An ontology-based product design adviser for assessing End-of-Life (EoL) performance

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**AN ONTOLOGY- BASED PRODUCT DESIGN
ADVISER FOR ASSESSING END-OF-LIFE (EoL)
PERFORMANCE**

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An Ontology-Based Product Design Adviser for Assessing End-of-Life (EoL) Performance

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SUMMARY

Over the last decade, environmental sustainability has become an important focus of the international community. In the years to come, it will be even more imperative as the environment continues to deteriorate and an energy crisis continues to loom. Manufacturers are under pressure to practise sustainable product development in the light of more legislation and more emphasis on corporate social responsibility. Manufacturers are adopting the life cycle approach in product development in which the product life cycle loop is closed through considering a product's end-of-life (EoL) performance at the design stage. Such an approach is fundamental for sustainable product development. The challenge lies in filling the knowledge gap between the end-of-life stage and the design stage. More tools and methodologies for Design for End-of-Life (DfEoL) are needed to assist designers in designing products with better end-of-life performance.

In the work of this thesis, an ontology-based product design advisor for EoL performance is proposed. This design advisor is based on a novel framework, Design and End-of-Life Information Integration (DELII), that provides a mechanism for information feedback from the EoL stage to designers and a method to assess the EoL performance of design alternatives. This framework leverages on the capabilities of the semantic web services and ontology to provide standardised nomenclature over a distributed environment for the enhancement of information sharing and communication. It consists of four layers, namely, data source, information, analysis and reasoning, and decision support. The EoL engineers would be the ones supplying and managing the information at the data source layer. These data sources will be

processed by information layer before going to the analysis and reasoning layer. Lastly, this information will be transformed into knowledge for decision support layer for the designers to access. Ontology is used in the process of managing the information in the framework.

The transformation of the information to knowledge that can help designers to make decisions is achieved through an End-of-Life (EoL) index methodology. This EoL index is a quantified methodology to assess the EoL performance of a product design. It is divided into three major sub-indices according to the three aspects of EoL, namely, disassembly, disposal and recovery. A case study on a power tool is being investigated using the proposed product design advisor. Subsequently, a system design based on an Integrated Manufacturing and Services System framework is proposed for the realisation of the product design advisor. In this system design, emerging semantic web services technologies are employed.

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchical Process
CSR	Corporate Social Responsibility
DAML	Darpa Agent Markup Language
D-BOM	Design Bill-of-Material
DELII	Design and End-of-Life Information Integration
DfE	Design for Environment
DfEoL	Design for End-of-Life
DfR	Design for Recycling
ELDA	End-of-Life Design Advisor
ELV	End-of-Life Vehicle
EoL	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
EuP	Energy-using Product
EVCA	End-of-Life Value Chain Advisor
HTTP	Hypertext Transfer Protocol
IEC	International Electrotechnical Commission
IEEE	Institute of the Electrical and Electronic Engineers
IMPSS	Integrated Manufacturing and Product Services System
IMSS	Integrated Manufacturing and Services System
IPCC	Intergovernmental Panel on Climate Change
IPP	Integrated Product Policy

ISO	International Standard Organisation
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCE	Life Cycle Engineering
MNC	Multi-National Company
OECD	Organisation for Economic Cooperation and Development
OEM	Original Equipment Manufacturers
OIL	Ontology Inference Layer
OWL	Web Ontology Language
PLM	Product Life Cycle Management
PROMISE	Product Life Cycle Management and Information Tracking Using Smart Embedded System
PSS	Product Services System
QWERTY	Quote for environmentally weighted recyclability
RDF	Resource Description Framework
RoHS	Restriction on Hazardous Substance
SAWSDL	Semantically Annotated Web Service Description Language
SOAP	Simple Object Access Protocol
UDDI	Universal Description, Discovery and Integration
UI	User Interface
UN	United Nations
UNEP	United Nations Environment Programme
VDI	Verein Deutscher Ingenieure
W3C	World Wide Web Consortium
WEEE	Waste in Electronic and Electrical Equipment

WSDL	Web Service Description Language
WSML	Web Service Modelling Language
WSMO	Web Service Modelling Ontology
XML	Extensible Markup Language

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the light of the heightening of environmental awareness at an unprecedented international level after the announcement of the Intergovernmental Panel on Climate Change (IPCC) Report on Climate Change [1, 2], efforts are pouring from all areas to work towards environmental sustainability. Environmental sustainability of the world has become a major concern internationally over the last decade. More international organisations are giving negative indicators to illustrate the deteriorating conditions of our planet Earth. Increasing pressure, attention and effort are being placed on various aspects of sustainable development. According to the World Commission on Environment and Development set up by the UN, sustainable development refers to the development that meets the needs of present generations without compromising the ability of future generations to meet their own needs [3]. It is imperative to maintain a balance in economic development, environmental protection and social equity. Sustainable Product Development, which aims to deliver better performing products

using fewer resources, cause less waste and pollution and contribute to social progress worldwide, is becoming and must be essential. In particular, product manufacturers are expected to exercise corporate social responsibility to promote sustainable product development and achieve the triple bottom line, namely, people, planet and profit [4, 5]. At the same time, the US National Science Foundation has also proclaimed that one of the visionary manufacturing challenges in 2020 is to reduce production waste and product environmental impact to "near zero" environmental impact [6].

1.2 Motivations for End-of-Life Research

Going green in the manufacturing sectors is not new. In recent years, however, it has risen to unprecedented levels of involvement for all manufacturers, especially in the electrical and electronic industries. There are many activities that prompted this development and more sustainability related manufacturing activities are set to take the stage. Amongst these, vast interests and efforts are invested into End-of-Life (EoL) research and activities.

EoL is the last phase of a product lifespan. The EoL stage has always been a neglected stage in the past when disposal was not viewed as a problem to many countries. However, with the escalating amount of waste being generated, the environmental impact has become an important issue to tackle. Consequently, other EoL options need to be explored and EoL becomes one of the primary topics for discussions in the last few years [7].

The drivers for EoL research include legislations, corporate social responsibility, market force and consumer demands, economic incentives, improving environmental performance, and life cycle approach to product development. The following section gives the background and status of these drivers.

1.2.1 Legislation and Standards

The main driving force behind greener product or sustainable product development is legislation. International organisations such as Greenpeace [8] and United Nations Environmental Programme (UNEP) [9] are pushing for more environmental related legislation and standards to be in place to improve environmental sustainability. The approaches taken in different regions varied. In Asia, Japan is leading with Law for Promotions of Effective Utilisation of Resources [10], End-of-Life Vehicle [11], Home Appliances Recycling Law [12] and Containers and Packaging Recycling Law [13], followed by Taiwan and South Korea. The latter two countries have set electronic take-back regulations [14]. Over in the US, while there is no legislation at the national level, the US Congress are looking at setting up E-waste standards [15] and at the state level, there are already law to mandate e-waste [16] such as the California Electronic Waste Recycling Act, Maine and Maryland. The European Union is the strictest and most comprehensive in this aspect. The EU has taken a holistic approach with initiatives and legislation for environmental sustainability. The range of legislation encompasses a wide range of directives that set out to address the different disciplines of sustainable development. Amongst them, there are a few significant directives and policies that are directly affecting the product development cycle in a great way. These include:

- 1) Directive on Waste in Electrical and Electronic Equipment (WEEE) [17]

This directive went into effect in year 2006, mandating all manufacturers to provide take back services to recover at least 60% of the volume (depending on the type of equipment) that they produced. The purpose of this Directive is, as a first priority, the prevention of waste electrical and electronic equipment (WEEE), and in addition, the reuse, recycling and other forms of recovery of

such wastes so as to reduce the disposal of waste. It also seeks to improve the environmental performance of all operators involved in the life cycle of electrical and electronic equipment, e.g. producers, distributors and consumers and in particular those operators directly involved in the treatment of waste electrical and electronic equipment.

2) Directive on Restriction of Hazardous Substances (RoHS) [18]

This directive which is bundled with the WEEE sets to ban the use of hazardous substances in the design and manufacture of the product. These substances are toxic and will pollute the environment which subsequently might affect human health when used during production and at its EoL. The purpose of this directive is to approximate the laws of the Member States on the restrictions of the use of hazardous substances in electrical and electronic equipment and to contribute to the protection of human health and the environmentally sound recovery and disposal of waste electrical and electronic equipment.

3) Directive on Energy using Products (EuP) [19]

This directive is a follow up to the Integrated Product Policy and Amsterdam Treaty [20]. The objective is to promote sustainable development through free movement of EuP, environmental protection and increase security of energy supply. It identifies the significant environmental aspects of the products on the basis of a list of eco-design parameters and search for design options that could improve the product environmental performance in balance with technical and economic constraints. Implementation measures for eco-design requirements which will address the significant environment impacts of the examined

product throughout the entire product life cycle will be given out to the manufacturers.

4) Directive on End-of-Life Vehicles (ELV) [21]

This directive legislates the compulsory recovery of EoL vehicles. It lays down measures which aim, as a first priority, at the prevention of waste from vehicles. In addition, it also includes guidelines for the reuse, recycling and other forms of recovery of end-of life vehicles and their components so as to reduce the disposal of waste and to improve the environmental performance of all of the economic operators involved in the life cycle of vehicles. This is especially specific to the operators directly involved in the treatment of end-of life vehicles. This is a directive dealing with a specific sector.

5) Eco Labelling Schemes [22]

There are various eco labelling schemes being introduced over the past 2 decades by different countries and organizations. The purpose is to provide consumers with a better distinction between environmentally superior products and the normal ones. The labels will certify that the product has attained a certain level of environmental standards as recommended by the administration body. There are both voluntary and mandatory schemes available.

Since the beginning of sustainable design and manufacture research, various standards pertaining to the environment have also been established. These include the ISO 14000 series [23], International Electrotechnical Commission (IEC), Institute of Electrical and Electronic Engineers (IEEE) standards, British Standards (BS) and Germany's Verein Deutscher Ingenieure (VDI). Notably some standards which affect design and EoL of electrical and electronic equipment include the IEEE Standard 1680

[24], British Standard 8886-1:2006 [25], IEC Guide 114 [26] and VDI 2243 [27]. While these standards are of voluntary basis, more manufacturers are adhering to them for the purpose of improving the product's sustainability.

1.2.2 Corporate Social Responsibility

Corporate Social Responsibility (CSR) is an emerging trend for many companies to improve their corporate image and branding. It generally refers to concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis [28]. The World Business Council for Sustainable Development defined CSR as “the commitment of business to contribute to sustainable economic development, working with employees, their families, the local community and society at large to improve their quality of life”[29]. Many manufacturers are contributing back to society in a myriad of ways. Taking up extended producer responsibility (EPR) and pledging to improve environmental sustainability have been popular choices since the late 1990s. They have implemented more environmentally friendly measures in both management and productions. EPR as defined by the Organisation for Economic Cooperation and Development (OECD) is the principle that manufacturers and importers of the products should bear a significant degree of responsibility for the environmental impacts of their products throughout the product life cycle, including impacts from the initial selection of materials to the use and disposal of the products [30]. Being known as an environmentally responsible or a green producer will give a manufacturer a niche and competitive advantage by having a good corporate image [31].

1.2.3 Market Forces and Consumer Demands

As the consumer markets progress and the quality of life improve, consumers are demanding more from product manufacturers. On top of the traditional speed, aesthetics, ergonomics, quality, technology, safety and cost, well-informed consumers are getting more conscious about intangibles such as environmental sustainability and value of the services. Given this shift, the competitive advantages of a manufacturing enterprise are no longer those traditional aspects but other economic dynamics that will determine the success of a manufacturing enterprise in this robust economy. Besides providing affordable, quality and innovative products in shorter lead-times, manufacturers also need to look into bundling affordable, efficient and quality and environmentally conscious services with their products in order to distinguish themselves from the rest of the competitors [32, 33].

Those environmentally savvy consumers will support products that are more environmentally-friendly, look out for eco labels and no longer just go for lower costs. In surveys from different regions including US, EU and Asia by Global Market Insight, Inc [34], there is a general consensus that consumers are placing environmental sustainability as one of the top priorities and do not mind paying more for the green benefits. Notably, an emerging market segment Lifestyles on Health and Sustainability (LOHA) [35] in Japan is growing rapidly. Hence, in response to this, the manufacturing landscape has changed drastically over the last few years. Manufacturers have to establish a new niche area to enhance their competitive edge such as leading more sustainable initiatives and providing quality services together with the product through a total life cycle management approach to bring about an integrated and holistic management of a product from its cradle to grave[33].

1.2.4 Economic Incentives

Going green can also bring about cost savings and improve profit margins in the operations of manufacturers by leveraging on the Life Cycle Engineering (LCE) approach. Firstly, having EoL management with a take back system will provide manufacturers with an alternative source of materials for production that might lower production cost. This will reduce their reliance on virgin raw materials which could be priced higher due to the environmental burden created in extracting them. Secondly, reuse, remanufacturing and recycling activities can form new revenue streams. These activities target new market segments such as the second hand markets. The collected used products after disassembly and cleaning can be sold as re-conditioned modules or recycled materials. Today, most of the second hand markets are dominated by disparate independent companies. Manufacturers are able to gain more control over the second hand market through remanufacturing their own product at the EoL stage. In this way, they can increase their profit margin through gaining larger market share and decreased competition. Thirdly, by positioning themselves as a green manufacturer, there is an incentive for charging a premium for the green branding that they carry and this will help them to capture a specific higher end segment of consumers who look for environmental features.

Next, wastages of resources and energy usage can be reduced in the process if the entire life cycle cost is being optimised through careful life cycle considerations to minimise changes and reworks. Lastly, by moving on to sustainable manufacture, there could be tax incentives in certain countries and regions which could bring down the total cost. Companies might get tax relief for meeting certain green requirements or they could avoid the penalty incurred in the case of not complying with environmental legislations.

1.2.5 Improve Environmental Performance

The fundamental objective of sustainable product development is definitely to improve environmental performance of the product and to preserve environmental sustainability. For this purpose, manufacturers adopt measures that minimise the environmental impact in the product development process. It is necessary to pre-design a closed product life cycle and to manage it for less products and energy flow without excessive overheads load [36]. These efforts can be applied in each and every stage of the product life cycle and will be especially effective if appropriately implemented at the EoL stage due to the significant environmental burden that the EoL stage incurs currently. EoL has great potential for environmental improvements as this is a stage whereby resources are being managed and channelled to the various EoL options instead of being dumped in the landfill or incinerated. The demand for more disposal channels, which could cause more pollution, is eased, giving a cleaner environment. This can also ensure that the hazardous and toxic substances are being properly managed to minimise the environmental risks to human health and the natural surroundings. These decisions will affect the amount of resources retained in the product life cycle as well. When resources are being fed back to the material acquisition stage, the supply of materials to the production stage is increased and this lessens the need to tap onto virgin resources. The resources are more optimally utilised in this case and not wasted, especially for valuable resources such as precious metals and engineered plastics.

EoL management is gaining importance in this rapidly advancing digital age due to the escalating number of electronic waste being generated. The issues of electronics waste have risen to an alarming rate to be of concern by many stakeholders in the international community. Improper management of e-waste is hogging up the waste

stream and creating environmental as well as human health hazard in some areas of developing countries, such as Geyu in China [37-40].

1.2.6 Life Cycle Approach to Product Development

In addition, manufacturing enterprises have been gearing towards a product-centric approach and Design for Environment in developing a product. They look at the entire product life cycle and manage the product from “cradle-to-grave” in an attempt to maximise the value of the product. In view of the various legislations, standards and constraints, in recent years, many manufacturers are adopting the life cycle approaches to design and develop products, in particular for complex products such as electrical and electronic products [41]. There is a need to integrate both the product and process from a life cycle perspective

For instance, MNCs such as Hewlett Packard(HP)[42], Dell [43], Nokia [44] and Panasonic [45] have implemented programme for designing and developing their products using the life cycle approach. Using the holistic life cycle approach reaps two benefits: it will be able to lower both the ecological and economical cost; this approach also calls for system tools that are applicable to multi-stages and be able to link up the various stages.

1.3 Aims and Objectives

The main aim is to propose an ontology-based product design advisor for End-of-Life (EoL) performance. This advisor is to facilitate and enhance the communications between the design stage and the end-of-life stage of the product life

cycle to provide advisory to the designers for more effective and efficient sustainable product development. This aim can be split into three main objectives:

- 1) To provide a feedback mechanism in terms of a novel framework for the EoL engineers to send relevant information back to the designers for references.
- 2) To transform the data into information and knowledge for the designers to understand and assess the EoL performance of a product.
- 3) To establish a web-distributed system design to implement this feedback mechanism and manage the information.

1.4 Major Contributions of the Thesis

The major contributions of the thesis are as follows:

- 1) A novel framework for promoting and facilitation of communications between the design stage and EoL stage.

This work enhances the information flow from the EoL stakeholders to the designers through the application of the framework. The designers are able to make use of up to date information from the EoL stakeholders to assist them in assessing the EoL performance. The assimilation of EoL information for closing the information loop in the product life cycle is achieved.

- 2) A new EoL index for assessment of EoL performance of product design alternatives.

The factors included are more comprehensive and holistic than those for existing indices. Most of the aspects relating to the EoL of a product especially an electrical product are being considered during the development of the index.

- 3) The application of ontology for information management in product design and EoL management.

The nomenclatures used in both design and EoL are standardized through the application of ontology. This will reduce the possibility of miscommunications and allowing the players from both stages to speak a common language.

- 4) A new semantic web service based distributed system design for implementing the proposed framework.

This system design allows the designers and EoL engineers from different geographical locations to log in and use the system anytime. It is not a standalone system whereby the use is constrained to a specific location.

1.5 Organization of Chapters

In this thesis, Chapter 2 will be a literature review on the issues and current state-of-art technologies relating to EoL research. Chapter 3 proposes and introduces the framework Design and EoL Information Integration (DELII). It will describe the framework as to what it does, how it works and where it is applicable. It also elaborates on the End-of-Life stage and discusses the relationships between design and the EoL stage. The detailed methodology of the EoL index is described in Chapter 4. In this chapter, the factors being considered in the EoL index calculation and how to calculate the index will be included. Chapter 5 is to describe the system architecture and the system design. The semantic web service technology which is employed in our work will be included. Chapter 6 gives a case study of a power tool which the EoL index is applied to. Chapter 7 suggests future works and concludes this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to End-of-Life Research

End-of-Life (EoL) research for products is an emerging trend in the recent years [7, 31, 46]. More and more research focus is directed at the engineering and management of product EoL. This kind of research is of a multidisciplinary nature and has a wide scope. It ranges from technical issues to socio-technical issues and to management issues. In the past, most of the EoL measures and issues tackled were process based and focused on end-of-pipe emissions controls and remediation measures for pollution controls [46, 47]. Researchers studied and researched into treatment processes and methods to reduce environmental impact at individual industrial facilities [48]. These efforts are very piecewise and neglected the impacts from the product itself. Thus, the need for product-centric research arose.

There is already a myriad of different kinds of project and research efforts in various disparate topics addressing product-centric environmental impacts [49]. It started with product recovery, then to disassembly efforts, then to recycling and

remanufacturing. There are innovations in the technicalities of doing disassembly [50-53], recycling [54] and remanufacturing [55-57] in the past decades. On top of this, other aspects of EoL activities are also considered in some research projects [31], for instance reverse logistics [58], forecasting of return rate for used products [59, 60], design for EoL [61], information management of EoL [62, 63], modeling of take back systems [64], policy making of EoL [65] and economic analysis of EoL activities [66, 67].

There are two main aspects of EoL research, namely the technical and management aspects. Under the technical aspects, three important sub-sections, the physical recovery and systems design and information management are identified. As for the other, the sub-sections will be policy-making, economical analysis and information management [31].

