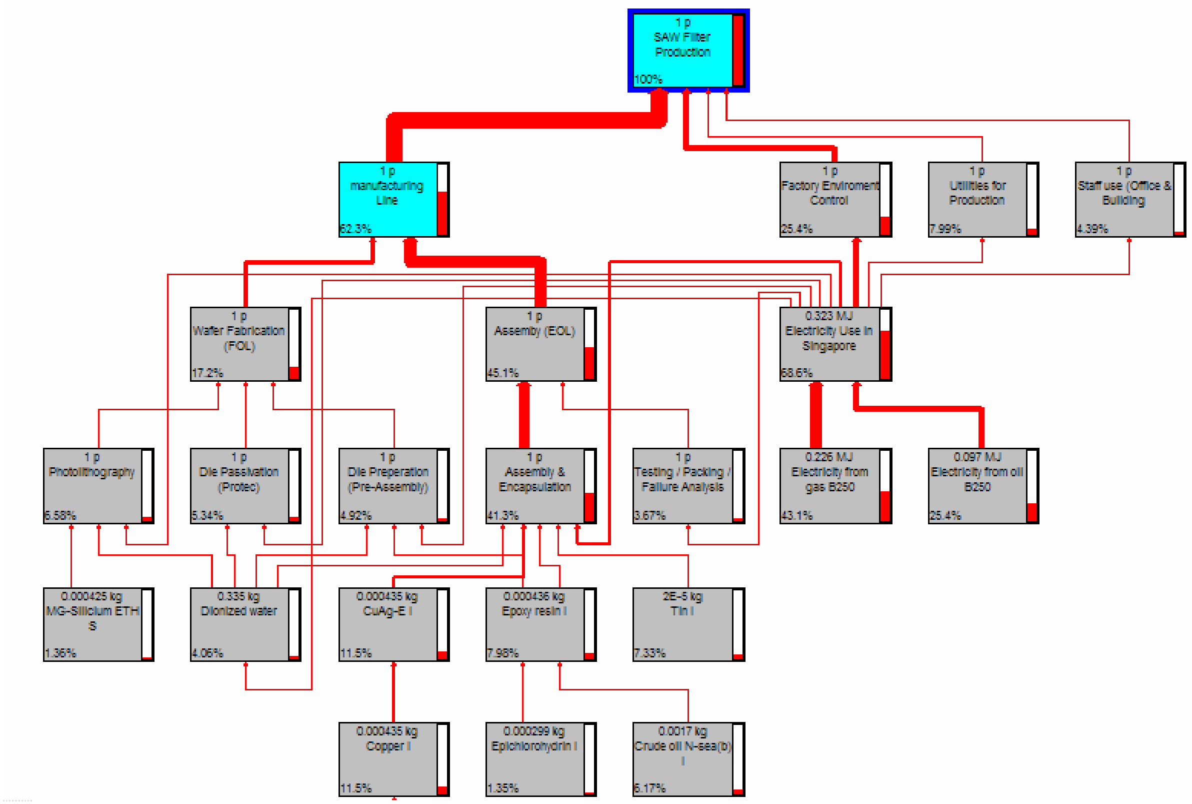


Figure 6.7: Network analysis of damage category - Resource damage

Shown above in figure 6.7 is the characterised network showing environmental impacts results for damage to resources. The results are shown on the network in percentage to the actual damage score of 0.187MJ surplus energy. It can be seen that the manufacturing line is the main contributor to resource damage, of which wafer fabrication (Front-Of-Line (FOL) manufacturing) contributes 17.2% and Assembly (End-Of-Line (EOL) manufacturing) contributes 45.1%. The rest of the contribution comes from facilities modules (factory Environment control and utilities for production – 33%) and staff use (4.36%).

On closer observation, about 68% of the total contributions to resource damage come from the energy consumption (electricity from oil and gas). The heavy use of deionised water in production process contributes a total of 4% to resource damage. For facilities modules and staff/office use, the main contribution again comes from electricity consumption.

EOL - Damage to Resources

Of the 0.116MJ surplus energy (64.5% of 0.187MJ surplus) associated with EOL, about 91.6% comes from the Assembly and Encapsulation (see figure 6.8 below). Total Energy consumption of production machines in EOL amounts for 33.94% of the resource damages linked to EOL processes.

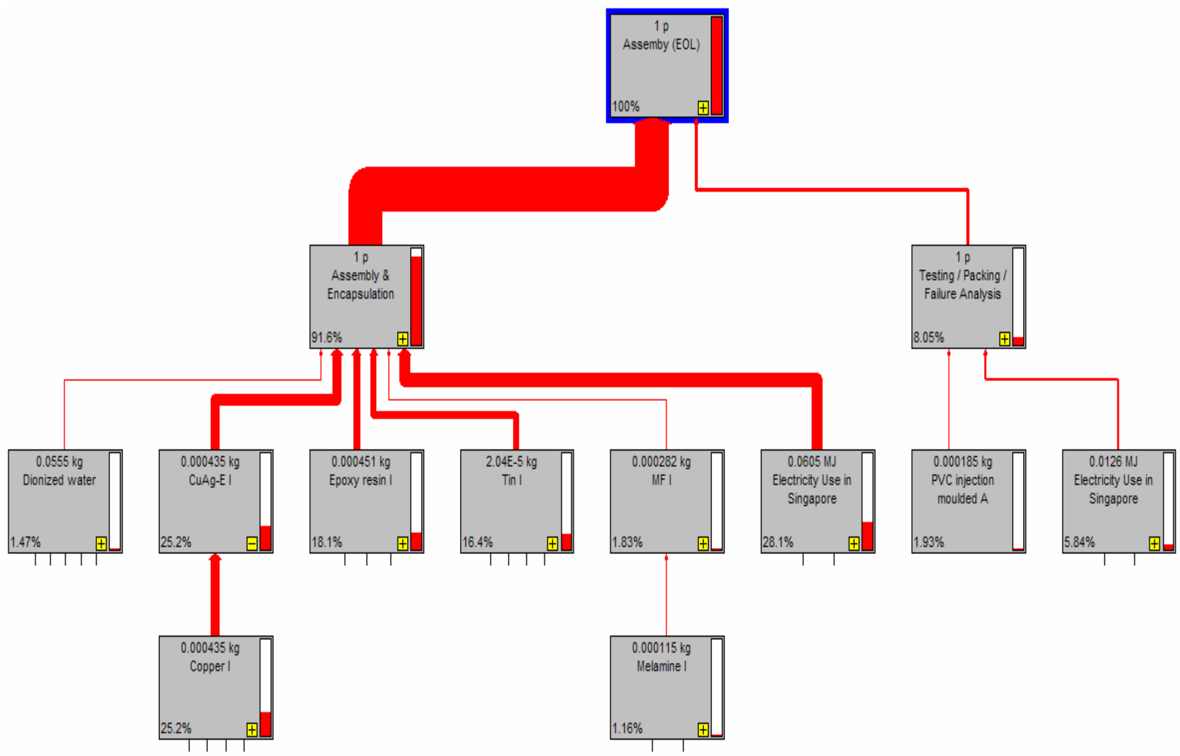


Figure 6.8: Network showing contributions to resource damage (EOL)

Next highest contributor to resource damage from EOL is copper leadframe (25.2%) followed by thermoset epoxy resin used for both mold compound and die boding glue (18.1%). The tinning process which uses tin for soldering of the SAW filter leads contributes about 16.4% of the damage. The PVC packaging material used after testing contributes about 1.93%.

FOL - Damage to Resources

From figure 6.9 below, the resource damage score for FOL is 0.032MJ surplus energy. Of this, the contributions from processes photolithography, Protec and pre-assembly is 0.0123 (53.5%), 0.0099(23.5%) and 0.0091(21.2%) in MJ surplus energy respectively. The main contributing factors to the total damage score are the electricity consumption (45.4%), deionised water (14.9%) and the SAW wafer (29%). It should be noted that silicon was used as a substitute for lithium niobate for this LCA due to the unavailability of data in Simapro database (already discussed in goal and scope section).

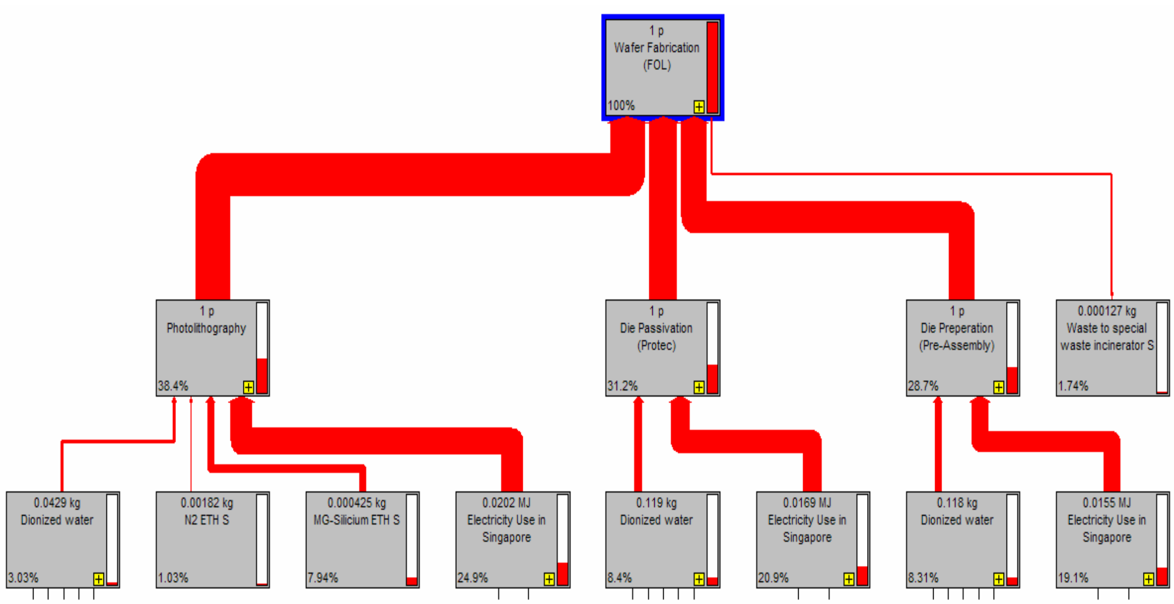


Figure 6.9: Network showing contributions to resource damage (FOL).

Two impact categories (mid-points) contributing to the damage category ‘resources’ (end-point) are depletion of fossil fuels and minerals expressed in MJ surplus energy. Figure 6.10 on the next page shows characterisation results for depletion of fossil fuels.

6.5.1.1 Impact category – Fossil fuel depletion

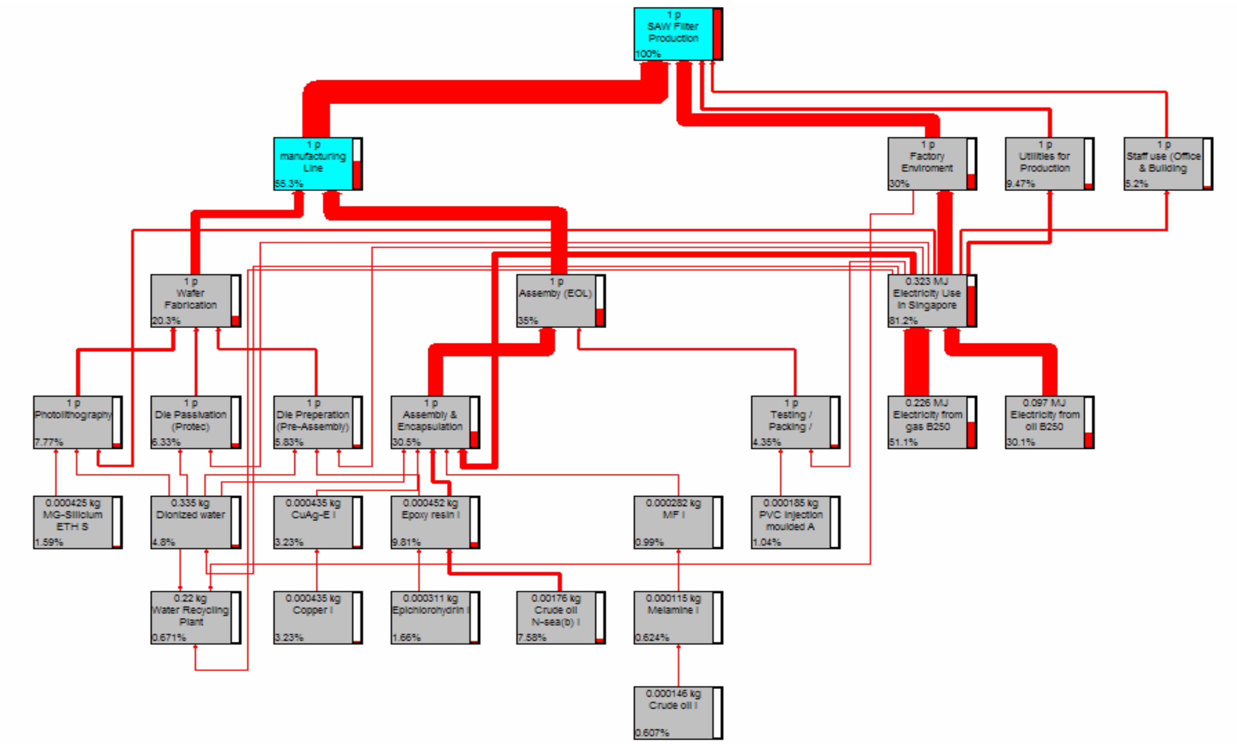


Figure 6.10: Network analysis of impact category - Fossil fuels depletion.

The total score of the fossil fuel depletion is 0.157MJ surplus energy. About 55.3% of this score is associated with the manufacturing line, of which 35% comes from the end-of-line. The contribution from factory modules is about 40% while 5.2% can be attributed to staff use. Fossil fuels such as natural gas, oil and coal are mainly used to generate electricity. Here, quite logically, a very high percentage (81.2%) of fossil fuel depletion is contributed by the energy (electricity) consumption.

The second most contributing factor is epoxy resin used for molding and diebonding process followed by copper leadframe (3.23%). The wafer contributes to about 1.6% of total impact. The contribution from water recycling plant is a low 0.68%. The main contributing factor of the recycling plant is its energy consumption.

EOL - Fossil fuel depletion

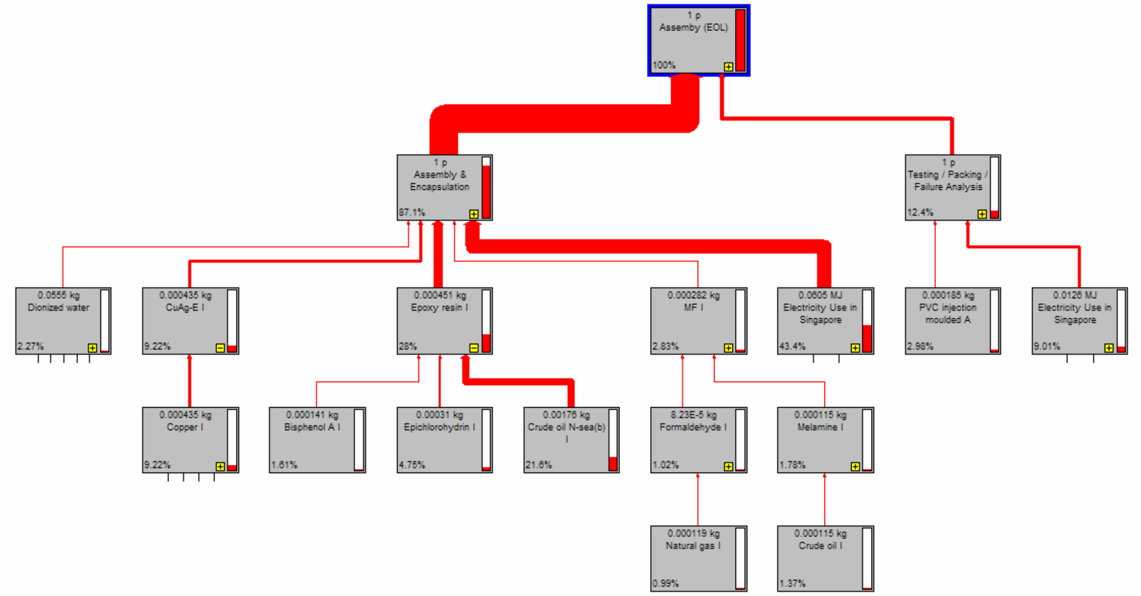


Figure 6.11: Network showing contributions to fossil fuels depletion (EOL).

Almost half of contribution from EOL towards fossil fuel depletion comes from energy consumption of the production machines as shown in figure 6.11. The next highest contributor is the thermoset plastic used for encapsulation and diebonding of the chip (28%) followed by copper leadframes. Other notable contributions include the final packaging material (PVC tube), deionised water and melamine formaldehyde used for tinning process.

FOL - Fossil fuel depletion

The network showing contribution to fossil fuel depletion from FOL is shown in figure 6.12 on the next page. Of the 0.032MJ surplus energy (20.3% of 0.157MJ), the contributions from the three sub-assemblies are photolithography (38.3%), Protec (31.2%) and preassembly (28.7%). The main contribution comes from energy consumption of the production machines. Deionised water contributes a combined total of 19.76% of the fossil fuel depletion linked to FOL. Hazardous waste send special waste incinerator is the next highest contributor followed by nitrogen.

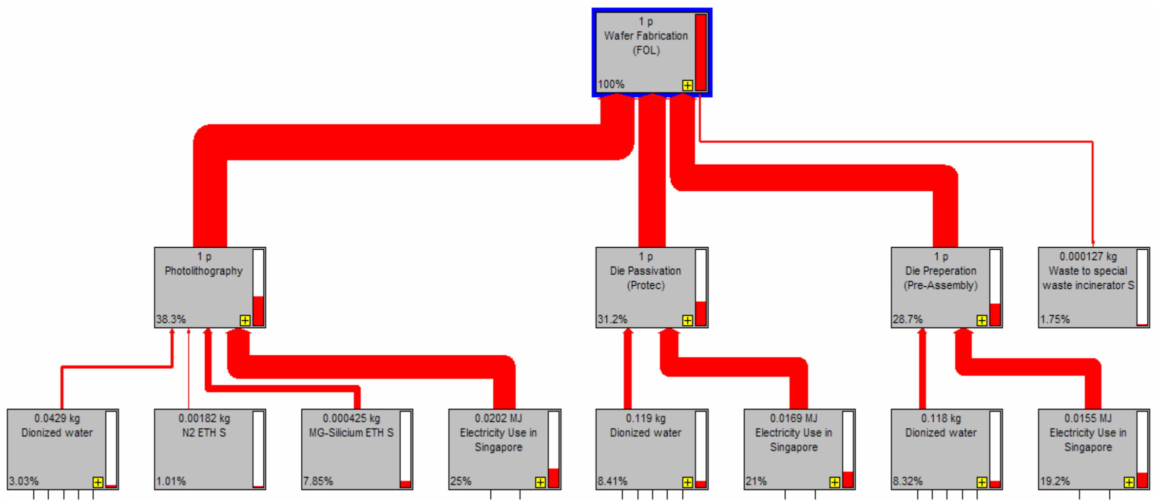


Figure 6.12: Network showing contributions to fossil fuels depletion (FOL)

6.5.1.2 Impact category - Minerals depletion

Shown in figure 6.13 below is the characterisation result for minerals depletion. The only contribution to minerals comes from the manufacturing line. It can be seen that almost all of the mineral depletion related to the SAW filter production is linked to copper leadframes (54.9%) and tin (44.9%) used for soldering of the chips leads.

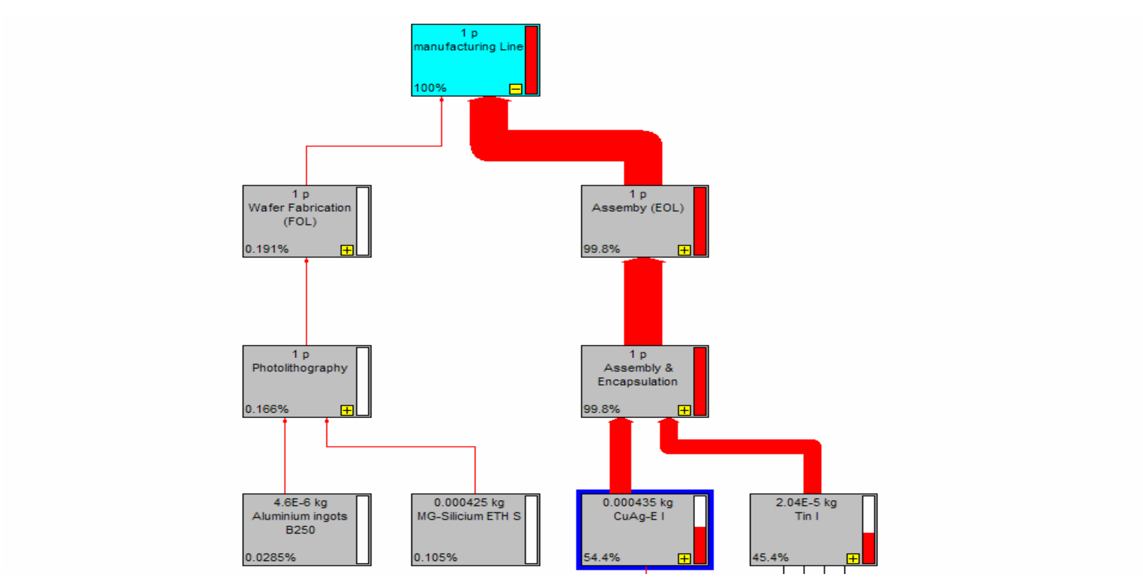


Figure 6.13: Network analysis of impact category - Mineral depletion

6.5.2 Damage to Human health

The total score for human health is calculated to be 4.39E-9 DALY. From figure 6.14 below, a high percentage (63.5%) of the contributions to human health comes from the electricity consumption. About 24% of impacts are associated with the Copper leadframe. The next highest contributor is the SAW wafer (6.6%). The high usage of nitrogen in manufacturing processes contributes about 1.3% while the PVC packaging material used for packing of the final product and inorganics chemicals used during production both contributes about 0.75%.

Overall, the actual production stage (manufacturing line), contribute mainly to human health impacts (65%). Within the manufacturing line, 42.3% of the impacts come from the end-of-line production. The facilities support, factory environment control and utilities for production contributes a total of about 31% of the human health impacts associated with the manufacturing of a SAW filter.

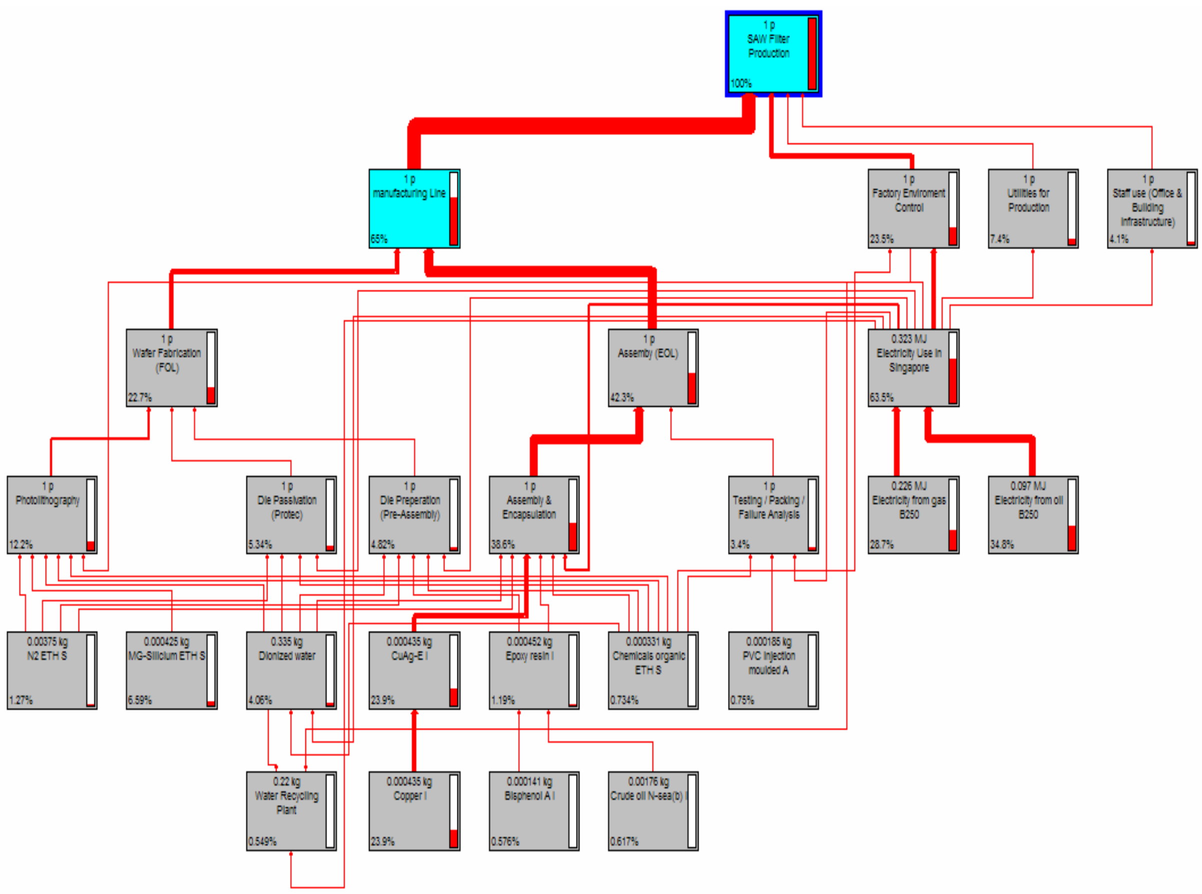


Figure 6.14: Network analysis of damage category - Human health

EOL - Damage to Human health

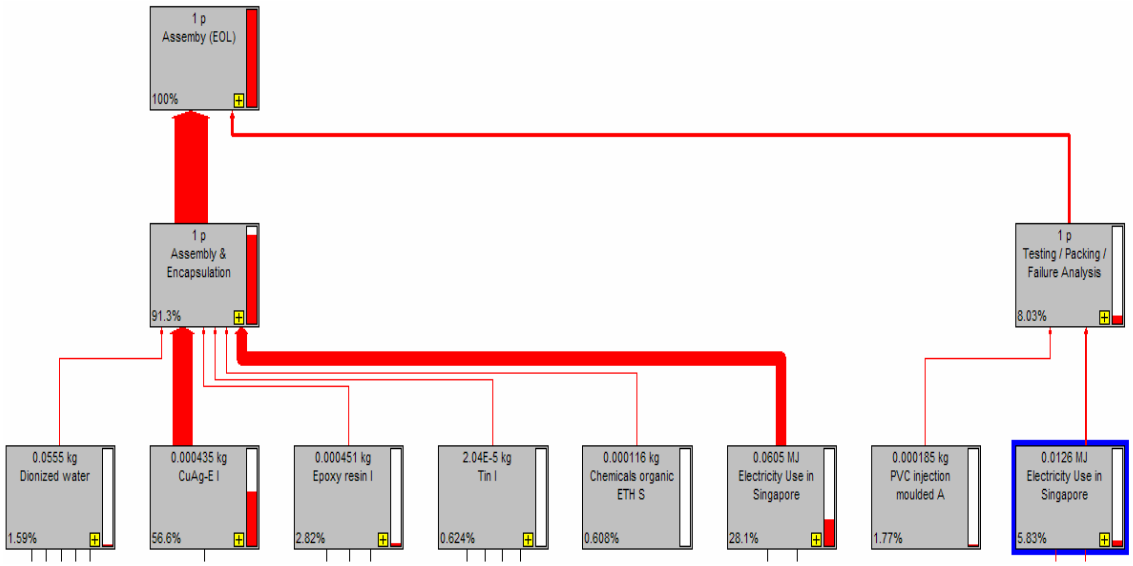


Figure 6.15: Network showing human health damage assessment (EOL)

From figure 6.15, the contribution from EOL to human health damage comes mainly from the sub processes, assembly (die-bonding) and encapsulation (molding). The total human health score for EOL is 3.12e-8 DALY. Copper is the main contributor with a 56.6% share of the environmental burdens followed by energy consumption of the machines. Other notable contributions include PVC tubing used for final packing (1.77%) and deionised water (1.59%).

FOL - Damage to Human health

The major contributor from FOL to human health damage is the photolithography (53.5%) processes followed by Protec and pre-assembly processes. Energy consumption of the machines is again the highest contributing factor followed by SAW wafer (29%). The contribution from deionised water is a combined total of 14.9% of the impact.

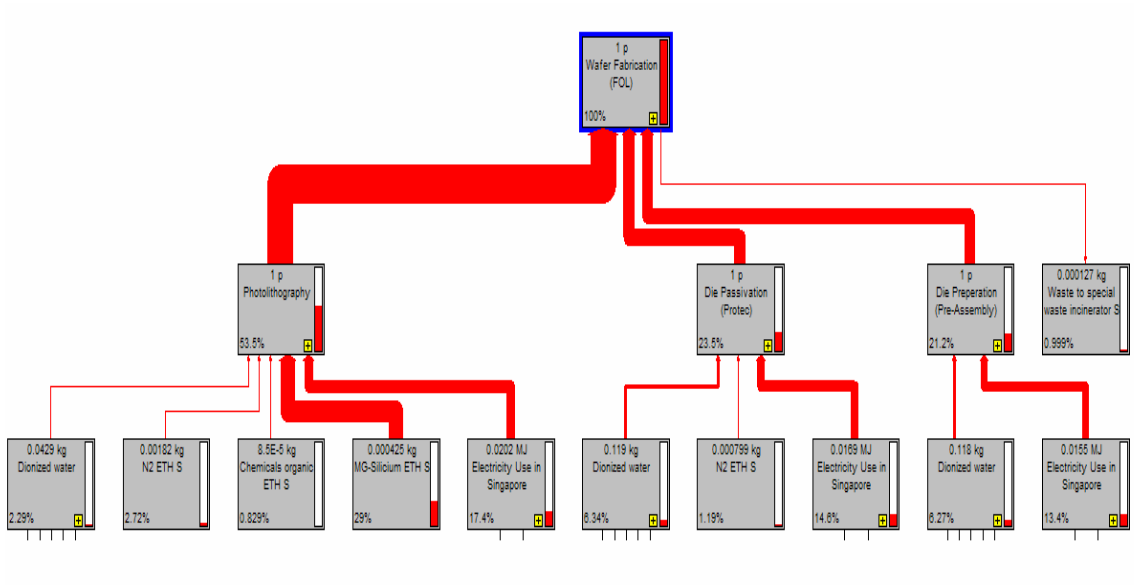


Figure 6.16: Network showing human health damage assessment (EOL)

6.5.2.1 Impact Category – Respiratory inorganics

Damage category respiratory inorganics refers to the microscopic inorganic airborne particles that can travel into human lungs and cause a variety of respiratory problems. Particulates such as nitrogen dioxide and sulphur dioxide are some of the major threats.

Some of the biggest sources of particulates in the air are caused by combustion sources such as burning of fossil fuels and industrial sources such as melting of copper (Copper smelting 1998). This explains the high contributions related to electricity from oil (36.9%) and copper leadframes (32.1%) shown in the network below in figure 6.17.

Other major contributors include SAW wafer (6.61%), nitrogen (1.15%) and inert waste to incinerator (0.32%). Overall, about two-thirds of the respiratory inorganics originate from the manufacturing line. The contribution from EOL processes accounts for almost half of the total respiratory inorganics (48.8 %).

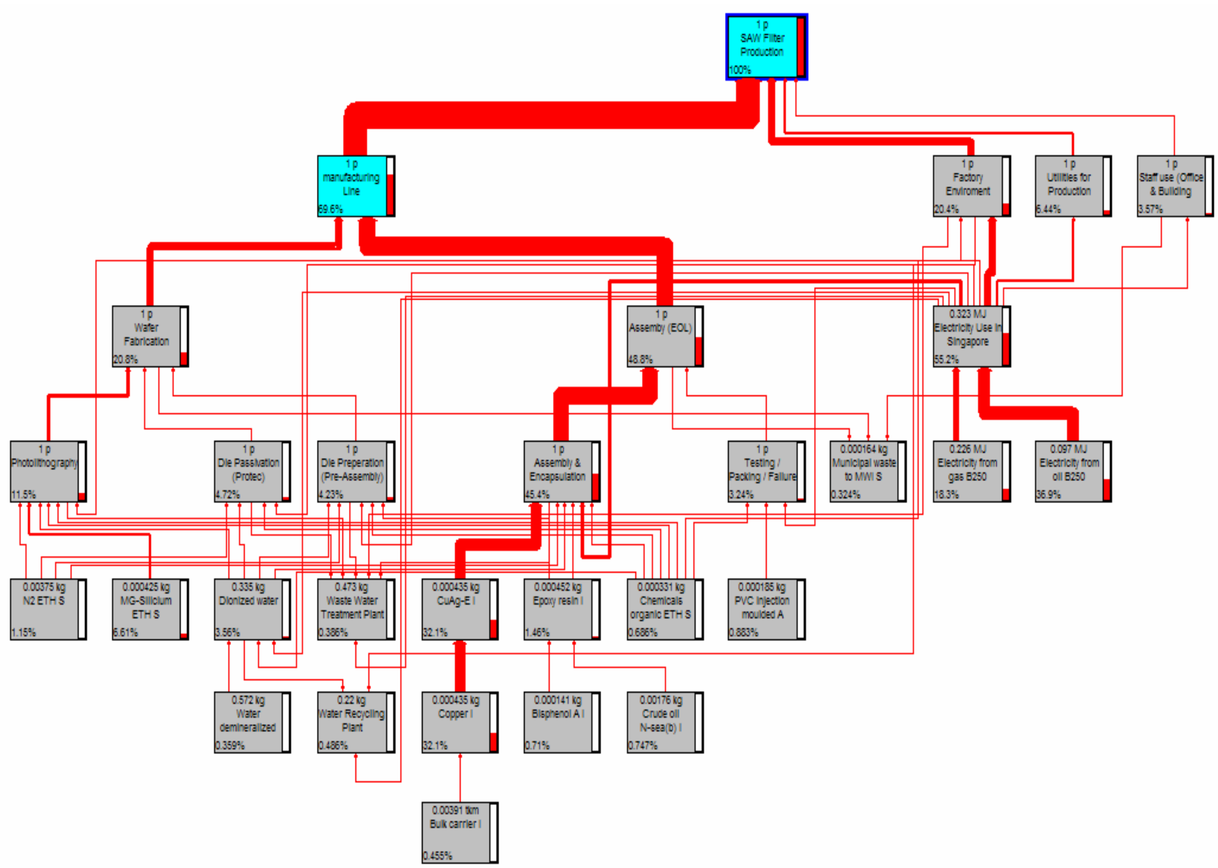


Figure 6.17: Network analysis of impact category - Respiratory inorganics

EOL – Respiratory inorganics

Figure 6.18 shows the characterized results of EOL. The major contributor to the impact is quite clearly the copper leadframe (65.8%) used in assembly. The next highest contributor is the electricity consumption of the production machines followed by encapsulation and packaging materials.

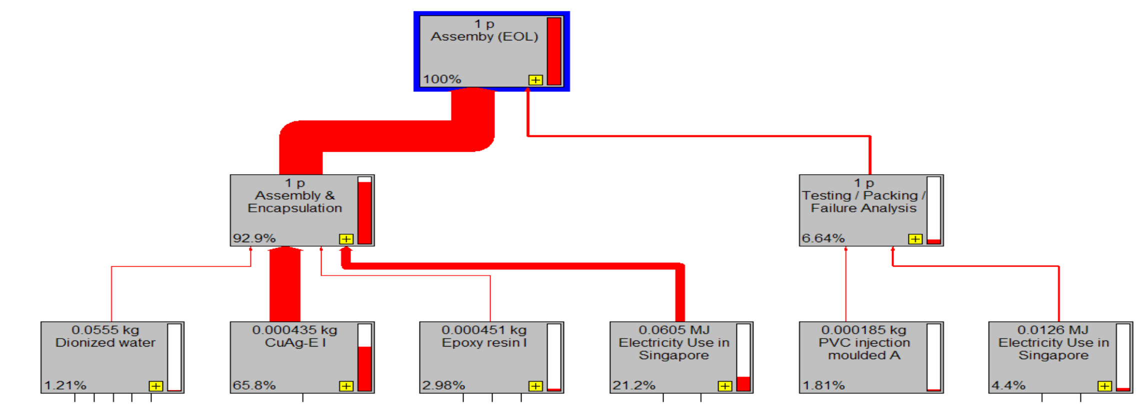


Figure 6.18: Network showing contributions to respiratory inorganics (EOL)

FOL – Respiratory inorganics

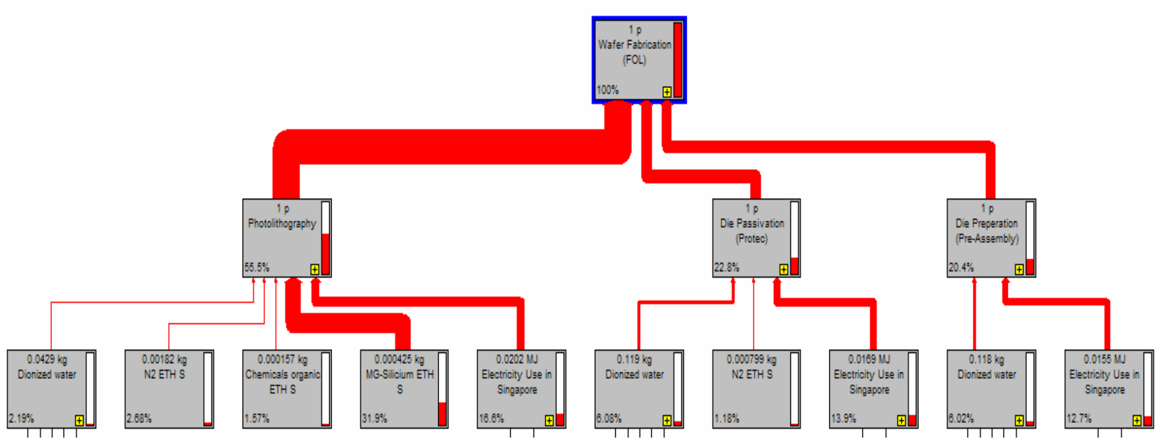


Figure 6.19: Network showing contributions to respiratory inorganics (FOL)

Energy consumption of the production machines is the highest contributor from FOL followed closely by the SAW wafer. The total contribution from all the deionised water used in the FOL processes is 14.29% of the total contribution while nitrogen and organic chemicals each contribute 2.68% and 1.57% respectively.

6.5.2.2 Impact Category – Climate change

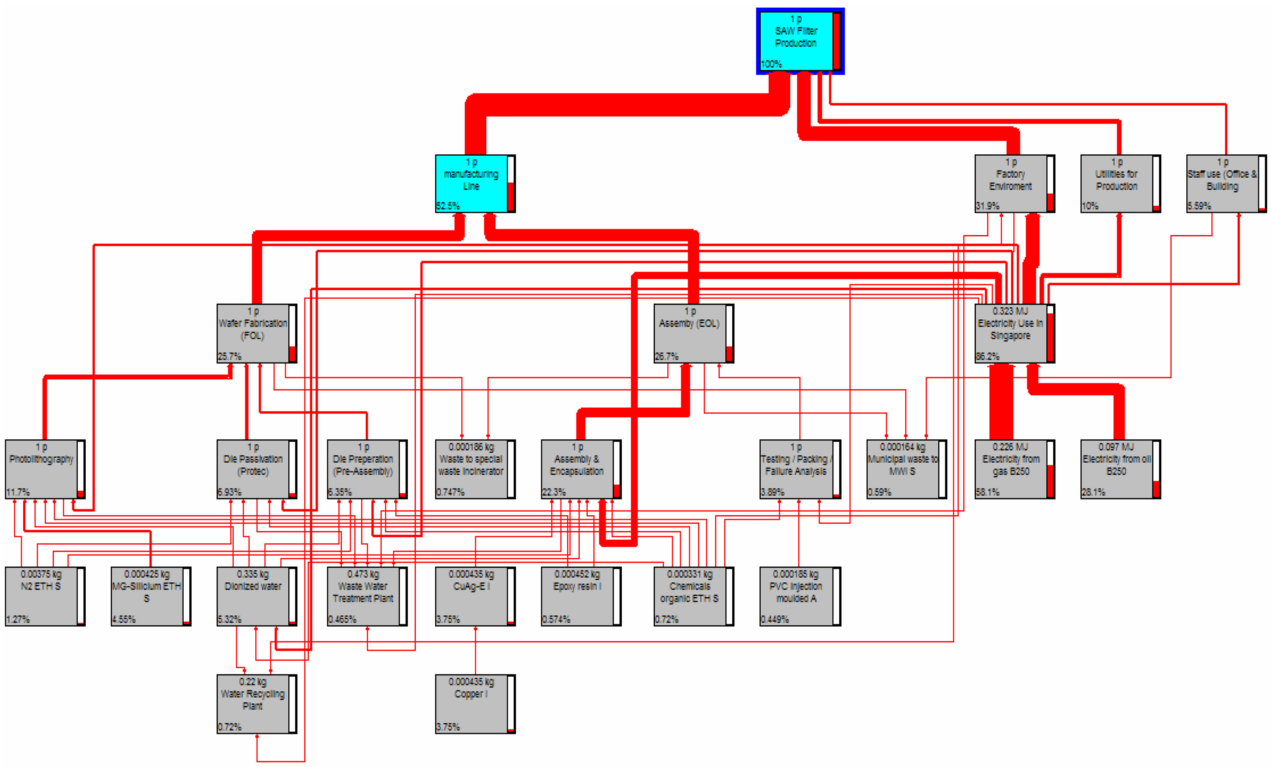


Figure 6.20: Network analysis of impact category - Climate change

The impact score for climate change is 7.37E-8 DALY. This impact category, otherwise known as global warming refers to change in earth's temperature due to the emission of greenhouse gases (Pennington, Norris, Hoagland & Bare 2000). The electricity consumed during the manufacture of a SAW filter is the largest contributor to the climate change with 86.2% out of total impact score (see figure 6.20). This is largely due to the combustion of fossil fuels that emits a high amount of greenhouse gases such carbon dioxide.

The second highest contribution comes from the production of silicon (4.55%), followed by production of copper leadframes (3.75%) and nitrogen (1.27%). Waste send to incinerators, both inert and hazardous contribute only in small percentages of 0.747% and 0.59% respectively to climate change. Overall, the contribution from the manufacturing line is just about the half of the total impact score because of the high energy consumption of the facilities modules.

EOL - Climate change

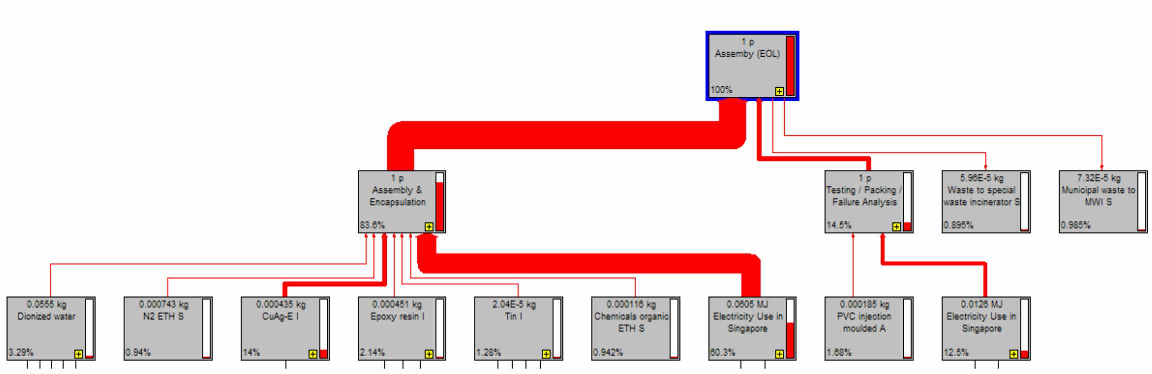


Figure 6.21: Network showing contributions to climate change (EOL)

The climate change score for EOL is 3.12E-9 DALY. Of this, 83.6% of the contributions are related to assembly and encapsulation. Overall, consumption of energy is the highest contributor to climate change from EOL (60.3%) followed by copper leadframe (14%) and deionised water (3.29%).

FOL - Climate change

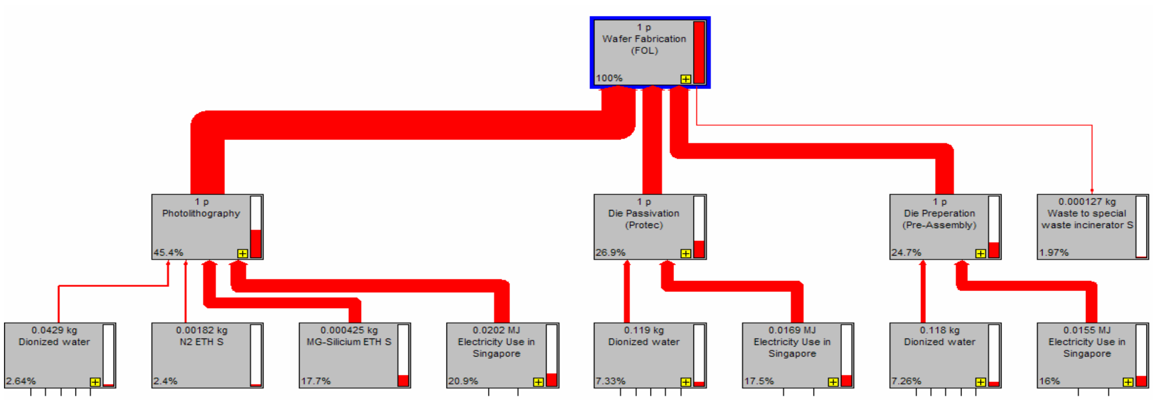


Figure 6.22: Network showing contributions to climate change (FOL)

From FOL production, almost half of the contributions to climate change can be linked to photolithography (45.4%) processes. The rest of the load is shared almost equally by pre-assembly and wafer passivation processes. Hazardous waste sent to special waste incinerator contributes about 2% to the impacts associated with FOL. Other major contributors to climate change include SAW wafer (17.7%) and DI water (17.3%).

6.5.3 Damage to Ecosystem Quality

The ecosystem quality damage score related to SAW filter production is 0.00418 PDF* m^2 *yr. The ecosystem damage assessment network shown below in figure 6.23 indicates that the energy consumption is again the major contributor to this end-point category. Copper leadframe is the next highest contributor (18.7%) followed by SAW wafer (8.3%), melamine formaldehyde (6.21%) and deionised water (4.04%).

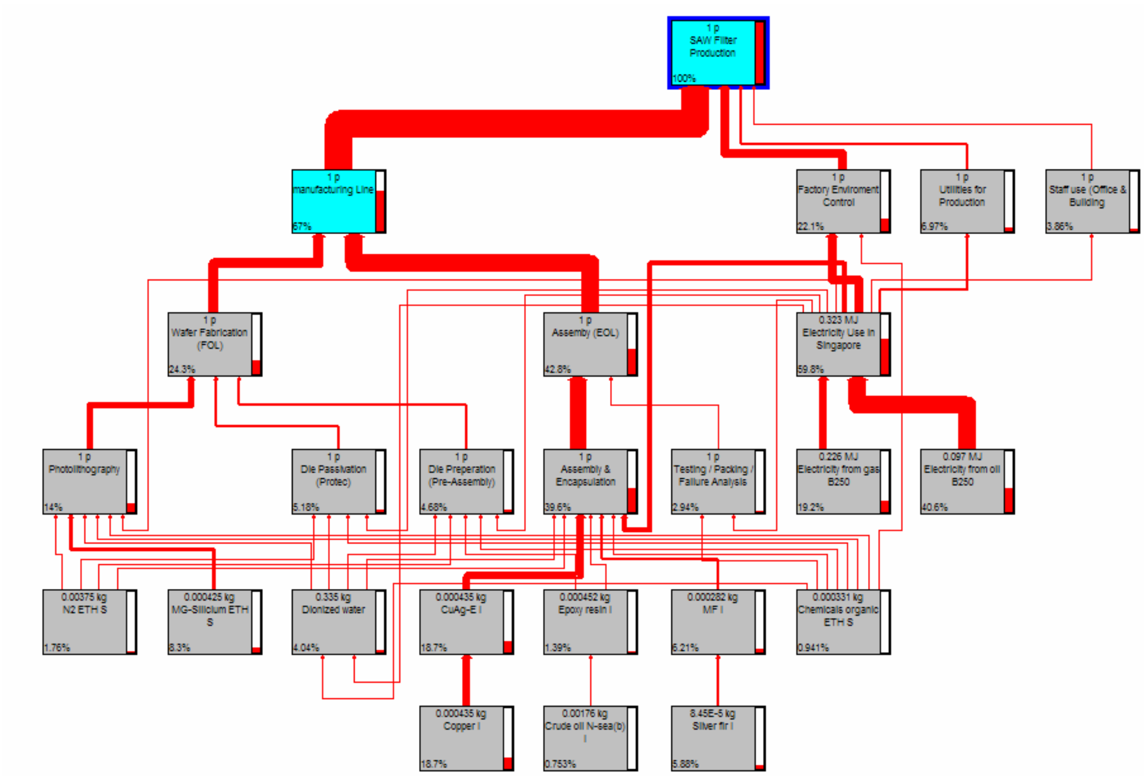


Figure 6.23: Network analysis of damage category - Ecosystem quality

Overall, the main contributions to Ecosystem damage comes from the manufacturing line (67%). The rest of the contribution comes from facilities modules (factory Environment control and utilities for production – 29%) and staff use (3.86%). Of the impacts associated with the manufacturing line, 42.8% is linked to end-of-line (EOL) production.

EOL - Ecosystem Quality

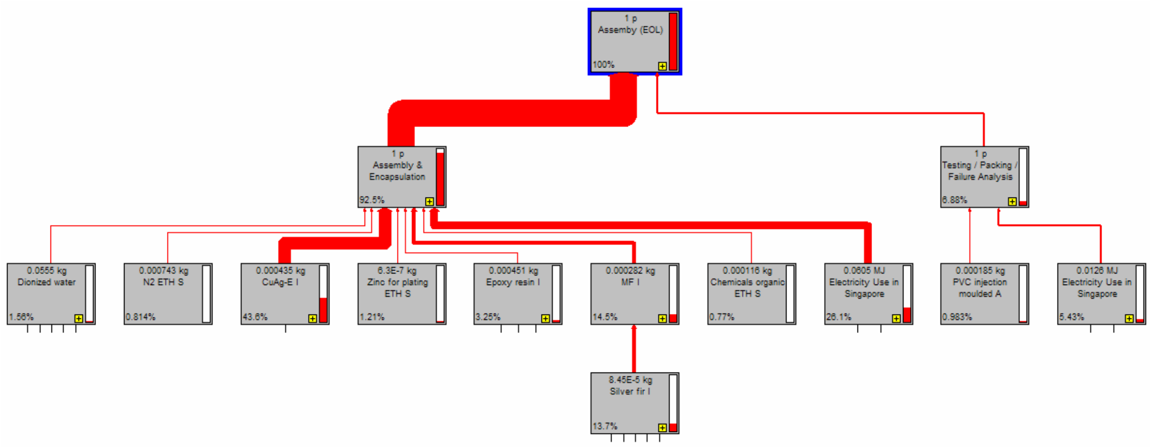


Figure 6.24: Network showing contributions to ecosystem Quality (EOL)

For EOL, over 90% of the contributions come from assembly/encapsulation processes. The highest contributor to ecosystem quality is the copper leadframe. Other than the energy consumption of the production machines, melamine Formaldehyde used for deflashing process is the next highest contributor with 14.5% share of the impacts.

FOL - Ecosystem Quality

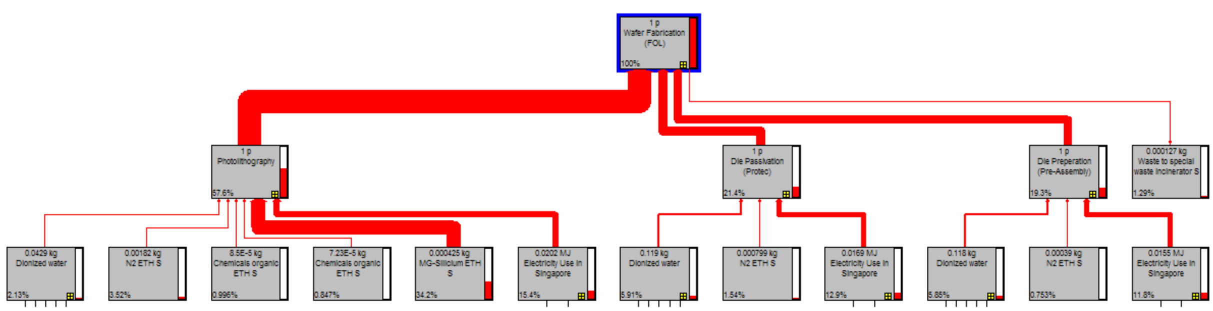


Figure 6.25: Network showing contributions to ecosystem quality (FOL)

From FOL production, more than half of the total contribution originates from photolithography. This is mainly due to the high impact caused by the SAW wafer (34.2%). Overall, the energy and deionised water consumption of the FOL amounts for a share of 35.1% and 11.38% of the ecosystem quality impacts linked to FOL respectively.

6.5.3.1 Impact Category – Acidification/Eutrophication

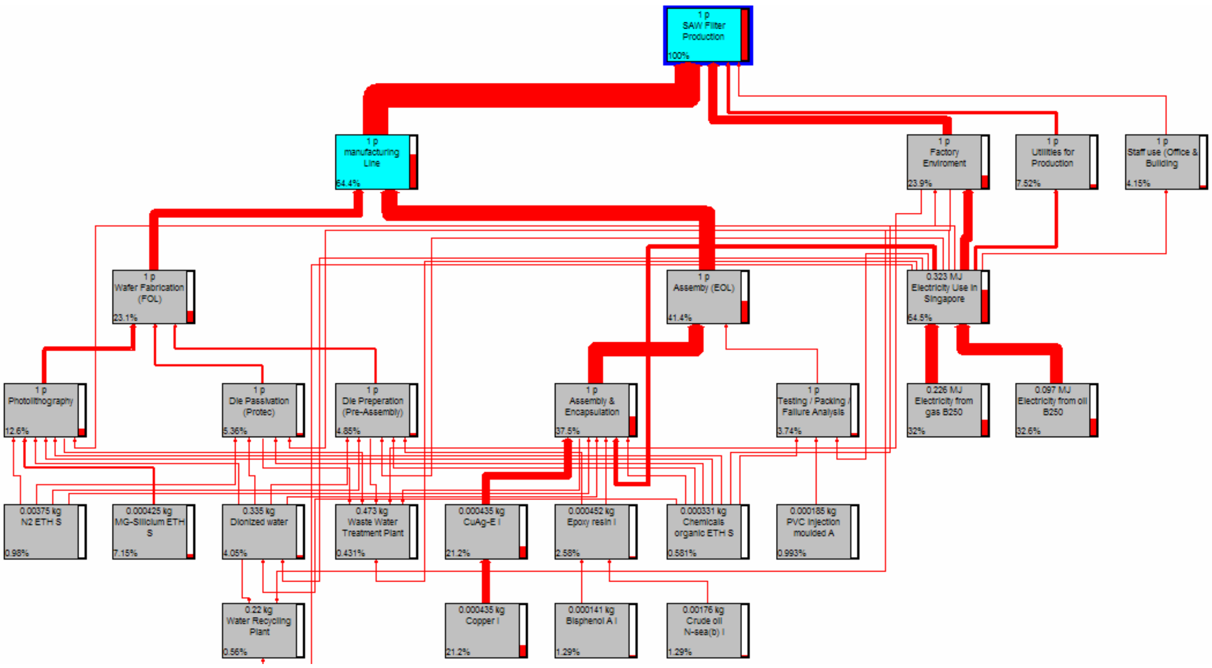


Figure 6.26: Network analysis of impact category - Acidification/Eutrophication

From figure 6.26, the energy consumption during the production of a SAW filter is the largest contributor to acidification/eutrophication (64.5%). Acidification/eutrophication occurs when gaseous pollutants are emitted to the atmosphere. Examples of gaseous pollutants include sulphur dioxide, nitrogen oxides, ammonia and solvents that are commonly used in industries (Cofala et al. 2000). Fuel combustion is one of the major sources of sulphur dioxide and nitrogen oxides. Smelting of copper emits large quantities of sulphur oxide in to the atmosphere (Copper smelting 1998). This explains the significant contribution to acidification/eutrophication from copper leadframe, presumably linked to its production (21.2%).

The next highest contributor is the SAW wafer (note that silicon wafer was used for analysis). This is mainly because the production of silicon also releases some sulphur oxide pollutants into the atmosphere. Other notable contributions come from thermoset plastic (2.58%) used for molding and diebonding (epoxy resin), nitrogen use (0.98%), and organic chemicals (0.58%). Overall, the manufacturing line accounts for 64.4% of acidification/eutrophication damage.

EOL - Acidification/Eutrophication

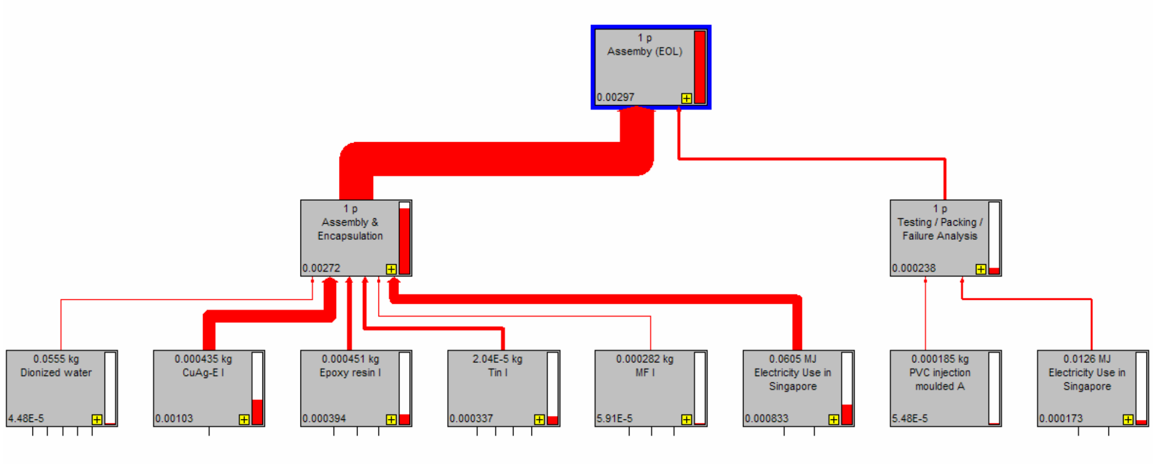


Figure 6.27: Network showing contributions to acidification/eutrophication (EOL)

From EOL production processes, the main contribution to acidification/eutrophication comes from the copper leadframes. The next highest contributors are the energy consumption of the machines followed by thermoset plastic (epoxy resin) used for encapsulation of the filter.

FOL - Acidification/Eutrophication

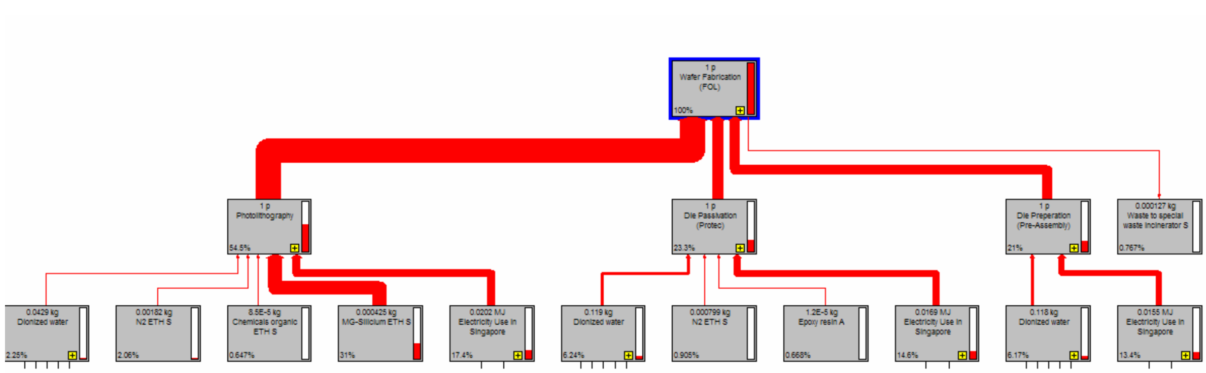


Figure 6.28: Network showing contributions to acidification/eutrophication (EOL)

More than half of the Acidification/Eutrophication impact from FOL production is linked to photolithography, where the SAW wafer the major contributor. Overall though, the major contribution comes from the energy consumption of the machines of the FOL machines.

6.5.3.2 Impact Category – Ecotoxicity

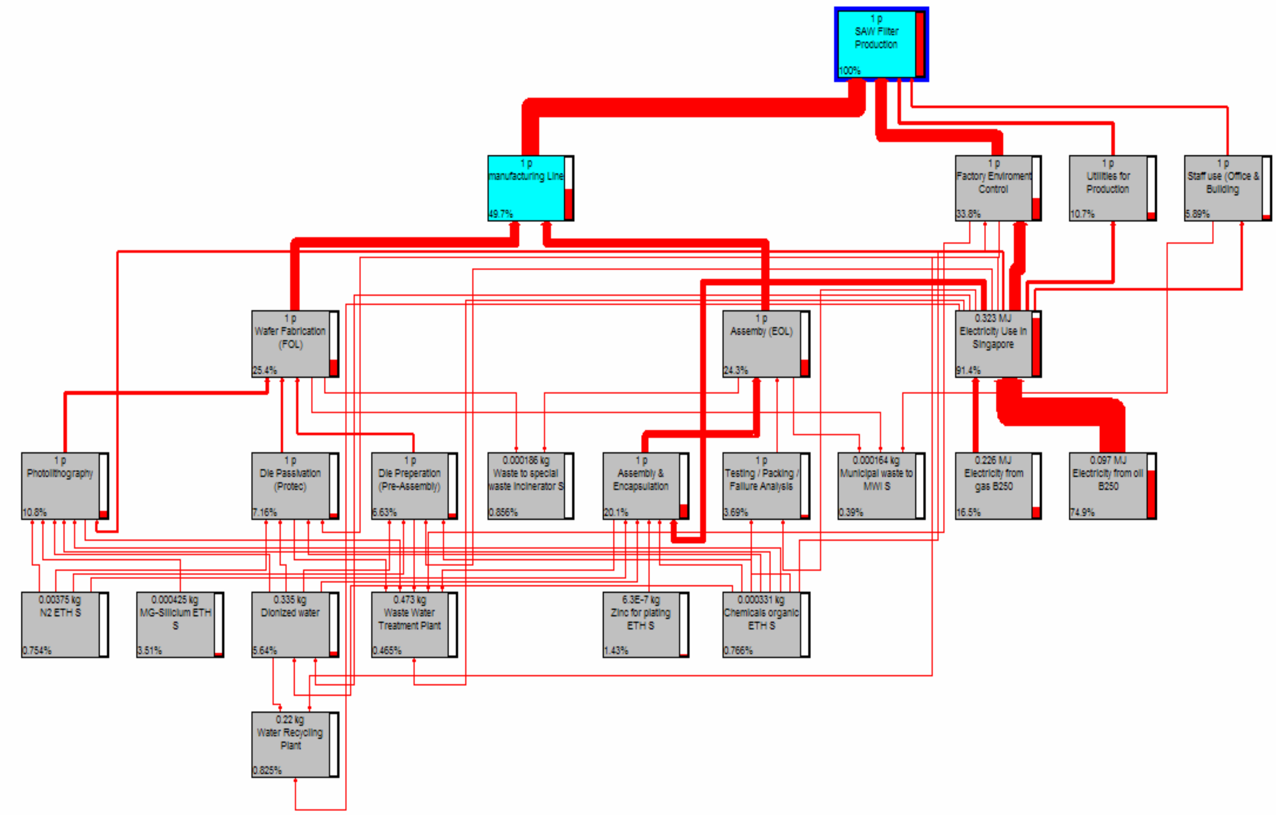


Figure 6.29: Network analysis of impact category - Ecotoxicity

Some the major causes of ecotoxicity include the release of organic pollutants with waste water, release of metals, emission of oil from oil extraction and atmospheric disposition of metals and dioxins (Danish Environmental Protection Agency 2005). In comparison with other metals, Zinc is one of the largest contributors to ecotoxicity.

These facts can clearly be seen from the figure 6.29, the electricity consumption accounts for 91.4% of the ecotoxicity. 74.2% of this comes specifically from electricity from oil, even though only 30% of the overall electricity generation is from oil. The amount of zinc (in weight) used for the plating of the leadframes is less than 0.001% of total inventory data, but a disproportional impact can be seen. The contribution related to zinc used for plating is 1.43%. Waste send to incinerators, both inert and hazardous contribute about 0.85% and 0.4% to ecotoxicity respectively.