2.2 Physical Aspect of End-of-Life

Much has been talked about the physical recovery of products in terms of collection and take-back of used products, the efficiency of doing disassembly, the various methods of improving recycling and remanufacturing technology. Researching into each technique of EoL is very focused and disjointed from the rest of the EoL segment. In the earlier days, disassembly and recycling techniques and methods were studied widely [50, 68-74]. These are very much reactionary as they are often developed based on the design of the product. On the other hand, if the design is adapted for the products' use and/or EoL phases, one can achieve economic and environmental benefits [75]. This is further elaborated in the next section.

EoL stage is widely being included in product development life cycle in these few years but different researchers have their own way of defining EoL stages.

Generally, EoL refers to the stage when the product is no longer useful to the initial owner or purchaser, which is the stage after usage stage. EoL options include disposal options and recovery options such as recycling, remanufacturing and reuse. Different researchers specify different EoL activities and options in EoL stage [76, 77]. Nokia defines recycling as the main recovery option in the EoL [7]. This is too narrow as a definition, since recycling is on the lower priority of the EoL options hierarchy. Other recovery methods such as remanufacturing, refurbish and reuse should be considered as well. According to the EoL hierarchy defined by OECD [78], once the product is spent and needs to be got rid of by the owner, the most ecologically method is to reuse or refurbish the product by a second hand owner unless the continual usage of the product will lead to higher energy inefficiency. The hierarchy is followed by remanufacturing, where the whole module is being reconditioned and used in another product. Next is recycling where the product is broken into material level and recycled. Recycling here will include recycling with energy recovery too. Finally when all the above-mentioned options are not feasible, the product will be properly disposed of. They will be disposed of either by treatment and incineration, dumping at a landfill or dumping at sea, in that order of consideration.

2.3 Design for End-of-Life

Design for EoL is one aspect under Design for Environment. Design for Environment (DfE) is the systematic consideration of design performance with respect to environment, health and safety objectives over the full product and process life cycle [79]. It aids designers to design products with better environment performance by taking into consideration the ecological impact that the design will incur. The desired environmental attributes are considered as design objectives instead of

constraints [80]. Under this, there are three broad categories namely, Design for Waste Minimisation, Design for Low Environmental Impact and Design for Energy and Water Efficiency. Design for EoL is one sub-category of Design for Waste Minimisation. Table 2.1 below shows the various sub-categories under Design for Waste Minimisation.

Table 2.1 Different sub-categories for Design for Waste Minimisation

Design for Service	Design for EoL
Design for dematerialization	Design for remanufacturing
Design for durability	Design for recycling
Design for upgradeability	Design for proper disposal
Design for modularity	Design for disassembly
Design for functional sales	Design for refurbishing
etc.	Design for repair
	etc.

End-of-Life research has evolved into meeting both environment and business requirements. There are efforts being put in for Design for EoL (DfEoL) at the forefront design stage and also EoL stage. In order for the close-loop product life cycle to work, there must be effective feedback from the EoL back to other earlier stages, in particular the design stage due to the large proportion of the decision making involved.

A fundamental approach to overcome the problems is to take End-of-Life (EoL) management as an integral part of product development life cycle so as to alleviate the problem of rapidly accumulating waste and increasing environmental impacts from product development. Studies have shown that a large part (about 80%) of the cost and environmental impact is locked at the design stage where most decisions on the use of materials and processes are made [81-84]. Therefore, design is the key stage whereby decisions are made and this can greatly impact the success of product recovery.

Currently, however, the EoL management activities are disjointed from the rest of the product life cycle activities and focus more on remediation than prevention [82,

85]. This is not economically and ecologically sound in most cases. The shift in product development paradigm requires the designers to consider EoL performance of a product in the design stage, or Design for EoL (DfEoL), forming a closed loop in the product life cycle. Thus, designers have to be furnished with information about the environmental burdens of the planned product plus guidelines on where and how to improve the product [63, 86-88]. Figure 2.1 shows the environmental conscious design paradox [89] where the room for environmental performance improvement will decrease as knowledge of design increases.

Figure 2.1 Environmentally Conscious Design Paradox is explained here. The relations between “Freedom of action”, “Product Knowledge” and “Modification Cost” [89].

2.4 Information Management in End-of-Life

Information management transcends between both the management and technical aspects and is a very important part of EoL research. The effectiveness of

information management will affect the success of EoL directly. Product environmental information is very important to the success of sustainable product development and good product information is needed for effective implementation to improve environmental performance of the product. This also means that the communication between various levels in a product life cycle is essential [90]. Knowledge of the product specifically is crucial in helping to reduce environmental loads and hazardous materials remaining in the environment at the EoL stage. Knowledge at the EoL stage for the product will also help the other stages to reduce the environmental loads, particularly design stage.

Without information management, the stakeholders at each stage will not have the relevant knowledge to handle the products in an appropriate manner consistently [91, 92]. EoL information is especially difficult to collect due to the nature of the stage. The disparity of the information is increased as the product moves down the life cycle stages and at EoL, the information that needs to be collected is scattered and distributed over more channels. As the product moves down the life cycle to EoL, the information flow breaks down after the delivery of the product to the customer [93]. Owing to this, the activities at the EoL stage are very disparate and not properly managed, resulting in a lot of potential recyclables going into the general waste stream or improperly disposed [92]. Understanding the relationship through products, information and financial flow from the consumer to the producer or other take-back organisations assist the organisation of the EoL system [31]. Recognizing this fact, EU commissioned a study in 2006 to look into the establishment of a framework for introducing and implementing product environmental information as part of the IPP efforts. This study is set to look into the barriers to effective product information communication and to call for research in providing the solutions to these barriers

bringing about seamless flow of information amongst the different stakeholders of the various stages, as the current drivers for good information management is weak [94].

EoL has also moved away from the reactionary “end-of-pipes” solutions to more inclusive/pro-active approaches like design for EoL and life cycle assessment [46, 47]. This paradigm calls for more information and knowledge to be acquired by the designer during conceptual design stage and hence it is imperative to have feedback from the later stages such as EoL stage to provide more information for that purpose. Designers are prone to designing the products without the knowledge of the EoL stage just like how EoL stakeholders also handle retired products at their own discretion [85, 91]. Currently the product recovery activities are often hampered by the lack of information and communication amongst the different stakeholders of the various stages. Many reports have noted that lack of information from other stages of product life cycle is very common and this is limiting environmental efforts. Nilsson et al [63] have pointed out that there is a general lack of knowledge among manufacturers as to where and how information on the life cycle chain is to be found.

In particular, the EoL stakeholders are often lacking in product information for proper handling of spent products. They are often handling the products with their experiences, opinions and market demands. The products are dismantled and only the valuable components or materials are retrieved for recycling or remanufacturing, and the rest is shredded regardless of whether or not recycling is the best option. Even when they have gained sufficient experience and expertise in managing the EoL stage at some time, this information remains with them as there is no proper channel or mechanism for them to pass on this information to the other stakeholders. EoL stakeholders do not present designers with relevant information of the EoL options and the impact of design decisions on EoL that comes directly and dynamically. Most of

the designers also do not have contacts or interactions with the other stakeholders in the later stages of the product life cycle, leading to a gap in the environmental information of the product [92].

One of the earlier significant works is the establishment of design for recycling standards by the German engineers' institution VDI in 1993. The VDI 2243 Recycling-Oriented product development guidelines [27] provides developers and the designers, in particular, in addition to all stakeholders for the product, with information, instructions, and decision-making aids for the individual phases of the product development, in order to prepare and select technical and economic possibilities and alternatives for improving the recyclability of technical products. It is noted that high value recycling of complex products in the EoL stage is dependent on the quality of the product on top of good design [27]. However, this is only a starting point for Design for EoL as only recycling is considered here which might not be the most optimal choice. There is also a lack of life cycle thinking in this guideline. The information management aspect of the EoL is often neglected.

The existing attention and efforts that are being showered on each individual stage are mainly stage specific and issues are being addressed taking into consideration only factors within the stages and not beyond. The sets of data and information within each method deployed at various stages are not being properly exchanged. This results in a lack of exchange of information amongst the different actors along the entire value chain and thus leading to the ineffective and inefficient adoption of sustainable product development. This is especially true for the electronics product industry. It has been reported that one major barrier to encourage sustainability in the computer industry is the absence of accurate information on material flow through the industry supply chain [91].

A few papers have mentioned that there is always a lack of information and coordination, in particular at the end-of-life stage [91, 92]. For instance, there are take-back systems and service networks designated for some electronics products but these two systems might not interact and may not deal with the product in a most optimal manner. Similarly, consumers are also suffering from a lack of knowledge of proper disposal or alternative end-of-life management and normally discard e-waste into the normal waste stream [92]. Thus there is a need to adopt a holistic and integrated approach in designing and developing a sustainable product development framework where information can flow and be exchanged effectively and efficiently. One recent on-going work to further reflect the emerging needs for having a harmonised and standardised global ecodesign is the “Environmental Standardisation for electrical and electronics products and systems” by the International Electrotechnical Commission [95]. Also another initiative that adopts a holistic approach towards sustainable product life cycle management is the implementation of Integrated Product Policy (IPP) in the European Union for manufacturers. IPP attempts to stimulate each part of these individual phases to improve their environmental performance [20].

Another significant project to suggest that information management is essential for product life cycle management is the Product Lifecycle Management and Information Tracking using Smart Embedded Systems – PROMISE project. This was funded by the EU under the sixth Framework Programme and aimed to allow information flow management to go beyond the customer, to close the product life cycle information loops, and to enable the seamless e-Transformation of Product Lifecycle Information to Knowledge [93].

Environmental Information flow was discussed previously by Bhander et al.[82]. Here the main aim was to incorporate life cycle information into product development

so that the information can be transformed into design processes to be embedded into the design. Figure 2.2 depicts the flow of environmental information in the product life cycle.

Figure 2.2 Flow of Environmental Information in Product Life Cycle [82]

This is a holistic approach of integrating life cycle information into the design process for Life Cycle Assessment during design stage. The information is very environment related and for the purpose of LCA. The main gist is to interface LCA and CAD systems. In this work itself, it is mainly a review and identifying of meta-knowledge about product design and there is no mention of actual tools being implemented.

McAloon [96] also pointed out that in order to make environmental considerations incorporated easily into the product development process, there are some pre-requisites conditions needed. These include accessible and usable information that will be commonly understood by stakeholders from different stages. Standard nomenclature and data structure are essential.

2.4.1 Tools and Systems for End-of-Life Design

Information technology is definitely an enabler for incorporating environmental information into the entire product life cycle [97]. However, lack of design tools and methodology for DfE is often the main challenge that designers meet with in adopting greener design. Even those product developers who claimed that environmental requirements were met are simply using checklists for compliance instead of practicing it as a creative and interactive process. Many companies have recognised the lack of integration of DfE tools and LCA into current product development tools and they do not want standalone tools [92].

This is indeed the case as many aspects of the eco-design concepts are often incompatible or even contradictory to the traditional design workflow leading to the need of integrating and balancing the green aspect with the existing ones [98]. This will result in a demand for integrated DfE solutions and decision-making tools. DfEoL, being part of DfE also encountered the same issues. Some of the tools developed in the recent years to help DfEoL still fall short of certain requirements needed to popularise the tools. Furthermore, Wayne et al [99] have identified that the optimal system for DfEoL is to integrate both the product design and EoL management.

Tanskanen [7] mentioned that recycling could be approached from both directions: building a product for easy recycling and building a recycling process for effective recycling of the product. In the same way, EoL management, which is a superset of recycling, can be approached from these two ways: the design way by means of design for EoL and the EoL way by means of setting up EoL system. Looking at the characteristics and nature of the two stages, it is more appropriate that the preemptive way is chosen by incorporating Design for EoL thinking into product design rather than using the reactionary method of designing EoL system for the

product. The latter stage normally involves more infrastructure development and also lags behind the design stage by some time depending on the product. It is more of reactive in response to how the product was designed. It could actually incur more environmental impact instead of reducing it due to the extra resources being put in to customise the system and also due to the fact that EoL is at the end of the life cycle.

ELDA and EVCA devised by Rose [100] are two of the first methodologies for EoL management looking from both the technical and business issues to close their gap for more possible industrial applications. ELDA works out the recommended product EoL strategy based on the technical characteristics by means of CART analysis. This is done together with EVCA which evaluates and examines the flows of cultural and financial issues among the different actors in the EoL stage. Here, the issue flows are in form of information and are typically separated into 4 main types, namely, complaints, information exchanges, top-down information and feedback [101]. In Rose's work [98, 99], the objective was to help developing an EoL system. It is not to help design advisory. It only helps the designers to decide the product EoL strategy given the product technical characteristics and is not to help designers to design for EoL. It is more of post design evaluation to decide the EoL strategy instead of taking pre design considerations and design according to the preferred EoL options, which is more proactive. It is a forward process where recyclers are not involved in the process as the inherent technical characteristics are used. The dominant players in this work are the planners and designers which might not have the best knowledge of the EoL stage since they do not typically belong to stakeholders of that stage.

The "Green Design Adviser" [102] is amongst the first few pioneering DfEoL tools developed for designers. It uses a set of 8 metrics to determine the EoL of a product and make recommendations for redesign. Notwithstanding the efforts in

incorporating the various factors for EoL advisory in design, there is a lack of consideration for remanufacturing and also the number of factors being considered is not comprehensive enough. SortED [81] by Lofthouse and Bhamra and EEE-Pilot [103] by Wimmer et al are considered as compliance tools to guide designers during design process for WEEE. Information/Inspiration [104] by Lofthouse acts like an online guidebook. These tools are html-based and act more like a web-based guidebook with minimal analysis and intelligence.

Another tool ProdText [105, 106] by IWP, which incorporates product analysis into the workflow, however, is not web-enabled. It is by far the most similar to the work done here in terms of workflow and purpose. However, the approach and methods are different. ProdText is a DfR software tool that incorporates real recycling market data, feedback and development experience into a tool for comprehensively evaluating EoL performance of products [106]. This tool will calculate the EoL performance of the product by calculating the recycling rate, recycling cost/profits and optimal disassembly depth. While this is a comprehensive EoL advisory tool, this is data intensive and does calculation for the EoL performance. This will make it too quantitative for the designers to understand and use. The qualitative aspects of DfR are not clearly taken into consideration in this tool. Another drawback of the system is also the lack of web-enabled facility. The proposed work here has already taken into consideration the extent of relative influence of the factors by normalising the values into a scaled indicator for easy application.

A web service-based infrastructure project by Toyohashi University of Technology has attempted to promote multidisciplinary cooperation in Life Cycle Engineering through the provision of a collaboration environment [107]. This is a system that uses IDEF definition to define a product life cycle model and proposed a

platform independent web service system for collaborative decision making over the web. In spite of this, this kind of system is plagued with the inherent needs to seek for user input and lacks intelligence. Moreover, the focus of the system is not to enhance the communication between the design stage and EoL stage but rather across the entire product life cycle. Another project which focuses on the feedback of information to product designers to stimulate redesign for recycling by Hitachi [108] is however not web-enabled and the focus is on recycling evaluation for design support. Another project by Gonzalez and Adenso-Diaz [109] using a BOM-based approach for EoL decision making in DfE is also related to what the thesis here is going to work on but it has a focus in only disassembly, hence lacking in more holistic considerations of other aspects such as recovery and disposal.

One of the common deficiencies that all the above-mentioned tools share is that there is no mention of the sources of the information from the EoL stakeholders. The tools are all designed to be a standalone tool in the design stage with information obtained from the EoL stage previously but there is no updating of the information. Most of the systems are not web-enabled for distributing environments either, and none of them are semantically enhanced for better understanding amongst different stages.

2.4.2 Index for Design for Environment

The indexing method is to assist designers in determining the relative differences between designs by providing a quantitative assessment. It is a simplified and normalised representation of certain aspects of a product. For instance, the Sustainability Scoring method is designed to quantify sustainability elements in manufactured consumer electronic products at University of Kentucky and Lexmark

[110]. This index is meant for general assessment of how sustainable the product at a more holistic level. Zooming down to a specific stage, there are also several indices designed for EoL stage. Nonetheless, these indices are mainly designed for only one aspect of EoL options such as for disassembly only [53, 68, 73, 111], for remanufacturing only [75] or for recycling [112, 113] only, and lack the considerations for other factors involved.

As for those with other factors, they have their own limitations. Quote for environmentally weighted recyclability (QWERTY) [114] index is developed to calculate the recyclability of a product based on the net “environmental value” recovered over the “total environmental value” of a product. This is a purely environmental index and lacks the considerations of the rest of the factors such as economical factors. Economic and Ecological Material Index for EoL [115] by Herrmann et al focuses on materials and is data intensive although economic considerations are included. Design for Remanufacturing Metric [116] by Bras and Hammond also are meant for one of the EoL options, remanufacturing only.

2.5 Gaps in End-of-Life Research

Research in Design for EoL is still considered to be at the infancy stage and there are growing efforts being put into this field of research. From the early days of working on technical issues enabling product EoL activities such as disassembly and recycling to moving up the value chain to do design for environment, there is a lack of research being done in the aspect of holistically considering all the factors affecting the EoL activities. Also, there is a dearth in tools for DfEoL that leverages on emerging web-based ICT technology to deliver the software tool away from the traditional model of standalone system. As mentioned, several integrations of systems from

different stages of the product life cycle were proposed and developed but they are not web enabled. They are not even part of Product Lifecycle Management (PLM) tools but just standalone systems. In this era of highly distributed product design and development team, it is desirable to have systems that are easily available and accessible for the stakeholders to use, regardless of location. Here, the ease and accessibility refer to both the tool and methodology used. Furthermore, web-based technology will make the handling of the ever-growing amount of information easier to handle as well [117].

2.6 Summary

Summarizing the reviews in Design for EoL, issues occur in three aspects namely, information exchanges and communication, system tools and methodology. This research will seek to fill up these gaps concurrently by integrating, incorporating and deploying semantic web services technology, ontology based information management and comprehensive quantification of EoL Index methodology to design a new framework for design advisory of EoL. In this thesis, a novel product ontology-based product advisor for EoL performance based on semantic web services technology is proposed.

CHAPTER 3

FRAMEWORK FOR

DESIGN & END-OF-LIFE

INTEGRATED INFORMATION

(DELII)

In this chapter, a Design & End-Of-Life Integrated Information (DELII) framework will be proposed. The proposed framework stems from a holistic concept of Integrated Manufacturing and Product Services System (IMPSS) [118-120]. DELII fits into the feedback link between the End-of-Life (EoL) stage and Design stage where the closure of product life cycle is attempted.

3.1 Research Methodology

The research methodology for this thesis work is depicted in Figure 3.1. With the motivations outlined in Chapter 1, more in-depth literature search in the area of EoL research is conducted. After the literature review, the gaps in the area of LCE and EoL research are identified. It has shown that there are no methodology for EoL research that bridges the designers and EoL engineers. With the understanding, a concept is proposed to address the issues mentioned in the gaps. This concept is aimed at improving the communication and flow of information between the designers and EoL engineers through a web-enabled information management platform. A detailed framework based on this concept will then be developed, and the detailed flow and transformation of information will be defined. Within the framework, a methodology for an EoL index shall be developed to provide the means for assessing and quantifying the EoL performance of a product at design stage using information from the EoL stage. This framework is deemed to be feasible as it is self sustained by the users of the system and also it is scalable. It is expected to have far reaching impact to players in design and EoL. Based on the framework, a system platform based on semantic web services system design and development will be identified. Using the platform, the various components for the framework can be mapped for system realization. Subsequently, a case study on power tool will be used as a proof of concept for the framework. Finally, the results will be interpreted and analysed before reaching to a conclusion for this work. Within this new approach, there are some proven methodologies that are included and integrated together.