EOL - Ecotoxicity

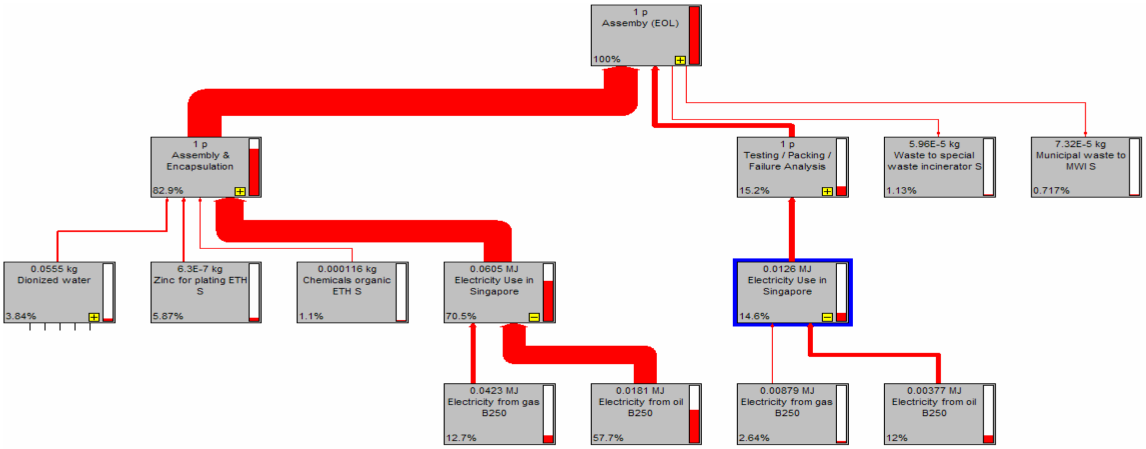


Figure 6.30: Network showing contributions to ecotoxicity (EOL)

From figure 6.29, it can be seen that EOL of the manufacturing accounts for roughly one quarter of the ecotoxicity impacts related to SAW filter production. Out of this one quarter, 82.9% impacts are linked to the assembly and encapsulation processes. One the whole, the major contributor from EOL is the energy consumption of the production machines. The next highest contribution comes from zinc that is used for the plating of the copper leadframes and deionised water.

FOL - Ecotoxicity

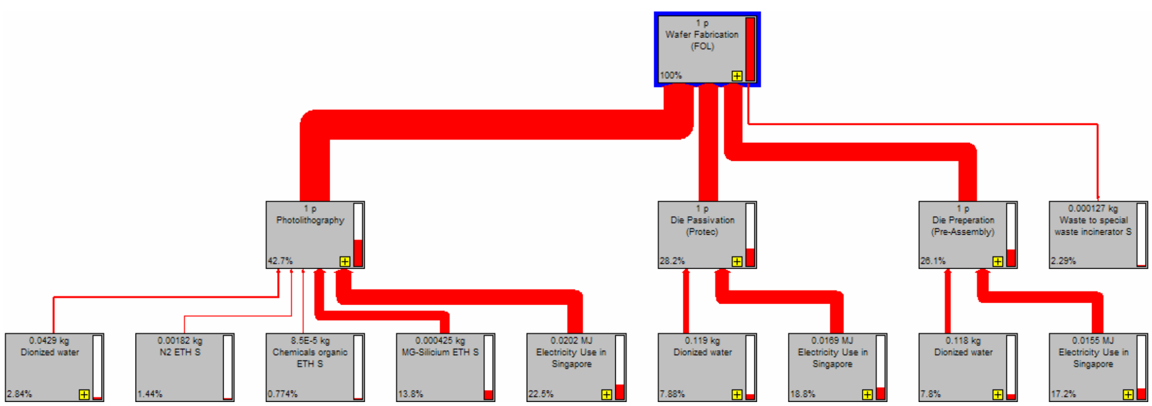


Figure 6.31: Network showing contributions to ecotoxicity (FOL)

From FOL, the major contribution again comes from photolithography process. Overall energy consumption is the major contributor followed by the deionised water (18.4%), SAW wafer (13.8%) and hazardous waste send to incinerator.

6.5.3.3 Impact Category –Land use

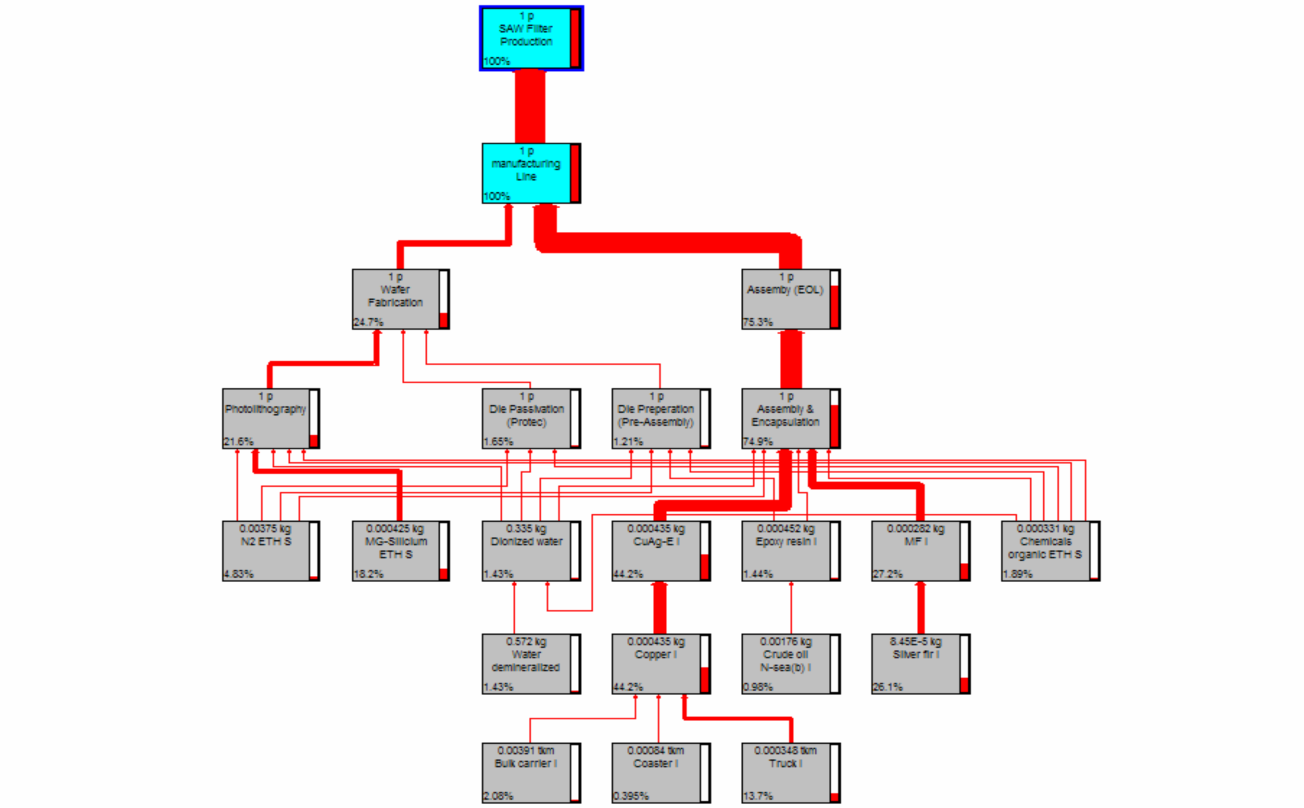


Figure 6.32: Network showing contributions to impact category - Land use

Land use is an impact category that is difficult to comprehend. Land use could be interpreted as a decrease in biodiversity and the possible impairment of life support systems due to use of land by man. Some of the major causes of land use include mining and loss of forest. All the land use impacts associated with the SAW filter comes from the manufacturing line (figure 6.16). The main contributor is copper (44.2%) followed by melamine formaldehyde used for the deflashing process. The contribution related to copper is most probably linked to the mining of copper ore.

The same reasoning can be extended to the high contribution (18.2%) from silicon chip. The deflashing media blast, melamine formaldehyde is an engineered wood that is made from silver fir wood and hence can be seen as contributing to forest loss. Other notable contribution to land use includes nitrogen (4.83%), organic chemicals (1.89%) and epoxy resin (1.44).

6.6 Conclusions and Analysis of LCIA Results

This section draws conclusions regarding the impact assessment using the results obtained from the previous section. At the same time it also analyses the results for the reliability and accuracy. It should be noted that the single score (aggregation of weighted impacted category scores) charts used in this section are not used as basis for drawing conclusion on this LCIA, but rather used to substantiate the analysis and the findings from the previous the section.

From the analysis, it was clearly seen that the highest contributing factors to the environmental burdens associated with a SAW filter is linked to the high energy consumption of production machines and facilities modules.

Taking an overall picture, it was seen that on average about two-thirds of the impacts are linked to the manufacturing line (for almost all of the impact categories). The rest of the impacts are linked to facilities modules with a small percentage share linked to staff and office use (~ 5%). The weighted single score chart of the SAW production shown below backs the reasonings made.

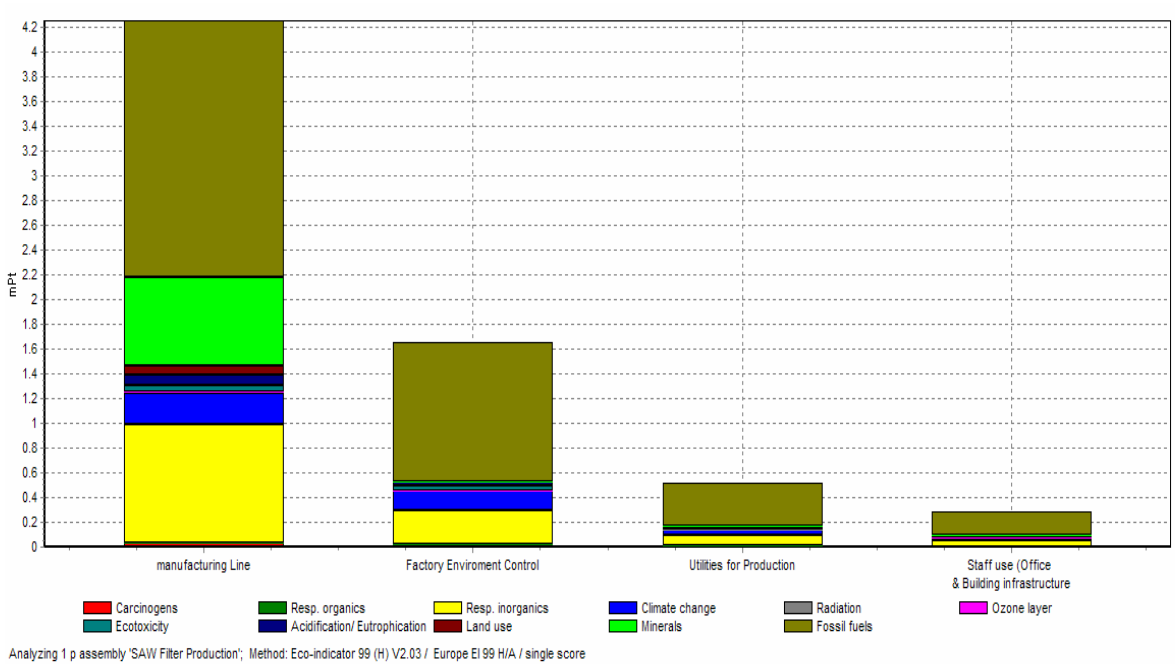


Figure 6.33: Single score results for the SAW filter production

The manufacturing Line

Majority of the environmental impacts from the manufacturing line are linked to the End of Line (EOL) production. It was seen that the highest contribution is again linked to the energy consumption of the production machines. Shown in figure 6.34 on below is the single score result for the manufacturing line.

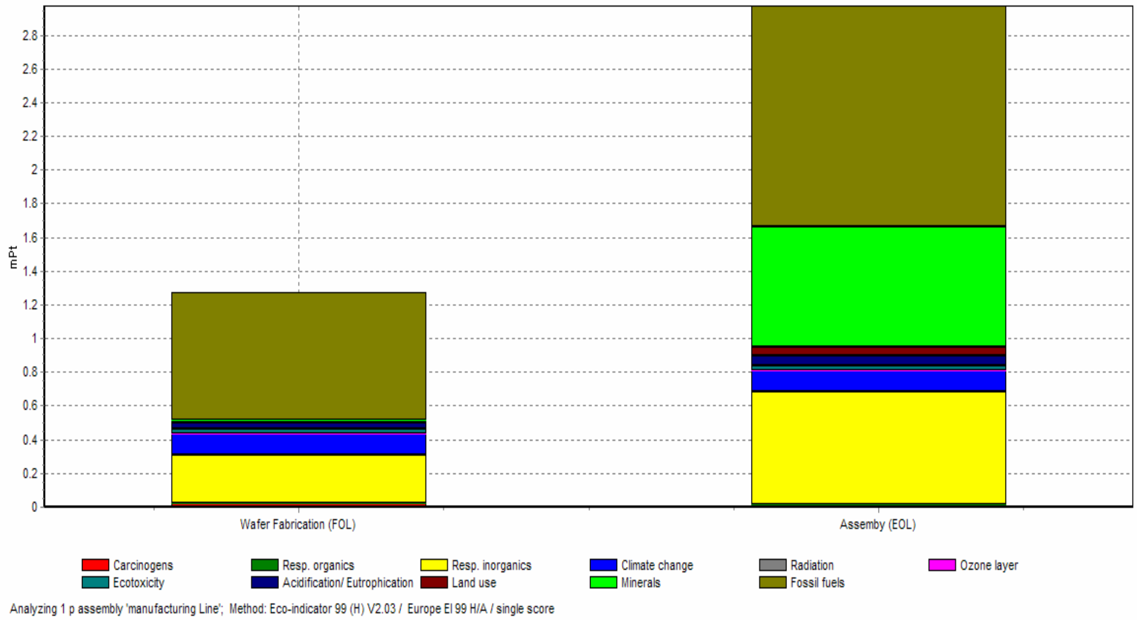


Figure 6.34: Single score results for the SAW filter manufacturing line

For environmental impacts related to EOL, on average almost 90% of the contributions originate from the assembly and encapsulation production area. The highest contributors from the assembly/encapsulation area are the copper leadframe and energy consumption of the production machines. From the LCIA results in the previous chapter, it was noted that copper contributes significantly to impact categories respiratory inorganics and mineral depletion.

Other notable contributors include the thermoset plastic (epoxy resin) used for encapsulation of the chip and diebonding purposes, tin based solder used for tinning of SAW filters leads, melamine formaldehyde used for deflashing media blast and the deionised water used in the deflashing process.

As for testing and packaging processes, the main contribution to the environmental load other than the energy consumption of the machines comes from the PVC tubes that are used as packing materials for finished SAW filters. Shown in figures 6.35 and 6.36 below are the single-score results for assembly/encapsulation and testing/packing processes respectively.

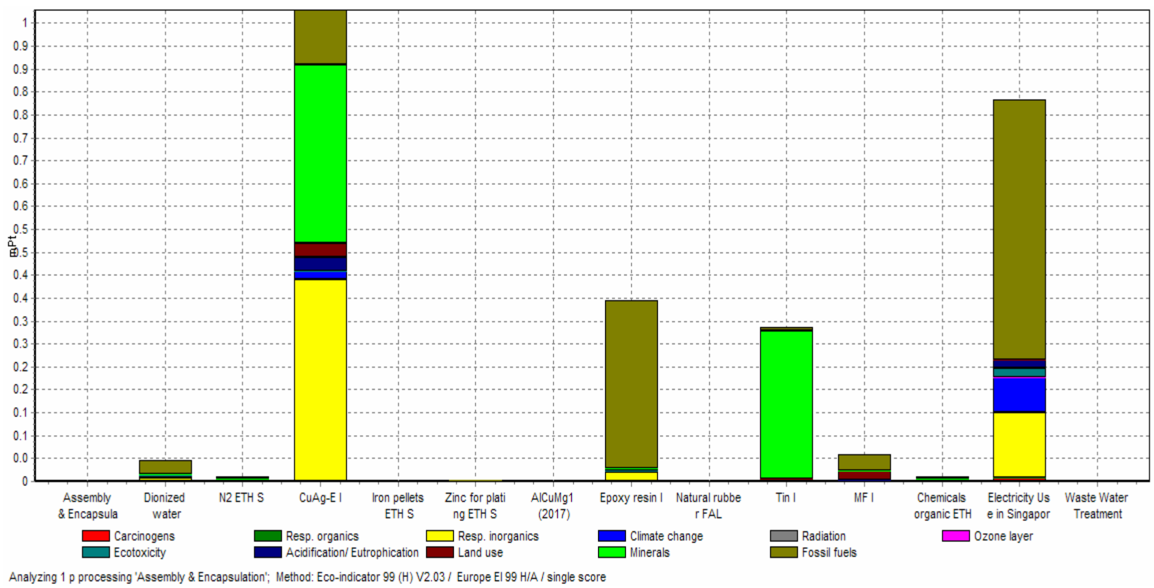


Figure 6.35: Single score results for the Assembly/Encapsulation processes

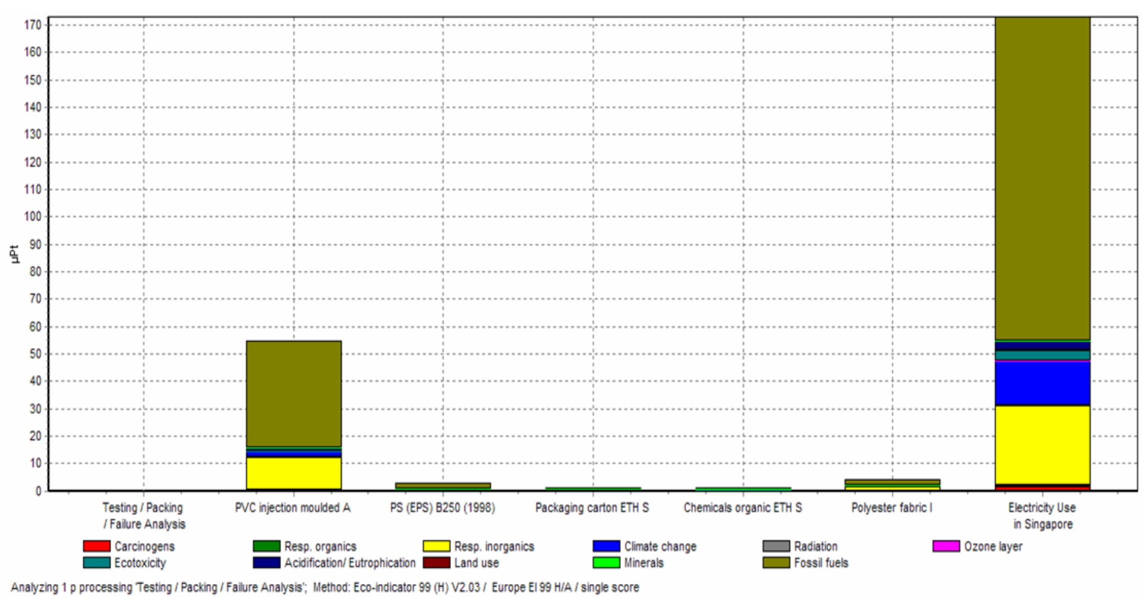


Figure 6.36: Single score results for the Testing/Packing processes

For FOL, quite predictably, the highest contributor is the energy consumption of the production machines. Photolithography processes are the main contributors to the environmental load. All impact categories analysed in the last chapter showed that photolithography processes are environmentally more culpable than pre-assembly and Protec processes. The main reason for this is the SAW wafer. Wafer contributes significantly to impact categories respiratory inorganics, fossil fuels, respiratory inorganics and land use.

The next highest contributor from FOL is the deionised water that is quite extensively used in all processes. On comparison, the impacts related to deionised water are more significant for Protec and pre-assembly processes than photolithography processes. The significance factor is directly opposite in the case of nitrogen, which is next highest contributing material. Shown below in 6.37 is the single score result for FOL.

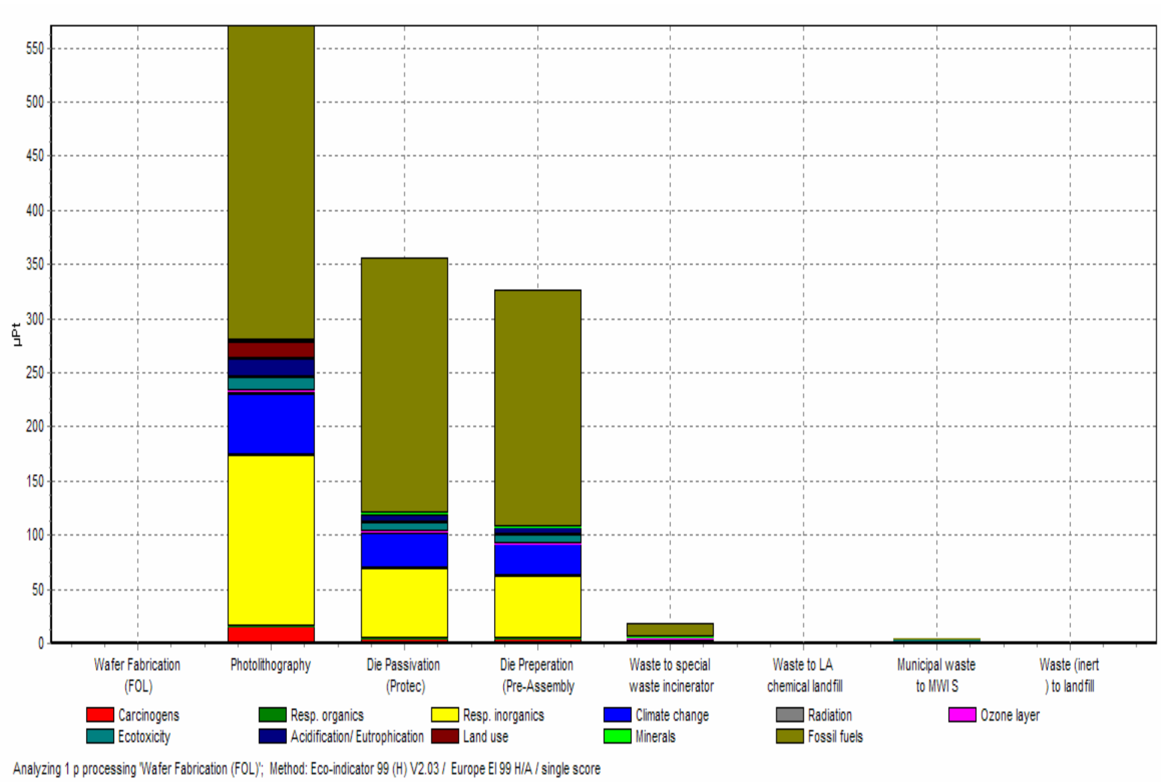


Figure 6.37: Single score results for the FOL processes

Facilities modules and staff/office use

From the results, it can be concluded that the environmental impact contribution from facilities modules is roughly about one-third of the total impacts associated with a SAW filter. The vast majority of the contribution within the facilities comes from the energy consumption of the heavy machineries used; chillers, air-compressors, fresh air make units, exhaust and so on. Quite expectedly, majority of the contribution is related to the factory environment control (HVAC system).

Overall it was seen that the chemicals and water consumption of the facilities modules are rarely highlighted in the results. This is because the environmental impacts associated with the energy requirements of these modules far outweigh the impacts from the other inputs.

Another interesting point that was noted during analysis is minute positive impacts made by the water recycling plant. The positive environmental impact made is extremely small in comparison to the overall negative impacts. The reason for this could be the geographical difference in the data used for the analysis. Had the recycling been modelled using local data (of course none was available!) the positive impacts made would have been much greater. In Singapore, water is definitely much more precious and expensive than in Europe because of the perpetual water shortage.

In the case of staff and office use, again the major contributing factor is the energy consumption.

Waste

Only the hazardous waste send to special incinerator contributes noticeably to the total impact score (contribution of 0.5%, on single score results).

Chapter 7 LIFE CYCLE INTERPRETATION

7.1 Introduction

Interpreting the results of a complex and detailed study such as a LCA is not simple because of the engineering estimates, assumptions, and other choices made during the course of the study. For LCAs to be used as a decision making tool, its results should be robust against these uncertainties and variables. Interpretation stage provides this robustness to a LCA study, as it scrutinises and analyses the results the obtained from the previous LCA stages and validates them. The other main objective of this stage is to formulate the conclusions drawn from a LCA study.

This chapter documents the final stage of this life cycle assessment study, 'Life Cycle Interpretation'. In the first section, some background information and the methodologies used in the interpretation stage are explored. Following that, life cycle interpretation steps done for this LCA are documented, beginning with the identification of significant issues in section two, the evaluation of LCIA results for completeness, sensitivity and consistency in section three and lastly, the conclusions and recommendations for this LCA.

7.2 Methodology

According to the International organisation for standardisation (ISO), 'life cycle interpretation stage is a systematic technique to identify, quantify, check and evaluate information from the life cycle inventory (LCI) and/or life cycle impact assessment (LCIA)' and communicate them effectively (Skone 2000). The objectives for the interpretation stage is defined in ISO document, ISO 14043 as to,

- Analyse results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA and to report the results of the life cycle interpretation in a transparent manner.

- Provide a readily understandable, complete and consistent presentation of the results of a LCA, in accordance with the goal and scope of the study (this explains the interconnectedness of the ISO's LCA framework shown in figure 2.2).

The interpretation stage can be divided into three major steps as shown in figure 7.1, which is an extension of the LCA framework diagram shown in chapter 2. The three major steps are,

- The identification of major/significant issues.

- Evaluation of the completeness, sensitivity and consistency of the data.

- Conclusion and recommendations.

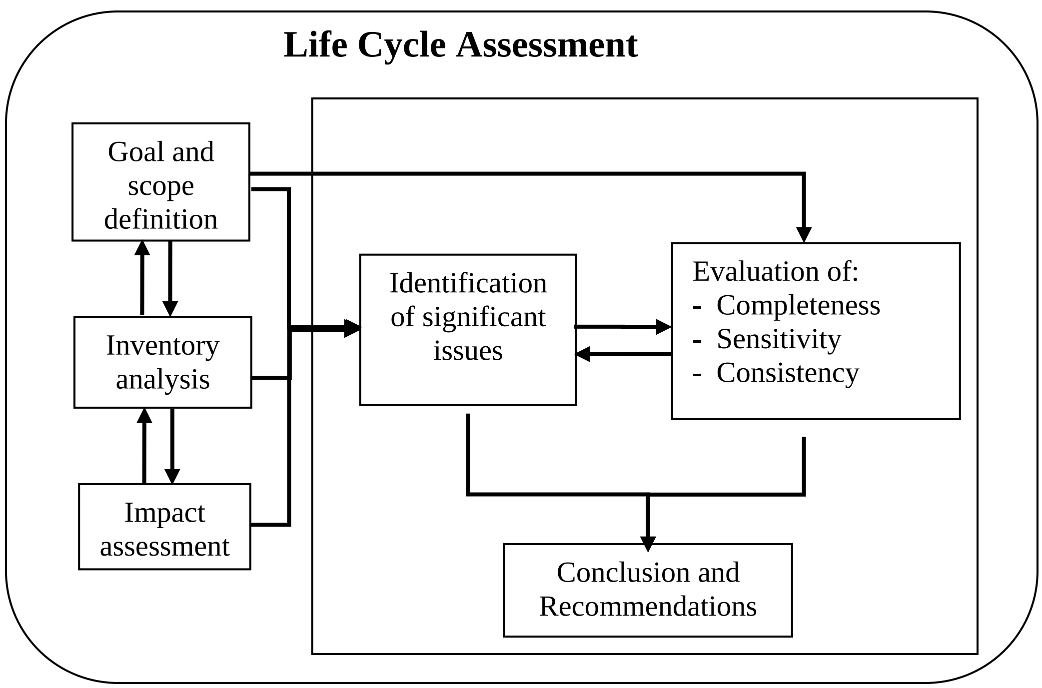


Figure 7.1: Relationship between interpretation and other stages (LCA101 2000, p. 26)

7.2.1 Identification of Significant Issues

The identification of significant issues involve the reviewing of information from which the critical processes/products and other ‘hotspots’ in a life cycle of a product can be identified. The review is usually based on all three previous stages which involves details such as the study goals, study scope, life cycle inventory, the weighing and allocation methodologies used (if any), the modelling of the product in a software, impact assessment methods used and finally the results obtained.

Some of ‘issues’ that could be identified include the inventory items (energy, water, chemical, raw material use etc), the impact categories used (Climate change, acidification, land use, etc), the individual processes and the life cycle stages involved (manufacturing, delivery to customer etc). Often in practice however, because the complexities involved in a LCA study, the significant issues are identified mainly based on the impact assessment scores. That is to say, the process or products that have the greatest influence on the impacts assessment results are identified for further analysis.

The very first step before the identification of the significant issues is to review the results of the LCIA in tandem with the goal and scope stage to check if the objectives set have been achieved. Once this step is accomplished, the following steps could be adopted to identify the significant issues (Skone 2000).

- Contribution analysis – whereby the magnitude of environmental impacts associated with life cycle stages, processes and the by-product used are compared to the total impacts associated with the product of the study.

- Anomaly assessments – evaluation of the results to check if any of the results shows any unusual or surprising trends. The results are usually compared to studies conducted on similar products.

- Dominance analysis – identification of significant issues using statistical methods or other tools such qualitative or quantitative rankings.

Another important data that could be identified is the disproportionalilty of the inventory data towards the final LCA results. In a LCA study, it is common that some of the inventory items are quantitatively insignificant but contribute rather significantly towards the final results and hence, it is important that the data regarding these items should be known most precisely. At the same time, data uncertainties in large quantity inventory items that contribute minimally to the environmental impacts can be tolerated.

7.2.2 Evaluation

The *evaluation* step of the interpretation stage analyses in detail the 'significant issues identified' to establish validity and credibility for the final results of a LCA. The following three major tasks are involved.

- Completeness check
- Sensitivity check
- Consistency check

The purpose of the *completeness check* is to ensure that all relevant information and data needed for the Interpretation phase is available and complete (Heijungs 2004). This is usually completed with the help of an independent LCA expert and technical expert/s.

LCA expert can examine the study for issues such as the methodologies adopted for the different phases, the software models created, the results and conclusion of the study. Other important issues such as the assumptions used, the process flows, inventory data and the mass flows can be analysed by technical experts who are familiar with the product's characteristics. Another easy way in which a completeness check can be conducted is by comparing the LCA to other studies done on similar products.

Sensitivity check is the stage in which the uncertainties and other expected variations in identified significant issues are evaluated to determine their sensitivity towards the final results of the LCA. The sensitivity check can be done using the following two techniques,

- Uncertainty analysis – determines the degree of expected variation in the significant issues relative to the originally calculated data in life cycle inventory (base data that was used for life cycle impact assessment).
- Sensitivity analysis – determines the effect of these variations on the final results of the study. Results are usually presented as a percentage variation from the original results or in comparative graphs.

The purpose of the *consistency check* is to determine if the assumptions, models, methods and data used in a LCA are in accordance to the goal and scope of the study. This check is of great importance in comparative LCAs, where a selective decision is based on results. Thus, the differences in issues such as data sources, data quality indicators, temporal and geographical representations have to be taken in to account to get a highly accurate result.

7.2.3 Conclusion and Recommendations

In this last step of the interpretation stage, the conclusions are drawn and recommendations are made based on the results of the previous stages of a LCA in combination with the information drawn from the interpretation stage. ISO defines this step as, “to draw conclusions and make recommendations for the intended audience of the LCA study”.

The conclusions presented should not only underline the major results of the study but should also include a discussion regarding the reliability and validation of these results. The inconsistencies, incompleteness and other errors, which have been found during the interpretation stage, should also be highlighted. A clear and concise conclusions and recommendations at the end of a LCA, increases the confidence of the audience in the final results of the study.

7.3 Identification of Significant Issues

The identification of significant issues for this LCA was carried out using two of the recommended steps that were discussed in the previous section, namely, the contribution analysis and the anomaly assessment. Because of the time limitation and the restrictions in the actual modelling of the SAW filter, the significant issues were identified mainly based on the magnitude of the impact assessment results. To begin with, the results of the LCIA were reviewed in tandem with goal and scope stage to make sure the results were in accordance with goal and scope of the study. Once this task was accomplished, contribution analysis and anomaly analysis were carried out.

7.3.1 Contribution Analysis

The first step in contribution analysis was to understand where impacts actually originated from, and then subsequently the magnitude of these impacts. In fact, a detailed contribution analysis for this LCA was already carried out in the previous chapter in section 6.5 'Analysis of LCIA results'. As such, the results presented here with the aid of pie-charts, complements the results from chapter 6.

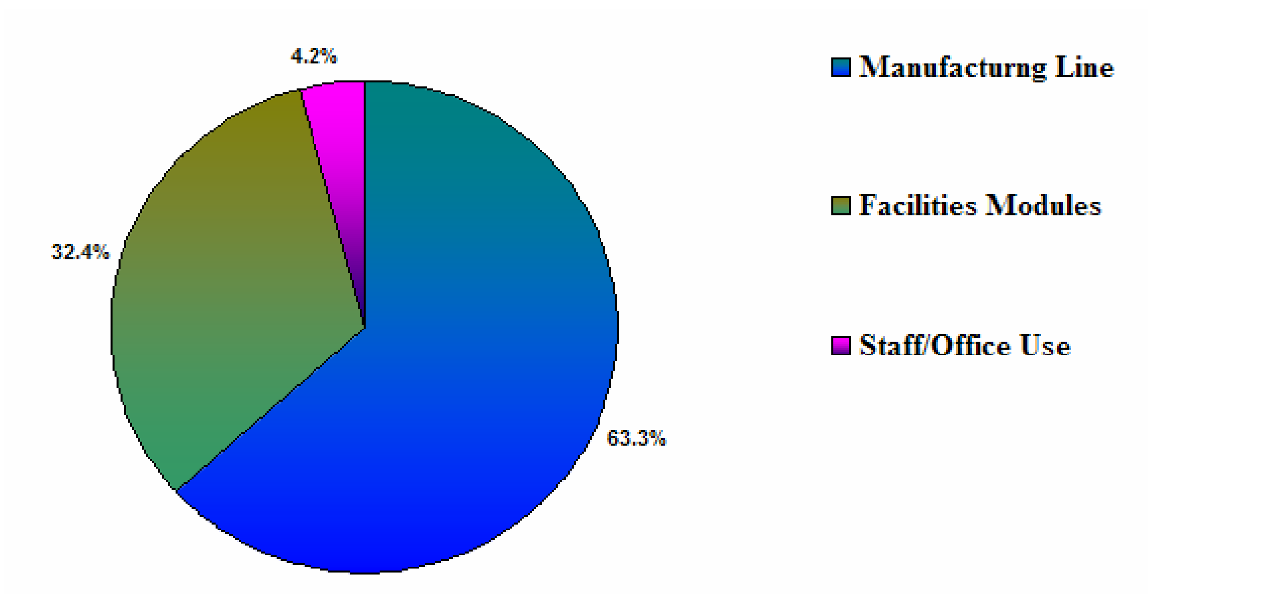


Figure 7.2: Pie-chart showing single score results for the SAW filter production

To reiterate the magnitude of contributions from the cluster identified for SAW filter production, a pie-chart based on single score for environmental impacts was plotted as shown in figure 7.2. It can be seen that almost three quarters of the total impacts are related to manufacturing line. The contributions from facilities modules account for about 32%.

The next step was to conduct a contribution analysis for the life cycle inventory. Ideally, this could have been done with outputs from the Simapro, but in this case because of the modelling restrictions it was not possible. Hence, a network diagram showing the single score results was used to gather the contribution data and then this data was manually keyed in to an excel spreadsheet to produce the pie chart shown below.

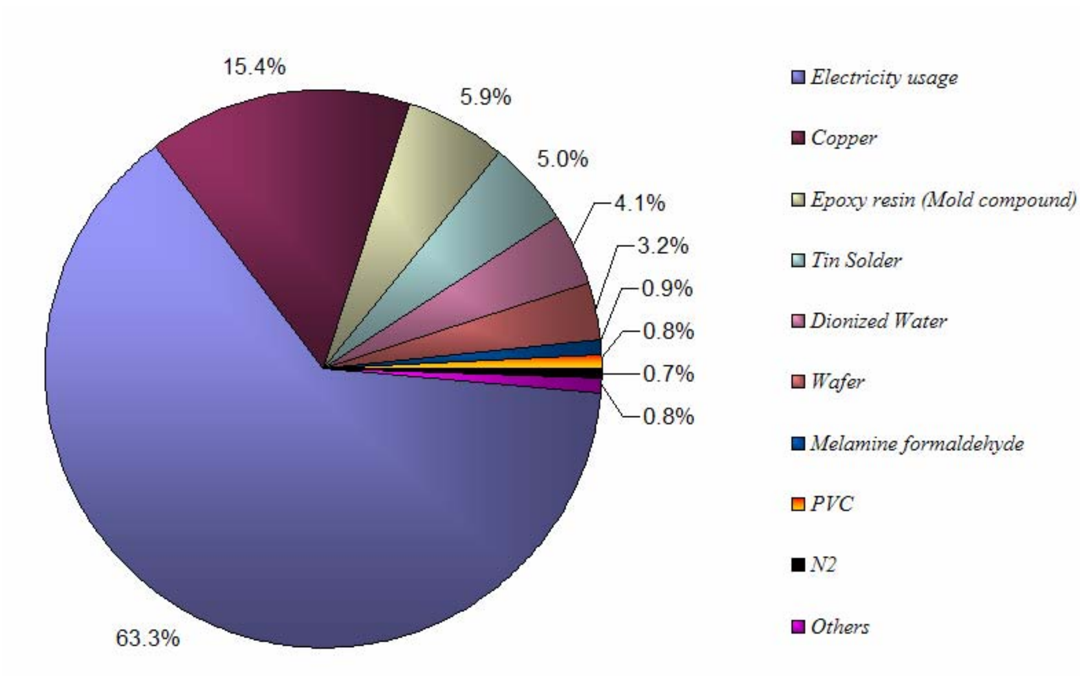


Figure 7.3: Contribution analysis of inventory data (Single score results)

From the pie-chart it can be seen that only a handful of items from over a hundred items from the inventory list that was complied, actually contribute significantly to the final environmental impact score. The results shown here confirm the fact that highest contribution to total environmental score comes from energy consumption.

The second highest contributor is the copper leadframe used (15.4%) followed by sizeable contribution from the mold compound that is used for filter encapsulation(5.9%), tin solder that used for the tinning of filter's leads (5%) and deionised water that is used extensively in FOL production (4.1%) and the wafer used (3.2 %). The combined contribution from the other numerous inventory items accounts for a mere 2.7%.

Checking for the disproportionalilty of contribution from the pie-chart, an item can be identified at once. Tin solder, which weighs about less than half a percentage of the total inventory weight, actually contributes about 5% of the impacts. Another significant item that could be identified is the PVC tubing used for the packing of the final product. This item was identified as it is not an absolute necessity in the actual production process of a SAW filter compared to other inventory items such as energy, water or chemical usage and hence, it could provide an avenue for improvement in future. Overall the inventory items that have been highlighted here were identified as significant issues and these items will be further evaluated in the following sections.

7.3.2 Anomaly Assessment

The easiest way to conduct an anomaly assessment is to compare the results obtained to other studies that have been conducted on similar products. This meant comparing the results of this LCA to other LCAs conducted on similar microelectronic products. Three such LCAs were reviewed in chapter 2 section 8, "Life Cycle Assessments and Microelectronics Industry". Using these literatures as a basis for comparison, two anomaly assessments were conducted.

The first assessment was carried out to assess the reliability and accuracy of the inventory data collected. Some of the important data from the life cycle inventory stage of this LCA study were compared to the study on energy and material use in the production of the microelectronic devices by Williams, Ayres & Heller (2001). This study was chosen for the comparison mainly because of its detailed approach to documenting the life cycle inventory data.

Table 7.2 on the next page shows the comparison between energy, water, gas and chemical consumptions calculated for a SAW filter and those calculated by Williams et al for a 32 DRAM chip.

Here, it should be noted that, all the data have been converted to a common unit, $1\,cm^2$ of input wafer. This was necessary not only for the ease of comparisons but also because Williams et al used $1\,cm^2$ of input wafer as the functional unit for most of the data collection. The inventory data for $1\,cm^2$ of input wafer represents the data for a device that has an encapsulated chip (wafer) that is $1\,cm^2$ in surface area. The calculation details and the results are illustrated in the table 7.1 and 7.2 respectively.

Inventory data	Single SAW Filter (0.2163 Cm2)					1 Cm2 of SAW (Total)	U.O.M
	FOL	EOL	Facilities	Staff use	Total		
Electricty Usage	0.0144	0.0191	0.0464	0.0057	**0.086**	**0.40**	KWh
Water Usage	0.2015	0.1397	0.0800	0.0370	**0.458**	**2.12**	liters
Elemental Gas Usage	3.1201	0.7430	0.0000	0.0000	**3.863**	**17.86**	grams
Chemical Usage	0.2920	0.1428	0.0454	0.0000	**0.480**	**2.22**	grams

Table 7.1: Calculation of inventory data of a SAW filter for anomaly assessment

From the table 7.1, the second to sixth columns show the total inventory data collected across the manufacturing clusters, for a single SAW filter (see chapter 5). The total data for a single SAW filter is then converted in to 1 cm^2 of input SAW wafer in the next column. The last column shows the unit of measurement. The calculated data from this table is then compared to a DRAM device in table 7.2.

Inventory data	Single SAW filter (0.2163 cm2)	1 cm2 of SAW filter	1 cm2 of DRAM chip	U.O.M
Electricty Usage	0.086	**0.40**	**1.92**	KWh
Water Usage	0.458	**2.12**	**20 - 22**	liters
Elemental Gas Usage	3.863	**17.86**	**437.50**	grams
Chemical Usage	0.435	**2.01**	**45.00**	grams

Table 7.2: Comparison between LCI for a SAW filter and DRAM chip

It can be seen from table 7.2, that the data calculated for a SAW filter pales very much in comparison to a DRAM chip. The reason for this can be understood if one takes a detailed look at the processing steps involved in the manufacturing of these two devices.

The manufacturing processes or rather specifically, the wafer fabrication of a DRAM chip is much more complex in comparison to that of a SAW filter. The wafer fabrication for an active microelectronic product such a DRAM device involves many patterned layers of circuitry and insulations build one on top of the other. Hence, the wafer fabrication processes for these devices are very repetitive. Fifteen to twenty-five layered devices are quite common in the market today (Murphy et al. 2003, p. 3). In comparison, it can be seen from chapter 4 that wafer fabrication process for a SAW filter is a simple single layered process.

This explains the reason why the inventories collected for a SAW filter pales in comparison to the inventories calculated for a DRAM device. To substantiate this point and to check the reliability of the data collected, a hypothetical inventory of a SAW filter with twenty-five layers of circuitry was then calculated and compared to a DRAM device. The calculation steps and the subsequent results are shown in figure 7.3 and 7.4 respectively.

The values shown in the table 7.4 were calculated by assuming that the wafer fabrication (FOL) processes for the SAW filter is repeated 25 times. Since, only the data from FOL had to be made-up for the analysis, the total inventory data was separated into 'FOL' and 'rest of the process' (combination of EOL, facilities and staff use data) as shown in the second and third columns of the table 7.3. This data was then converted into a common unit, $1\,cm^2$ of input wafer, which is shown in the fifth and sixth columns of the table.

Inventory data	Single SAW Filter (0.2163 Cm2)			1 Cm2 of SAW			U.O.M
	FOL	Rest of the processes	Total	FOL	Rest of the processes	Total	
Electricty Usage	0.0144	0.0713	**0.086**	0.0666	0.3294	**0.40**	KWh
Water Usage	0.2015	0.2567	**0.458**	0.9316	1.1867	**2.12**	liters
Elemental Gas Usage	3.1201	0.7425	**3.863**	14.4251	3.4327	**17.86**	grams
Chemical Usage	0.2920	0.1428	**0.435**	1.3501	0.6602	**2.01**	grams

Table 7.3: Calculation of inventory data of a hypothetical SAW filter

The data from the fifth column (FOL) of the table 7.3 was then multiplied by 25 to simulate the twenty-five repetitions of the wafer fabrication process (twenty-five layers of circuitry), while the 'rest of the process' column was left as it is. The results are shown in table 7.4 below.

Inventory data	1cm2 of SAW filter with 25 layers of circuitry			1cm2 of DRAM device	U.O.M
	FOL	Rest of the processes	Total		
Electricty Usage	1.665	0.3294	**1.99**	**1.92**	KWh
Water Usage	23.29	1.1867	**24.48**	**20 - 22**	liters
Elemental Gas Usage	360.6275	3.4327	**364.06**	**437.50**	grams
Chemical Usage	33.7525	0.6602	**34.41**	**45.00**	grams

Table 7.4: Comparison between LCI for a hypothetical SAW filter and DRAM chip

From the results calculated and shown in figure 7.4, it can be seen that the inventory data for a hypothetical SAW filter with 25 layers of circuitry is very similar to the calculations made by Williams et al for typical microelectronic product. At the same time it should be noted that, for this analysis all the possible increases in inventories from other factory clusters were ignored. Taking a closer look, the inventory data from EOL processes are expected to remain the same as the increase in layers of circuitry will not affect the processes there. However, an increase in inventories items related to the facilities (could be significant because the facilities would be expected to produce more compressed air, vacuum, process water and other items needed for production) and staff/office use (most probably minor) can be expected. Then, the actual results could be even higher than those shown in table 7.4! This compares well the inventory data calculated for a DRAM chip as Williams (2004, p. 21) claims that the inventory data collected were the lower bound values.

The aim of the second anomaly assessment was to check the reliability of the SAW filter modelling used for Simapro analysis and the LCIA results obtained. Many of the literatures reviewed (Williams, Ayres & Heller 2002; Murphy, Allen, & Laurent 2003), highlight the fact that about 50% of the energy consumption of a microelectronic factory is linked to its facilities modules, which supports the production. Shown in Figure 7.4 below is the distribution of electricity consumption for the manufacturing of $1\,cm^2$ of input SAW filter. It can be seen that about half of the energy consumption (54.14%) is indeed associated with the facilities modules.

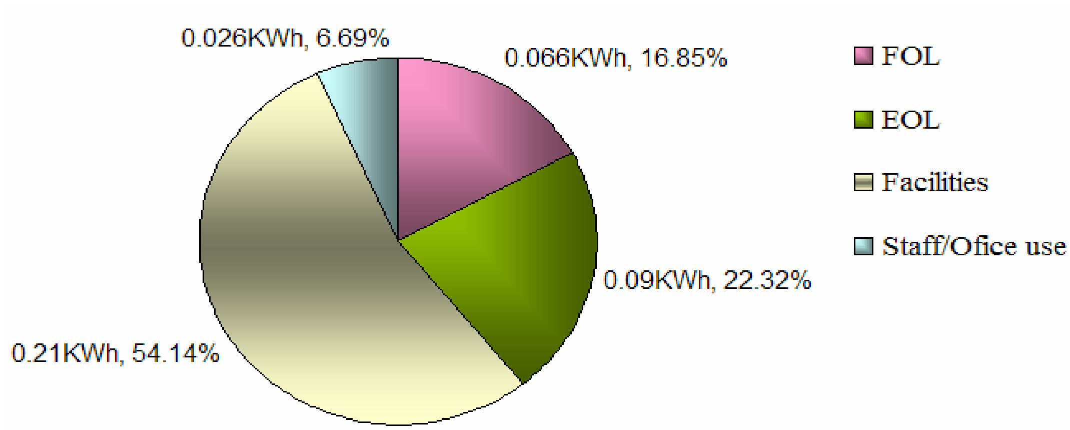


Figure 7.4: Electricity consumption for the manufacturing of $1\,cm^2$ of SAW filter

The majority of the consumption from the manufacturing line is linked to its EOL processes (22.32%), while the share of the FOL (wafer fabrication) processes is about 16.85%. This is in contrary to the findings of Williams et al and the common belief that wafer fabrication processes are much more energy intensive compared to EOL processes. Once again this variation can be justified if we adopt the same thinking as shown previously regarding the number of layers on a microchip.

This anomaly assessment was restricted to the above mentioned two evaluations mainly because of time limits. From the analysis done, it can be concluded with some degree of confidence that the inventory data collected, modelling of a SAW filter for Simapro analysis, and the subsequent results obtained are accurate and appropriate.

7.4 Evaluation of significant issues

The significant items identified in the previous section are evaluated here in detail to understand their impact on the final results. On top of that, a completeness and consistency check was also carried out to ensure that the parameters used through out this LCA study was in accordance with the goal and scope of the study.

7.4.1 Completeness check

The completeness check for this LCA was carried out with the help of technical experts, namely the process engineers involved in the production flow of the SAW filter and facilities engineers/technicians who were in charge of the daily running and maintenance of the facilities modules. The inventory data was checked for its reliability and accuracy by adopting the following methods.

- Firstly, the process flows diagrams that were used as a basis for collection of inventories were inspected for any anomalies.

- The completed inventory checklists that are shown in figures 5.2 To 5.13 were checked and verified.

- The assumptions that were used to fill up the gap in inventory data were counterchecked and verified.

Unfortunately, an analysis of the SAW filter mass flow (which would have been useful) could not be carried out as the waste disposal from the factory was difficult to interpret and broken down in to a functional unit. This limitation is mentioned in chapter 5, "Life Cycle Inventory".

This LCA study was conducted very much in accordance with the international standards. However, it should be noted that the LCA lacks an independent review by an LCA expert. The main reason for this is that this LCA study was carried out primarily for educational purposes.

7.4.2 Sensitivity Check

From the contribution analysis and the anomaly assessment done for this LCA, a number of significant issues were identified. These included life cycle inventory items such as energy consumption, copper leadframe, molding compound, tin solder, deionised water, wafer and the PVC material that is used for packaging of the finished SAW filter before delivery to customers.

7.4.2.1 Uncertainty Analysis

The first step in conducting this sensitivity check was to conduct an uncertainty analysis. The identified data were all examined in detail to check for any possible variance or irregularities that could influence the results of the LCIA.

Firstly, the highest contributor to environmental impacts, the energy consumption data was checked for its accuracy and validity. No gap in any data or any issues regarding the quantity of the data was detected. However, it was noted that the electricity model used for the impact assessment was created using two of the electricity models available in Simapro to suit the local (Singapore) conditions. The model was created using a combination of electricity generation from oil (30%) and electricity generation from natural gas (70%). This issue is highlighted in section 6.3 of the previous chapter. Since the energy consumption, turned out to be the major contributor of the environmental impacts, it was appropriate to conduct a sensitivity analysis on the electricity model for its influence on the LCIA results.

All the other inventory items identified were similarly analysed. No possible variance or irregularities were found in the cases of deionised water or the PVC material. For the wafer used, it was already highlighted in the goal and scope section that silicon was used as a substitute for lithium niobate due to the unavailability of data in Simapro database. Since there were no other models or data set available in the Simapro database, it was not possible to do a sensitivity analysis on the wafer substrate used.

As for some of the other inventory items identified, namely copper leadframe, molding compound, and tin solder, it was discovered that there could be some variance in the data that could ultimately influence the final LCIA results. The data for three items had been quantified based purely on their consumption rate, ignoring all recycling possibilities.

Table 7.5 on the next page shows the relationship between the consumption of these materials and the amount of that actually reside on a SAW filter. The second column shows the consumption data that was used for this LCA. The actual amount that should be used for the inventory data, if one hundred percent recyclability (no waste) is assumed, is shown in the third column. The excess material that could be waste or be recycled for future use and its percentage are shown on the fourth and fifth columns respectively.

Inventory Data	Consumption (mg)	Actual amount used (mg)	Waste / recycled (mg)	Waste / recycled (%)
Copper Leadframe	435.4	150	285.4	65.5%
Mold compound	447.3	196.6	250.7	56.0%
Tin Solder	20.26	2.5	17.76	87.7%

Table 7.5: Identifying the expected variance in the inventory data

The data shows that in all cases, less than half of these materials identified actually reside on a finished SAW filter. As such, in the context of this LCA, it was important to understand this variance in data. Upon investigation, it was understood that the company sold these excess materials to licensed vendors and there was simply no data available on how much of these devices were actually recycled.

Hence it was decided to conduct a sensitivity analysis on these inventory data to enhance the understanding of this variance and its impact on the impact assessment results. The next task was to find out the degree of variance involved. Considering the amount of excess material and the wastages produced during the production process flow it would have been naïve to suggest at any time that either 0% or 100% of these materials are recycled. And so, some plausible values had to be identified for the sensitivity analysis. After some consultations with the sales personnel in the company, three values (20%, 45% and 70% recyclability) were identified, as shown in table 7.6.

The following methodology was used for the calculation of consumption at different rates of recyclability. For example, if a recyclability of 20% (80% waste) was assumed for copper leadframes, the consumption was calculated to be,

$$
\begin{aligned}
Consupmtion\,(mg) &= (80\%\ \ of\ \ Waste\ Amount) + Actual\ Consumption \\
&= (80\%\ \times\ 285.4) + 150 \\
&=\ 378.3\ \ m\ \ grams
\end{aligned}
$$

Similarly, all values shown on the last three columns of the table were calculated. These degrees of variances were then used for the sensitivity analysis which is documented in the following pages.

Inventory Data	Actual Consumption (mg)	Actual amount used (mg)	Waste (mg)	Usage in mg (20% recycled)	Usage in mg (45% recycled)	Usage in mg (70% recycled)
Copper Leadframe	435.4	150	285.4	378.3	307.0	235.6
Mold compound	447.3	196.6	250.7	397.2	334.5	271.8
Tin Solder	20.26	2.5	17.76	16.7	12.3	7.8

Table 7.6: Calculation of consumption at different rates of recyclability

7.4.2.2 Sensitivity Analysis – Electricity models used

This objective of this sensitivity analysis was to find out the degree of variation in the impact assessments results when different electricity models were used. The methodology adopted for this task was to change the electricity models and analyse the single score environmental impacts contribution data for any noticeable changes.

The base electricity model that was used for the impacts assessment was created using a combination of electricity generation from oil (30%) and electricity generation from natural gas (70%) from the BUWAL250 library/database in Simapro (highlighted in chapter 6). This allocation was used to replicate the electricity generation in Singapore.

Hence, for this analysis, the same allocation was used to develop electricity models from three different databases in Simapro. The databases used for the modelling, their descriptions and the allocations used are shown in table 7.7.

Library/Database	Orgin	Allocation used for models
BUWAL 250	Switzerland	Natural gas (70%), Oil (30%)
FRANKLIN USA 98	USA	Natural gas (70%), Oil (30%)
ETH-ESU 96	Western Europe	Natural gas (70%), Oil (30%)
IDEMAT 2001	Netherlands	Natural gas (70%), Oil (30%)

Table 7.7: Electricity models used for sensitivity analysis

Once again, the contribution analysis from Simapro would have been the ideal in presenting this data but it was not possible because of the modelling restrictions. Hence network diagrams showing the single score results were used to gather the contribution data (the network diagrams are shown in Appendix D1 to D3). This data was then manually keyed in to an excel spreadsheet to produce the charts shown below in figure 7.5 and 7.6.

From the analysis it was seen that the only the model created from the Franklin USA 98 database varied significantly in comparison to the other models created. Shown in figure 7.5 is the contribution analysis data using electricity models created from Franklin USA 98 database. The difference can be easily noticed when compared to the contribution analysis result shown for a BUWAL 250 in figure 7.3.

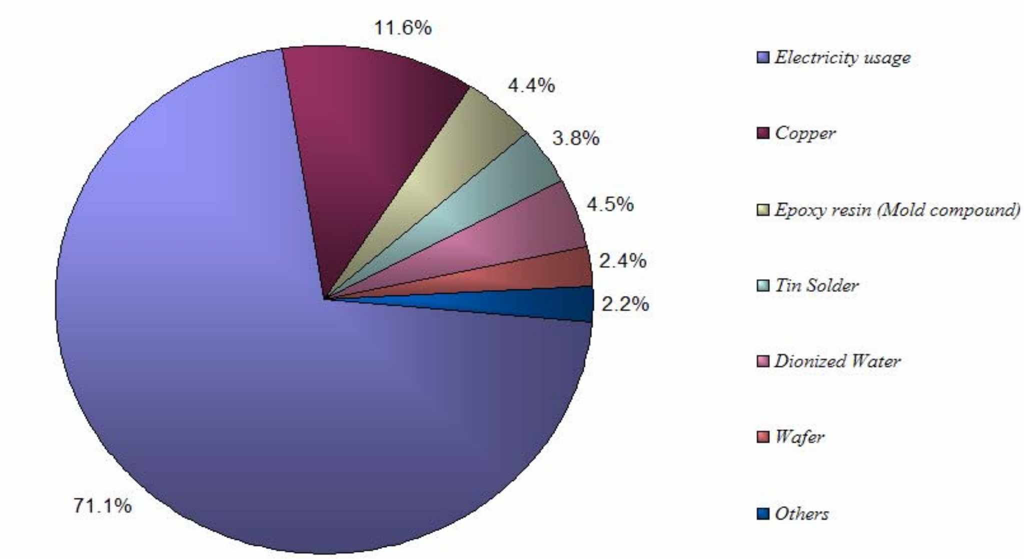


Figure 7.5: Contribution analysis using Franklin USA 98 electricity model

The results from the other two models (IDEMAT 2001 and ETH-ESU 96) were identical. This can be confirmed by the bar chart shown below in figure 7.6 which shows the relationship between the contribution analysis data and different electricity models that were created.

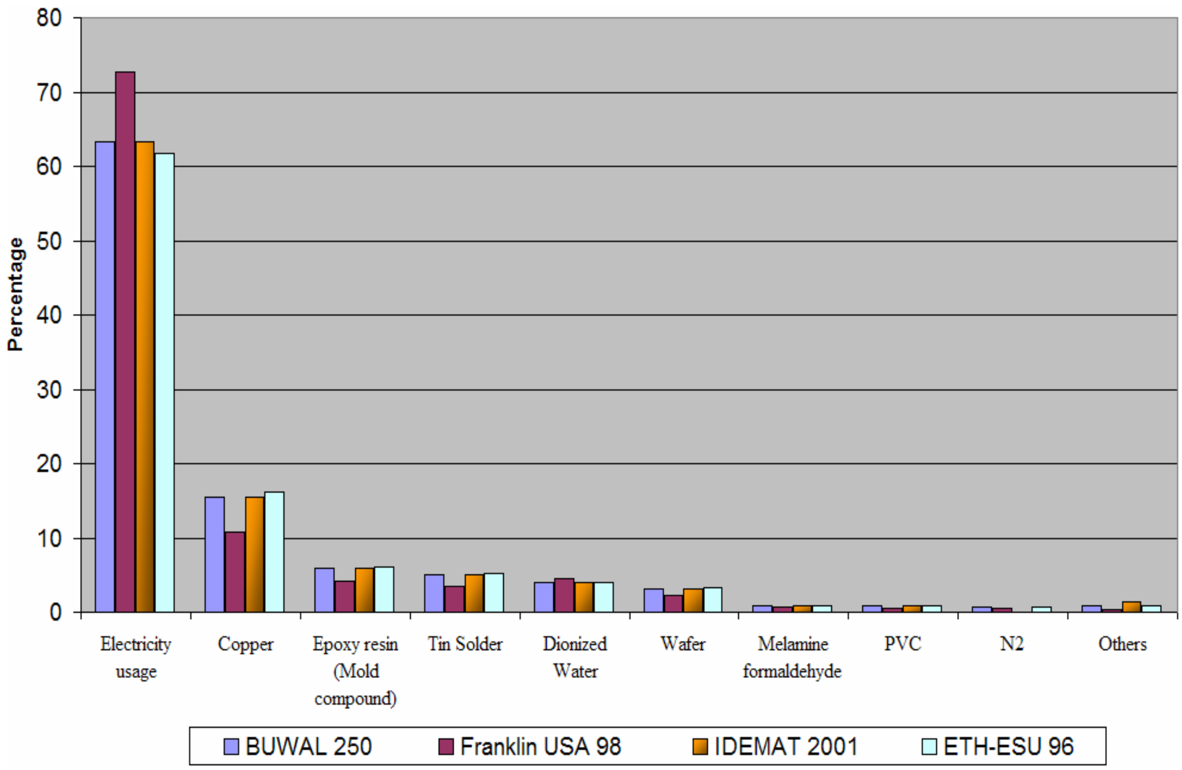


Figure 7.6: Contribution analysis data for different electricity models

7.3.2.3 Sensitivity Analysis – Copper, Mold Compound, Tin solder

Using the uncertainty data that was established in table 7.4, this sensitivity analysis for copper leadframe, mold compound and tin solder was carried out. Firstly, these inventory items were varied as 80%, 60% and 30% recyclable by changing their values accordingly in Simapro. Then, using the same methods adopted in the previous sections, a bar chart showing the resulting variance in contribution data was plotted as shown in figure 7.7. The single score network diagrams used for this analysis are shown in Appendix (D4 to D7). It should be noted that in the network diagrams, the weight of the mold compound (Epoxy resin) shown includes 5mg of epoxy resin used for diebonding.

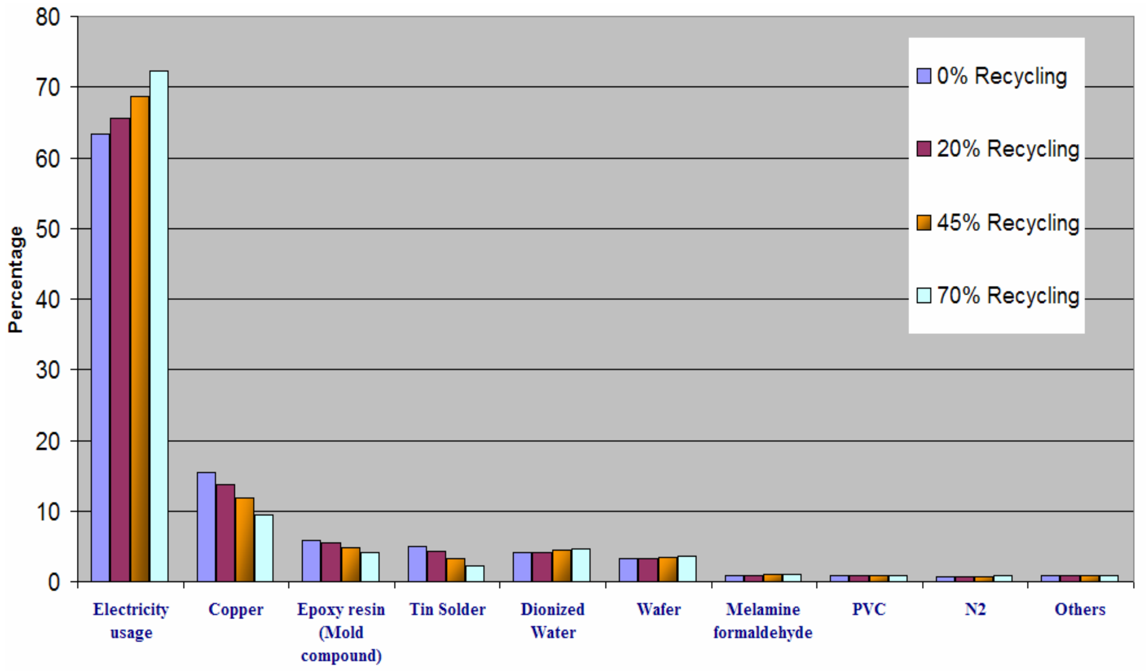


Figure 7.7: Contribution analysis data for different recyclable rates

From the figure 7.7, it can be seen that as the recycling rate of the three inventory items are increased, the actual contribution from these items towards the final impact scores are reduced as expected. On the contrary, the contributions from other inventory items increased, which was rather significant in the case of electricity usage. Its contribution jumps from about 63% for 0% recyclability to about 72% for 70% recyclability.

Another interesting factor that can be noticed is that, when a recyclability of 70% is assumed, the contribution from deionised water is actually higher compared to the epoxy resin used for encapsulation (mold compound) and tin solder. This makes deionised water the third highest contributor to environmental impacts after energy consumption and copper leadframe.

This analysis shows that the impact associated with copper, mold compound and tin solder could be reduced if they are managed more efficiently. (this view is solely based on the single score results shown here). It should also be noted that this sensitivity analysis had been done ignoring additional impacts that could occur due to the recycling of these products.

7.4.3 Consistency Check

This LCA was carried out in accordance to the goal and scope of the study. All the assumptions used, modelling restrictions and the consequent methodologies adopted were indeed as stated in the scope of the study. For this LCA, being a non-comparative study, this step of the evaluation process is of minor importance.

7.5 Conclusion and Recommendations

The results obtained from the contribution analysis substantiated the conclusions from LCIA results regarding the environmentally culpable inventory items. Anomaly assessments showed that the life cycle inventory data collected for this LCA is comparable to other LCAs done on similar products. From the sensitivity analysis done on electricity models, the similarity in results in between three of the four models created showed that the model used for this LCA was the best choice under the circumstances. The sensitivity analysis done on copper leadframe, mold compound and tin solder, proved that the uncertainties in these inventory items could influence the magnitude of the final environmental scores. At the same time on a positive note, it showed that a significant reduction in environmental impacts is possible if these materials are used more efficiently. A more detailed sensitivity analysis would have been ideal to establish the differences in the actual magnitude of the environmental impacts but again, the limitation of the software used, did not allow it.

The unpopular ‘single score’ results (aggregation of weighted impact categories) were used for most of the analysis done in this chapter. But it has to be noted that all the use of ‘single score’ has been limited to analysis whereby the actual magnitude of the impacts was of secondary importance. It has also been avoided in analysis whereby comparative assertions have made (with respect to similar products).