Figure 3.1 Research Methodology Flowchart

3.2 Proposed Design

The proposed design is an effort to provide information feedback to design from the EoL stage. This is a framework that manages information from the EoL stage and generates an index for the design stage. This is a framework that is strategically placed between the design stage and EoL stage to manage and use the information being captured in these two stages. It leverages on the capabilities of the semantic web services and ontology to provide standardised nomenclature over a distributed environment for the enhancement of information sharing and communication. Figure 3.2 shows the concept of the proposed framework.

Figure 3.2 Proposed Conceptual Framework

In this framework, the EoL engineers will be those who supply and manage the information at the data sources layer. These data sources will be processed by the framework to move up to the information layer before going to the analysis and reasoning layer. Finally, this information will be transformed into knowledge for the decision support layer which the designers can access. The detailed framework will be illustrated later in this chapter.

3.3 Background on Integrated Manufacturing and Product Services System (IMPSS)

The traditional product development life cycle ends when the product is mass-produced for the market. The manufacturers are generally not concerned with what happens to the product after it is being sold to the customers. In general, work in each individual stage of the product life cycle is rather independent and does not really consider the other stages. Even when environmental factors are taken into consideration; it is more for cleaner production which only focuses on reducing waste and pollutions during the manufacturing processes. There was no notion of life cycle

thinking or life cycle engineering. However, in the early 90s, there was a growth in environmental awareness, which led to a new concept termed Extended Producer Responsibility (EPR). At the same time, tools, such as Life Cycle Assessment (LCA), were introduced to assess the environmental impacts in the product life cycle. Then Life Cycle Engineering (LCE) was born in the late 90's [119].

LCE refers to engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimising the product life cycle and minimising pollution and waste [121]. This concept is aptly being exemplified in the development of the Integrated Product Policy (IPP) [20] in the EU. The approach taken for this policy was to reduce environmental impacts from products throughout their life cycle, harnessing where possible, a market driven approach within which competitiveness concerns are integrated. This is a more feasible model for balancing both the ecological and economic considerations and will be favourable to reach out to more manufacturers. For instance, a pilot project was carried out by Nokia for this purpose [122-125].

Product manufacturers then look into the possibility of closing the product life cycle loop with the incorporation of service stage and End-of-Life stage to better manage the entire product life cycle both ecologically and economically. In fact, over the years, there are many models and framework drawn up for closing the product life cycle loop, different stages were identified and defined differently for various purposes [31, 61, 126, 127].

In this chapter, an overall conceptual framework integrating manufacturing products and services [118-120] together is presented. This is part of the author's

previous work. This is a framework that enables development of more sustainable products and services along with the manufacturing of discrete consumer electronics. The approach taken was a holistic and integrated one looking at the entire product development and manufacturing life cycle from cradle to grave. The general framework of the proposed Integrated Manufacturing and Product Services System (IMPSS) is shown in Figure 3.3.

Figure 3.3 The General Framework for Integrated Manufacturing and Product Service System

The IMPSS is a framework concept that combines the management of every stage and activities across the entire manufacturing chain and services line with considerations for the environment. It aimed to provide a holistic approach and closed life cycle perspective to the manufacturers for integrated product development and management. IMPSS features the closure of the product life cycle by incorporating the end-of-life stage and service stage. Under this concept, manufacturers would consider the Service and End-of-Life stages during the product conceptualization stages, making service design and EoL design an integral part of design process. In Figure 3.3, the dotted lines represent information feedback from the various stages back to the

design stage and the solid lines represent the physical recovery of the product back to the relevant stages according to the respective EoL options.

All these service processes are interconnected to each other through the use of informatics applications amongst various stages within the entire product life cycle. The product life cycle referred here is a closed loop one, starting from design, resources provision, manufacturing, logistics, marketing, usage, service to end-of-life, which is to be connected back to resources provision. The manufacturers are also responsible for the ownership of the product throughout the entire product life cycle even though the physical product is being transferred to different actors at different stages.

There is a flow of information throughout the entire product life cycle enabling the respective actors to have a better understanding, which will in turn help them to deal with the product more effectively and efficiently. Feedbacks and queries can be channelled to the relevant stages through the system. In this framework, the important thing is to highlight the feedback of both the physical product and information from the end of the life cycle back to the earlier stages. The physical feedback of product is usually in the form of take back system which could belong to the EoL system or exists independently from the EoL system. As for the information feedback, there are various channels for that exchange. At different stages, there are different mechanisms facilitating the feedback of information back to the design stages. They can be in the form of survey questionnaires, online survey feedbacks, interviews and with the data sent automatically from the product during the usage phase. However, in all these channels, it is rather dependent on the interpretation and relay of the messages to the different stakeholders. A lot of clarity is traded off with ambiguity. The feedback channel here refers to a systematic way of managing the data and information to form

knowledge bases for the designers. Information feedback is a systematic way of collecting the data from the EoL stage to create a knowledge base which will be informative for the designers during the design process. This is to be done by having an integrated information system that can link up the stages and be able to communicate with the rest of the stages as and when necessary. The details are found in later chapters.

At each stage, the four elements of Product Service System [128] on top of the environmental tool are being identified and formalised. In this concept, there is a coordinated effort to exchange and share knowledge for optimal operations from the conceptual stage of product design to the end of life. The environmental considerations will be taken care of in the decision-making and information-sharing processes. In effect, this is an attempt to form a closed loop for product development life cycle, both in terms of physical product and information flow. The entire life cycle in this new framework was segregated in these stages namely, in sequential order, resources provision, design, manufacturing, logistics, marketing, usage, services and end-of-life (to be connected back to resources provision). These various stages will be modular but yet be able to exchange product life cycle information effectively.

Table 3.1 Elements of the New Stage

Stages	End-Of-Life
Product	Spent Physical Product
Service	Recycling Remanufacturing Refurbish Proper Disposal Disassembly Reuse
Network of Actors	End-of-life Management Engineers
Infrastructure	Take Back system
Environmental Tools	WEEE Environmentally responsible disposal

The new stages being included are end-of-life (EoL) stage and service stage but the focus here is on the EoL stage. The elements of the EoL stages are shown in Table 3.1. From a system perspective, end-of-life options include reuse/refurbishing, remanufacturing, recycling and proper disposal. Depending on the choice of handling, the products (both hardware and software) will be fed back to different earlier stages. The main objective of the EoL management is to make sure that each and every product is being given the most suitable treatment and that dematerialization of the economy is achieved through the channeling of used products back to the earlier stages. This helps to bring about a more optimal use of raw resources and cut down the demand for raw resources.

One of the main characteristics of this system is in the feedback loops, involving both tangible physical products and non tangible information. The inclusion of these loops in the product life cycle helps to close up the flow of materials and enhance the flow of information and knowledge. Out of all the stages, the most information and knowledge intensive one will be the design stage whereby most of the information and knowledge will be fed back to the design stage in aid of the designers to better design and improve the product's environmental performance [84]. The design stage is where most decisions are being made, hence the need for more information and knowledge. There are three main information flow loops being depicted in this concept back to the design stage from, namely EoL stage, marketing stage and service stage. The first loop is from the EoL stage to design stage. This is the most significant information feedback loop as the information apropos end-of-life stage is important and very useful to the designers, given the fact that end-of-life stage is newly added to product life cycle.

Also, often the activities in this stage are independent from the rest of the stages in general and largely depends on experience instead of tacit formal knowledge. They are mainly done by individual and independent contractors who most probably are not collaborating with the Original Equipment Manufacturers (OEM) and are disjointed with the rest of the stages, in particular the design stage. They do not have the proper knowledge and expertise on the products and there is also no established system in both formal and informal way for knowledge in the EoL stage to be forwarded back to the relevant actors to improve the design. The kinds of information that flow in this loop include disassembly information, product information at spent stage, material performances of the products and other information that allow designers to have more insights and understanding about the EoL of the electronics product. The information will be beneficial to the designers during the design stage when certain design decisions need to be made. Emphasis is being placed at this stage by virtue of the fact that design decisions and changes always attribute to approximately 80% of the cost of development [83, 129] and most of the environmental impacts are locked in at this stage when the choice of technologies, materials, processes and functions, etc. are made. Hence, it is always better to incorporate any necessary requirements into early design stages. It is estimated that \$1 spent on prevention saves \$10 otherwise spent at end-of-pipe or \$100 expended on environmental remediation [130].

As for the four feedback loops of physical products, they involve the flows of the product together with the relevant information. It is rather straightforward and these flows are part of reverse logistics operations. They need a proper infrastructure system both in terms of hardware and software to be in place for realisation purposes. These are the loops that close the product life cycle by channeling the spent products back to one of the earlier stages in the product life cycle and reducing the amount of waste

being disposed. Through this, the physical goods or resources are put back to use until when it is fully utilised to the optimum and proper disposal is the best option. The four paths are namely recycling, remanufacturing, refurbishing and reuse which will go back to the resources acquisition, manufacturing, marketing/sales and usage respectively. The advantage of this is that more resources are being made available to meet the demand for materials in the manufacturing and hence cut down the reliance on virgin materials as well as create less solid waste pollution and disposal.

3.4 End-of-Life Stage

The EoL stage of a product refers to the stage whereby the product goes beyond its useful lifespan and is no longer in use by the consumers or the spent product stage. EoL management is about how products are being handled after the useful lifespan is over or when consumers grew out of preference during the usage stage. The activities in this stage start from the moment the consumer decides not to use it anymore and wants to discard it. This is the last stage of a product life cycle before looping back to the other earlier stages. The EoL is given attention from manufacturers mainly due to the problems of e-waste and the efforts to lower environmental impact from the entire life cycle [131]. If the EoL stage is not handled properly, especially with products with hazardous substances and non-biodegradable materials, it can cause a lot of environmental health problems. The blind disposal of all EoL products into the waste stream is also not sustainable as resources which could otherwise be still useful when recycled are wasted. Incineration plants and landfill also have a saturation capacity for these wastes. Hence, the optimal way is to better manage EoL. Figure 3.4 shows the general scenario of how products transcend different stages after leaving the manufacturers.

Figure 3.4 Scenario of Product Flow

The product is sold on the market to the individual customer for usage upon the malfunction or obsolescence of the product, the customer will bring it to the manufacturers, service centre or EoL centre depending on the mode of retail and the customers' preference. If the product is acquired under product service system (PSS) or leasing system, the ownership and responsibility of the product still lies with the manufacturers. The consumer can bring it back to the manufacturer for EoL management. Otherwise, the consumer has to decide whether to repair or discard the product. The only difference between these two modes is that the decisive power lies with the manufacturer in the former and with the consumer in the latter, it is with the consumer. The responsibility to ensure a proper and optimal EoL decision to minimise environmental impact is on different players in the two cases. In IMPSS, the mode of retail is recommended to be on PSS and hence the manufacturer will decide the EoL options. In this way, the EoL options decision making process can be more streamlined and standardised as it goes through the manufacturer. Manufacturers will have

guidelines and more knowledge of the product, thus ensuring a more systematic and less random decision making process than it would have been if left to individual consumers. Individuals will make decisions differently. With the lack of information as surveyed previously [118], many resources which would otherwise be still useful in another product are disposed of earlier. This will also reduce the existing disparity among the EoL operations and management, reaping environmental benefits and economic value.

In the event of selecting repair, the product will be sent to the service centre for diagnosis and repair before returning to the consumer or manufacturer. However, if the cost of repair outweighs the gain in environment benefits or beyond repair technically, then the product will be recommended for EoL management. As for the case of discarding the product, the product needs to be sent to an EoL centre. This centre will collect all the products, sort out according to the product types and conditions before assessing which EoL options to choose.

In this scenario, there are a few decisions to be made and these are areas where information plays a great part in influencing the decisions. The information in turn generated or related from these decisions are valuable and significant to design process. These information need to be captured, organised and retained for retrieval when necessary by the different players in the different stages. The data that need to be collected includes the product information, market data for the current cost and prices of the various recycled materials and technological capability

3.4.1 End-of-Life Sub-stages

Within the EoL stage, there are several sub-stages the spent product will go through. Figure 3.5 shows the different EoL sub-stages that a product will typically go through and this is also the definition of EoL stage in this work.

Figure 3.5 End-of-Life Sub-Stages

Looking at EoL activities depicted in Figure 3.5, EoL stage is generally divided into a few stages and with a few options. The few sub-stages that a product will go through are collection, including transportation, classification, disassembly and then

EoL options. The first stage is usually the take-back stage where the products are often collected back either from the collection centre, service centre or disposal facilities. This take back stage can exist in a few different modes and this is very instrumental in determining how successful the entire EoL system will be. The modes are retailer take back scheme in the form of trade-in or refund, drop off point scheme at recycling centre or central depository, door to door collection scheme and courier services from the manufacturers. This is the starting point of the reverse logistics and hence if it is effective, it will ensure that the volume of take back will be huge, increasing the volume for proper EoL management and reducing the amount of waste generated, especially e-waste. More materials are also being put back into another product life cycle again and thus reducing the demand of extracting virgin materials from the environment.

Then, assessment will be done to decide which of the options to choose for EoL of the product. The assessment will be dependent on many factors such as conditions of the products, economic incentives, environmental benefits, level of technology, availability of the facilities, the materials and structure of the products. This is an important decision-making point as the amount of resources being retained in the product life cycle and amount of waste is dependent on the assessment results. This assessment can be any form of assessment method suitable for the product, for example, Life Cycle Assessment (LCA). Therefore, information management at this sub-stage is very crucial.

3.4.2 End-of-Life Options

The options available are disposal and recovery by recycle, remanufacture, refurbish and reuse. There are 5 options, other than the normal general disposal for

EoL management; namely refurbishing, remanufacturing, recycling, proper disposal and reuse. Many definitions have been developed for these terminologies over the years [77]. Hence, Table 3.2 will state the definition of each option adopted in this work.

Table 3.2 Definitions of EoL Options

	EoL Options	Definitions
1.	Reuse	The products are being passed on to another person for use informally. This happens within the usage stage itself. (Not a formal process that is being considered here)
2.	Refurbish	The product being put collected and put into a formal second hand market after a round of re-conditioning and cleaning for sales. .
3.	Remanufacture	The products are being dismantled to component level and these components being used in the manufacture of another product.
4.	Recycle	The products are being broken down to material level and being processed into other form of components for other uses.
5.	Proper Disposal	The non-recoverable parts that are to be thrown away in a proper way that does not harm the environment. The products may or may not go through additional treatment before disposal depending on the nature of the materials.

The products are most likely to go through a disassembly process in most of the options as the parts need to be disassembled and sorted out for the respective recovery or disposal activities. No disassembly is needed for general disposal into the waste stream. Finally, the dissembled products are sent to the respective EoL options. Products and components that are to be disposed of will be sent to the incineration plants and landfill; for those that need to be treated before dumping will be sent to the treatment facilities; those products in good conditions with a second market will be sent back for refurbishing; those components that are still in shape for remanufacturing in another type of product will be sent to the remanufacturing plant and those materials which are recyclable will be sent to the recycling plant for material and energy

recovery. To better represent and formalise the concept of EoL options, a taxonomy for EoL options is being developed here, as shown in Fig 3.6.

Figure 3.6 Concept Map of EoL Options

EoL options are divided into two main categories, recovery and disposal. For recovery, it involves the feedback of the products to other earlier stages physically in various forms such as materials, components or as whole products. This is the path to be taken in order to form a closed loop. This will decrease the demand for virgin raw materials, hence achieving a lower environmental impact level. At times, additional energy recovery can also be obtained. Under recovery, it is further split into formal and informal type. The informal type of recovery is reuse as this is mainly taking place within the usage stage among the consumers, for example, the passing on of a spent handphone from a brother to the sister. The formal type is what the manufacturers are most concerned with. The three formal types of recovery are remanufacture, refurbish and recycle.

Reuse and refurbish are rather straight forward and clear. The main deciding factors for these two methods are social and economical considerations, instead of technological and hence the detailed discussion is being left out. The other two main recovery methods remanufacturing and recycling are more technologically dependent. Remanufacturing is getting popular with the trend of bigger brands switching to

original equipment suppliers and hence generating a lot of standardised parts available for many different products [76]. As for recycling, since the early 1990s, there are many activities ranging from research to government to industry and to household taking place. Recycling can be broadly divided into post-consumer recycling and pre-consumer recycling. It is also classified into recycling with energy recovery and recycling without energy recovery. In the work here, recycling is being discussed and treated as one general option as the focus of this work is EoL stage, hence mainly post-consumer recycling. In addition, the presence of down-cycling of materials in the recycling process must be noted [36]. After one life cycle, the value and quality of most of the materials, for example plastics, will drop and only be suitable for a lower grade of application. After a certain number of life cycles, the material will be deemed as worthless and cannot be recycled anymore. For example, when the paper pulp gets too short, the paper cannot be recycled anymore.

3.4.3 Hierarchy for End-of-Life Options

As mentioned in Chapter 2, recycling and reusing as much materials as possible in the product life cycle might not be the most optimal with respect to the environmental benefits. This is because resources may not be utilised to the full potential. There is a hierarchy associated with this. This hierarchy is widely accepted and discussed [27, 30, 129]. Based on the hierarchy as shown in Figure 3.7, the decision-making process for EoL is being designed as in Figure 3.8.

Figure 3.7 EoL Hierarchy

From the standpoint of resource consumption and environmental effects, reuse and refurbish are preferred over the others as they prolong the lifetime of a product [36]. This is followed by remanufacturing where part of the product's components are given a second life cycle. Recycling of materials is the next before disposal is called for. This is because material, components and product are refined by using energy and materials for higher value add. The higher the level of refinement, the higher the consumption of the materials and energy will be [61]. However, one point to note is that while disposal is lowest in the hierarchy, sometimes it makes more environmental sense to replace and dispose of obsolete products. This is particularly true for technology products. Replacement of the product could yield environmental benefits due to higher efficiency brought by the improved technology, as compared to prolongation of the product life span. This is also the reason why EoL needs to be managed and assessed systematically. Rose [100] has earlier devised a method for formulating EoL strategy based on product technical characteristics. This could be complementary to the work done here. Figure 3.8 depicts how EoL options are being considered and decided here, based on the EoL hierarchy.

Figure 3.8 Decision Making Process for EoL

In this decision making process, the considerations are based on the EoL hierarchy and the breakdown of the product structure. While this is a general procedure, sometimes, the most optimal way might not be the option on the highest hierarchy. Thus, an assessment method to determine which EoL option is the most environmentally benign and economical is needed. One assessment method called End-of-Life (EoL) Index to address this problem is being proposed and discussed in Chapter 4.

3.5 Relationship between Design Stage and End-of-Life Stage

Traditionally, product design is at the forefront of product development and is highly independent from the rest of the stages. It is almost isolated from EoL stage. With the incorporation of EoL stage into the product development life cycle to close the loop, EoL and design are directly interacting with each other now. This new relationship sees the feedback of product from EoL to the design stage, both in physical and information aspects. This feedback from EoL to design is significant, as it will allow the designer to have a perspective of the EoL stage and be able to design the product to better facilitate the EoL activities. The feedback loop is represented by the most outer dash line from EoL stage to design stage in Figure 3.3.

The demand for having a framework for incorporating design information is not unheard of. It is gaining popularity and significance in the recent years for promotion of environmentally conscious design. LCA was one major early reason for the need of this kind of framework as environmental information from the entire life cycle is required in the process. The approach was holistic to cater for the high degree of environmental coupling that occurs across the life cycle stages. However, information for LCA is too intensive and only focuses on environment aspects.