In conclusion, the interpretation stage has proved that the results obtained from the other stages of the LCA are largely valid and reliable. The results of the interpretation stage are used in conjunction with the other LCA stages to draw final conclusions and recommendations in the next chapter.

Chapter 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

The chapter documents the conclusion and recommendations for this LCA study. All the major results of the study are reiterated and the reliability and validation of these results are discussed based on the analysis carried out in the previous chapters. Following that, the major limitations and other problems faced during this study are presented. Conclusions and recommendations based on the results of this LCA are made and finally, some recommendations are made for future/further work. But firstly, a summary of what has been achieved so far.

8.2 Summary of Achievements

The main objectives of this research project were to assess and appreciate the environmental performance of a typical microelectronic product through a Life Cycle Assessment (LCA) and to use the results of the LCA to identify options for improving the environmental performance of the product at a process level. The project specifications are attached in Appendix. A.

To begin with, a thorough literature review was conducted to understand the LCA methodologies, techniques, current international standards, uses, limitations (Chapter 2: Literature Review)). Then, a LCA study was conducted largely in accordance with the international LCA standards. Following that, the purpose, scope, system boundaries and the functional unit of study were identified (Chapter 3: Goal and Scope).

A Surface Acoustic Wave (SAW) filter was chosen as the functional unit for the study. The next step involved spending considerable time in a SAW manufacturing plant understanding the processes involved in the manufacturing of a SAW filter (Chapter 4: SAW filter). With the knowledge gained, Life Cycle Inventory (LCI) for the LCA was collected (Chapter 5: Life Cycle Inventory). Clusters were used for the ease of the data collection and the subsequent modelling of the product in software for analysis. The clusters identified were, the manufacturing line where the actual manufacturing takes place (Front of line (FOL) and End of line (EOL)), facilities modules which supports the production and staff/office use.

Next, the collected inventory data was analysed using a demonstration version of Simapro 7.0 software (Chapter 6: Life Cycle Impact Assessment). The data was analysed using impact assessment method 'ECO-indicator 99' for a number of impacts categories. Finally life cycle interpretation was conducted to establish validity and reliability of the LCI and LCIA results (Chapter 7: Life Cycle Impact Assessment).

8.3 Major Results

Summarised below are some of the major findings of this study.

- Overall, it was seen that almost two-thirds of the impacts is linked to the manufacturing line. The rest of the impacts are linked to facilities modules with a small percentage share linked to staff and office use (~ 5%).

- Majority of the environmental impacts from the manufacturing line are linked to the End of Line (EOL) production where, the assembly, encapsulation and final testing of the filter take place.

- For the facilities modules, the major contributions comes from the factory environment control system that is made up of heavy machineries such as chillers, air-compressors, fresh air make units, and air exhausts.

- In the case of staff and office use, the major contributing factor is the energy consumption (electricity usage).

- The LCIA results and later, the contribution analysis (see figure 7.3) proved that the highest contributing factors to the environmental burdens associated with a SAW filter can be linked to the high energy consumption of production machines and facilities modules.

- Overall, the total energy consumption between the production modules and the facilities modules was roughly equal (see figure 7.5).

- Though the total inventory list had over a hundred items, only a handful actually contributed significantly to the environmental impacts.

- These items other than the energy consumption were, copper leadframe, mold compound (epoxy resin) used for encapsulation of the chip and diebonding purposes, tin solder, deionised water and the wafer substrate (see figure 7.5).

- Through normalization, it was found that damage to resources (fossil fuels and minerals) is the worst affected damage category (see figure 6.4). This is linked to the high energy consumption of SAW filter manufacturing processes and the use of minerals such as copper and tin.

- Of the analysed impact categories (see section 6.5) Ecosystem quality is the least affected damage category, with acidification/eutrophication and ecotoxicity, the main contributors.

- Acidification /eutrophication are caused by emission of gaseous pollutants to the atmosphere, and are attributed mainly to electricity generation and copper smelting (copper leadframe). Ecotoxicity can be linked to the oil extraction for electricity generation.

- Respiratory inorganics and climate change are the main contributors to human health damage category. The main contributions to respiratory inorganics came from the burning of fossil fuels for electricity generation and smelting of copper. Burning of fossil fuel was also the main the contributor to climate change.

- Only the abovementioned seven out of the eleven impact categories in ECO-indicator 99, contributed notably to the final environmental results. And hence, the rest of the impact categories, namely, respiratory organics, radiation, carcinogens and ozone layer depletion were not considered for further analysis.

- An item that showed a major disproportionalilty of contribution was the tin solder. Though its weight was less than half a percentage of the total inventory weight, it actually contributed about 5% of the environmental impacts (single score result).

- It was found that there was an opportunity to reduce the environmental impacts associated with three of the significant inventory items, copper leadframe, tin solder and mold compound through recycling.

- Process wise for EOL, the majority of the impacts come from assembly and encapsulation. As for testing and packaging processes, the main contribution to the environmental load other than the energy consumption of the machines came from the PVC tubes that are used as packing materials.

- Process wise for FOL, photolithography processes are the main contributors to the environmental load. All impact categories analysed in the chapter 6 showed that photolithography processes are environmentally more culpable than pre-assembly and Protec processes.

- Environmental impacts associated with chemicals and water consumption of facilities modules paled in comparison to the impacts caused by their energy requirements.

- In the case of water recycling plant the positive environmental impact made is extremely small in comparison to the total negative impacts and such are not reflected significantly in results.

8.4 Limitations and Assumptions

Throughout the course of this LCA there were many limitations faced. Some of the important ones are discussed here. The major limitations for the project involved the use of a demonstration version of Simapro software for the life cycle impact assessment stage. The use of demonstration version of Simapro software meant certain restrictions in the actual modelling of the product for analysis. The depth of analysis which could have been possible with the detailed LCI was limited and hence system boundaries in goal and scope of the study had to be altered accordingly (see chapter 3).

The next issue regarding Simapro, concerned the inventory database, or rather the lack of it (inventory could have been limited because of the demonstration software used). The databases did not contain many of the specialised chemicals and other raw materials that are commonly used in the microelectronics industry. One of the major limitations of LCAs done on microelectronics products have been the lack of clarity on data associated with the production of ultra pure chemicals used extensively in the industry. This was also a factor in this LCA. Because of these difficulties with inventory, the following assumptions had to be made when modelling the product in Simapro (see chapter 3 for justifications). All the chemicals used were classified as either as organic or inorganic. Electronic grade silicon was used as a substitute for lithium niobate wafer that is used in SAW filters.

Another limitation of Simapro was that almost all of the inventory datasets used for modelling of the SAW filter and impact assessment methods used for LCIA are based mostly on European data. The only exceptions to this are the damages to resources, damages created by climate changes, ozone layer depletion, air emissions of persistent carcinogenic substances and radiation. Assumptions also had to be used for some of the data during the inventory collection stage. All the assumptions used were done in consultations with technical experts who were familiar with SAW filter characteristics and hence it can be concluded that this issue was of minor importance. Because of all these assumptions, it can be noticed that throughout this dissertation, the actual magnitude of the impacts are rarely referred to, rather percentage values are used.

8.5 Recommendations based on Results

Sensitivity analysis done in section 7.2 on copper leadframe, mold compound (epoxy resin) and tin solder showed that by reducing the amount of waste associated with these materials, their environmental impacts can be reduced. One of the ways of achieving this would be a more efficient use of these materials in production.

Take for example, the copper leadframe. The consumption of copper per SAW filter is 435 milligrams (mg), of which only 150 mg is left behind on the final product. The excess material is waste and is cut out during various assembly processes. The feasibility of recycling this waste material was explored in the sensitivity analysis. Recycling a material in itself cost energy, it is always better not to use the material in the first place than to recycle it later. Hence, a more efficient way of using these identified materials (may be a better design of the leadframe to reduce the losses) would significantly improve the environmental performance of a SAW filter.

Another item that was identified during the contribution analysis was the PVC tubing that is used for packaging of finished SAW filters. From LCIA it was seen that these materials made sizeable contributions to some of the impact categories. A better environmental performance can be achieved if this material is replaced by some other materials that are environmentally friendlier than PVC.

The easiest recommendation that could have been made here would have concerned the use of electrical energy in the factory. But in this case it has to realised that minimising the energy consumption of production machines that are operated with over of 95% of production time daily for 365 days a year is not an easy task!

It should be noted that the recommendations made here are based solely on results of this LCA. In a practical engineering world other constraints and criteria have to be taken in to account before a major decision can be made. Again take for example the copper leadframe. If the design of the leadframe is changed to reduce the losses then machine and other modifications may result, which would inevitably mean time and money.

8.6 Recommendations for Future work

In view of limitations that were faced during the course of this research project, the following recommendations for future work can be formulated.

An area where the further work can be done with regards to this research project is to use better quality and accurate Simapro data for impact assessment. As mentioned earlier in this chapter, many of the inventory data were unavailable in the demonstration version of Simapro libraries and many of those available were ambiguous. Hence, an even more reliable and accurate LCIA results could probably be achieved by doing the same analysis on a full version of Simapro.

An important issue that needs further consideration is the data quality indicators (DQI) used. Both geographical and temporal differences in datasets were ignored for this LCA because of the limited resources. If an impact assessment is carried out in future using the LCI from this project, these differences should be addressed.

Some of the LCA softwares in the market today do address these differences found in data quality. They do have various versions of the software suitable for different regions. For example, Simapro do have a Japanese version and most likely the dataset is made for use in Japanese conditions. However, no such versions were found for other regions of Asia, which is major manufacturer of microelectronic products. As such, it is recommended that more research should be done on this area.

Another issue that should be addressed in future LCAs done on microelectronics products is the quality and clarity of chemical data that are used for impacts analysis. Many of the LCA databases do contain a vast number of chemical, but they do no specify the grade of the chemicals. The microelectronic industry in general use specialised high grade chemicals (high purity) whose manufacturing processes are energy intensive and hence it is important that they are taken into account in an LCA. Actually, this problem is not just confined to LCA databases and softwares. There is a lack of publicly available data on manufacturing of these specialised chemicals generally. Researches in future should address this problem.

8.7 Final Conclusions

Overall this research project was able to meet most of the objectives set. It was able to establish with a certain degree of confidence, the environmental impacts associated with a typical microelectronic product.

Thorough literature review conducted at beginning of this project ensured that the LCA was conducted mostly in accordance with the existing international standards. The life cycle inventory data was collected meticulously and systematically. The validity and reliability of the life cycle inventory data was established by the anomaly assessments conducted in chapter 7. It is hoped that this information can be beneficial to researchers who hope to do LCA on similar products

The project was successful in assessing and appreciating the environmental performance of a SAW filter. Through the inventory analysis done at the end of chapter 5, an idea of impacts associated with a SAW filter was first established. The results from the impact assessments done in chapter 6 further strengthen these findings.

The major limitation of this project was the use of demonstration software for the impact assessment and interpretation analysis. The analysis was conducted using the best available options but a much clearer and accurate environmental impact scores could have been achieved if proper software was available for analysis. Though, some valid concerns can be raised regarding the actual magnitude of the impacts, it is expected that the major result obtained, the identification of environmentally culpable product/processes is accurate and reliable. The interpretation stage, which is documented in chapter 7, proves this.

Based on the results of the LCA, some recommendations were made. However, if this LCA is to be used in future to make major decision regarding the SAW filter or its manufacturing processes, it should be kept in mind that the LCA results presented in this dissertation are not the answers to environmental impacts associated with a SAW filter but simply a guide to better the environmental performance. LCA is a tool that helps in decision making, but it does not replace it.

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Appendix A – Project Specification

A1. Project Specification

Faculty of Engineering and Surveying

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Deepu Mohan

TOPIC: Life Cycle Assessment (LCA) of a SAW filter.

SUPERVISOR: David Parsons

SPONSERSHIP: Own

PROJECT AIM: This project aims to evaluate the environmental impacts of a SAW filter using the Life cycle assessment methodology.

PROGRAMME: Issue A, 27th March 2006

1. Research information on using life cycle assessment techniques to evaluate environmental impacts by reviewing past and present literatures published on similar topics.

2. Review the current life cycle assessment techniques to identify concept and ideas being used such as building model of process, finding specific data, using models of environmental impact based on scientific knowledge and how LCAs are done using software.

3. Understanding how Life cycle assessment fits in to general International situation and review international life cycle assessment Standards that are being used.

4. Investigating the processes involved in the manufacturing of a SAW filter.

5. Identifying life cycle assessment's scope such as the purpose, the product of the study, the system boundaries and impact categories.

6. Collection of Life cycle inventory data (LCI). Quantifying industry data for all inputs and outputs from each stages of product life cycle.

7. Life cycle impact assessment (LCIA). Analysing the data collected for its impact on the physical environment.

8. Validation of results to show that they are sensible, that they compare well with any other related results, and that any data uncertainties do not dramatically change the outcomes.

9. Life cycle interpretations to identify, quantify, check, and evaluate information from the results of the LCI and LCIA, and communicate them effectively.

As time permits:

10. Evaluate opportunities to mitigate energy inputs, material usage, and environmental impacts at each stage of product life cycle.

AGREED:

___________________ (Student) ___________________ (Supervisor)

Appendix B – Life Cycle Inventory Checklist

B1. Checklist for Front of Line (FOL)

B2. Checklist for Front of Line (FOL)

B1. Sample Checklist for Front of Line (FOL)

Process: ______________________________ **Date:** ____________________

Equipment Name: ____________________ **No of Machines:** __________

Wafer Processing: Single Wafer / Batch Wafer **Lot Size:** _________ (Wafers)

Consumption Detail: Continuous / Discontinuous

Energy Consumption		
Rated Voltage (V)	Load Active (A)	Load Idle (A)

Machine Utilisation				
	Week 1	Week 2	Week 3	Week 4
Production Time (%)				
Idle Time (%)				
Down Time (%)				

Water and Gas Consumption							
Consumption Detail	**Process Water**				**Elemental Gas**		
	Deionized Water	Process cooling Water	Cutting Water	Dicing Water	Nitrogen (N2)	Oxygen (02)	Others (Please specify)
Flow rate (Continuous Mode)							
Flow rate (if appli) Discontinuous Mode							

B2. Sample Checklist for Front of Line (EOL)

Process: ____________________________ **Date:** ___________________

Equipment Name: ___________________ **No of Machines:** __________

Consumption Detail: Continuous / Discontinuous **Lot Size:** __________ (Filters)

Energy Consumption		
Rated Voltage (V)	Load Active (A)	Load Idle (A)

Machine Utilisation				
	Week 1	Week 2	Week 3	Week 4
Production Time (%)				
Idle Time (%)				
Down Time (%)				

Water and Gas Consumption							
Consumption Detail	**Process Water**				**Elemental Gas**		
	Deionized Water	Process cooling Water	Cutting Water	Dicing Water	Nitrogen (N2)	Oxygen (02)	Others (Please specify)
Flow rate (Continuous Mode)							
Flow rate (if appli) Discontinuous Mode							

Appendix C – Network Analysis (LCIA)

C1. Damage to Resources

C2. Damage to Resources - EOL

C3. Damage to Resources – FOL

C4. Impact category – Fossil fuel depletion

C5. Fossil fuel depletion - EOL

C6. Fossil fuel depletion - FOL

C7. Impact category - Minerals depletion

C8. Damage to Human health

C9. Damage to Human health - EOL

C10. Damage to Human health - FOL

C11. Impact Category – Respiratory inorganics

C12. Respiratory inorganics - EOL

C13. FOL – Respiratory inorganics

C14. Impact Category – Climate change

C15. Climate change - EOL

C16. Climate change – FOL

C17. Damage to Ecosystem Quality

C18. Ecosystem Quality - EOL

C19. Ecosystem Quality - FOL

C20. Impact Category – Acidification/Eutrophication

C21. Acidification/Eutrophication - EOL

C22. Acidification/Eutrophication - FOL

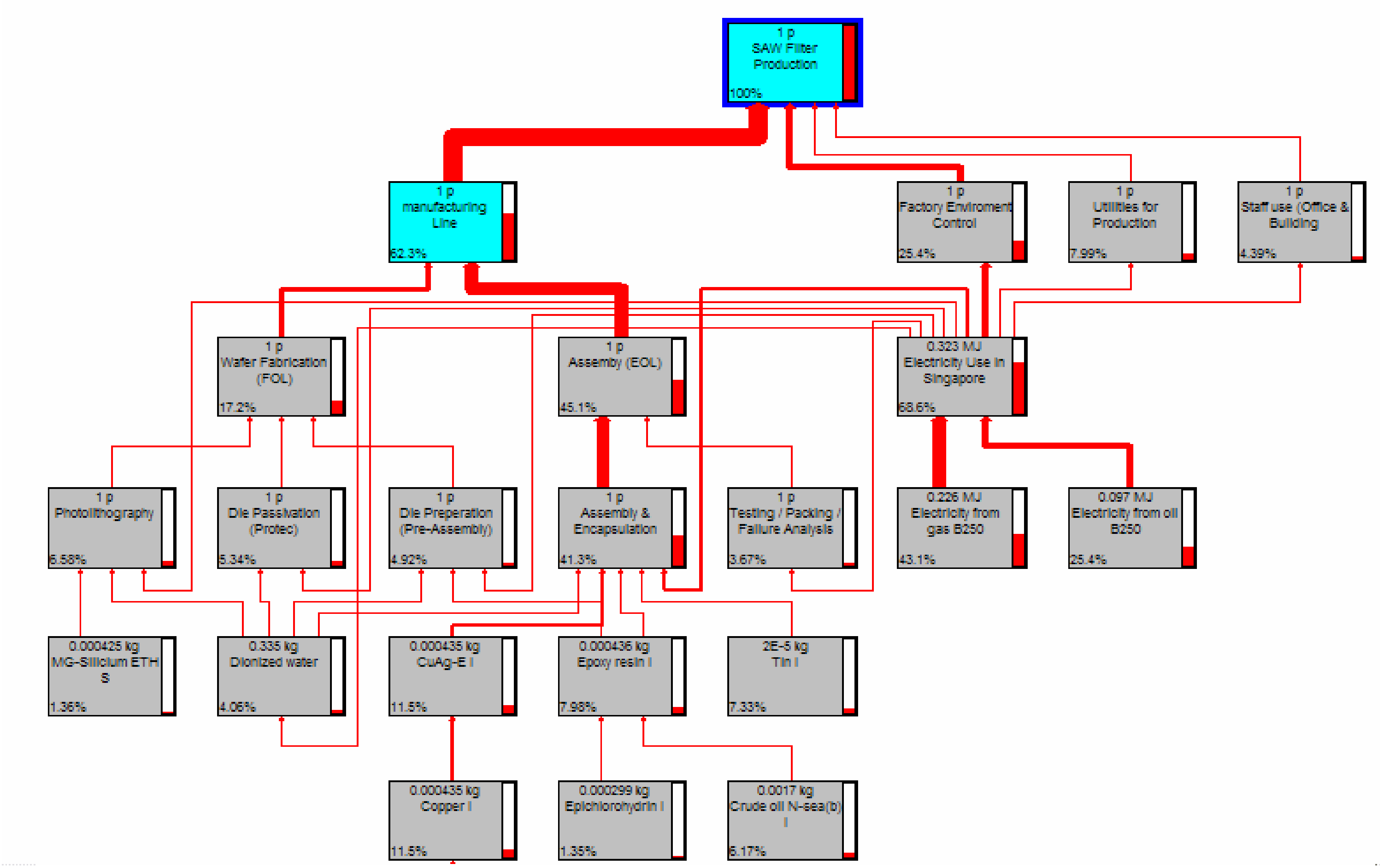
C23. Impact Category – Ecotoxicity

C24. Ecotoxicity - EOL

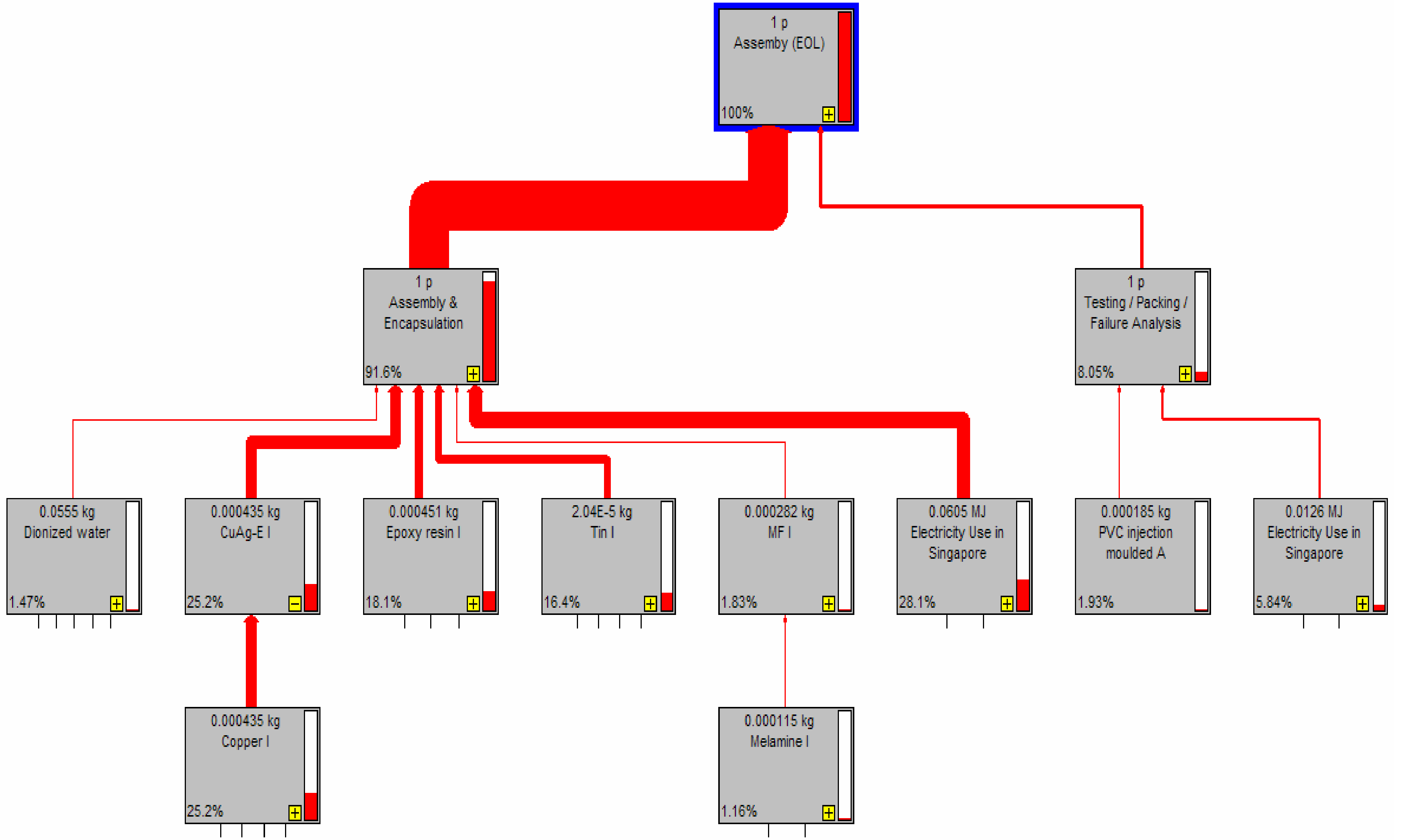
C25. Ecotoxicity – FOL

C26. Impact Category –Land use

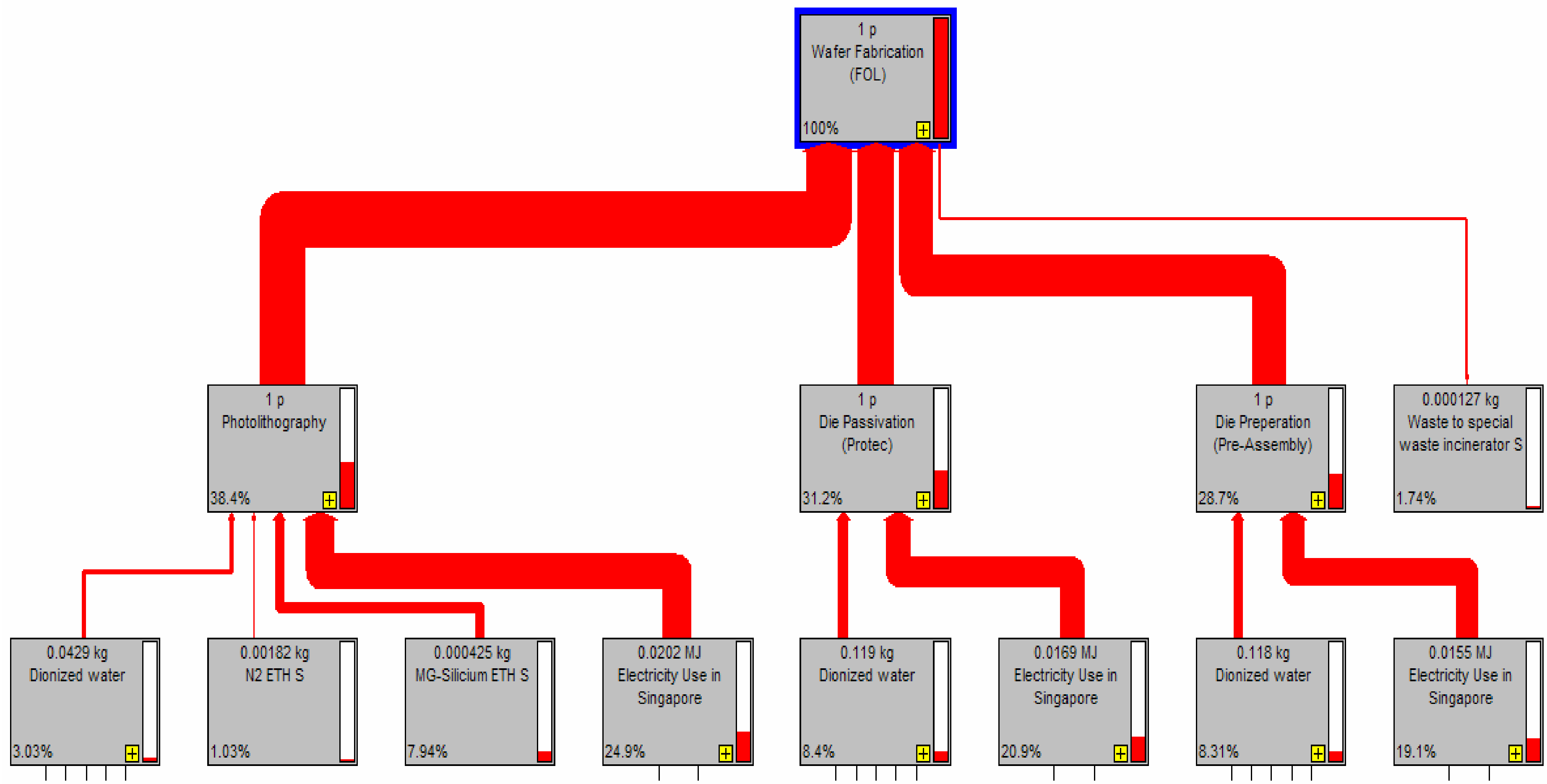
C1. Damage to Resources



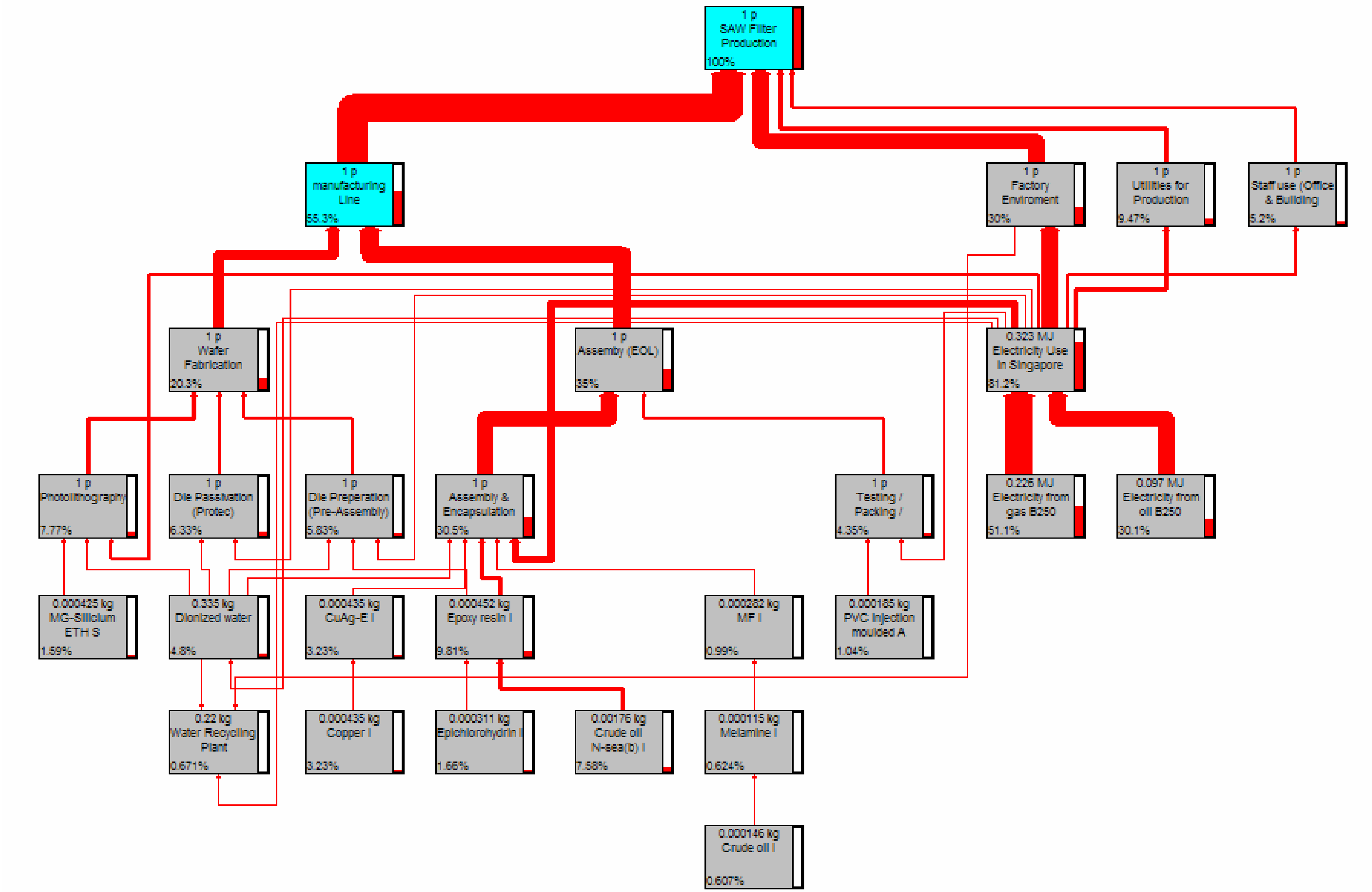
C2. Damage to Resources - EOL



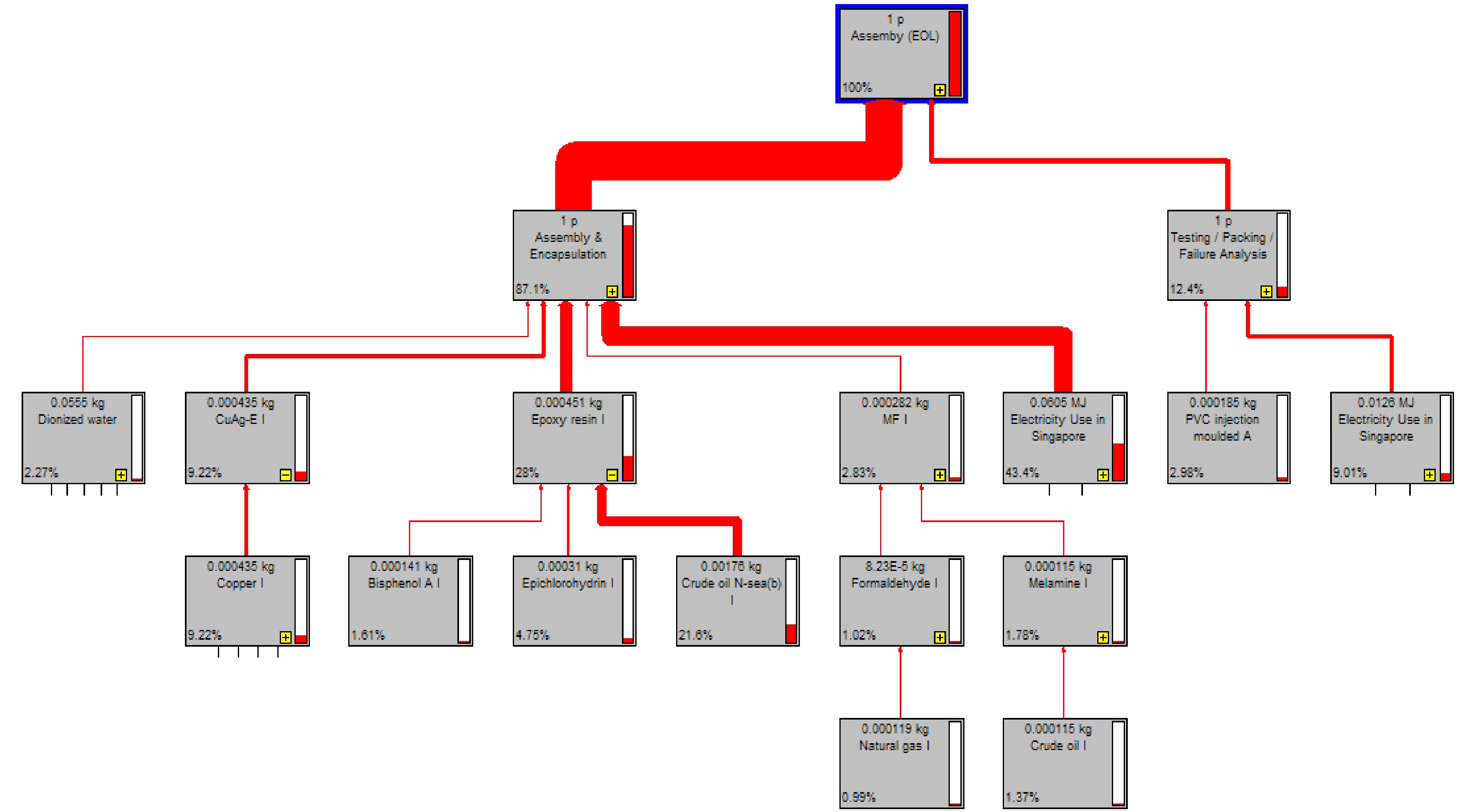
C3. Damage to Resources – FOL



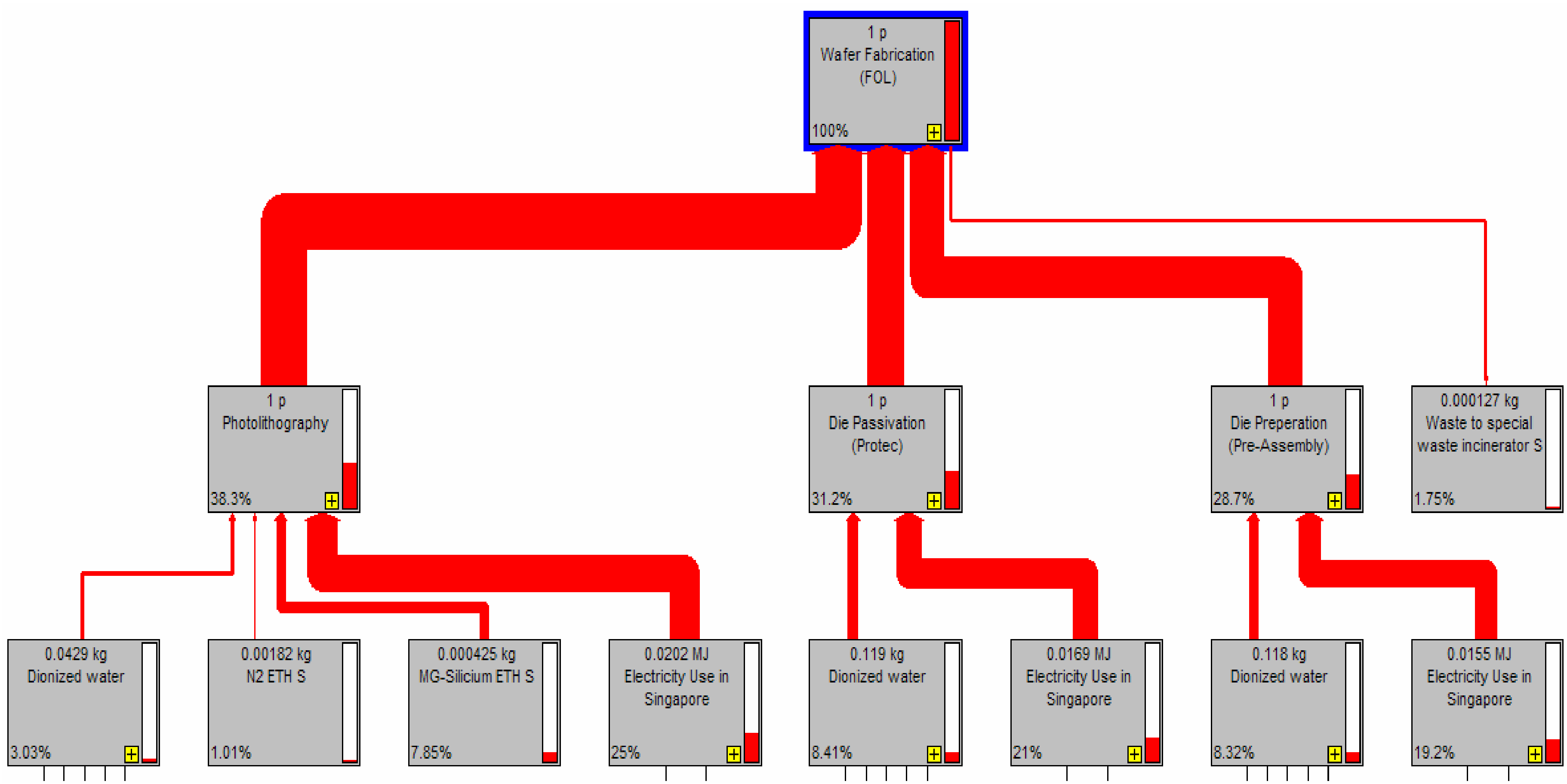
C4. Impact category – Fossil fuel depletion



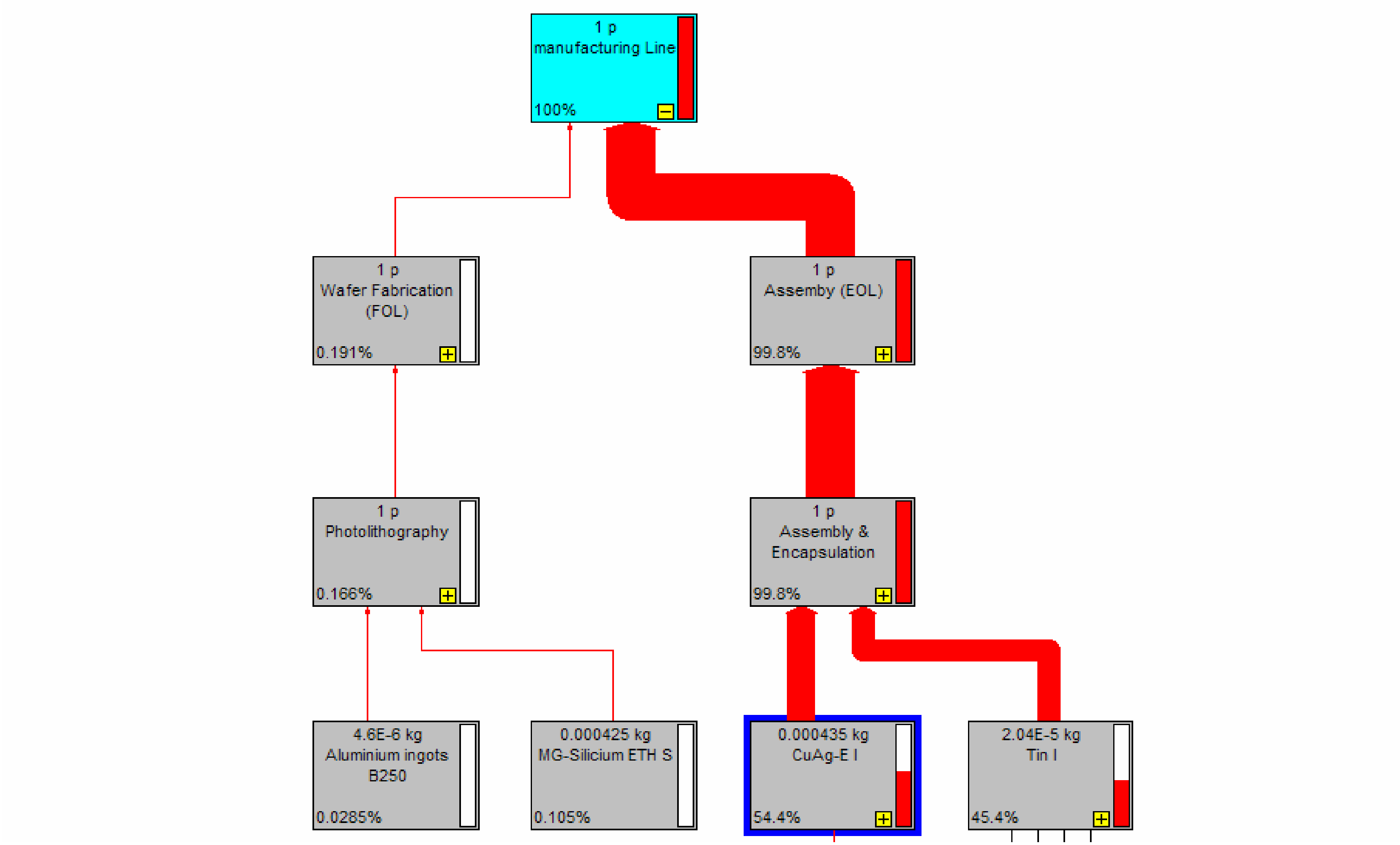
C5. Fossil fuel depletion - EOL



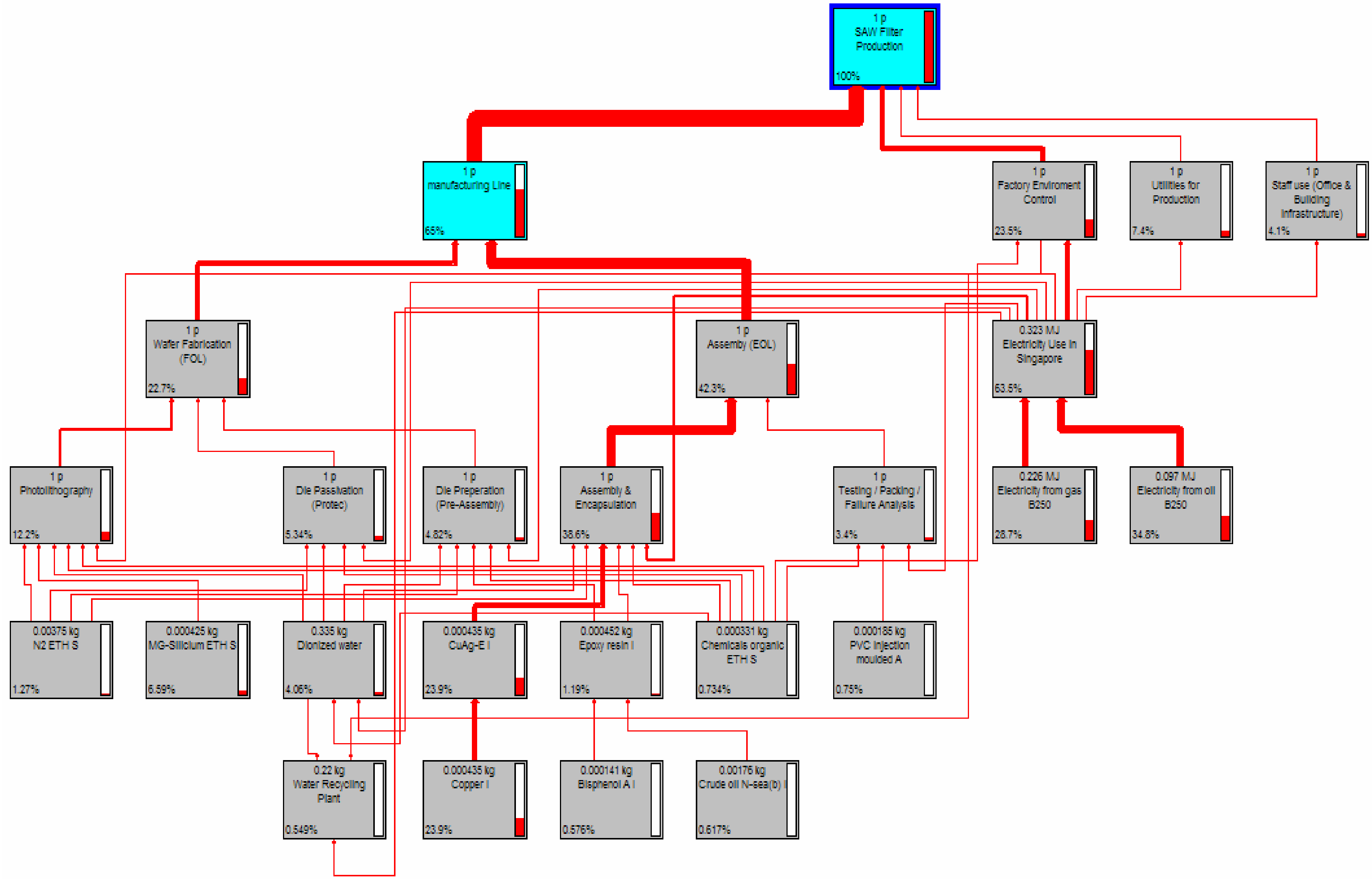
C6. Fossil fuel depletion - FOL



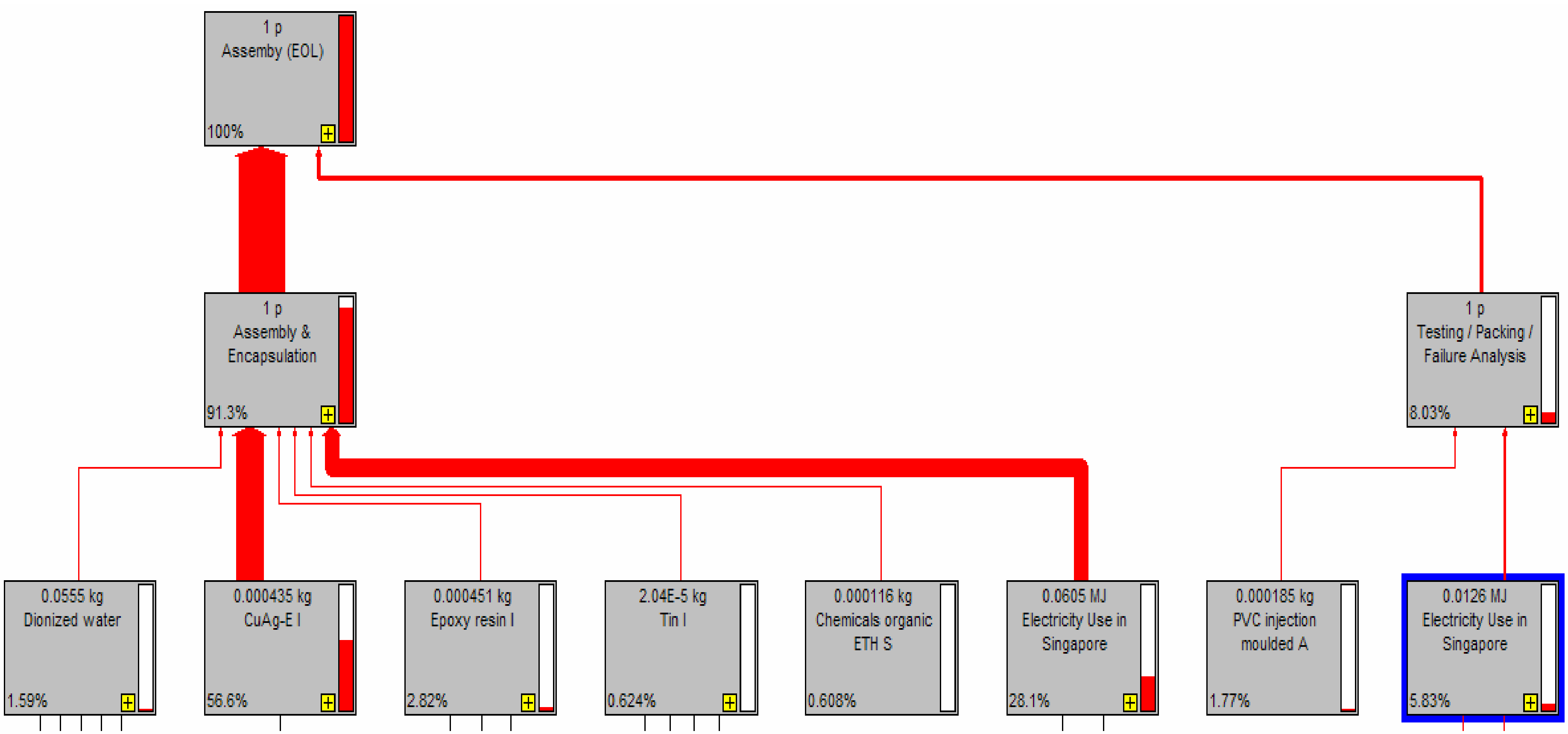
C7. Impact category - Minerals depletion



C8. Damage to Human health



C9. Damage to Human health - EOL



C10. Damage to Human health - FOL

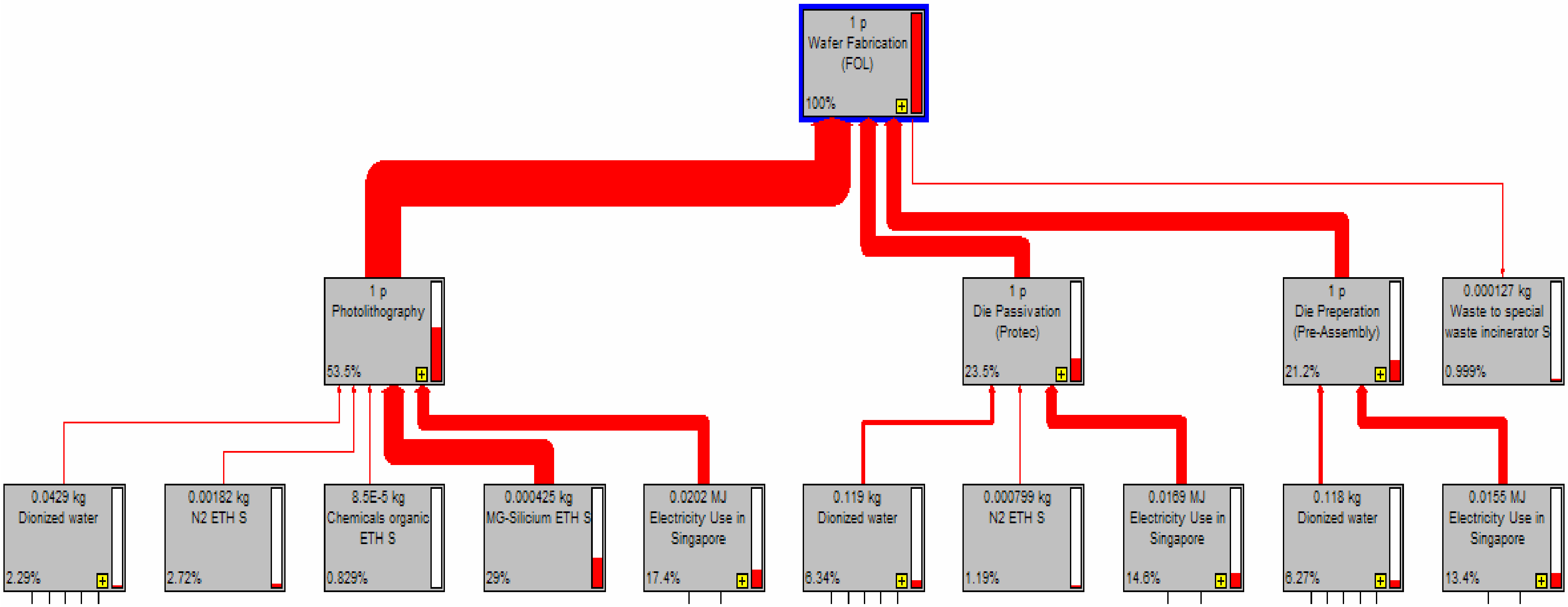
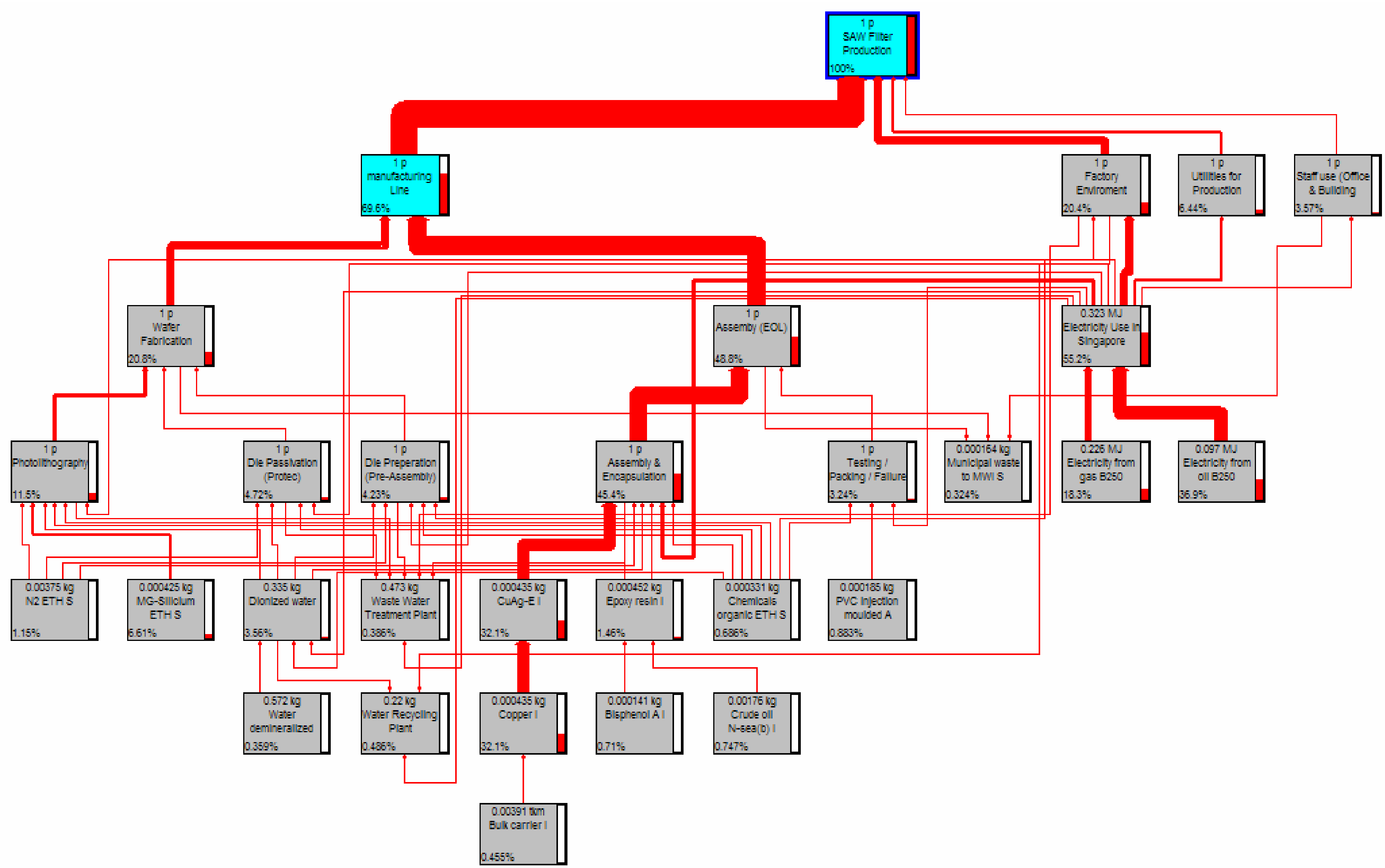


Figure 6.16: Network showing human health damage assessment (EOL)

C11. Impact Category – Respiratory inorganics



C12. Respiratory inorganics - EOL

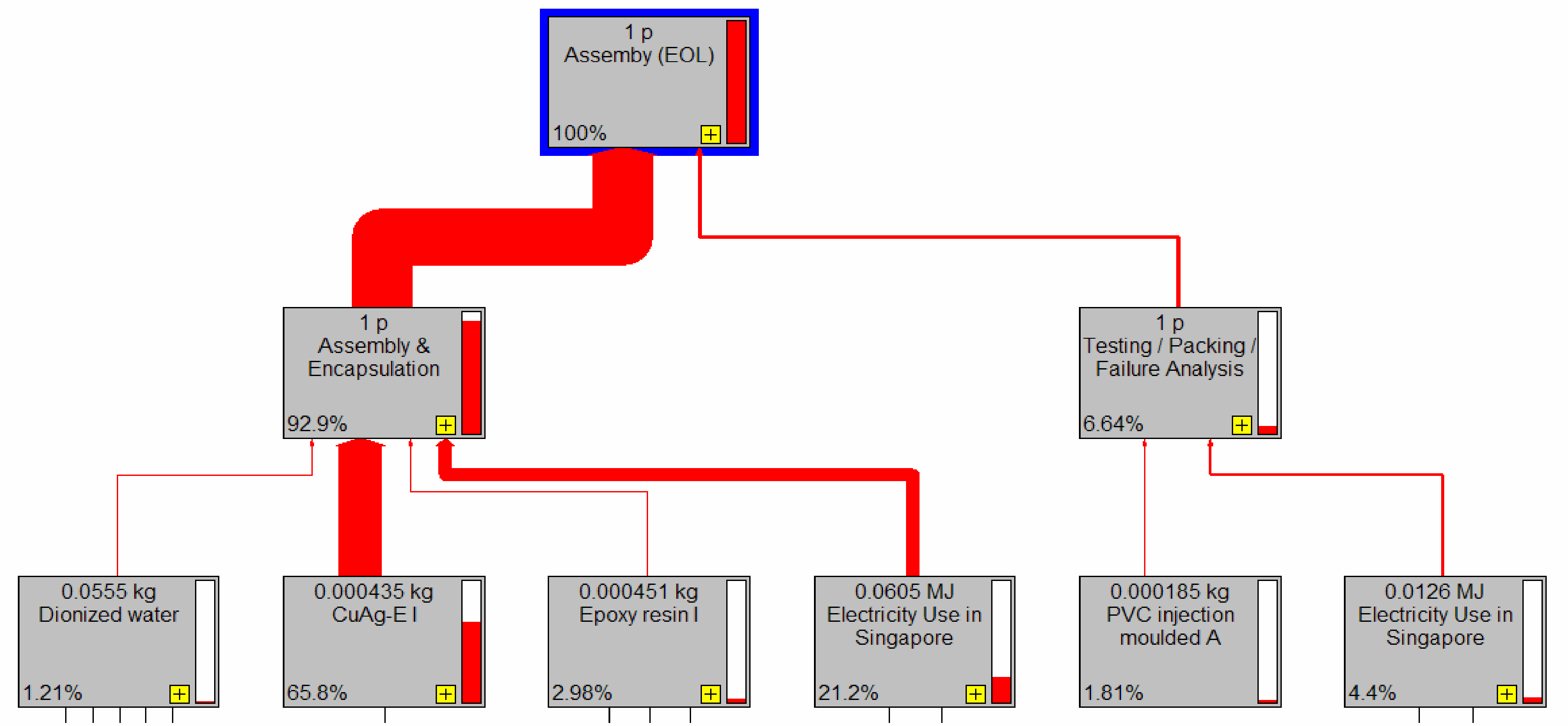
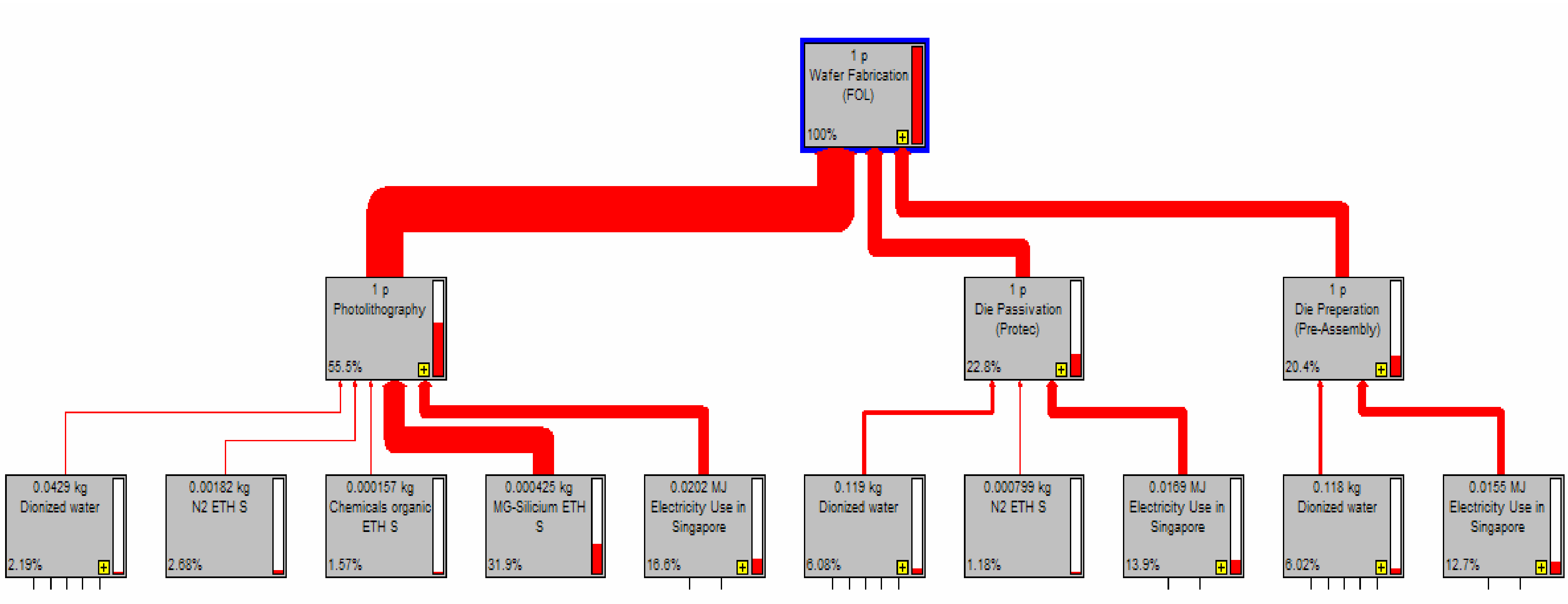
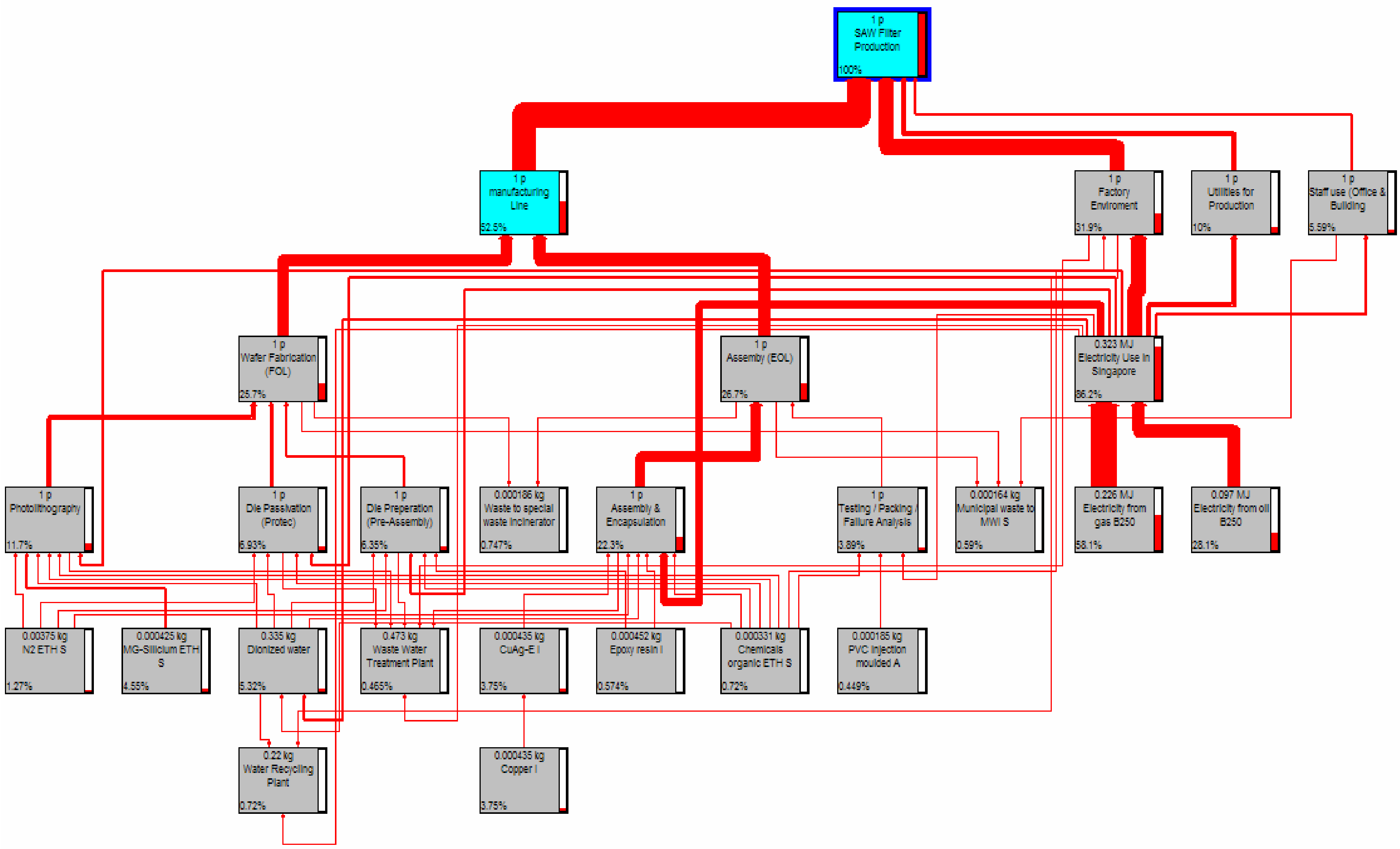