Over the years as the design process gets more sophisticated; the leap in research efforts in providing information to the designers is small as compared to the growing demands, both in terms of quantity and quality, from designers. Thus, gradually the need for better information management gets more imminent and also harder to fulfill. Information provision is no longer sufficient to satisfy the needs of the designers but this information must be transformed into knowledge that can be embedded into the design of the products. The design stage is influential in the EoL stage owing to the fact that designers make many decisions with respect to the product that will affect the

EoL handling of the product. These factors include material content, product structure, assembly methods, process used and labeling of materials. EoL stage can influence the design stage by giving active feedback of issues and preferences in the EoL stage for design considerations. Given this, it is imperative that the information exchanges between the two stages become clear, effective and efficient. The information exchanges are two-way: the information related to EoL is available for designers' reference in the design stage and the product information are easily accessible to the EoL engineers for decision making in the EoL stage. The purpose of design for EoL and feedback for design will be defeated if there is weak or no information flow between EoL and design.

Given the current state of art in this area, this type of communication channel is still lacking and not many systems have this feature of involving the EoL engineers and designers directly for information sharing and exchanges. There are systems for interfacing both stages but it is normally done at either end, normally not an integrated effort between the two stages. For example, there are systems that add recycling profiles and EoL considerations to product design tools but they are not meant for the use of EoL players. This knowledge gap must be filled by devising a common framework that interfaces both the design stage and EoL stage in terms of information and systems. This framework must be accessible to players from both stages and promote integration of information for advisory in both stages.

3.6 Design and End-of-Life Integrated Information Framework (DELII)

To design and create this communication between these two stages directly, a framework to encompass the essential components required is being proposed. The framework is shown in Figure 3.9

Figure 3.9 Design and EoL Integrated Information Framework (DELII)

This framework is proposed to provide a link for the stakeholders in the design and EoL stage. It serves to fill up the information gap between conceptual design and EoL assessment. It will make up for the lack of communication between the design stage and EoL stage by facilitating and organising the flow of information between the two stages. It will manage and mediate the information from both the design and EoL

stages. Integration of the databases, sharing of data and standardisation of some common terminologies from the two stages are expected under this framework. In addition to that, the framework aims to perform advisory roles to the designers and EoL engineers by forecasting the EoL performance for designers to have an assessment of the expected EoL performance for the product and by recommending feasible EoL options for EoL engineers to have a reference during EoL decision-making process. The computation and analysis of the information are included in the framework for these purposes. This framework will sit between the design stage and EoL stage and act as the feedback from EoL stage back to design stage in order to close up the product life cycle loop. This is designed for the use of designers and EoL engineers primarily but at times, manufacturers are needed to provide data during production stage.

3.6.1 Application of DELII

3.6.1.1 Stakeholders

The two main players in this framework are the designer and EoL engineer/manager. They are primarily the stakeholders in this framework and will be using it more often. They are the focus of the framework as the underlying purpose of the framework is to enhance the knowledge of these two sets of players by facilitating better communication and information exchanges between them in order to encourage more effective and efficient sustainable product development. Design of a product comes from designers; hence designers are the main decision makers who can make a huge difference to the environmental performance of the product. By virtue of this, designers need to be well informed of the related information affecting the EoL performance. EoL engineers/managers are the handlers of the EoL products hence they

will have first-hand experience on the activities in EoL stage. They will have a better understanding of the difficulties, issues and what are essential for the EoL products to be handled at a lower environmental impact. There might be some other actors from the other stages to input the information into the framework in future but this is not considered here.

3.6.1.2 Design Advisory

Design advisory will manage all the information related to design and be responsible for generating any useful output for design advisory. In this component, an EoL index forecast is a major part of this design advisory. This EoL index will help to inform the designers what is the EoL performance of the proposed design for the product given the current state of technology, economic conditions, designer's priority and proposed structure. The data required for the EoL index are obtained from various knowledge sources from both design and EoL stages. The EoL engineers/managers are supposed to input information related to the EoL activities for the advisory to work on. They are also the experts that will create, determine, monitor and update the EoL scale tables that are used in the EoL index computation. In the event of missing information, the designer will have the priority to input his preferred values for comparing alternative designs. The EoL index methodology will be discussed later in Chapter 4.

Another part of the design advisory is to manage the design information and guidelines for the benefits of the designers during design process. Queries on any design issues or process can be answered by this advisory to enrich the knowledge of the designers for better understanding of DfEoL. This aspect of the design advisory is to assist the designers in searching for related information and guidelines when proposing new product concept and design. The kind of information and guidelines comprise legislation, standards, DfEoL guidelines and environmental data. Legislation

and standards are essential because adherences to these are necessary for the product to be more marketable and of higher quality.

3.6.2 Elements of DELII

There are four main layers in DELII framework as can be seen from Figure 3.8. These layers are knowledge bases, information, analysis and reasoning, and decision support.

3.6.2.1 *Knowledge Bases*

This is where all the knowledge sources from the various stakeholders are. This is like the brain of the framework where all the contents are consolidated and managed. There are enormous amounts of data that demand management in both the design stage and EoL stage. These data are from various sources from the two stages. They are in different formats, thus filtering and classification are required. Databases schemas are to be created for the purpose of providing the relevant information and generating the knowledge for advisory. The types of databases involved here are D-BOM, EoL options data, environmental data, legislation, standards, guidelines, material data and process data.

3.6.2.2 *Information Layer*

This is the layer where the various types of information are located. These are results of retrieving the relevant data from the databases to form the necessary information structures. There are three main sections for this layer, namely the scale table for EoL index, the product structure ontology and design information. Each of them serves a purpose of this framework.

The EoL scale tables are look-up tables to normalise all the values of the factors into indicator value that can be summed up for the generation of the EoL index. This is where most of the EoL information will be sorted, classified and ranked accordingly in terms of how they will contribute to EoL performance of a product. It is divided into three sub-categories, specifically disposal, disassembly and recovery. The ranges of these factors under these categories are being arranged in a scale from 0-10 according to the extent of their influence on EoL performance in terms of both environmental and economical cost. During the computation of the EoL index, these look up scale tables will serve as a reference for the normalised indicator values to be obtained. These factors are being defined using two attributes, the quantitative unit of measure and the qualitative description of how the factor influences EoL performance.

Once there is a request for EoL index to be calculated, the factors that need to be included are identified and the corresponding parts of the life cycle stage where the factors to be measured are located by the indicator values query component. The values of the factors will be obtained from the product structure ontology and matched against the scale tables to find out the corresponding normalised indicator values for further index computation. The weights of these factors are to be generated according to the designers' preferences and priorities in the analysis and reasoning layer. This forms an important part of this layer as this is where the values to be used will be determined as this is the representation and collection of information from the EoL stage to be used for design advisory. If there is any error in this section, the EoL index will mostly likely be erroneous too. These tables are updated and maintained by the EoL stakeholders. They act as a means for feedback from the EoL stage to the design stage. The fact that EoL stakeholders are taking care of the tables will ensure up-to-date EoL information being reflected on the tables.

The second section is the product structure ontology which collects all the information of the product structure through the Design Bill-of-Material (D-BOM) that designers will provide. The product structure is being stored in a form of ontology where each of the components, sub-assemblies and modules are being represented in classes with the relationships between them representing the joints between them. The attributes of the classes will represent the attributes of the components, sub-assemblies and modules. Each individual design instantiate an instance with attributes of values from that particular design. Ontology is a specification of a concept and it is being employed here for specifying the concept of how a product is designed structurally. This is suitable for representing the structure of a product because of the ability of ontology to define and specify relationships between two classes. With ontology, certain terminology and names can be standardised or be understood to be equivalent, hence be able to enhance communication between the different stakeholders.

Product structure is very important to the effectiveness of disassembly which is a big influencer on EoL decisions. During the generation of the EoL index, the indicator value query is required to find out the actual value of all the factors in their respective measurable units here before proceeding to read off the indicator values on the scale tables.

3.6.2.2.1 *Ontology Management*

One of the issues that is widely being identified and cited is the lack of standardised nomenclatures and relationship that is well understood by all the members of the product development team [96]. An ontology-based approach to standardise the concept and terminology used between the designers and EoL engineers is thus adopted. Ontology management is meant for standardising the terms and relationships being used in a product. At the same time, it also ensures that the

product structure is uniformly presented across different players at both the design and EoL stage. It will provide a common understanding among all the players about the products and processes involved. It formalizes and provides a formal representation of the product information so that the data can be effectively shared and managed. This improves the current practice in which the EoL engineers need to be trained to understand CAD drawings and BOMs. Another advantage is that ontology can be translated in a multilingual environment due to the structure.

There are a few types of ontology that will be created, developed and updated in this component. They are the stages ontology, product structure ontology and processes ontology. The ontology of the stages is pre-defined and is to be referenced to find out where the information is to be obtained during the advisory process. Ontologies about the products are to be created from D-BOM of the product. Ontology editing and updating are also managed by this component.

The third section is the design information that is associated with design for EoL. It will keep the design guidelines relating EoL, the designers' preferences and priorities and also the D-BOMs. This design information is mainly used by the weights generation component to compute the weight of each of the factors that will contribute to the EoL index. The preferences are given in pairwise comparison between all possible pairs among the factors that affects the same sub-index.

3.6.2.3 Analysis and Reasoning Layer

This is where all the analysis and reasoning of the computation of the index will be done given the inputs from the information layer. The main unit is the computation unit which will generate first all the functions then the sub-indices at the various levels and finally the overall EoL index for the product given inputs from the two smaller units, indicator value query and weights generation. The main algorithms, logic and

formulae for computation are found at this layer. The details are found in the Chapter 4. Using rule-based algorithms, which equations and what factors to include into the calculation of the EoL index are determined and used in the computation. Computation of the EoL index is based on two main sets of values, namely the designers' preferences/ priorities and equivalent indicator value of the contributory factors. Analytic Hierarchy Process (AHP) [132] is employed in this calculation to derive the weights of the individual factors in the process of computing the EoL index.

3.6.2.4 Decision Support Layer

Given the results from the analysis and reasoning layer, the decision support layer is to assist the designers in making decisions based on the results. The results will be fed into a result analyser which will identify the weak points and also come up with suggestions for improvements. This analyser will go through all the values of the sub-indices and functions generated by the computation unit and then pinpoint the strong and weak points before looking for possible improvements. There are rule-based systems for the result analyser to see which values are on the low side and flagged them as weaknesses. From these weaknesses, the analyser looks for the factor with the highest weight first then check the feasibility and potential for improvement of this factor by checking the indicator values. The analyser will rank the potential improvement for the factors according to the priority for considerations. Then these pointers will be output to the screen for designers' to work on for re-design. This analyser will facilitate and not do the work of a designer. The outputs of the index, which comprise the various sub-indices and functions, are displayed in a bottom up and departmentalised approach together with the analysis report, which consolidates all the pointers for improvement, through the user interface. This will guide the designers in the re-design of the product for better EoL performance.

There is always a gap of at least a few years between the product design stage and the EoL stage, depending on the lifespan of the product [63]. Most of the past efforts were tackling the problem at either the product stage or the EoL stage. This framework is an effort to bring design stage and EoL stage closer by integrating the information that is available at both stages. It starts by managing the information at the EoL stage, making it useful and accessible to both the designers and EoL engineers/managers. Further on, it allows the designers to do assessment of the EoL performance of the design by computing an EoL index based on the various knowledge sources and designers' priorities.

3.7 Summary

In this chapter, an Integrated Manufacturing and Product Service System framework is being presented with the addition of Service stage and EoL stage and from there; another Design & EoL Integrated Information (DELII) framework is being derived. The IMPSS framework emphasizes the closed product life cycle loop with a focus in information feedback from the EoL stage to the Design stage. To begin with, the EoL stage is defined here and the various EoL options are being elaborated before the DELII framework is drawn up. The DELII framework is one that manages the information from both the design stage and EoL stage for the utilisation of both the designers and EoL engineers/managers. This framework aims to manage the information and at the same time provide advisory services to the design for EoL performance. It is a novel attempt to systematically manage, integrate and share information for the benefits of the design stage and EoL stage.

CHAPTER 4

A METHODOLOGY FOR END-OF-LIFE (EoL) INDEX

This chapter will describe how the information management and EoL index are instrumental in the scenario between the End-of-Life (EoL) stage and Design stage. It will depict a typical communication scenario for design stage and EoL stage, and give a detailed elaboration of the methodology of the EoL index. The structure and computation of the index, the decomposition of factors, the generation of the weights and values for computation are all described in the subsequent sections.

4.1 Scenario for Communication between End-of-Life and Design Stage

The lack of information is often the bane of designers when it comes to DfE. At present, designers at best can obtain typically incomplete historical EoL data. Whenever designers want to design a product with EoL considerations, they suffer from a lack of information from the EoL stage due to the current disparate nature of

the stage. A designer needs to have EoL information to aid in design on top of the existing design guidelines.

The communication between the EoL and Design stage is usually through the use of historical data available to the designer at the design stage and there is always a time lag in the data validity due to the lack of updating mechanisms. These data are normally being taken off during the EoL stage in form of documents to be referred to at the design stage. Depending on the version of the data, the data might be obsolete and not reflect the current situation. Also these data might not make sense to the designers when presented, as the designers might not have the expertise to interpret the meaning of the data.

The scenario shown in Figure 4.1 will be one that allows the designers and EoL engineers/managers to communicate with each other through the DELII framework for more effective and efficient design for EoL. The designers and EoL engineers/managers can interact with each other through the use of the framework. This framework encompasses few functions that manage the information and compute the EoL index with the support of knowledge bases from the two stages. This can be realised through a supporting system, as shown in Figure 4.2.

Figure 4.1 Scenario between the Design Stage and EoL Stage

Figure 4.2 Supporting System for the DELII Framework

4.2 Information Management

Information management is an important part of EoL research. Information management in product design is not new, but to have information management in the EoL stage to drive Design for EoL is virtually non-existent to the best of our knowledge. Abundance of information is available at the EoL stage and this information, when captured and reorganized, can be knowledge sources. Data that are pervasive in the EoL stage include the recycling cost, recycling technology, disposal cost, treatment cost, remanufacturing cost and etc. Information management is for sharing knowledge between the stages. Information when shared must also be used in a purposeful way in order to fully maximise the benefits of enabling information sharing. Hence, information management here is to support and provide the necessary input to the EoL indexing.

From the DELII framework, there are three main categories of information that need to be managed. First category is the EoL scale table which subsequently will be used in the computation of the index. This table is to be determined by the EoL stakeholders using information and expertise from the EoL stage to draw up the normalised scale from 0-10, according to how the factor affects EoL performance. Second category is the list of designers' preferences and priorities of the various factors. This list is to be provided by designers and will be used for weight generations for different factors. For the same sets of indicator values, different preference list can be used to generate the EoL index for comparison. This list of preference is to be given in a pair wise comparison format by designer for input into Analytic Hierarchy Process (AHP). Pair wise comparison is suitable also because it will take into account the relative importance of the various factors, instead of randomly assigning weights to the various factors. The last category is the product D-BOM document. This is to be an XML format document specifying the materials for each component, sub-assembly and module together with the joining relationship. This D-BOM will then be converted to product structure ontology to be stored in the ontology database. For certain attributes that are not directly obtainable from the D-BOM, the designer is to input the values.

4.3 End-of-Life Index

To further make the collected data more meaningful to the designer, these data are being sorted and arranged for computation of an EoL index to help designers to have an estimate of the EoL performance of the product. In this section, an End-of-Life Index is being proposed to assist the designer in decision making by evaluating and predicting the EoL performance. A methodology for deriving the index will be

introduced and explained. This is an index for measuring and evaluating the forecast performance of a product at the end of its life. This index is designed to be holistic and inclusive of many aspects of EoL options. The concept is to include as many factors as possible for the index to be holistic and general. The factors being taken into consideration are of wide range from disassembly, disposal to all the various EoL options. It is an attempt to include as many factors as possible for the index to be holistic taking into consideration of many possible factors that affect the EoL of a product. The nature of the factors in the EoL definition is diverse and generic. In many past works, the considerations of factors affecting the indices are constraints to that specific option of EoL only and did not include the factors from the other EoL options. This index is hence designed in a modular structure by which factors that are irrelevant to certain product under assessment can be left out with minimum effect on the results.

There are three main categories of the sub-indices to represent the three important aspects of EoL management, namely disposal, recovery and disassembly. This is a two dimensional indexing method. The index is being generated from the product structure point of view and from the three main sub-indices point of view. In this index, the product structure, as shown in Figure 4.3, is divided into four levels, namely product, module, sub-assembly and component.

Figure 4.3 Different Levels of Product Structure

The top level is “product” which is separated into smaller modules and loose components that do not belong to any modules at the second level. Then, modules are further split into sub-assemblies and loose components that do not belong to any sub-assemblies at the third level. Finally, sub-assemblies are broken down into components level. The different components of the index are summarised and presented in Table 4.1. It shows all the sub-indices for the different product levels and the rows record all the sub-indices for the same level according to the decomposition in product structure. DI, DAI, RCI and RMI denote the disposal, disassembly, recycling and remanufacturing sub-index respectively. The subscript will indicate the product level that the sub-index is referring to, eg. DI_C refers to the Disposal sub-index for component. $\alpha, \beta, \gamma, \lambda$ are weighting factors for the different factors in the various equations.

Table 4.1 Different Types of Sub-indices at Different Levels

	Disposal (DI)	Disassembly (DAI)	Recovery (RI)		Total
			Recycling	Remanufacturing	
Components	DI_C	-	RCI_C	RMI_C	CI_T
Sub-Assembly	-	DAI_{SA}	RCI_{SA}	RMI_{SA}	SA_T
Module	-	DAI_M	RCI_M	RMI_M	MI_T
Product	-	DAI_P	RCI_P	RMI_P	PI_T
Total	DI_C	DAI_T	RCI_T	RMI_T	

Equation 4.1 depicts the general form of equation to calculate the overall EoL index

Product Index

$$PI_T = \alpha DAI_P + \beta RI_P + \frac{1}{n} \sum_{k=1}^n \gamma MI_T^k + \frac{1}{m} \sum_{j=1}^m \lambda CI_T^j \quad (4.1)$$

Where DAI_P is the disassembly sub-index for the product,

RI_P is the recovery sub-index for the product,

MI_T is the module overall EoL index of modules in the product,

CI_T is the components EoL index of the loose components attached to the product directly,

n is the total number of modules in the product

m is the total number of the loose components attached to the product directly

$\alpha, \beta, \gamma, \lambda$ are weighting factors for the indices

The other equations for the index at different level are depicted in Equation (4.2) - (4.4).

Module Index

$$MI_T = \alpha DAI_M + \beta RI_M + \frac{1}{n} \sum_{k=1}^n \gamma SAI_T^k + \frac{1}{m} \sum_{j=1}^m \lambda CI_T^j \quad (4.2)$$

Where DAI_M is the disassembly sub-index for the module,

RI_M is the recovery sub-index for the product,

SAI_T is the module overall EoL index of modules in the product,

CI_T is the components EoL index of the loose components attached to the module directly,

n is the total number of sub-assembly in the module,

m is the total number of the loose components attached to the module directly

$\alpha, \beta, \gamma, \lambda$ are weighting factors for the indices

Sub-assembly Index

$$SAI_T = \alpha DAI_{SA} + \beta RI_{SA} + \frac{1}{n} \sum_{k=1}^n \gamma CI_T^k \quad (4.3)$$

Where DAI_{SA} is the disassembly sub-index for the sub-assembly,

RI_{SA} is the recovery sub-index for the product,

CI_T is the component EoL index of the components in the sub-assembly,

n is the total number of components in the sub-assembly,

α, β, γ are weighting factors for the indices

Component Index

$$CI_T = \alpha DI_C + \beta RI_C \quad (4.4)$$

Where DI_C is the disposal sub-index for the component,

RI_C is the recovery sub-index for the product,

α, β are weighting factors for the indices

Note that $\alpha, \beta, \gamma, \delta$ are weight coefficients to be determined by AHP according to priorities of the factors.

This index is obtained by aggregating the disassembly index (DAI), disposal index (DI) and recovery index (RI) from the lower level to form the higher level index. RI can be represented by recycling index and remanufacturing index. It starts by using the base factors affecting the three main sub-indices, as shown in Figure 4.3, to sum up from the component level to product level through the sub-assembly and module level. At each level, there are different base factors that contribute to the sub-indices and

different inputs are needed for the different sub-indices at each level. As shown in Equation 1, the product overall index is a summation of the disassembly index which measures the cost of disassembly process of the product into its modules; recovery index which reflects the reuse or remanufacturing feasibility of the product as a whole and lastly the disposal index which represents the cost of disposing the product.

These three aspects of EoL are chosen after analysis of the EoL activities on how each activity affects the EoL system. Figure 4.4 illustrates the transformation of data from the user input to the final EoL index, step by step. The boxes represent the data and the arrows represent the process that took place for the data to be transformed into the next step. This will be translated to the system workflow during the implementation stage.

The transformation starts after user input into the D-BOM and designer's preferences. From here, the designer's preferences will go through the AHP processes to generate the respective weights of the factors. Those weighting factors were determined by the designers' preferences or design objectives. The relative importance of each possible pair of permutation is given by the designers in a pair wise comparison manner. These values are then used in Analytic Hierarchy Process (AHP) to calculate the final ranking of these preferences. AHP is a process that takes all the values of the relative importance and normalise it against each other to obtain a final weight for each factor. These weights are given with respect to the final goal of the design to reflect the importance of the respective factors. They provides the indication on which design alternative will bring about a higher resultant change in the final EoL performance once a design change has been considered. A higher weight will imply that the factor is of more importance. It will bring about a higher magnitude of change

in the EoL index result given the same magnitude increase in the indicator values as compared to the rest of the factors with lower weight.

There are three type of weights to be generated, first the weights for the various factors being used in the lower level functions, then the weights for the functions which is being used in the sub-indices and finally the weights for the sub-indices which adds up to the overall EoL index. Parallel to this transformation, the D-BOM will be used to create product structure ontology. After which the attributes of the ontology will be filled up by querying the databases. Next, during the generation of the EoL index, an ontology search will be performed to retrieve all the values of the factors needed in the computation. The values of the factors will be compared at the EoL scale tables to read off the indicator rating to represent each of the factors.

At this juncture, the indicator ratings, together with the weights of factors, will be substituted into the various function equations to calculate the functions values. These functions values will then be aggregated with the weights of the functions to obtain the sub-indices values through the sub-index equations. Finally these sub-indices value will be transformed into the overall EoL index together with the weights of sub-indices by using the EoL index equations.

The total real cost structure of each sub-index is calculated in the same way by taking the aggregate of the factors. The decision making currently for determining which EoL process is taken is intuitive and depended on the quality tradeoffs. This process is a way to formalise and systematically arrive at a quantified value for decision making. While this is multi criterion scenario, it has been assumed that the factors are independent of each other and the factor is only affected by the sub-factors in the lower hierarchy as modelled in the AHP model. Then by using AHP, the relative

importance of each factor are taken into consideration thus with the eventual weights from AHP calculation, the cost can be simply aggregated to arrive at a final cost.

The transformation in Figure 4.4 will aid designers in the design process by transforming the input into an EoL index where the designers can make decision with. This transformation is beneficial to the designers as there is minimal need to provide additional non-design information by the designers. The factors are quantified in this transformation and represented in terms of real cost and not monetary cost.

Figure 4.4 Transformations of Data into EoL Index

This EoL index is to give designers an indication and expectation of how the product will perform at the EoL and whether or not it is in compliance to the related legislation. It can help in the process of redesign by identifying the weakest aspects of

the design through departmentalisation of the factors into the various sub-indices and levels. It can also be used to compare and evaluate the different designs in consideration. Lastly, it can be used by EoL stakeholders to compare and decide which of the EoL options is the most optimal. This index is designed to be simple yet still effective in pointing out the weaker environmental aspects of a product.

4.3.1 Sub-Indices

The three main sub-indices are disposal, disassembly and recovery. For each of the sub-indices, further decompositions are done until the simplest measurable contributory factors are obtained. Figure 4.5 show the breakdown of all the factors affecting EoL under each sub-index that are being considered here. Each of these sub-indices is being computed differently at different product structure level. Different factors are being taken into consideration at the different product levels due to the differing nature of the levels. A component will not be concerned with the number of joints, unlike at the module level. The influence of these factors will be quantified through the transformation process as shown in Fig 4.4 into different indicators values for each factor individually. The final index is a summation of the real cost of EoL of a product and not only the monetary cost. Under the sub-indices, a holistic approach was taken, considering the many different aspects of EoL from cost to environmental to technological and including possible factors from every possible options of EoL.

4.3.2 Disposal Sub-Index

Disposal is the most common option for EoL as it is always the last resort and it is, in general, easier to handle from the view of consumers. There are two main types of disposal methods available, general waste disposal and disposal with proper

treatment. Under the general waste disposal, there are incineration and landfill but in this thesis, they will be treated as one general category as many of the countries, especially developed ones now have both processes in managing their waste. As for disposal with proper treatment, the different treatment processes will be looked into depending on the products being investigated. This is an important factor as it will directly affect the environment if not done properly and also it will increase the cost of disposal thus making recovery a more attractive option.

Under the disposal sub-index, the different types of disposal are being studied and decomposed into the affecting factors. Here, it is assumed that the product will go through disassembly to component level before being disposed.

Figure 4.6 shows the breakdown of the factors affecting disposal and this brings about the following equations for disposal sub-index.

Figure 4.5 Hierarchical breakdown of factors affecting disposal

Total cost of disposal, TC_{DI}

$= f(\text{Time- } t_{DI}, \text{Environmental Impact- EI, Value of Recycled Material-VaRM})$

$$= \alpha_{TC_{DI}} t_{DI} + \beta_{TC_{DI}} EI + \gamma_{TC_{DI}} VaRM \quad (4.5)$$

The total cost of disposal is determined by the amount of time needed, the environmental impact created by the disposal and the value of recycling the material.

The environmental impact will determine disposal as certain materials will pose more environmental impact when disposed, for example, plastics is better being recycled than disposed. The higher the environment impact, the higher the cost.

The value of recycling the material is to compensate for the loss of value that the material can generate when recycled. It will lead to higher disposal cost if the material has high value after recycling.

$$t_{DI} = f(\text{Treatment Process} - TP, \text{distance} - Dt) = \alpha_{TDI} P_T + \beta_{TDI} Dt \quad (4.6)$$

From here, time can be further broken into a function of treatment and distance to the dumping ground. Treatment process needed before the disposal is crucial to time as it will translate into additional disposal cost if the process is more tedious and distance to the disposal site is also instrumental in determining the time as it will affect the transportation time. Time is directly proportional to the distance needed to travel to the disposal site.

$$TP = (\text{Material} - MDI, \text{Legislations} - L) = \alpha_{TP} MDI + \beta_{TP} L \quad (4.7)$$

At this stage, treatment process is in turn dependent on the materials present in the product and current legislation in force for the materials. The stricter the legislation, the higher will be the cost of the treatment process and hence increasing the index for treatment process. Material will directly affect the treatment process, depending on the level of toxicity defined, nature of the material and biodegradability. The level of toxicity is defined by the amount of hazardous substances present and how much it contributes to the destruction of the natural environment and human health. The higher the level of toxicity, the higher the material index will be. Nature of the material refers to the broad category which the material belongs to. This nature of material will determine generally how the treatment process is like and hence is a consideration here.

Figure 4.6 Different Factors affecting the EoL Index considered in this thesis

Biodegradability is needed here to indicate if disposal of this material will cause more land pollution or not if the material is being landfilled. Then higher the biodegradability is, the lower the environmental cost will be and hence material index will be lower.

$$M_{DI} = f(\text{Toxicity-Tx, nature of material-NaM, biodegradability-Bg})$$

$$= \alpha_{MDI} \text{Tx} + \beta_{MDI} \text{NaM} + \gamma_{MDI} \text{Bg} \quad (4.8)$$

In the case of comparing two options between disposal and recovery, the overall end of life index that is to be compared will only consist of disposal and disassembly against disassembly and recovery.

4.3.3 Disassembly Sub-Index

Disassembly is the process of physically separating a product into its modules, sub-assembly or components. It is a major compulsory stage that most EoL products will go through during the EoL stage, especially for recovery purposes. This is one of the main determinants to decide whether recovery is viable or not. Disassembly occurs at different levels of the product structure and different factors are being considered at different level. Table 4.2 lists the different disassembly sub-indices at the various product level and which process it represents. Figure 4.7 shows the breakdown of the disassembly index.

Table 4.2 Disassembly Sub-Index

	Disassembly Sub-Index Notation	Disassembly process under study
Components	-	-
Sub-Assembly	DAI _{SA}	From each sub-assembly to the different components
Module	DAI _M	From each Module to the different sub-assembly and loose components

Product	DAI _P	From the product to different modules and loose components.
Total	DAI _T	The total disassembly efforts

Figure 4.7 Hierarchical Breakdown of Factors affecting Disassembly

This leads to a few equations being formed to express the relationships amongst factors. The total time will be determined by the ease of dismantling and technology available for disassembly. Technology available refers to available equipment and how established as well as how commercialised the technology is in dismantling certain joints.

$$\text{Total Cost of Disassembly } TC_{DAI} = f(\text{Time}, t_{DAI}) = \alpha_{TC} t_{DAI} \quad (4.9)$$

$$\begin{aligned} t_{DAI} &= f(\text{Ease of dismantling-Ed, Technology available-Tech}) \\ &= \alpha_t Ed + \beta_t Tech \end{aligned} \quad (4.10)$$

$$\begin{aligned} Ed &= f(\text{Visual perceptibility-Vp, Accessibility-Acc, Detachability-Dt,} \\ &\quad \text{sequence of dismantling-Sd}) \\ &= \alpha_{Ed} Vp + \beta_{Ed} Acc + \gamma_{Ed} Dt + \delta_{Ed} Sd \end{aligned} \quad (4.11)$$

Ease of dismantling in turn is defined by the summation of visual perceptibility, accessibility, detachability and sequence of dismantling. Of which each of the factors is further compounded by other sub-factors. They are determined by the expressions below

$$V_p = f(\text{Type of modules-Mod, Identification of material-ID})$$

$$= \alpha_{V_p} \text{Mod} + \beta_{V_p} \text{ID} \quad (4.12)$$

$$D_t = f(\text{Type of joints-J, Number of joints-No_J}) = \alpha_{D_t} J + \beta_{D_t} \text{No_J} \quad (4.13)$$

$$S_d = f(\text{Structure of the product-St}) = \alpha_{S_d} St \quad (4.14)$$

$$Acc = f(\text{Structure of the product-St}) = \alpha_{Acc} St \quad (4.15)$$

$$St = f(\text{Depth-Dp, Location-Loc, Shape-Sp, Size-Sz})$$

$$= \alpha_{st} Dp + \beta_{st} Loc + \gamma_{st} Sp + \delta_{st} Sz \quad (4.16)$$

Visual perceptibility will depend on the type of modules and the identification of the materials present in the product. The type of module refers to the broad category of functions that the module can perform. This will include electrical, electronics, mechanical and mechatronic modules. This factor will influence visual perceptibility as certain modules are easier to identify and see. The identification of materials measures the ease of identifying the materials through labelling, marking and visual inspection. The easier the identification of the material, especially the joints, the higher the visual perceptibility it will have and it will be easier to take out.

Both the sequence of dismantling and accessibility are dependent on the structure of the product, which is in turn determined by the depth, location, shape and size of the components. Depth of a product is determined by the number of levels that a product can be dismantled to reach the most basic components. Location refers to the position of that particular module, sub-assembly or components in the product structure. It is to describe how and where the components are placed so as to determine the accessibility and sequence of dismantling.

Shape and size play a part too. Shape will represent the shape of module, sub-assembly or component under study as to whether the shape is regular or irregular. Size will indicate the size of the module, sub-assembly or component under study as to whether the size is big or small with respect to the size of the product. Product, modules and components with regular shapes, non-bulky size, lesser depth and visible locations are easier to access for detachment and have lesser sequence for dismantling. Lastly, type of joints and number of joints will affect the detachability. The type of joints will include the various types of joints, both permanent and non-permanent, used in manufacturing processes. Products with non-permanent joints like snap fit and screws are easier to detach than permanent joints like welding and soldering.

4.3.4 Recovery Sub-Index

Under the recovery sub-indices, recycling and remanufacturing are two main activities to be included. Recycling refers to the reprocessing in a production process of waste materials for the original purpose or for other purposes but excluding energy recovery. Remanufacturing refers to the reuse of components or modules for the same purpose in the same type of products or other types of products after refurbishment. The third recovery option, which is the direct reuse of the products after refurbishment, such as selling in second hand market, is not within the scope of this project. Recovery is one of the most useful ways to reduce the environmental burden on the limited resources and also to reduce the impact on land usage. Recycling process is being carried out at material level mainly while the remanufacturing process is normally considered only at the module and sub-assembly level.

4.3.4.1 Recycling

The hierarchical breakdown of the recycling sub-index is shown in Figure 4.8. This leads to a few equations being formed to express the relationship between each factor.

Figure 4.8 Hierarchical Breakdown of Factors affecting Recycling

In this sub-index, the hierarchy is slightly different as material is a determinant for both recycling process and amount of energy recovered and hence material occurred at different levels of the sub-index. The total cost of recycling is made up by the amount of time needed for recycling to take place, the value of the recycled material and the amount of energy recovered through the entire recycling activity. The longer the time taken, the higher the cost will be as more resources and labour are needed. Both the value of material and amount of energy recovered will help to reduce the cost as they increase. Higher material value can fetch a higher price, hence lowering recycling cost. For every recycled material, depending on the grade after recycling, it will command different values. A higher grade recycled material will be more valuable and hence can bring about a higher selling price thus decreasing the net recycling cost. The same goes for amount of

energy recovered. The more amount of energy being recovered, the more it will help to offset the cost of recycling.

$$\begin{aligned} \text{Total cost } TC_{RC} &= f(\text{Time-}T_{RC}, \text{Value of recycled material-VaRM, Amt of} \\ &\quad \text{energy recovered-Engy}) \\ &= \alpha_{TCRC} T_{RC} + \beta_{TCRC} \text{VaRM} + \gamma_{TCRC} \text{Engy} \end{aligned} \quad (4.17)$$

$$T_{RC} = f(\text{Recycling Process-}P_{RC}) = \alpha_{TRC} P_{RC} \quad (4.18)$$

$$\begin{aligned} P_{RC} &= f(\text{Material-}M_{RC}, \text{Legislations-L, cost of energy-Cost}_E, \\ &\quad \text{Cost of consumables-Cost}_C, \text{emissions-E}) \\ &= \alpha_{PRC} M_{RC} + \beta_{PRC} L + \gamma_{PRC} \text{Cost}_E + \delta_{PRC} \text{Cost}_C + \varepsilon_{PRC} E \end{aligned} \quad (4.19)$$

Time is a factor entirely dictated by the recycling process needed to recycle the products. Recycling process is a function of materials present in the product, existing legislations for the products, cost of energy, cost of consumables and emissions given out during the process. The stricter the legislations are, more requirements must be met and hence the more tedious the recycling process will be, leading to longer time needed. This time also include compliance check time. Cost of energy and cost of consumables are set to bring up the recycling process sub-index as they increase. Higher emissions also will drive up the recycling process sub-index.

$$\begin{aligned} \text{Engy} &= f(\text{Material-}M_{\text{Engy}}, \text{energy recovery process-}P_{\text{Engy}}) \\ &= \alpha_{\text{Engy}} M_{\text{Engy}} + \beta_{\text{Engy}} P_{\text{Engy}} \end{aligned} \quad (4.20)$$

The amount of energy being recovered during the recycling process is determined by the material being used and the type of energy recovery process. This amount of energy refers to the amount of additional energy being generated during the process of recycling certain materials. It does not include the amount of energy saved from avoidance of extraction of virgin materials. Certain material

will provide more recovered energy and certain recovery process are more environmentally friendly.

$$\begin{aligned}
 M_{RC} &= f(\text{Recyclability-R, Contamination-C, Nature of material-NaM,} \\
 &\quad \text{Lifespan-Ls, Biodegradability-Bg, Degree of material mix-DegM}) \\
 &= \alpha_{MRC} R + \beta_{MRC} C + \gamma_{MRC} NaM + \delta_{MRC} Ls + \epsilon_{MRC} Bg + \eta_{MRC} \\
 &\quad \text{DegM}
 \end{aligned} \tag{4.21}$$

The most important factor in this sub-index is material as it is the most basic element that can decide what the recycling process to be used is and the amount of energy that can be recovered. The recyclability of the material, contamination of the material, the nature of the material, the lifespan of the material, biodegradability and degree of material mix are the determinants of the material index for recycling.

The higher the recyclability of the material, the better the material index will perform. This is an important consideration of recycling. Then, contamination and degree of material mix will bring down the index if both are high. Contamination refers to the conditions of the materials as in how dirty it is and if there are any other contaminants like adhesives. Degree of material mix will refer to the number of different substances present in the materials. Nature of the material is an indication of what broad category the material belongs to. These categories include, for example, glass, metal, polymer, plastics, organic and ceramics. Lifespan measures the expected lifespan of the material. If the lifespan of the material is expected to be very long, recycling it at an early stage will incur a higher cost as resource is not optimally utilised and vice versa. The downcycling of grade of material is also being incorporated into this factor. The expected number of cycles is being taken into consideration of the lifespan of the material as well. If the

material has already been recycled a few times, the downcycling effects should be prominent, hence giving a lower value for the recycled material.

The final recycling sub-index is an aggregation of all the factors from the lower levels. Starting from the lowest level, material index is a summation function of recyclability, contamination, nature, lifespan, biodegradability and degree of material mix. Then, in turn, amount of energy recovered index is dependent on material index and the energy recovery process. Together with legislation, cost of energy, cost of consumables and emissions, material index will also determine the recycling process sub-index.

4.3.4.2 Remanufacturing

The hierarchical breakdown of the remanufacturing sub-index is depicted in Figure 4.9. The final remanufacturing sub-index is an aggregation of all the factors from the lower levels. This leads to a few equations being formed to express the relationship between the factors.