Figure 6.18: Characterized network showing contributions to respiratory inorganics (EOL)

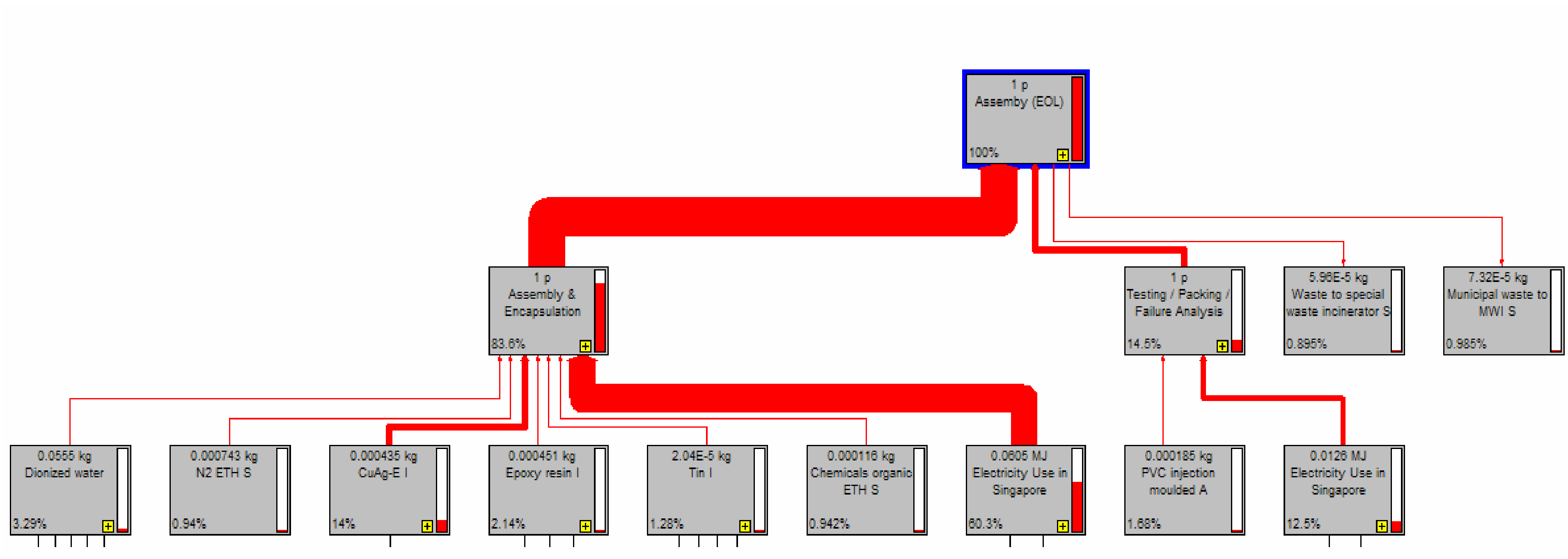
C13. FOL – Respiratory inorganics



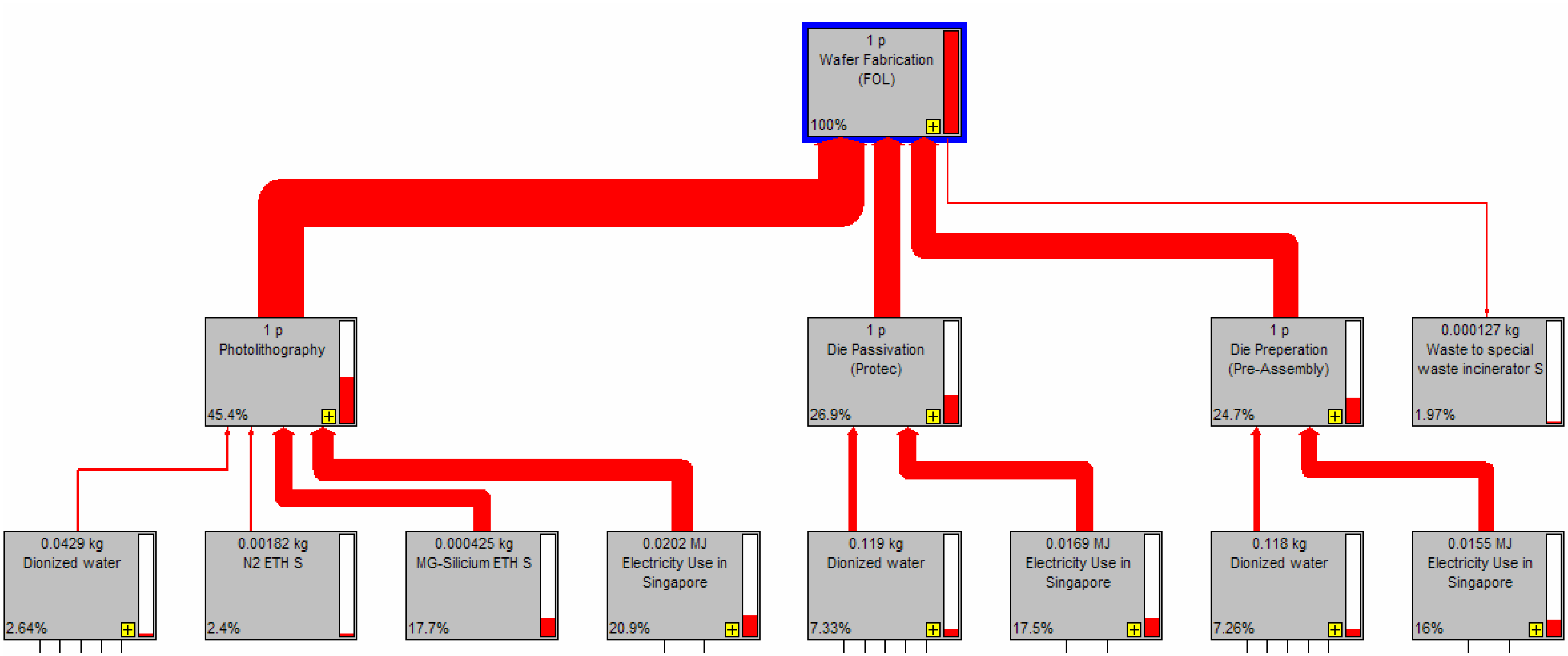
C14. Impact Category – Climate change



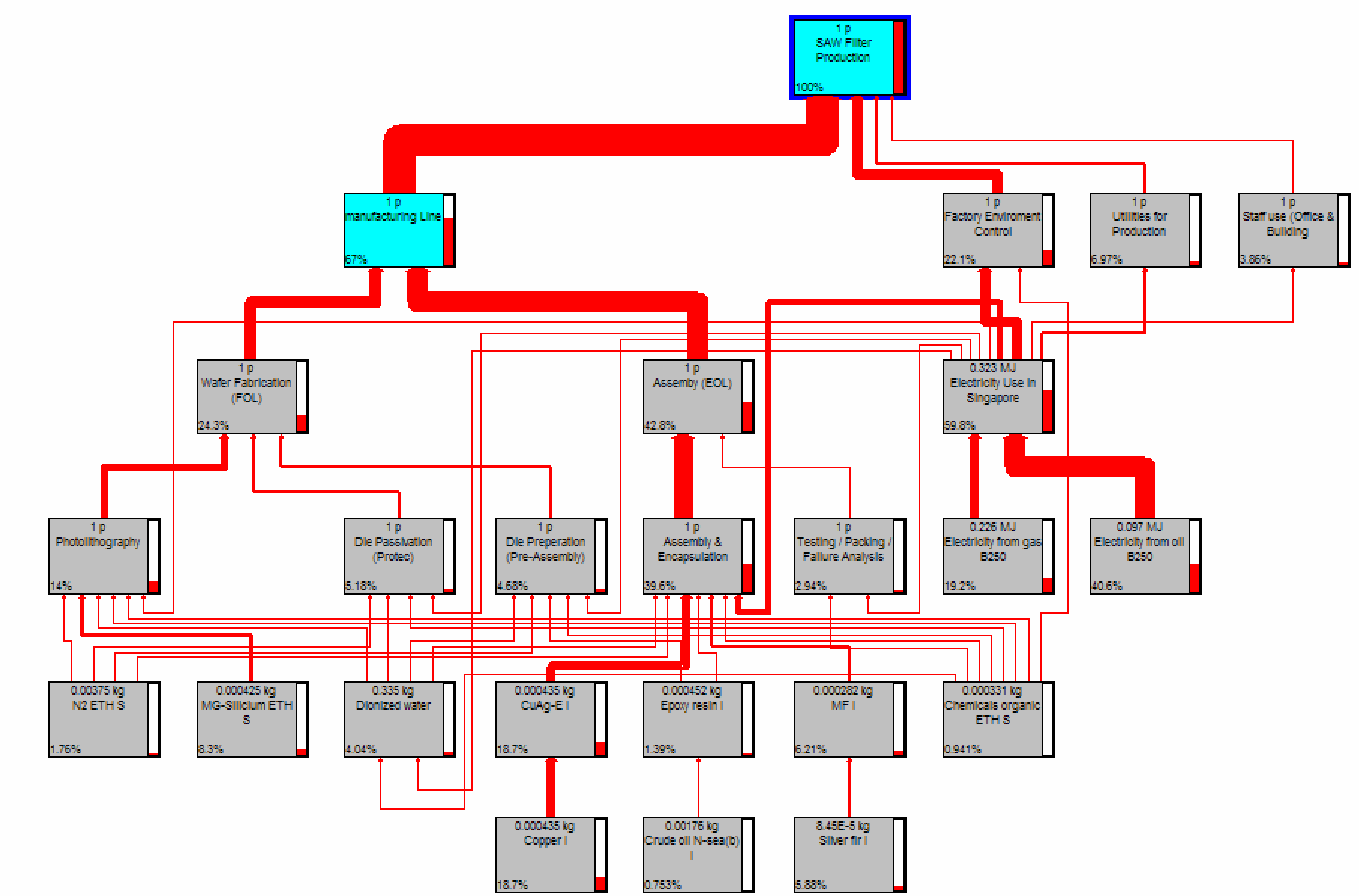
C15. Climate change - EOL



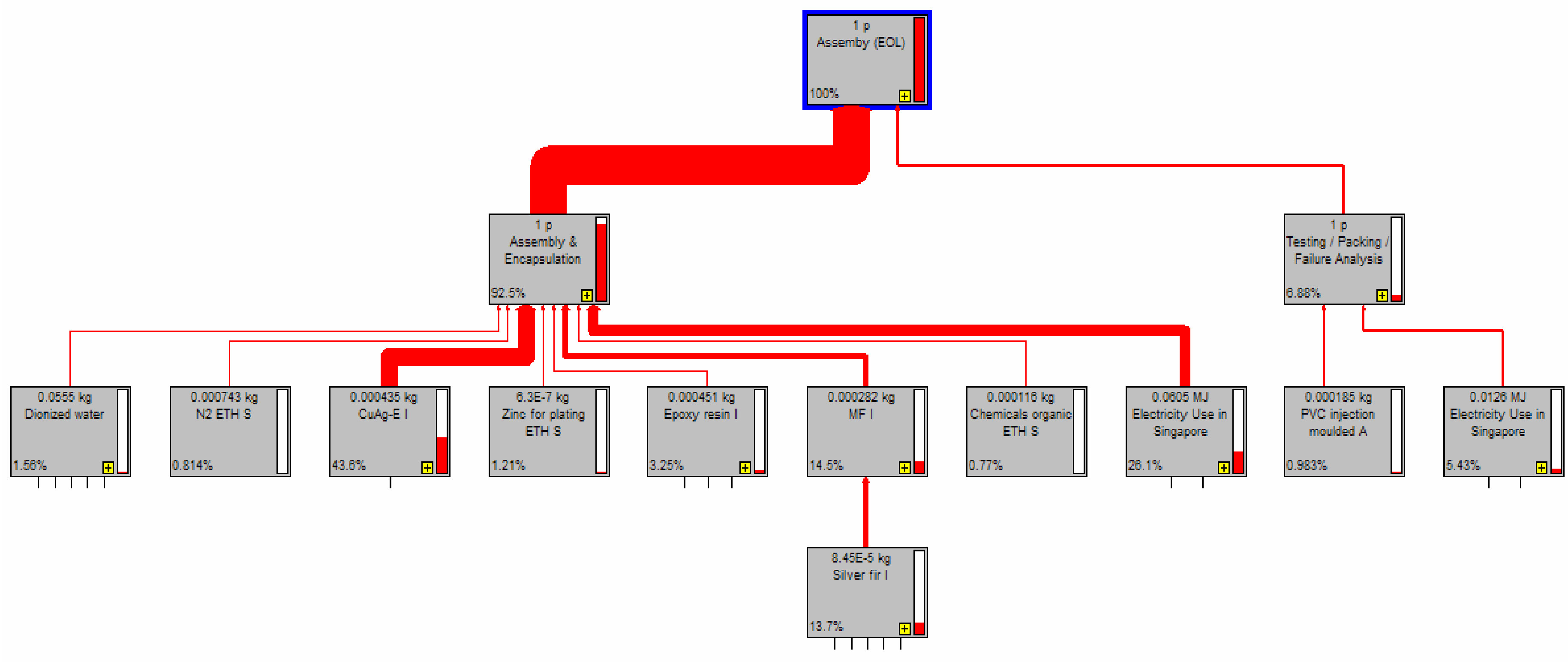
C16. Climate change – FOL



C17. Damage to Ecosystem Quality



C18. Ecosystem Quality - EOL



C19. Ecosystem Quality – FOL

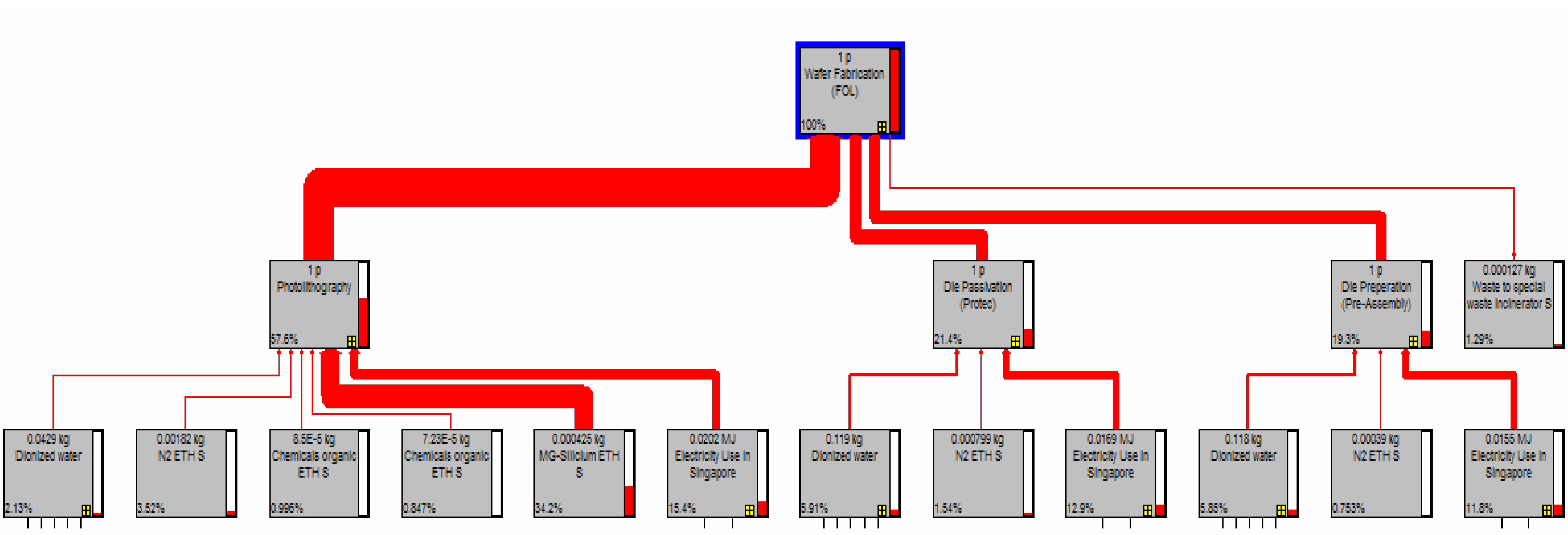
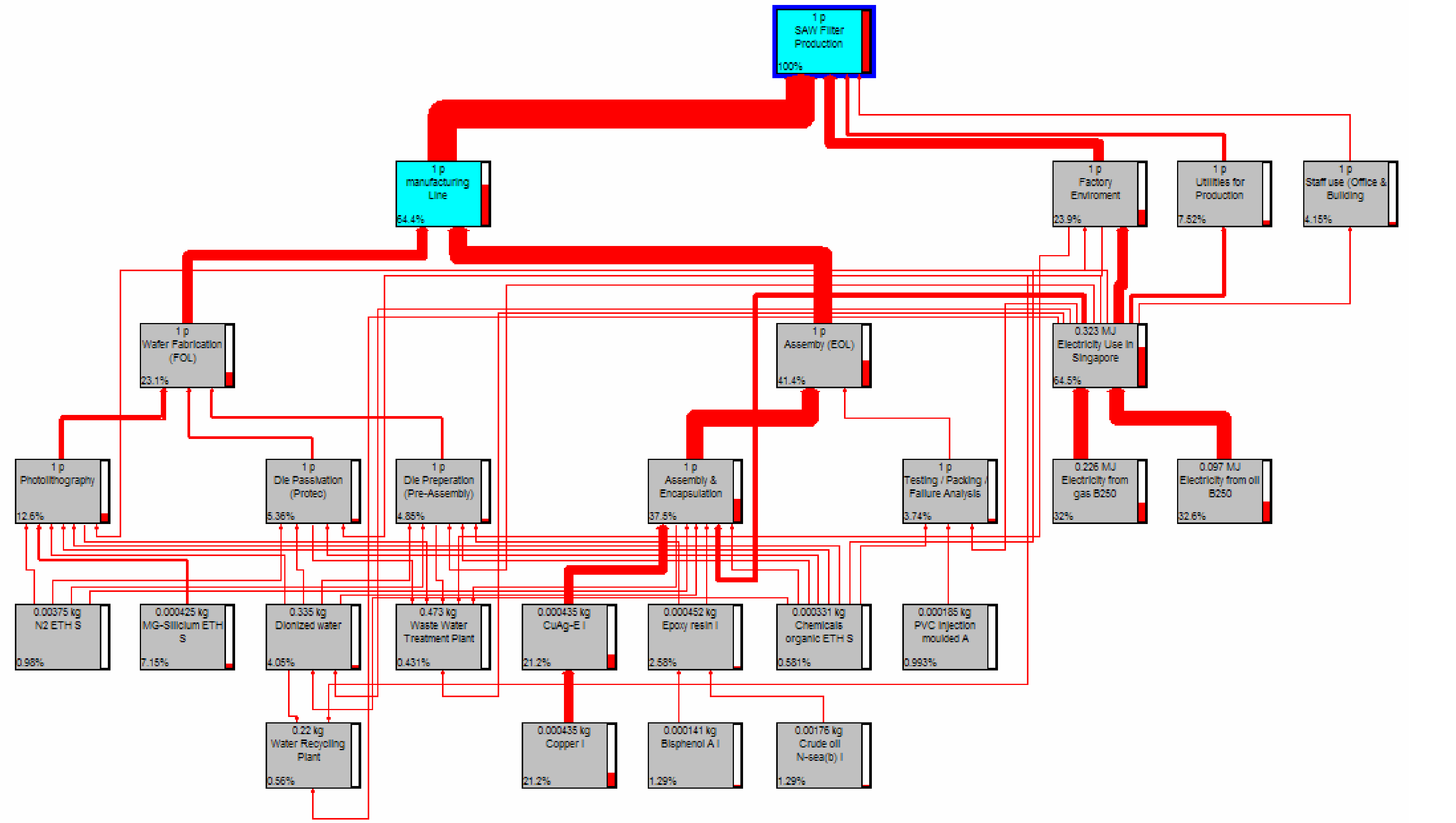
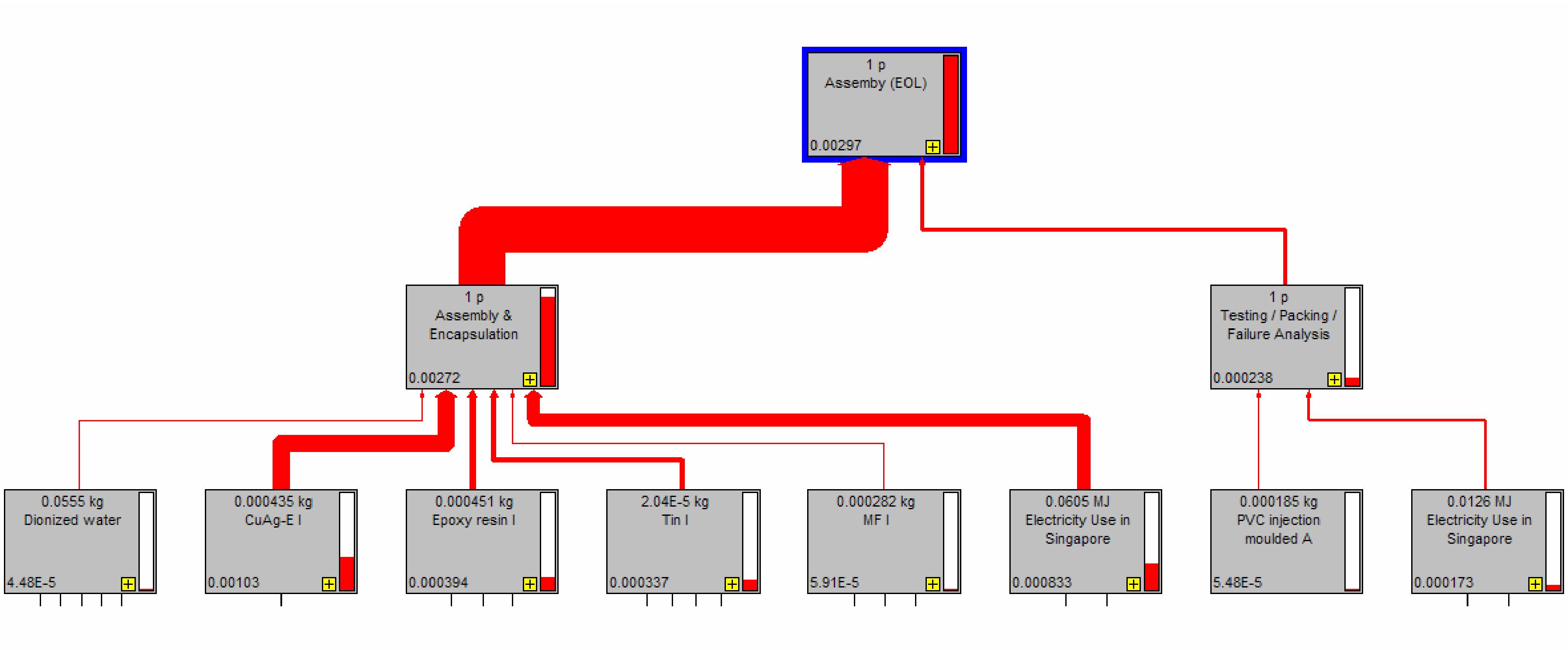


Figure 6.25: Network showing Ecosystem quality health damage assessment (FOL)

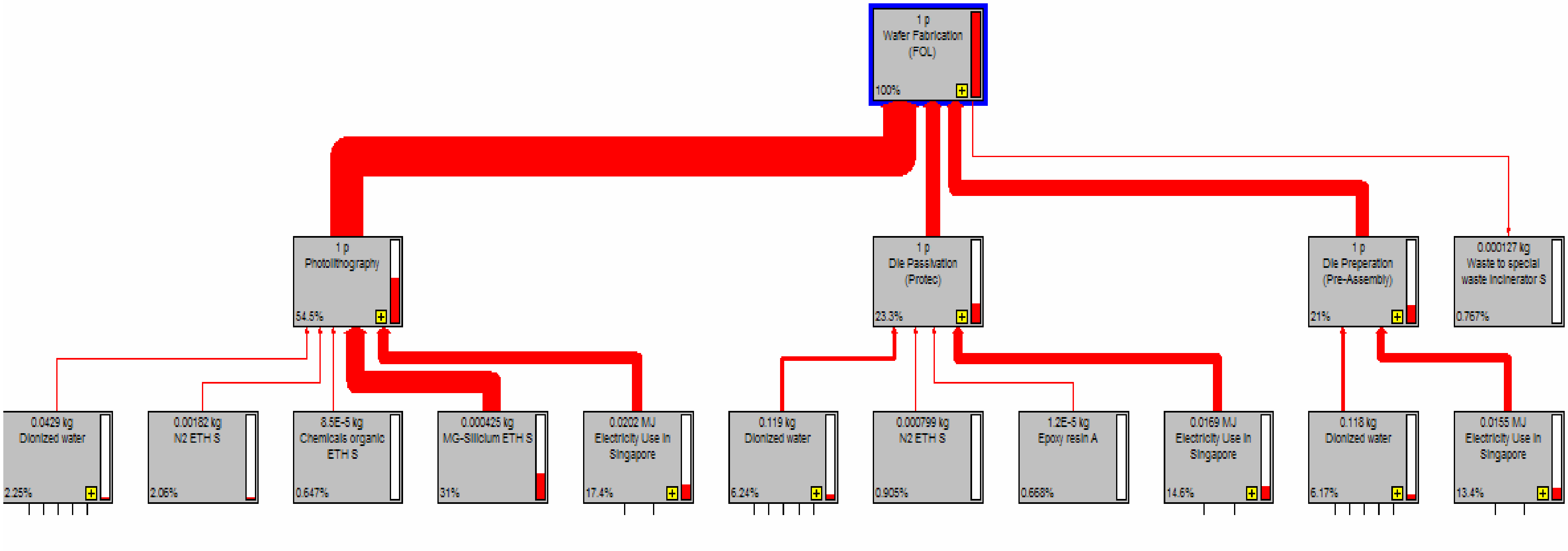
C20. Impact Category – Acidification/Eutrophication