Figure 4.9 Hierarchical Breakdown of Factors affecting Remanufacturing

$$\begin{aligned}
 \text{Total cost } TC_{RM} &= f(\text{Time-}t_{RM}, \text{Value of remanufactured product-VaRP}) \\
 &= \alpha_{TCRM} t_{RM} + \beta_{TCRM} \text{VaRP}
 \end{aligned} \tag{4.22}$$

The total cost for remanufacturing is defined by the amount of time taken for the remanufacturing process and the value of the remanufactured products. Time taken for the remanufacturing process to take place is in turn entirely dictated by the remanufacturing process needed. The more tedious the remanufacturing process is, the more time is needed and it will be more costly producing a higher index for remanufacturing process.

$$\begin{aligned} \text{VaRP} &= f(\text{Technical Compatibility-TechC, Age-A, Market Demand-d}) \\ &= \alpha_{\text{VaRP}} \text{TechC} + \beta_{\text{VaRP}} A + \gamma_{\text{VaRP}} d \end{aligned} \quad (4.23)$$

The value of the remanufactured product is determined by the technical compatibility of the old module with the new product, the age of the module and the market demand for that particular module. Both technical compatibility and market demand have a positive relationship with the value of remanufactured product whereas age of the module varies inversely. The higher the value of the remanufactured product, the lower the cost of remanufacturing will be as the remanufactured product will fetch a higher price hence lowering down the cost of remanufacturing.

$$\text{Time, } T_{\text{RM}} = f(\text{remanufacturing process, } P_{\text{RM}}) = \alpha_{\text{TRM}} P_{\text{RM}} \quad (4.24)$$

Remanufacturing process is a function of the condition of the module, type of module, amount of emissions, cost of consumables and cost of energy. The emissions, cost of consumables and cost of energy are the same as those in the recycling index. As for the conditions of the module, it refers to the cleanliness and workability of the products which is measured by the degree of weariness and amount of cleaning needed. Those that are cleaner and working better will contribute to a higher index since less cleaning is needed, and a lower degree of weariness.

$$\begin{aligned}
P_{RM} &= f(\text{Condition of Module-CMod, Type of Module-TMod,} \\
&\quad \text{Cost of Energy-Cost}_E, \text{Cost of Consumables-Cost}_C, \text{Emissions-E}) \\
&= \alpha_{PRM} CMod + \beta_{PRM} TMod + \gamma_{PRM} Cost_E \\
&\quad + \delta_{PRM} Cost_C + \varepsilon_{PRM} E
\end{aligned} \tag{4.25}$$

$$\begin{aligned}
CMod &= f(\text{Degree of Weariness-DegW, Amt of Cleaning Needed-AmtCl}) \\
&= \alpha_{CMod} DegW + \beta_{CMod} AmtCl
\end{aligned} \tag{4.26}$$

$$\begin{aligned}
TMod &= f(\text{Material Mix-MMix, Nature of Module-NMod, Type of Joints-J}) \\
&= \alpha_{TMod} MMix + \beta_{TMod} NMod + \gamma_{TMod} J
\end{aligned} \tag{4.27}$$

The type of modules is made up of material mix in the module, nature of the module and the joining method of the module. The higher the material mix, the harder remanufacturing process will be due to the fact that more compatibility must be met. Certain joining methods and material mix are easier to remanufacture than others. The table below denotes the various meaning of the various notation used in the equations listed earlier. They are weights to be determined by AHP according to the priorities of the factors.

Table 4.3 List of Notation used in Equations

Equation	Notation	Explanations
4.5	α_{TCDI}	Weight of the factor time affecting total cost of disposal
	β_{TCDI}	Weight of the factor environmental impact affecting total cost of disposal
	γ_{TCDI}	Weight of the factor Value of Recycled Material affecting total cost of disposal
4.6	α_{TDI}	Weight of the factor treatment process affecting time
	β_{TDI}	Weight of the factor distance
4.7	α_{TP}	Weight of the factor material affecting treatment process
	β_{TP}	Weight of the factor legislations
4.8	α_{MDI}	Weight for the factor toxicity
	β_{MDI}	Weight for the factor nature of material
	γ_{MDI}	Weight of the factor biodegradability
4.9	α_{TC}	Weight for the factor time affecting total cost of disassembly
4.10	α_t	Weight for the factor ease of dismantling
	β_t	Weight for the factor technology available
4.11	α_{Ed}	Weight for the factor visual perceptibility

	β_{Ed}	Weight for the factor accessibility
	γ_{Ed}	Weight for the factor detachability
	δ_{Ed}	Weight for the factor sequence of dismantling
4.12	α_{Vp}	Weight for the factor type of modules
	β_{Vp}	Weight for the factor identification of material
4.13	α_{Dt}	Weight for the factor type of joints
	β_{Dt}	Weight for the factor number of joints
4.14	α_{Sd}	Weight for the factor structure affecting sequence of dismantling
4.15	α_{Acc}	Weight for the factor structure affecting accessibility
4.16	α_{st}	Weight for the factor depth
	β_{st}	Weight for the factor location
	γ_{st}	Weight for the factor shape
	δ_{st}	Weight for the factor size
4.17	α_{TCRC}	Weight for the factor time affecting the total cost of recycling
	β_{TCRC}	Weight for the factor value of recycled material
	γ_{TCRC}	Weight for the factor amount of energy recovered
4.18	α_{TRC}	Weight for the factor recycling process
4.19	α_{PRC}	Weight for the factor material affecting the total cost of recycling process
	β_{PRC}	Weight for the factor legislations affecting the total cost of recycling
	γ_{PRC}	Weight for the factor cost of energy
	δ_{PRC}	Weight for the factor cost of consumables
	ε_{PRC}	Weight for the factor emissions
4.20	α_{Engy}	Weight for the factor material affecting amount of energy recovered
	β_{Engy}	Weight for the factor energy recovery process
4.21	α_{MRC}	Weight for the factor recyclability
	β_{MRC}	Weight for the factor contamination
	γ_{MRC}	Weight for the factor nature of material
	δ_{MRC}	Weight for the factor lifespan
	ε_{MRC}	Weight for the factor biodegradability
	η_{MRC}	Weight for the factor degree of material mix
4.22	α_{TCRM}	Weight for the factor time affecting the total cost of remanufacturing
	β_{TCRM}	Weight for the factor value of manufactured product
4.23	α_{VaRP}	Weight for the factor technical compatibility
	β_{VaRP}	Weight for the factor age
	γ_{VaRP}	Weight for the factor demand
4.24	α_{TRM}	Weight for the factor remanufacturing process
4.25	α_{PRM}	Weight for the factor condition of the module
	β_{PRM}	Weight for the factor type of module

	γ_{PRM}	Weight for the factor cost of energy affecting the total cost of remanufacturing process
	δ_{PRM}	Weight for the factor cost of consumables affecting the total cost of remanufacturing process
	ε_{PRM}	Weight for the factor emissions affecting the total cost of remanufacturing process
4.26	α_{CMod}	Weight for the factor degree of weariness
	β_{CMod}	Weight for the factor amount of cleaning needed
4.27	α_{TMod}	Weight for the factor material mix
	β_{TMod}	Weight for the factor nature of module
	γ_{TMod}	Weight for the factor type of joint affecting the type of module

4.3.5 End-of-Life Scale Tables

Having defined and elaborated all the relationships between the factors that made up the sub-indices, the next step is to detail the scale of each of the individual factors that the designers can use to give a rating. Each of the scales is to be determined by the EoL stakeholders and other relevant experts. The range and extent of influence of the various values are normalised into a scale of 0-10, according to how it will affect the function that it belongs to. Two of the factors will be discussed here and the rest are in the appendix.

The first factor is Type of joints-J. The type of joint refers to the joining methods between two components, subassemblies or modules. The different types of joints will be consolidated and be ranked from 0-10, based on the extent it will influence EoL. The type of joints will affect the ease of disassembly and eventually increase the cost if it is tedious. Joints can be largely divided into two broad categories, permanent and non-permanent. The permanent one will be the upper half of the index as they will increase the difficulty of disassembly and thus bring the total cost of disassembly up. The easier the joint can be separated, the lower the rating for the factor will be. Considering the various types of joints and their ease

of disjoining, the normalised scale table for rating of the factor into the indicator Type of Joints is developed, as illustrated in Table 4.3.

Table 4.4 Scale for Rating of the Indicator Type of Joints

Index Value	Criteria
10	Inseparable Permanent Joints
9	Very hard and costly to separate Permanent Joints
8	Joints that need to use machines to separate
7	Adhesive
6	Welding/ Soldering
5	Wire
4	Screws
3	Snap Fit
2	Clips
1	Velcro Type
0	Loose Fittings Temporary Joints

The second factor is recyclability. It refers to the recycling ability of the material with respect to technology. The scale is developed using actual data from the recycle fraction, it is a measure of the fraction of the material being recycled [133]. Table 4.4 shows the scale and criteria for the range.

Table 4.5 Scale for Rating of the Indicator Recyclability

Index Value	Recycle Fraction	Criteria
10	0.0	Inorganic Material – Not recyclable
9	0.1	Organic material for energy recovery and not material recovery
8	0.2	Organic material for energy recovery and material recovery
7	0.3	Recycling technology still in development and not stable
6	0.4	Recycling technology available but not commercialized
5	0.5	Recycling technology commercialized but need improvement
4	0.6	Recycling technology commercialized but not widely available
3	0.7	Recycling technology widely available but tedious
2	0.8	Easily recyclable with established technology but more steps in the recycling

		process
1	0.9	Easily recyclable with well established technology
0	~1	Recycling is the default EoL method

Each factor will be transformed into an indicator rating using a scale defined in this project. This rating value will be used in the computation of EoL index together with the weights generated according to the preferences of the designers. The designer will give his pair wise ranking of the different factors from the function at the lowest level to generate the weights for the first function. Then, this ranking exercise will continue up to the next function until the final EoL index of the product equation is reached. The system will ask for the input according to the product structure ontology and the level of the product structure which the sub-indices are at.

In the appendix, most of the tables are using percentages as indicator values. As decision making in EoL is very much reliant on relative cost/benefits with respect to the default method. This also enables the tables to be more generic for different product domains. These tables are to be populated with up-to-date data by the EoL engineers from time to time from there is a change in the situation.

The EoL scale tables are also the only mechanism to take into account future changes. As the model is fixed for the factor hierarchy that is the relationships between the factors are fixed it does not take into account the future uncertainties for EoL. Instead, the changes in EoL are to be reflected on the EoL scale tables. The EoL engineers will maintain and update the information on the EoL scale tables. When there is any advancement in the technology that enhances the EoL processes, the EoL engineers can log on to the system to change the indicator values of the EoL scale tables. For example, when there is an improvement in the

technology for disassembly making joints with screws easier to disassemble, the indicator value of screw will decrease to represent the lower cost of disassembling screws brought by the improvement in the technology.

4.3.6 Ranking using Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) [132] was developed by Thomas Saaty for easier multi-criteria decision-making, both qualitatively and quantitatively [134]. This method will hierarchically decompose the criteria for decision making into simpler and measurable indicators which will be compared amongst each other in a natural, pair wise mode to get the true weights or ranking of each individual factor according to the importance or preference of the decision makers [135]. AHP is suitable in this case because the way the complexity of the problem is being structured is similar and it provides a method to synthesise the measurements of the multi criteria into a single index for this purpose. AHP is chosen in this weight generation because of the multi-criteria decision-making here. There is a large degree of subjectivity and relativity of the preferences involved. The similarity in the hierarchical structure of the factors affecting the final goal also made AHP very suitable to be used here. One point to note is that the work here makes use of pairwise comparison for dissimilar things in multi-dimensional decision making principles to obtain the weightings. As such, it applied the underlying principles of AHP, but it is not a case of direct application of AHP in solving the problem to obtain the ranking for decision making.

The process of obtaining the weights is to be carried out based on AHP using Expert Choice [136]. This is a software designed specially for AHP calculation. The model of EoL index calculation is created in the software and designers only

have to indicate the pair wise comparisons for the different factors accordingly. Designers will give the relative importance of each factor according to design objectives. Depending on the level of product structure that is being calculated, an algorithm will decide what are the factors that are relevant to the calculation are. The system will then generate the resultant weights for each of the factors. Using the weights and the indicator values read off from the EoL scale tables, the various sub-indices can be calculated by the above equations (4.1)-(4.27).

Looking at the different factors for the EoL index, there are some factors which are of rather consistent importance and hence there can be a default value for those factors. These factors include legislations, the various cost, distance, age, identifications of materials and technical requirements. These factors are typically not found in design objectives. The default value of each factor is obtained by using typical scenarios to generate the value. These scenarios are specific to local context and are common for most design cases. The important weightings that need to be generated based on designers' preferences are materials, type of modules and ease of dismantling. They are usually included in the main design objective under DfE.

4.4 Summary

In this chapter, the scenario between the two stages has been depicted and how the system works in this scenario to support and enhance the communication between the two stages has been described. The DELII framework being introduced in the previous chapter has the details of each of the components explained here. The EoL methodology is also being discussed in great detail here.

This chapter forms the foundation of this thesis and is what the system design will be based on.

CHAPTER 5

SYSTEM DESIGN

In this chapter, the main focus is to describe and discuss the system aspects of the project. After getting the methodology defined and information organised, the next step is to provide support in terms of technology to realise the concept. Figure 5.1 shows the methodology for system design. First, the DELII framework components are mapped to the Integrated Manufacturing Service System (IMSS) [137, 138] platform for the system architecture to be defined. Then repositories and ontology are designed concurrently. Following this will be the definition of requirements and subsequently use cases are defined before the system workflow is mapped out.

Figure 5.1 Methodology for System Design

5.1 System Design

For the methodology to be executable, a system is designed to support the translation of this methodology into a framework that is executable. The use of semantic web services and ontology is introduced to manage and support the implementation of this framework. This system is based on a generic architectural framework for supporting physically separated manufacturing activities. The system is designed to be customised for the purpose of enhancing the communication between the design stage and EoL stage.

A system architecture will be designed for the DELII framework based on an Integrated Manufacturing Service System (IMSS) [137, 138] platform co-developed by the author. The IMSS framework is semantic web services based and aimed for supporting virtual enterprises where the different product development activities are being geographically distributed. In particular for this thesis, activities in the design and EoL stage are connected through this system. Both the players in these two stages are able to communicate through the system. The user interfaces are accessible to players in these two stages. This kind of system is apt for the scenario as manufacturing globalises, with designers housed in more developed economies such as Germany and the US, and the EoL activities located in developing countries like China and India.

5.2 System Platform Framework

The Integrated Manufacturing Service System (IMSS) is a research project by the Agency for Science, Research and Technology of Singapore, of which the author is a member of. In IMSS, the aim is to research into an integrated platform

to support the integration of all the services and activities across the entire manufacturing value chain. It focuses purely on technologies used to integrate services and systems. It is generic and hierarchical and can cater for granularities of services of any size. Figure 5.2 depicts the framework. With reference from this framework, a customised system architecture for the DELII framework is designed for integrating the information from the design stage and EoL stage.

Figure 5.2 Framework of Integrated Manufacturing and Services System (IMSS)

The framework can be divided into 4 main components as shown below in Figure 5.3. In the framework, the four main components are enterprise process modelling (A), main enterprise web services engine module (B), semantic enabled web services (C) and external web services provider (D). The first component, the enterprise process modelling component takes care of the higher abstract modelling of the entire process from the conceptual stages to the end of manufacturing process producing the product.

Figure 5.3 Four Main Components of IMSS

It spans across the entire process value chain. The second one is the main enterprise web service engine module where the executable files from the first component are sent to for implementation. The third one is concerned with the semantic enabled web services such as ontology development and semantic search. The last component is the external web services provider component, which is a collection of all the web services containing virtualised manufacturing tasks available over the Internet or manufacturing grid.

To customise this framework with the aim of connecting the designers and EoL stakeholders, the first component on enterprise process modelling will be replaced with the DELII framework methodology which will be inputted into the main enterprise web service engine module. This component will be a brand new component of this project. As for components B, C and D, they are purely technological components with no relevant domain knowledge; hence it is only modified to a small extent to suit the domain purposes. The modifications are concentrated on the semantic enabled web services components. The semantic web services no longer require the private Universal Description, Discovery and Integration (UDDI) as the incorporation of ontology aspect in the Web Service Modelling Ontology (WSMO) has already taken into consideration the semantics of web services. The ordinary UDDI is sufficient to store the location of the web

services. Ontology is being deployed here for both the information management and semantic annotations of the web services. However, it is not possible to merge both the ontology management required in component A to those that are needed in component C. As the requirements for both the ontology implementations are different thus needing another tool in Protégé [139] to handle the information management ontology instead of doing it within WSMO studio [140, 141]. WSMO is designed specially for semantic web services and it uses another ontology language WSMML instead of OWL for the semantic web service ontology. Table 5.1 records the mapping of the IMSS framework to the DELII system architecture.

Table 5.1 Mapping of the IMSS Framework to the DELII System Architecture

Component	IMSS	DELII System	Implementation
A	Business Process Modelling	EoL Index EoL Tables Manage Design Manage EoL	Eclipse [142]
A	Web Services requirement Generator	Indicator Value Query EoL Computation Weight Generation	Eclipse Eclipse Expert Choice
A	Executable Files	Weights D-BOM	Excel Sheet XML file
B	Web Service Orchestration	Web Service Orchestration	WSMO Studio
B	Enterprise Web Service Execution Engine	Enterprise Web Service Execution Engine	WSMO Studio
B	Web Service Management	Web Service Management	WSMO Studio
B	Semantic Search Service	Semantic Search Service	WSMO Studio
C	Ontology Repository	Ontology Repository	Protégé
C	Private Enhanced UDDI	NA	SAWSDL [143]
C	Ontology Development	D-BOM Generation Semantic Web Services	Protégé WSMO Studio
D	External Web Services Provider	Databases	Databases Providers – mySQL and MS Access

5.3 System Architecture

The layered system architecture is described in Figure 5.4.

Figure 5.4 System Architecture Design

There are 4 main layers in this system namely, backend repository, middleware component, application components and user interface. The arrows in the diagrams represent the interactions of components between the layers. The repository layer interacts with both the middleware layer and application layer. The web service management component in the middleware layer needs to access the

WS repository for the web services needed for execution and the ontology management component of this layer also accesses the ontology database for storage and retrieval. As for the interactions between the application layer and repository layer, they include the linkages between the databases and the DELII components, as well as the interactions of the ontology management component and the ontology repository. At the application layer, there is horizontal interaction between the ontology management and the DELII components. Both these two components at this layer are responsible for interfacing with the users. However, only the DELII components will exchange data with the web service management component at the middleware layer. The two ontology management components will not interact with each other across the two layers.

5.3.1 Backend Repository Layer

The bottommost layer is the backend repository layer where all the databases are located. There are three main types of repository that are involved here. They are the data repositories with all the relevant production data, the web service repository inclusive of the UDDI directory and the ontology repository. Data repositories include material database, process database, energy database, product database and cost database. They will provide the required data for the system and designers to fill in the attributes of the product structure ontology. Upon the first input of D-BOM, the system will query the databases and look for the necessary information of the components to store as the attributes. The result of this action, which is the product structure ontology with attributes from the databases, will be outputted to the designer for them to check and edit current attributes as well as to fill in the missing attributes. These data can also be retrieved directly by designers

for references. The databases can be stored in either mySQL format or MS Access format. The system will be able to connect to the databases through ODBC and JDBC to retrieve the data.

Web service repository is a collection of the web services that the system need to use. In this system, all the services available are being encapsulated into web services to be invoked when required. As most of the services are localized and developed in this system, there is a need for this repository. There is also the UDDI repository which stores the registry indicating the exact location of the web services. Access to these two repositories is controlled by the middleware component layer.

The ontology repository is being used to store the ontology created by the system after D-BOM is inputted. The repository for the project is accessed through the API for Protégé. It is stored both locally and globally over the Net. Ontology are consensual and formal specifications of conceptualisation. They capture the semantics of information and give them a concise, uniform and declarative description. They also provide a shared and common understanding of a domain that can be communicated across people and application systems. In practice, ontology are normally written as sets of definitions of formal or standard vocabulary and these help users to use a vocabulary (i.e., ask queries and make assertions) in a way that is consistent (but not complete) with respect to the theory specified by the ontology. Ontology also defines the standard structure or mappings between different structures for describing semantics of documents. They can be used by automated tools to power advanced services such as more accurate searching intelligent software agents and knowledge management [144].

After the construction of the concept, ontology is implemented and transformed into machine-accessible and machine-understandable semantics through the representation of web ontology language. There are a few types of Web Ontology Languages available such as Ontology Inference Layer (OIL), DARPA Agent Markup Language (DAML), DAML+OIL and OWL. OWL is chosen to define and instantiate these ontology and made available as web resources. An OWL ontology might include descriptions of classes, properties and their instances. It is chosen because it is a more complete version of Web Ontology Language given the fact that it was developed and extended from RDF and DAML+OIL. OWL is a revision of the DAML+OIL web ontology language incorporating lessons learned from the design and application of DAML+OIL. It is a vocabulary extension of RDF [145]. OWL is intended to be used when the information contained in documents needs to be processed by applications, as opposed to situations where the content only needs to be presented to humans. It has more facilities for expressing meaning and semantics than XML, RDF, and RDF-S, and thus OWL goes beyond these languages in its ability to represent machine interpretable content on the Web [146].

5.3.2 Middleware Component Layer

The middleware component will house the semantic web service components. This is the enabling technology layer whereby transport protocols, messaging protocols, web service annotation, ontology management, web service discovery, web service orchestration or web service choreography, all managed by a main web service inference engine, will reside. Figure 5.5 shows a general workflow of semantic web services.

Figure 5.5 General Workflow of Semantic Web Services

The Web Service Modeling Ontology Framework (WSMF) [147] is adopted here for the development of Semantic Web Services. Semantic web service is employed here to provide a platform independent and a distributed system that can be accessed from different geographical locations over the web with a common understanding. Within this framework, Web Service Modeling Ontology (WSMO) [148] is used for describing various aspects related to Semantic Web Service. The ontology language for the implementation of the semantic web service ontology is the Web Service Modelling Language (WSML) [149] which is also part of the framework.

According to the definition adopted by the W3C Web Services Working Group, a Web service is a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically WSDL). Other systems interact with the Web service in a manner prescribed by its description using SOAP(Simple Object Access Protocol)-messages, typically conveyed using HTTP with an XML serialisation in conjunction with other Web-related standards [150].

In brief, a Web service is a collection of protocols and standards used for exchanging data between applications. Software applications written in various programming languages and running on various platforms can use Web services to exchange data over the Internet. It provides a standard means of interoperating between different software applications, running on a variety of platforms and/or frameworks. In the context of service oriented architecture, it also refers to a next-generation distributed computing model. The model assumes that the various components of the architecture will be versioned, replaced or augmented. Thus, web services are packaged into self-contained, modular applications, which are named and versioned specifications that are designed to work together and will act as a pre-configured solution over the WWW [151]. It can also be seen as the middleware that enables and simplifies Web application-to-application connectivity. Web services differ from other forms of middleware in that they are based on XML standards. As web technology advances, the definition of Web service may deviate and be vague. However, the general direction and definition of web service should revolve about being service oriented and capable of distributed computing, based on specifications, preferably an open one, and involving the use

of meta-languages in order to be programming languages and platforms independent.

In addition, the development of Semantic Web will enhance the utility of Web Services when they are widely deployed. Furthermore, Web Services can be run dynamically and enable just-in-time integration given the loosely coupled nature. Then, there is encapsulation in Web Services, which also makes Web Services modular, flexible, scalable and extendable and hence reducing the complexity. Currently, the combination of Simple Object Access Protocol (SOAP), Web Service Description Language (WSDL) and Universal Description, Discovery and Integration (UDDI) will make up the most common Web Services. There are still other technologies which may be useful for deploying Web Services. Technically, Web Service Architecture consists of many layered and inter-related technologies. There are many ways of designing, building and deploying Web Services using the different technology families [151].

SOAP is a lightweight protocol for exchange of information in a decentralised, distributed environment. It is an XML-based protocol that consists of three parts: an envelope that defines a framework for describing what is in a message and how to process it, a set of encoding rules for expressing instances of application-defined data types, and a convention for representing remote procedure calls and responses. SOAP can potentially be used in combination with a variety of other protocols. More on SOAP can be found in the W3C Recommendation on SOAP Version 1.2 Part 0: Primer [152].

Semantic Annotations for WSDL and XML Schema (SAWSDL) specification that is being developed by this Working Group defines mechanisms using which semantic annotations can be added to WSDL components. SAWSDL

does not specify a language for representing the semantic models, e.g. ontologies. Instead, it provides mechanisms by which concepts from the semantic models that are defined either within or outside the WSDL document can be referenced from within WSDL components as annotations. These semantics when expressed in formal languages can help disambiguate the description of Web services during automatic discovery and composition of the Web services. WSDL is an XML format for describing Web services. It is a standard that defines service interfaces. It enables one to separate the description of the abstract functionality offered by a service from concrete details of a service description such as "how" and "where" that functionality is offered [153]. The supported operation and messages are described abstractly, and then bound to a concrete network protocol and message format. More on WSDL can be referenced from Web Services Description Language (WSDL) Version 2.0 Part 1: Core Language [153]. In order to enable semantic web services, the web services are described in SAWSDL instead. UDDI Service is a service discovery protocol to bring a common standard for business-to-business (B2B) integration. It defines a set of standard interfaces for accessing a database of web services [150]. Other types of discovery protocol available include ebXML, IBM WSFL and MS XLANG.

5.3.3 Application Component Layer

This is the layer where the domain specific applications are located. The bulk of the processing of the system with respect to the application is completed here. There are two main sections, one for the ontology management and the other for the DELII framework implementation. The ontology management is implemented using Protégé. This software is available as a plugin to Eclipse which is the IDE

environment for this system. Protégé will handle the creation of ontology from the D-BOM, the storage of the ontology, the creation and editing of attributes. The ontology search will be done through Protégé also, but with the assistance of an additional reasoner in Racer [154]. Racer is an OWL reasoner and inference server for querying ontology.

5.3.4 User Interface Layer

This is the web-based delivery service layer where the user interacts with the system. The user interface here is divided into two types: the client webpage display of the system where results and information are being displayed for the user and the API GUIs where the other applications such as Protégé [139] and Expert Choice [136], are invoked for user input. Looking at figure 5.4, the topmost layer highlighted the fact that this is a system designed for both the designers and EoL stakeholders to access and use, thus enhancing connectivity between the two stages.

5.4 Use Cases

In this system, the purpose is to enhance communication between the Design stage and EoL stage. Looking at the functions of the system and analyzing the case scenario, these use cases are being identified. Figure 5.6 depicts the use cases for the system involving the designer and EoL stakeholder.

Figure 5.6 Use Cases for the System

In this system, designer must be able to input query, input Design –Bill-of-Material (D-BOM), input preferences and trigger off to generate the EoL Index. The designer should be able to access the system to provide input and finally obtain an EoL Index results from the system. As for the EoL stakeholder, the system should allow EoL information input and EoL tables’ updates.

Based on these use cases, the function workflow of the system is defined and shown in Figure 5.7. The system functions are divided into 2 sets, namely, for the designers and for EoL stakeholders. Upon entering the system, the user will choose one of the set. The first set is for designers. Within this set there are three functions, to generate weights, input D-BOM and generate EoL index. User will choose one function to proceed. The details of each of the function are elaborated in the next section. As for the set for the EoL stakeholders, the EoL stakeholders either update the EoL scale tables or add new EoL table and store the EoL scale table in the system for retrieval purposes.

Figure 5.7 Functional Workflow of the System

5.5 System Modules

This is a system which is mainly Java-based with Eclipse as the IDE and Protégé [139] as the ontology manager. These two are the main applications of the system and they are Java based. The few main system modules are Ontology Management, Weight Generation, EoL Computation, Indicator Value Query, Databases Query and Semantic Web Services Module.

As mentioned earlier, the ontology is implemented using OWL. The ontology management of this system is to be handled through Protégé which is a Stanford developed toolkit for implementing OWL. Protégé is available as a plug-in to the IDE environment and the API will be invoked through command from the IDE environment. This will provide the interface for users to edit the ontology. In this arrangement, an external database program, MySQL is used for storing additional data apart from the ontology repository that Protégé manages.

The ontology management process is divided into ontology generation, ontology editing and ontology search. The process starts with ontology generation when a D-BOM document is inputted into the system. The system will read off the D-BOM, then create the product structure ontology. A D-BOM is an XML document and needs to be created by the designers in the desired format that the system will be able to read off.

Table 5.2 shows the different fields and data types that are required in the D-BOM. There are two parts to the D-BOM format. The first part is material information where all the different parts and components needed are listed down with the quantity, component number, descriptions, module and number of joints. The second part is joining information where the joints between the different components are listed down to give the relationship between two components.

With these two segments of D-BOM, the product structure is able to be constructed in ontology with each part as class in ontology and the joints as relationships.

Table 5.2 Field and Datatype of D-BOM

Name of field	Data Type
Material	String
Quantity	Integer
Component No	String
Description	String
No of joints	Integer
Parent Module	String
Product Level	Integer

Name of field	Data Type
Joint No	Integer
Joint Start	String
Joint End	String
Type	String

Figure 5.8 illustrates an example of an UI of an OWL file generated for the product structure.

5.5.1 Weight Generation

Weight Generation is done through the application of AHP on the designers' preferences/priorities. This application can be performed by invoking the software Expert Choice. This software can output the results of the AHP in a Excel Spreadsheet format for the designer's references and also for the system to take

note of the weights generated. These Excel files are saved in a file server and imported into a preferences database. Figure 5.9 shows a typical screen for inputting of the preferences.

Figure 5.8 UI of an Example of OWL Doc generated

Figure 5.9 A Typical Screen for Inputting Preferences

The EoL Index model which is shown in Figure 4.7 is first inputted into the Expert Choice System and stored. When the weight generation module is invoked, the API user interface for allowing input of preferences is displayed. There are three methods for the pair wise comparison to be keyed in, that is, the graphical

method of sliding bars, the numerical method of keying in numbers and the verbal method of choosing descriptions. Once all the preferences are indicated, the weights will be generated according to the EoL model. When the results are out, the designer can adjust the preferences to look at the effects on the weights using sensitivity analysis. This exercise will provide the designer an estimate of the changes that can be expected when the preference levels are adjusted. After the Excel file has been generated and inputted into the system, the system will read off the Excel file for the values to be used in the calculation unit. Figure 5.10 depicts a screenshot of the disassembly model after synthesis of the weights in Expert Choice.

Figure 5.10 Screenshot of Disassembly Model in Expert Choice

5.5.2 Indicator Value Query

Indicator Value Query is to be done through a module for querying indicator value. This module is developed using Eclipse. The main function in this module is

to retrieve all the values needed for the computation of the index. The query language that is being used in this module to query the ontology is SPARQL Query Language [155]. This is a query language for OWL and RDF model. In the process of query, the unit is able to find out the location to retrieve the data, also based on EoL activities ontology.

5.5.3 Databases Query Module

This is a module to handle all the database interactions. It manages the database connections, database retrieval and database storage. As the databases are available in various formats and some as online services, this module must be able to handle these.

The “manage design module” determines the databases where the data is to be retrieved from and then pass it on to this module where a web service will be invoked to establish a connection with the databases or database service. Databases in this system are not the main focus here and they are obtained through purchases. The formats of the database hence depend on the suppliers. The two databases that are developed for this project are the EoL table repository and designers’ preferences database. The EoL table repository is implemented through MySQL. The ontology repository is handled by Protégé. For the databases connection, JDBC is generally used as the system is Java based.

5.5.4 End-of-Life Index Computation

This is a calculation-intensive module where the EoL index is generated from the aggregation of the factors. There are a total of 9 computation processes separated into 9 units. It is divided according to the level of the product structure

and the three sub-indices with one unit for summing up all the values. Each of the units will have the computation algorithms stored and perform the calculation upon request. Figure 5.11 shows the different units.

Figure 5.11 The Various Calculation Units for EoL Index Generation

Within each unit, the respective related equations are stored and executed upon request. There are two ways of getting the final total product index; the first one is to calculate the total sub-index for the components, sub-assemblies and modules then sum them up and the other one is to add up the product disassembly sub-index and the product recovery sub-index. The detailed algorithm is found in Appendix C.

5.5.5 Semantic Module

This is the module where the management of the semantic web services is performed. The semantic web services development is handled through WSMO studio [141] which is available as an Eclipse plug-in. In this studio, the various semantic web services management applications needed are included, such as

SAWSDL editor, WSM Reasoner, Semantic Business Process Modeling editor, Choreography designer, ontology/ goal/ service repository, service discovery components and WSM editor. All the functions in this system are programmed as web services that are invoked when being called. Hence, one module such as in indicator value query is implemented as a series of web services or composite web services. Figure 5.12 shows a typical WSMO studio UI for development.

Figure 5.12 Screenshot of the WSMO Studio for System Development

5.6 Summary

In conclusion, this chapter presents the entire system development process from the identification of a suitable platform to the system design based on DELII framework using UML to mapping of various components from the platform to the framework and finally the system implementation on the various software applications. This chapter is mainly focusing on the system aspects of the

framework to show that the framework can be realized to be used by the designers and EoL engineers.

CHAPTER 6

CASE STUDY

In this chapter, the proposed DELII framework is applied to a case study of a power tool design. The case study will start from the D-BOM and preferences input by the designers. Information will go through DELII to be transformed into the EoL index for designers to make informed design decisions that will lead to better EoL performance.

6.1 Case Study Formulation

The power tool is a typical electrical product that needs careful considerations in its EoL stage. One critical requirement is that it can be disassembled for recycling or remanufacturing. The designers need to have more information on the power tool's EoL so that a more appropriate design is chosen. This is because it consists of parts which still can be recovered at the EoL stage. In this case study, the EoL index methodology is applied to the alternative variations of the power tool design. The study also analysed how and in what way EoL information is fed back through DELII framework for design advisory.

The study is carried out on three scenarios each of which represents an alternative design variant. An EoL index is computed for each scenario based on the D-BOM of the design variant using the framework presented in Chapter 3 and the methodology described in Chapter 4.

The first scenario takes the base design and computes its EoL Index. The second scenario studies the effect on EoL index when some design parameters of the base design are changed. In this study, designers look at various EoL factors and their effects on EoL design. These areas are identified by examining either the worst performing factors where there is relatively more room for improvement or the factors with the most significant influence on EoL index. The designers compute the EoL Index of each design variant and other design variants to evaluate which design is of better standing in terms of EoL performance. The third scenario studies the effect on EoL index when changes in weight are taken place through the changes in designers' preferences.

These studies demonstrate how the EoL performance of the power tool and its design variants can be accessed using the EoL index methodology. The purpose is to show that the EoL Index well indicates the relative performance of a product at the EoL stage. Through comparison of EoL indices of alternative design variants, designers have the needed factors to make design decisions that lead to a design with better EoL performance.

Figure 6.1 The Power Tool being used in the Case Study

6.2 Designers' Input

According to the design drawing, the product structure level, material, description, quantity and joints are noted down in a D-BOM format. Table 6.1 lists the D-BOM of the drill.

The ontology of the product structure is then created with the given attributes values. This ontology is displayed for the designer to have a look and fill in the missing attributes. The power tool is viewed as a class with the modules being the sub-classes. Figure 6.2 presents the ontology created for the power tool in Protégé [139].

Table 6.1 List of D-BOM

Component Number	Description	Material	Quantity	Product Level	No of Joints	Parent Module
1	Speed Change Level Assembly	Mix	1	3	1	Control Module
2	Housing Set	NA	1	2	9	Product
4	Tapping Screw Bind Point 3x6	Metal	9	4	NA	Housing
5	Leaf Spring	PolyCarbonate	1	4	NA	Control Module
6	F/R Change Lever	PolyCarbonate	1	4	NA	Control Module
7	Switch C3NA-1-M1	PolyCarbonate	1	4	NA	Control Module
8	Battery Holder	Nickel Brass	1	4	NA	Battery Module
9	-C Flat Head Screw M6x22	Metal	1	4	NA	Drill Mechanism
10	Keyless Drill Chunk	PF 66 + GF 33	1	4	NA	Drill Mechanism
11	Gear Assembly	Mix - Cast Alloy Steel	1	3	NA	Drill Mechanism
12	DC Motor	Mix	1	3	NA	Motor
13	Pan Head Screw M3x6	Metal	1	4	NA	Drill Mechanism
14	Label	Paper with adhesive	1	4	NA	Housing
15	Casing	Elastomer mounted on polycarbonate 15%	1	4	NA	Housing
A01	Battery Cover	PolyCarbonate	2	4	NA	Battery Module
A02	Battery Charger	PolyCarbonate	1	4	NA	Battery Module
A03	+/- BIT 2-65	Metal	1	4	NA	Drill Mechanism
A04	Plastic Tool Case	Plastics	1	2	0	Accessory
A05	Battery PA09	Lithium	1	4	NA	Battery Module
M1	Battery Module	NA	1	2	1	Product
M2	Drill Mechanism	NA	1	2	4	Product
M3	Control Module	NA	1	2	3	Product

Figure 6.2 Product Structure generated by Protégé

Next, the designers indicate their preferences and priorities of the factors through the invocation of Expert Choice and then save the output Excel file into the system for further calculation. The following section shows the list of preferences that the designers can specify. These preferences are influenced by the needs of the customers, the manufacturing facilities, economy, legislation and awareness. In this case, the main concern is environmental sustainability and hence other factors tend to have a lower ranking over environmental related factors.

6.3 Weight Generation

The weights of all the factors are generated according to the preferences using Expert Choice. This set of preferences is based on a moderate case with environmental considerations taking priorities and cost factors being constant. The

pairwise comparisons of the factors by the designers are recorded in Tables A1-D5.

The designers will decide the relative importance between the different factors by comparing two factors at a time for all the possible permutation pairs.