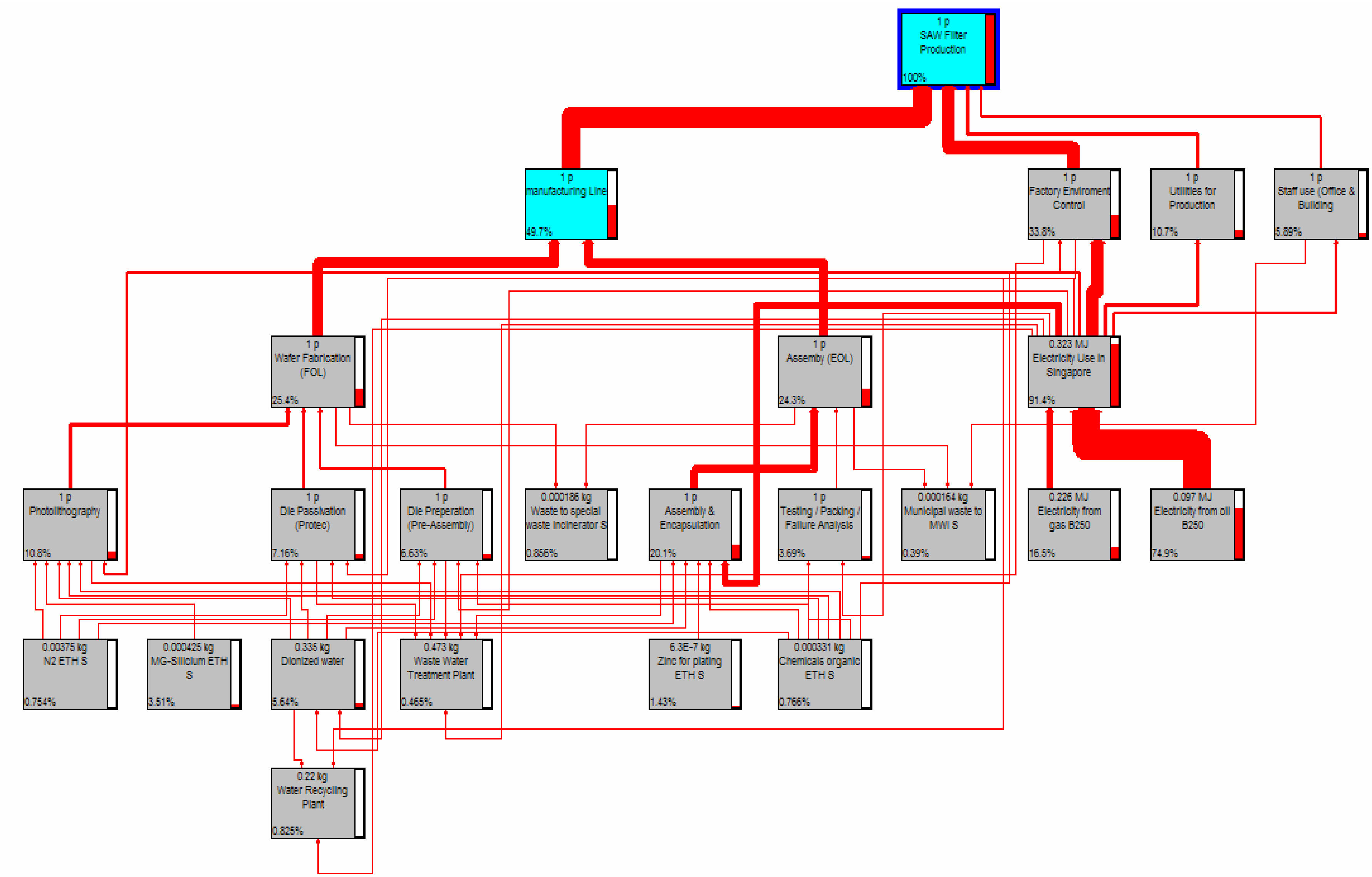
C21. Acidification/Eutrophication - EOL



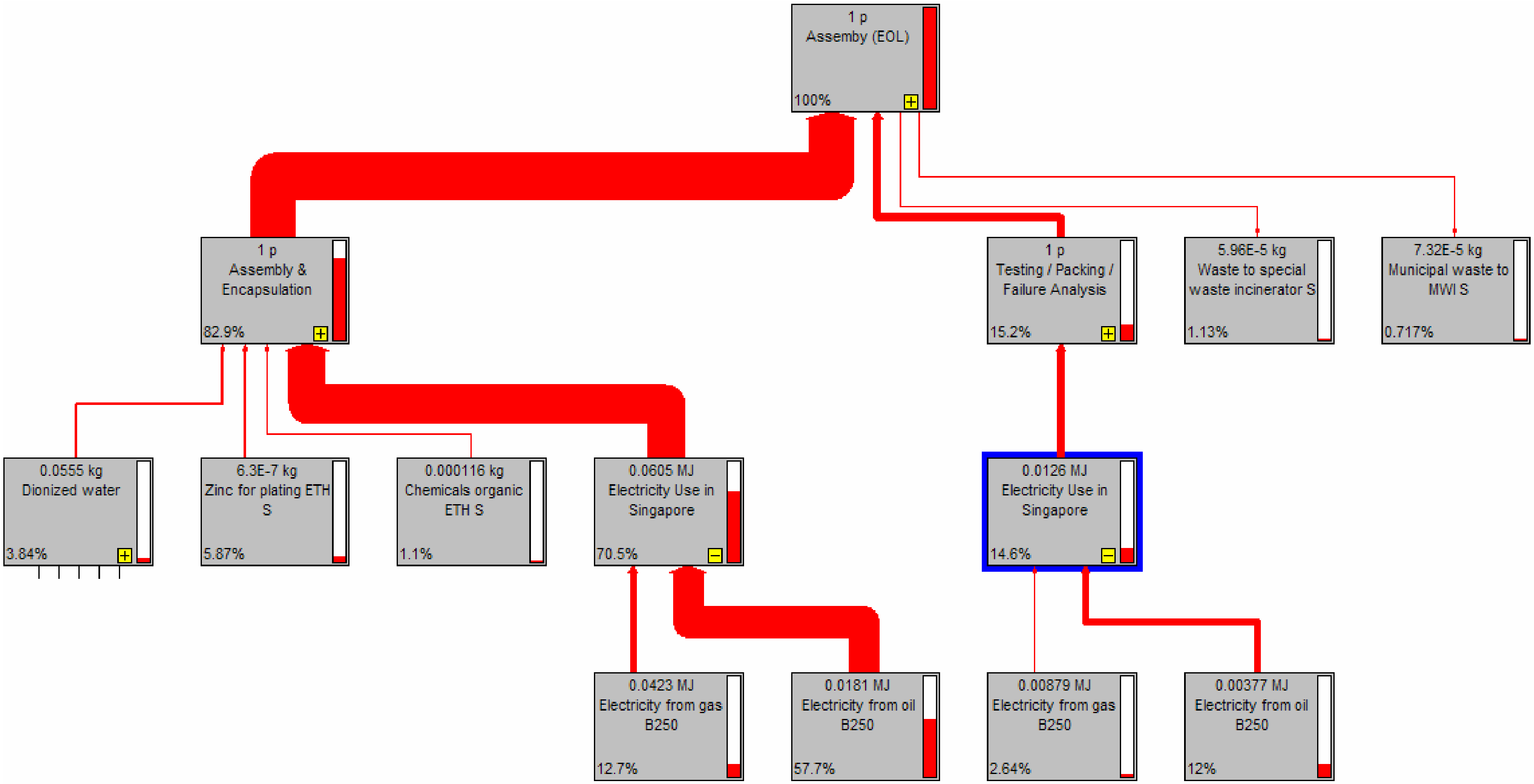
C22. Acidification/Eutrophication - FOL



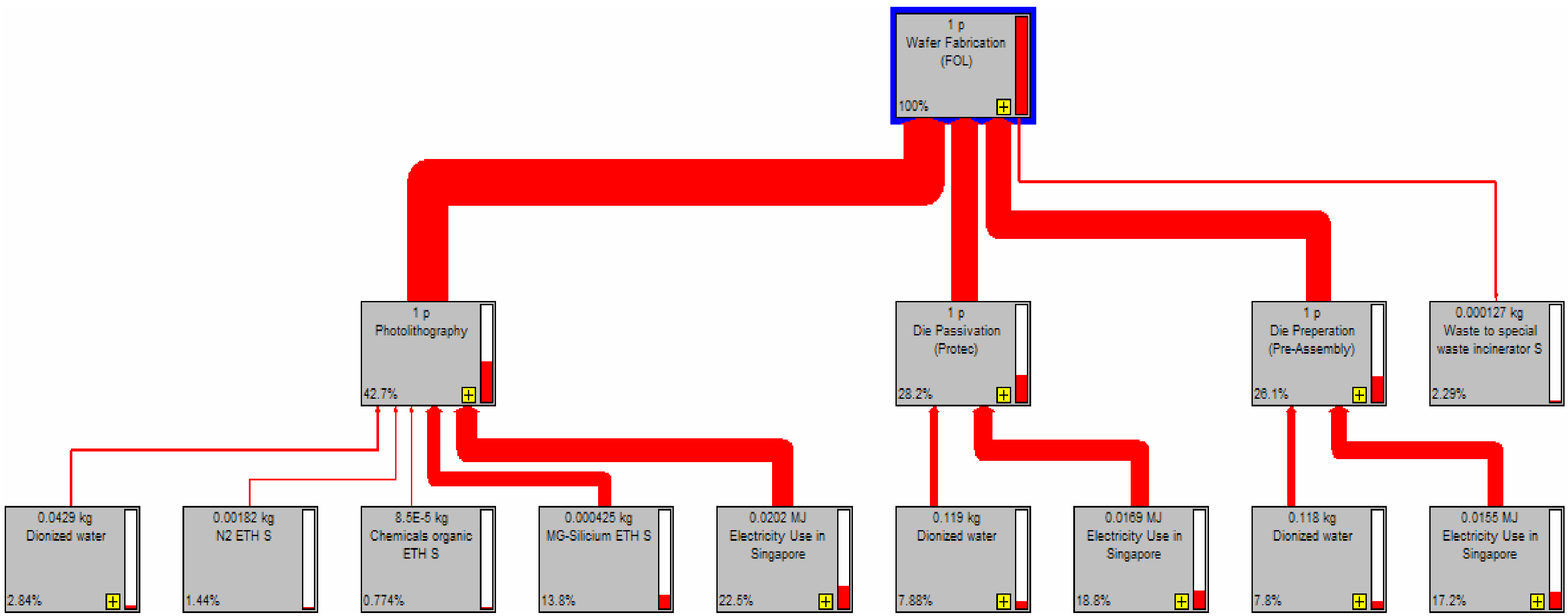
C23. Impact Category – Ecotoxicity



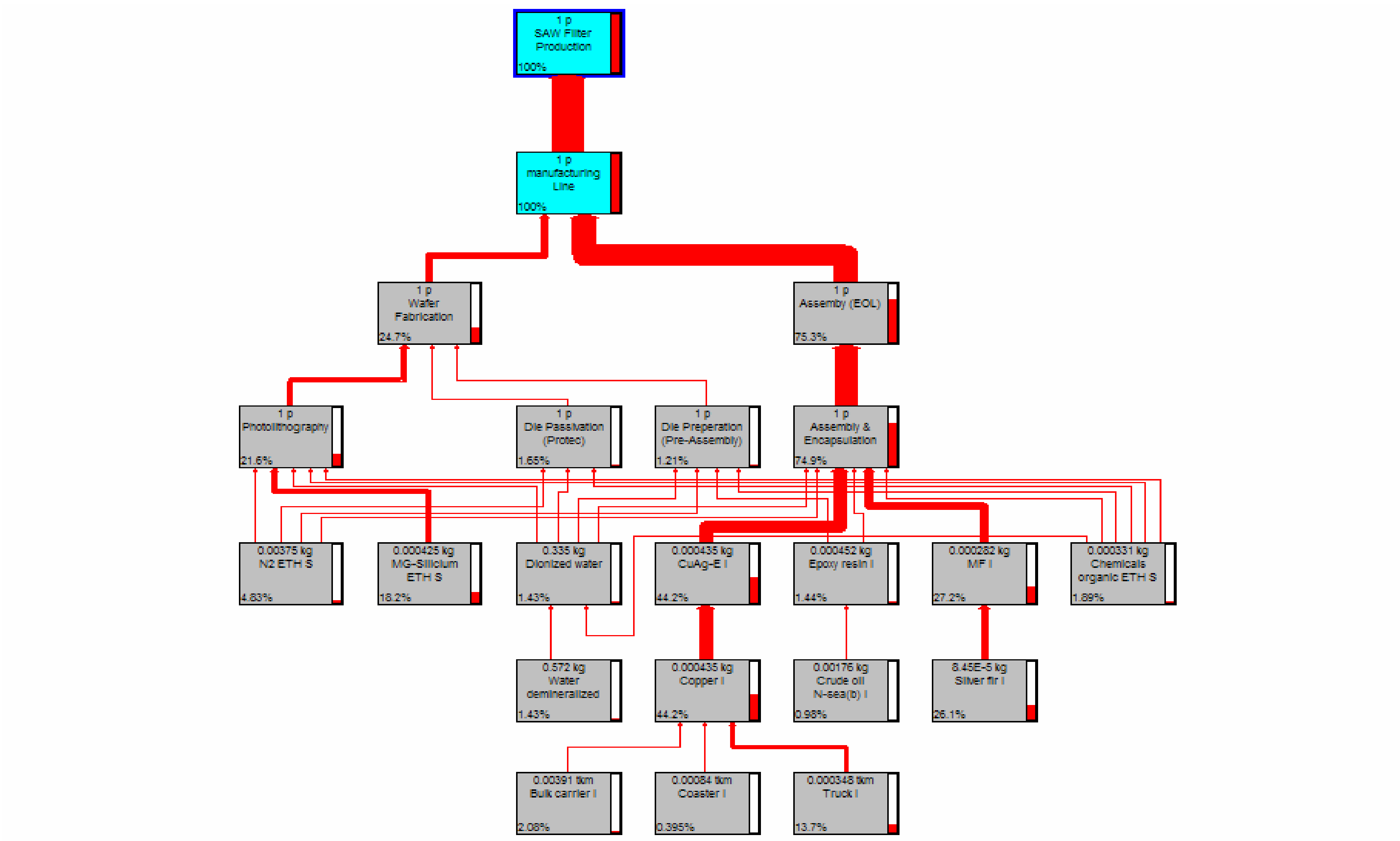
C24. Ecotoxicity - EOL



C25. Ecotoxicity – FOL



C26. Impact Category –Land use



Appendix D –Sensitivity Analysis

D1. Single score result using Buwal 250 electricity model

D2. Single score result using ETS-EHU 96 electricity model

D3. Single score result using Franklin USA 98 electricity model

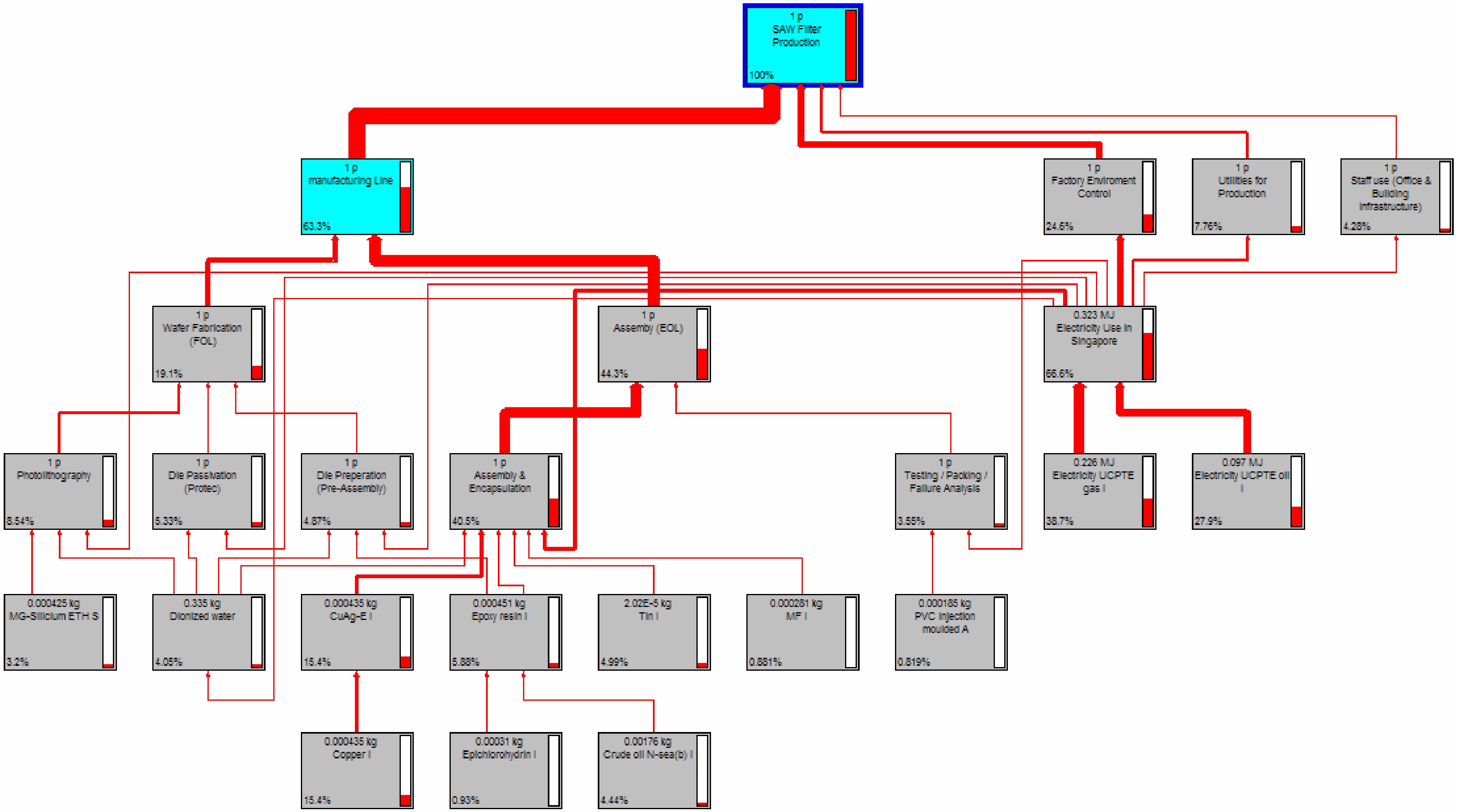
D4. Sensitivity analysis – 0% recyclable (Single score)

D5. Sensitivity analysis – 20% recyclable (Single score)

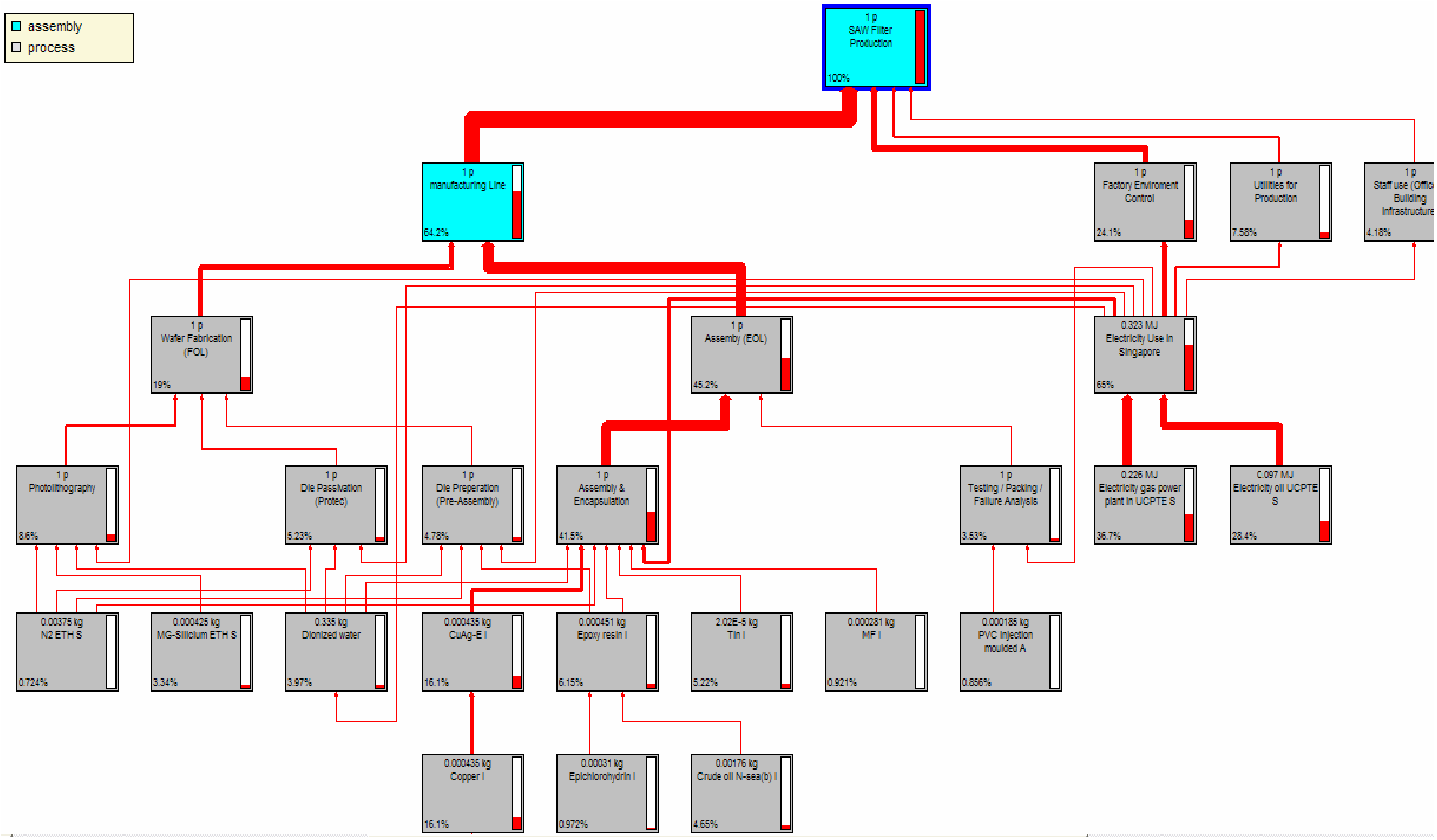
D6. Sensitivity analysis – 45% recyclable (Single score)

D7. Sensitivity analysis – 70% recyclable (Single score)

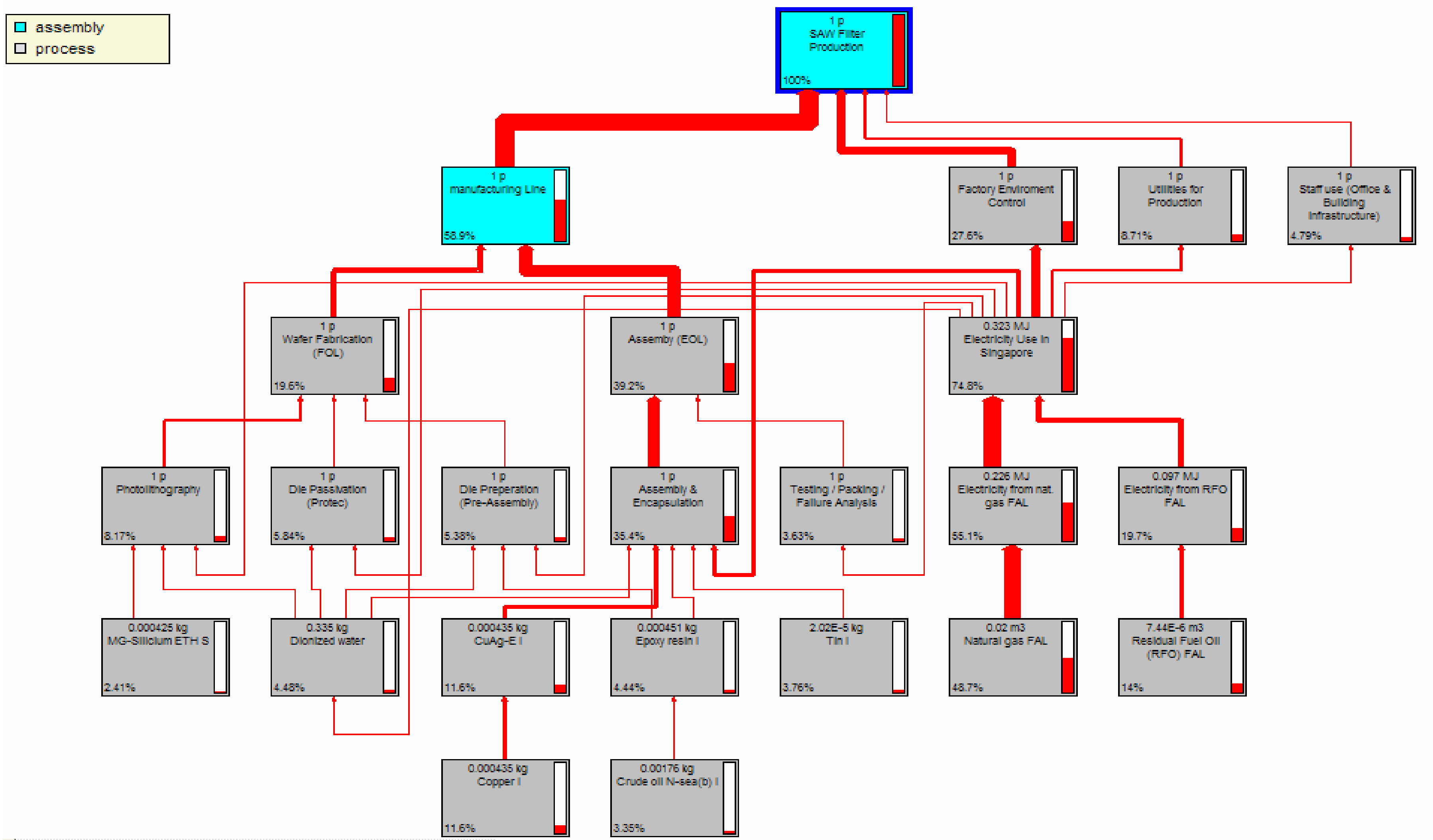
D1. Single score result using Buwal 250 electricity model



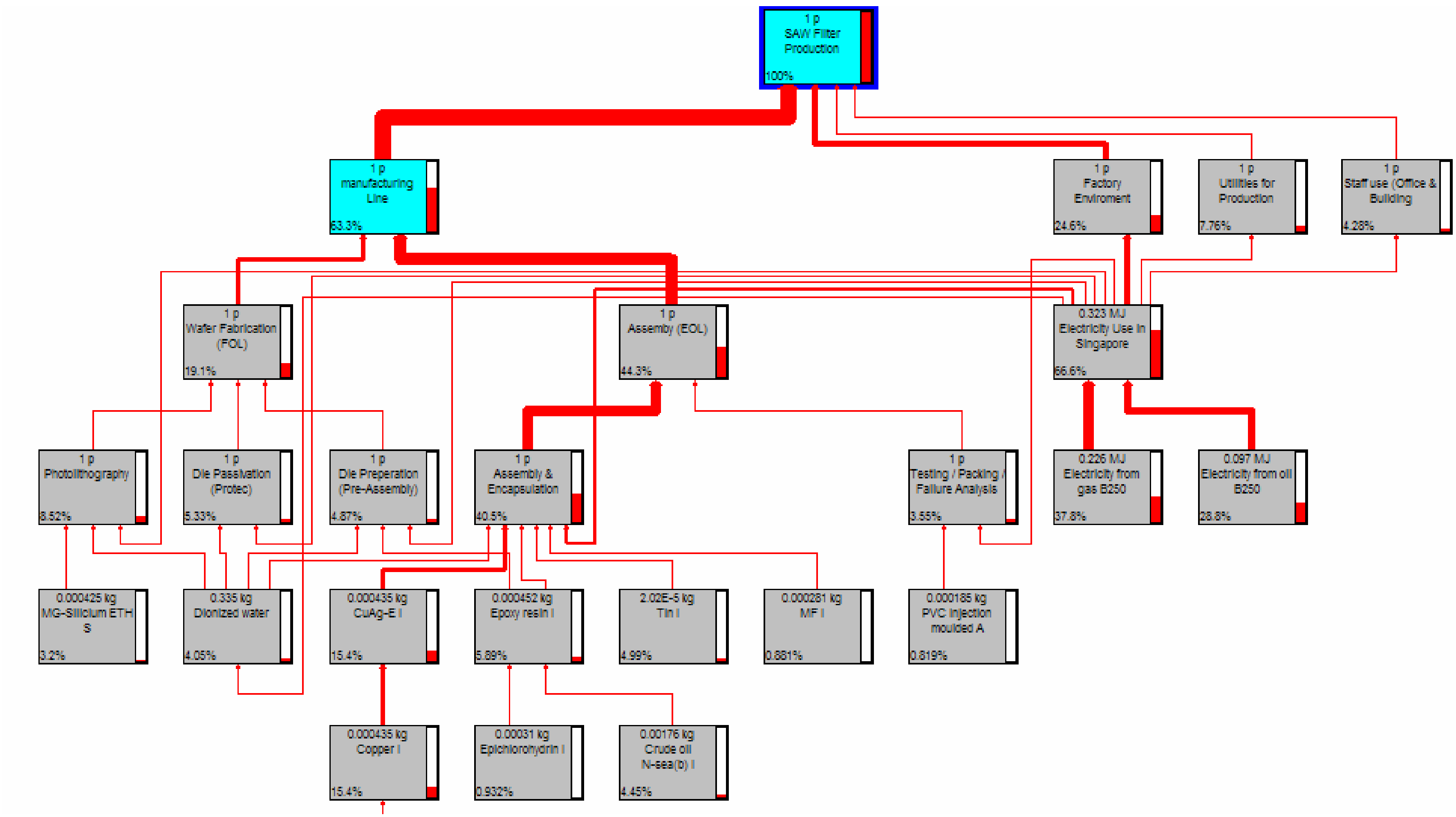
D2. Single score result using ETS-EHU model electricity model



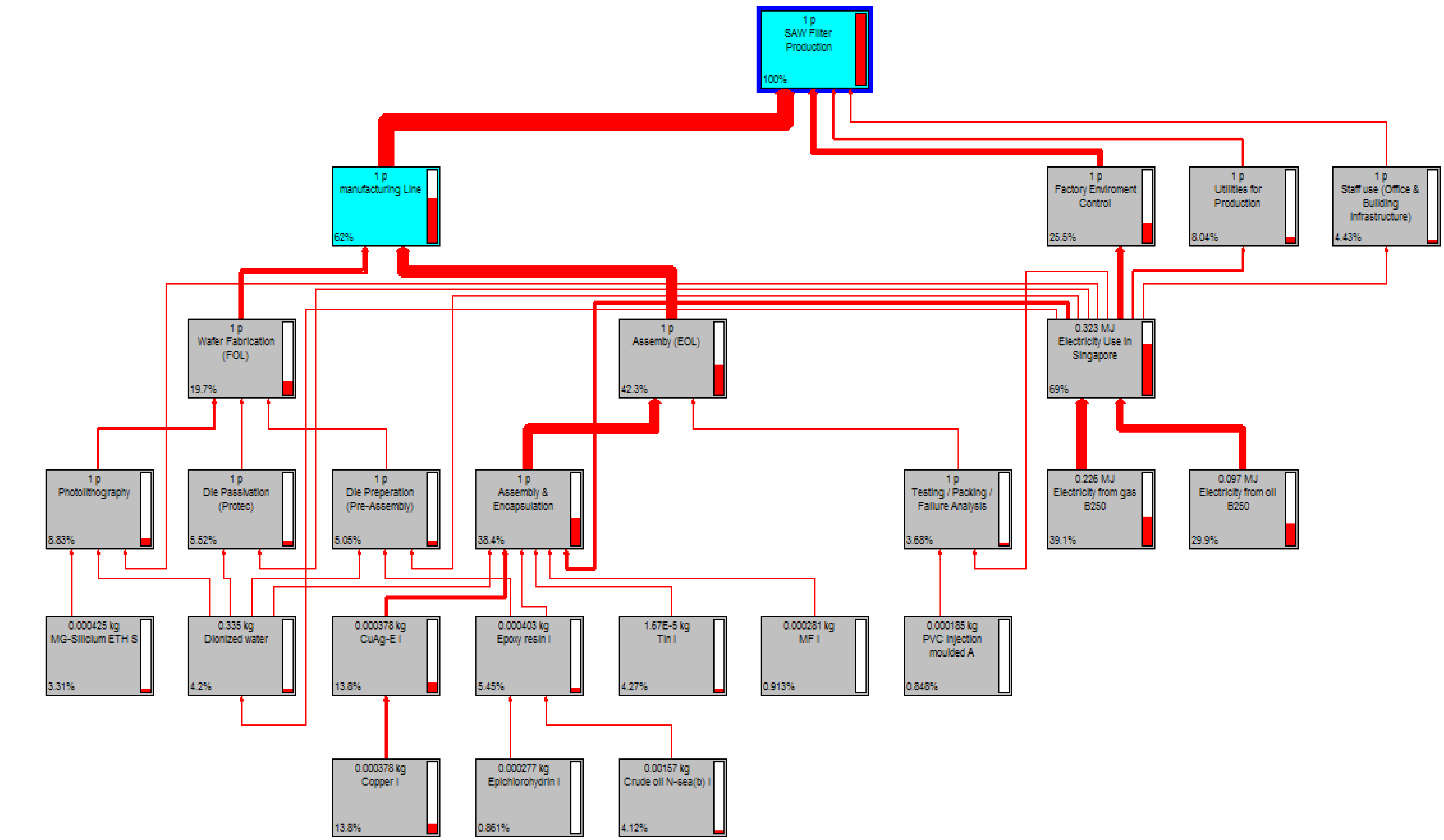
D3. Single score result using Franklin USA 98 model electricity model



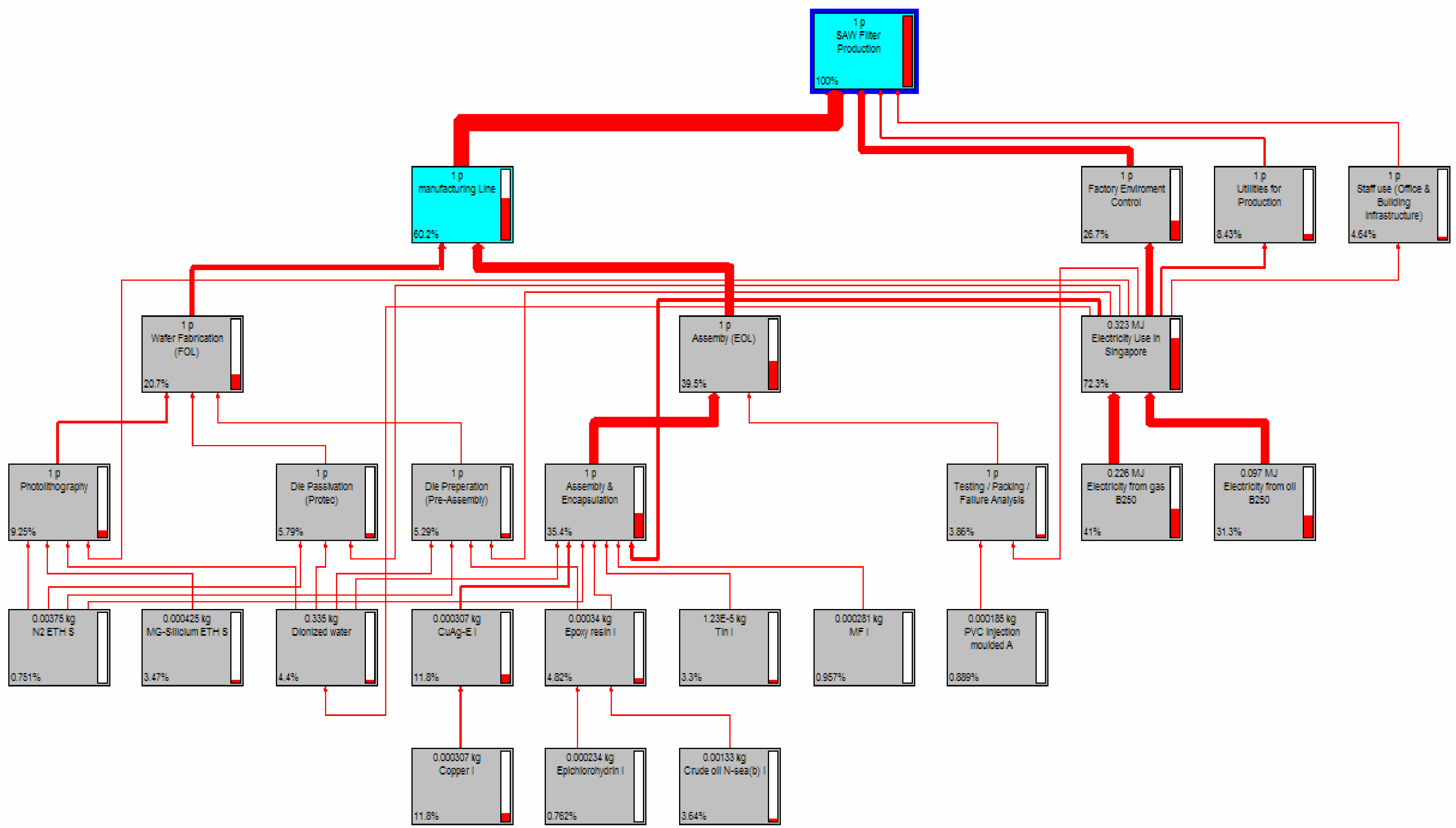
D4. Sensitivity analysis – 0% recyclable (Single score)



D5. Sensitivity analysis – 20% recyclable (Single score)



D6. Sensitivity analysis – 45% recyclable (Single score)



D7. Sensitivity analysis – 70% recyclable (Single score)