Disposal

A1) $M_{DI} = f(\text{Toxicity, Tx, nature of material, NaM, biodegradability, Bg})$

	Toxicity	Nature of Material	Biodegradability
Toxicity	-	1	
Nature of Material	1	-	$\frac{1}{2}$
Biodegradability	3	2	-

A2) $P_T = (\text{Material} - M_{DI}, \text{Legislations} - L)$

	Legislations	Material
Legislations	-	$\frac{1}{2}$
Material	2	-

A3) $t_{DI} = f(\text{Treatment Process} - P_T, \text{distance} - Dt)$

	Treatment Process	Distance
Treatment Process	-	$\frac{1}{4}$
Distance	4	-

A4) Total cost of disposal, $TC_{DI} = f(\text{Time- } t_{DI}, \text{Environmental Impact- EI, Value of Recycled Material- VaRM})$

	Time	Environmental Impact	Value of recycled material
Time	-	2	2
Environmental Impact	$\frac{1}{2}$	-	$\frac{1}{2}$
Value of recycled material	$\frac{1}{2}$	2	-

Disassembly

B1) $t_{DAI} = f(\text{Ease of dismantling-Ed, technology available-Tech})$

	Ease of Dismantling	Technology Available
Ease of Dismantling	-	$\frac{1}{2}$
Technology Available	2	-

B2) $Ed = f(\text{Visual perceptibility-Vp, Accessibility-Acc, Detachability-Dt, sequence of dismantling-Sd})$

	Visual Perceptibility	Accessibility	Detachability	Sequence of Dismantling
Visual Perceptibility	-	3	2	2
Accessibility	$\frac{1}{3}$	-	1	1
Detachability	$\frac{1}{2}$	1	-	$\frac{1}{2}$
Sequence of Dismantling	$\frac{1}{2}$	1	2	-

B3) $Vp = f(\text{Type of modules-Mod, Identification of material-ID})$

	Type of Module	Identification of Material
Type of Module	-	1
Identification of Material	2	-

B4) $Dt = f(\text{Type of joints-J, number of joints-No}_J)$

	Type of Joints	Number of Joints
Type of Joints	-	1
Number of Joints	1	-

B5) $St = f(\text{depth-Dp, location-Loc, shape-Sp, size-Sz})$

With respect to Accessibility

	Depth	Location	Shape	Size
Depth	-	1	$\frac{1}{2}$	$\frac{1}{2}$
Location	1	-	1	$\frac{1}{2}$
Shape	2	1	-	2
Size	2	2	$\frac{1}{2}$	

B6) $St = f(\text{depth-Dp, location-Loc, shape-Sp, size-Sz})$

With respect to Sequence of Dismantling

	Depth	Location	Shape	Size
Depth	-	2	1	1
Location	1/2	-	1/2	1/3
Shape	1	2	-	1
Size	2	3	1	

Recycling

C1) Total cost $TC_{RC} = f(\text{Time-}T_{RC}, \text{Value of recycling the material-VaRM, Amt of energy recovered-Engy})$

	Time	Value of Recycling the Material	Amt of Energy Recovered
Time	-	1/2	1/2
Value of Recycled Material	2	-	1/3
Amt of Energy Recovered	2	3	-

C2) $P_{RC} = f(\text{Material-}M_{RC}, \text{Legislations-L, cost of energy-Cost}_E, \text{Cost of consumables-Cost}_C, \text{emissions-E})$

	Material	Legislations	Cost of Energy	Cost of Consumables	Emissions
Material	-	2	2	1/2	1/2
Legislations	1/2	-	1/3		1/3
Cost of Energy	1/2	3	-		2
Cost of Consumables	2	4	1	-	3
Emissions	2	3	1/2	1/2	-

C3) $Engy = f(\text{Material-MEngy, energy recovery process-PEngy})$

	Material	Energy Recovery Process
Material	-	1/3
Energy Recovery Process	3	-

C4) $MRC = f(\text{Recyclability-R, Contamination-C, Nature of material-NaM, Lifespan-Ls, Biodegradability-Bg, Degree of material mix-DegM})$

	Recyclability	Contamination	Nature of Material	Life span	Bio-degradability	Degree of Material Mix
Recyclability	-	2	1/2	1/2	1/2	1/2
Contamination	1/2	-	1/3	1/3	1/2	1/2
Nature of Material	3	3	-	1/2	1	2
Lifespan	2	3	2	-	1/2	2
Biodegradability	2	2	1	2	-	2
Degree of Material Mix	2	2	1/2	1/2	1/2	-

Remanufacturing

D1) $VaRP = f(\text{technical compatibility-TechC, age-A, market demand-d})$

	Technical Compatibility	Age	Market Demand
Technical Compatibility	-	1/4	1/2
Age	4	-	2
Market Demand	2	1/2	-

D2) Total cost $TC_{RM} = f(\text{Time-}t_{RM}, \text{Value of remanufactured product-VaRP})$

	Time	Value of Manufactured Product
Time	-	1/2
Value of Manufactured Product	2	-

D3) $CMod = f(\text{degree of weariness-DegW, amt of cleaning needed-AmtCl})$

	Degree of Weariness	Amt of Cleaning Needed
Degree of Weariness	-	1/2
Amt of Cleaning Needed	2	-

Based on these preference tables, the input are keyed into the EoL models created in Expert Choice and AHP results from the Expert Choice after synthesis with respect to the EoL models created in the system. Each of the major equations is transformed into a model in Expert Choice according to the hierarchical breakdown. These models collectively formed a set of EoL models for the DELII. Figure 6.3 shows the disassembly model used. This is an example of the set of EoL models created in Expert Choice. Figure 6.4 depicts the synthesis results of the measurable factors with respect to their influence on ease of disassembly. Appendix D consists of the rest of the screenshots of the models and synthesis results.

Figure 6.3 Disassembly Model in Expert Choice

Figure 6.4 Synthesis Results of Measurable Factors with respect to Influence on
Ease of Disassembly

From the synthesis results, it shows that with respect to the ease of dismantling, the factor location has the biggest influence. This is followed by the type of joint and number of joints. On the other hand, the identification of the material has the smallest influence. This result suggests that in order to improve ease of dismantling, it is better to consider first changing the location of the components, the type of joints or the number of joints than to consider changing the type of module or identification of material. The ease of disassembly performance which subsequently affects the EoL index will most likely be improved to a greater extent. Next, the resultant weight for each factor is shown in Table 6.2.

Table 6.2 Resultant Weights from Expert Choice

Weights		Symbol	Disassembly
γ_{st}	0.195	Sp	Shape
α_{st}	0.231	Dp	Depth
δ_{st}	0.148	Sz	Size
β_{st}	0.426	Loc	Location
γ_{st}	0.174	Sp-Acc	Shape
α_{st}	0.335	Dp	Depth
δ_{st}	0.218	Sz	Size
β_{st}	0.273	Loc	Location
β_{Dt}	0.5	No_J	No of Joint
α_{Dt}	0.5	J	Type of Joint
α_{Vp}	0.667	Mod	Type of Module
β_{Vp}	0.333	ID	Identification of Material

β_t	0.333	Tech	Technology Available
α_{Ed}	0.125	Vp	Visual Perceptibility
β_{Ed}	0.306	Acc	Accessibility
γ_{Ed}	0.333	Dt	Detachability
δ_{Ed}	0.235	Sd	Sequence of Dismantling
α_t	0.667	Ed	Ease of Disassembly
			Disposal
α_{MDI}	0.333	Tx	Toxicity
β_{MDI}	0.387	NaM	Nature
γ_{MDI}	0.169	Bg	Biodegradability
β_{DI}	0.167	Dt	Distance
β_{PT}	0.667	L	Legislation
β_{TCDI}	0.493	EI	Environmental Impact
γ_{TCDI}	0.311	VaRM	Value of Recycled Material
α_{PT}	0.333	MDI	Material
α_{TDI}	0.833	TP	Treatment Process
α_{TCDI}	0.196	DI	Time
			Recycling
η_{MRC}	0.165	DegM	Degree of Material Mix
β_{MRC}	0.303	C	Contamination
γ_{MRC}	0.106	NaM	Nature
ε_{MRC}	0.096	Bg	Biodegradability
α_{MRC}	0.227	R	Recyclability
δ_{MRC}	0.103	Ls	Lifespan
ε_{PRC}	0.181	E	Emissions
δ_{PRC}	0.091	Cost _C	Cost of Consumables
β_{PRC}	0.391	L	Legislation
γ_{PRC}	0.153	Cost _E	Cost of Energy
β_{TCRC}	0.349	VaRM	Value of Recycled Material
β_{Engy}	0.25	P _{Engy}	Energy Recovery Process
α_{PRC}	0.184	MRC	Material-RP
α_{Engy}	0.75	Mengy	Material
γ_{TCRC}	0.168	Engy	Amt of Energy Recovery
α_{TRC}	0.484	RP	Recycling Process
			Remanufacturing
ε_{PRM}	0.249	E	Emissions
γ_{TMod}	0.349	J	Type of Joint
β_{TMod}	0.168	NMod	Nature of Module
α_{TMod}	0.484	MMix	Material Mix
β_{CMod}	0.333	AmtCl	Amount of Cleaning Needed
α_{CMod}	0.667	DegW	Degree of Weariness
δ_{PRM}	0.156	Cost _C	Cost of Consumables
γ_{PRM}	0.202	Cost _E	Cost of Energy
γ_{VaRP}	0.286	d	Market Demand

β_{VaRP}	0.143	A	Age
α_{VaRP}	0.571	TechC	Technical Compatibility
β_{PRM}	0.088	Tmod	Type of Module
α_{PRM}	0.304	Cmod	Condition of Module
α_{TCRM}	0.667	PRM	Remanufacturing Process
β_{TCRM}	0.333	VaRP	Value of Remanufactured Product
			EoL Index
α	0.484	DAI	Disassembly
β	0.349	RI	Recovery
γ	0.168	DI	Disposal

From the results, it can be seen that the disassembly is the most influential of all, accounting for 48.4% of the EoL index. This is also in line with the actual situation as many of the EoL options require the product to go through the disassembly process. Based on this set of preferences, it is more important to design with considerations for recovery over disposal. This goes to show that a product that has been designed with features that facilitate disassembly will be able to achieve a better environmental performance at the EoL.

6.4 End-of-Life Index Calculation

Based on the D-BOM and the product structure ontology generated, the various measurable values of the factors are queried and retrieved. These values are then being converted to indicator value using EoL tables being created and maintained by the EoL stakeholders. For example, in this design of the power tool, the measurable factor value for the type of joints in the housing set is screw and taking this value to compare against the EoL scale table for type of joints to obtain the corresponding factor indicator value. The corresponding indicator value for the factor type of type of joints from Table 6.3 is 4.

Table 6.3 EoL Scale Table for Type of Joints

Index Value	Criteria
10	Inseparable Permanent Joints
9	Very hard and costly to separate Permanent Joints
8	Joints that need to use machines to separate
7	Adhesive
6	Welding/ Soldering
5	Wire
4	Screws
3	Snap Fit
2	Clips
1	Velcro Type
0	Loose Fittings Temporary Joints

The rest of the indicator value for the different measurable factors are also determined in this way by looking up the respective EoL Scale table defined for the factors. These tables can be found in Appendix A. After reading off the EoL table, the indicator values of the different factors for this power tool are obtained and shown in Table 6.4.

Table 6.4 Indicator of Each Component

	Component No:	1	2	4	5	6	7	8	9	10	11	12	13	14	15	M2	M3
Symbol	Disassembly																
Sp	Shape	3	6	-	-	-	-	-	-	-	7	-	-	-	-	5	7
Dp	Depth	1	1	-	-	-	-	-	-	-	7	-	-	-	-	3	5
Sz	Size	1	4	-	-	-	-	-	-	-	6	-	-	-	-	2	5
Loc	Location	1	1	-	-	-	-	-	-	-	7	-	-	-	-	4	7
No_J	No of Joint	1	4	-	-	-	-	-	-	-	5	-	-	-	-	4	3
J	Type of Joint	3	.4	-	-	-	-	-	-	-	8	-	-	-	-	4	6
Mod	Type of Module	3	2	-	-	-	-	-	-	-	-	-	-	-	-	4	7
ID	Identification of Material	2	5	-	-	-	-	-	-	-	6	-	-	-	-	3	3-
Tech	Technology Available	2	1	-	-	-	-	-	-	-	5	-	-	-	-	3	3
	Disposal																
Tx	Toxicity	2	2	0	0	2	2	0	0	0	0	2	0	3	2	-	-
NaM	Nature	7	7	2	2	7	7	2	2	2	5	6	2	2	7	-	-

Bg	Biodegradability	8	8	9	9	8	8	9	9	9	7	9	9	4	8	-	-
Dt	Distance	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-	-
L	Legislation	3	3	0	0	3	3	0	0	0	3	3	0	1	3	-	-
EI	Environmental Impact	2	2	1	1	2	2	1	1	1	3	3	1	2	2	-	-
VaRM	Value of Recycled Material	6	6	8	8	6	7	8	8	8	6	5	8	4	6	-	-
	Recycling																
DegM	Degree of Material Mix	5	4	0	0	1	5	1	0	0	5	7	0	1	4	3	2
C	Contamination	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
NaM	Nature	8	8	3	3	8	8	3	3	3	5	5	3	2	8	3	7
Bg	Biodegradability	8	8	9	9	8	8	9	9	9	7	9	9	4	8	-	-
R	Recyclability	7	6	1	1	1	6	1	1	7	2	9	1	9	6	2	4
Ls	Lifespan	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
E	Emissions	5	5	3	3	5	5	3	3	4	6	6	3	2	5	3	4
Cost _C	Cost of Consumables	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
L	Legislation	3	3	0	0	3	3	0	0	5	3	7	0	1	5	3	3
Cost _E	Cost of Energy	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
VaRM	Value of Recycled Material	5	5	3	3	5	5	3	3	4	4	8	3	7	5	2	3
P _{Engv}	Energy Recovery Process	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	Remanufacturing																
E	Emissions	3	3	1	1	2	1	2	1	3	6	0	1	3	3	3	4
J	Type of Joint	4	4	2	4	0	0	2	4	4	8	0	4	4	3	4	3
NMod	Nature of Module	4	4	1	1	4	5	6	1	4	8	7	1	4	4	7	4
MMix	Material Mix	1	1	0	0	0	2	1	0	0	6	7	0	2	1	3	2
AmtCl	Amount of Cleaning Needed	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
DegW	Degree of Weariness	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Cost C	Cost of Consumables	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Cost E	Cost of Energy	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
d	Market Demand	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
A	Age	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
TechC	Technical Compatibility	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

As some of the information was not fully available at the point of study, assumptions for the factors were taken. For factors where information is not readily available, an average value of 5 was indicated and used in the calculation.

This is to simplify the information collection process when there is inadequate information during the design process. As for information related to the status of the products after usage stage such as conditions of the products are assumed to be relatively good conditions at a value of 3.

Point to note:

While DC motor is a sub-assembly, it is considered as a component while doing the evaluation as the disassembly of the DC motor is technologically very challenging in this case study.

Cost related factors are set to be constant as the focus here is really to study the EoL performance from the sustainability point of view. The influence of cost will be further investigated in the extension of the work. After gathering all the indicator values, the various sub-indices and final EoL index of the modules, sub-assemblies and components are calculated according to equation (4.1) – (4.26). Figure 6.5, Figure 6.6 and Figure 6.7 present the EoL index results of the various modules, sub-assemblies and components respectively. In the figures, the breakdown of the EoL index into the three sub-indices is given. Figure 6.5 shows the EoL index of the various modules in the power tool. There are five modules in the power tool. However, as the motor is considered as a component in this case, housing is considered as a sub-assembly and battery is an accessory thus these three components are left out, leaving only the drill mechanism module and control module.

Figure 6.5 EoL Index of Module

From the figure, it can be seen that it is more costly to disassemble and recover M3 which is the control module. In all the sub-categories except for the values contributed by the loose components attached to the modules, the index values for M3 are higher than M2. This implies that at the module level, M3 will perform worse at EoL and should be looked at for improvements, especially the disassembly and recycling aspects.

Next, the EoL Index of the various sub-assemblies are plotted in Figure 6.6. As can be shown from the results, disassembly contributed most in the overall index of SA2 and SA11. Based on this graph, designers are able to know that in order to improve the EoL performance of the product, improving the design of the product by focusing on the disassembly aspect will yield more improvements.

Figure 6.6 EoL Index of Sub-Assembly

It can also be seen that taking a closer look at SA11 which is the gear assembly and thinking of design alternatives for this sub-assembly might bring about a greater change in the improvement of EoL performance.

Figure 6.7 presents the results of the EoL index of the various components in the product. This graph shows the disposal sub-index, recovery sub-index, which is represented by recycling and remanufacturing, and the EoL index of all the components in the power tool. Component is the most basic level of the product and no more further disassembly will be performed, hence there is no disassembly sub-index. It can be seen from the graph that the EoL performance of similar components such as metal screws are approximately the same and they typically have lower EoL performance than the rest of the components. This is probably due to the fact that they are purely metal which are easier to handle at the EoL.

Figure 6.7 EoL Index of Component

The graph also shows that component 12, which is a DC motor, had the higher cost or worst EoL performance at 13.73. This implies that there is the greatest potential to improve on this. The designer can look into the worst performing factors from the list and try to alter that factor to improve the EoL performance. The designer can also look at the weights of the factors to see which factor is a heavier weighted factor that will give a greater change when modified.

This graph can also help the designer to decide which is a better EoL option for the component by comparing the disposal and recovery sub-indices. Like in the case of component 14, it might be better to dispose of the components than to recover it due to the complexities in recovering the components.

6.5 Modifications for Improvements

As each term in the equations for calculation of the EoL Index comprises two parts, the weight and the indicator value, there are two types of variables in the index that can be modified to improve the design. The following two cases present

the investigation and comparisons of the changes in EoL performance when the weight and the indicator value changes respectively.

6.5.1 Modifications to Design Leading to Changes in Indicator Values

To illustrate the application of the EoL index in helping designers to compartmentalise the EoL performance in certain aspects, a modification was made on the original design and the disassembly sub-index was recalculated. The change was done on the material choice of the casing of the housing module. Based on the original design where TPE mounted on PC was used, the material for the housing set was changed to only LCP. This is an attempt to improve the design in terms of materials while keeping the same grip as before. After changing the material, one fewer material is needed in TPE as there is no need to mount an additional layer for the grip. The LCP will be able to provide sufficient grip for the handle portion. This change will alter the value of the factor “no of joints” and also “identification of the material”. It will improve the identification of material as there is one less material to be identified and noted. Also due to the fact that there is no need to mount an additional material onto the handle, there is one less joint to take care of during disassembly. Table 6.5 shows both sets of indicator values before and after the change.

Table 6.5 Sets of Indicator Values for Comparison

Symbol	Disassembly	Weights		Indicator Value		Indicator Value	
Sp	Shape	γ_{st}	0.1950	6.0000	1.1700	6.0000	1.1700
Dp	Depth	α_{st}	0.2310	1.0000	0.2310	1.0000	0.2310
Sz	Size	δ_{st}	0.1480	4.0000	0.5920	4.0000	0.5920
Loc	Location	β_{st}	0.4260	1.0000	0.4260	1.0000	0.4260
Sp-Acc	Shape	γ_{st}	0.1740	6.0000	1.0440	6.0000	1.0440
Dp-Acc	Depth	α_{st}	0.3350	1.0000	0.3350	1.0000	0.3350

Sz-Acc	Size	δ_{st}	0.2180	4.0000	0.8720	4.0000	0.8720
Loc-Acc	Location	β_{st}	0.2730	1.0000	0.2730	1.0000	0.2730
No_J	No of Joint	β_{Dt}	0.5000	4.0000	2.0000	3.0000	1.5000
J	Type of Joint	α_{Dt}	0.5000	4.0000	2.0000	4.0000	2.0000
Mod	Type of Module	α_{Vp}	0.6670	2.0000	1.3340	2.0000	1.3340
ID	Identification of Material	β_{Vp}	0.3330	5.0000	1.6650	4.0000	1.3320
Tech	Technology Available	β_t	0.3330	1.0000	0.3330	1.0000	0.3330
Vp	Visual Perceptibility	α_{Ed}	0.1250	2.9990	0.3749	2.6660	0.3333
Acc	Accessibility	β_{Ed}	0.3060	2.5240	0.7723	2.5240	0.7723
Dt	Detachability	γ_{Ed}	0.3330	4.0000	1.3320	3.0000	0.9990
Sd	Sequence of Dismantling	δ_{Ed}	0.2350	2.4190	0.5685	2.4190	0.5685
Ed	Ease of Disassembly	α_t	0.6670	3.0477	2.0328	2.6731	1.7829
				DAI _{old} =	2.3658	DAI _{new} =	2.1159

After the disassembly sub-index is being re-generated, it showed that the new disassembly sub-index is lower than the previous one. It would imply that using the new design, the housing assembly is expected to perform better during the disassembly stage and contributing to an easier EoL operation. Another point to note here is that with the results are listed out in a systematic way for designers to look at each individual aspect forecast and come up with solutions for the respective factors.

6.5.2 Modifications to Preferences Leading to Changes in Weights

For the same set of values for disassembly sub-index of the housing assembly, the designer's preference was changed. The importance of the detachability over accessibility on ease of disassembly is increased. Now detachability is perceived to be more influential and significant for ease of disassembly and hence the pairwise comparison between the two factors has changed from equally important to detachability to be twice as important as

accessibility. Table 6.6 shows the new preference table for ease of disassembly.

The underlined entries are the modified values signifying the change.

B2) $E_d = f(\text{Visual perceptibility-Vp, Accessibility-Acc, Detachability-Dt, sequence of dismantling-Sd})$

Table 6.6 New Preference Table for Ease of Disassembly

	Visual Perceptibility	Accessibility	Detachability	Sequence of Dismantling
Visual Perceptibility	-	3	2	2
Accessibility	1/3	-	<u>2</u>	1
Detachability	1/2	<u>1/2</u>	-	1/2
Sequence of Dismantling	1/2	1	2	-

With this new set of preferences, the corresponding changes are made in the AHP model in Expert Choice to generate the new weights. Table 6.7 lists the new weights and note the changes in weights for the four factors affecting disassembly, namely; visual perceptibility, accessibility, sequence of dismantling and detachability. Note that the change in the pairwise ranking between the detachability and accessibility has also affected the weight of sequence of dismantling and visual perceptibility. This is because by using AHP, it has taken into account the relative importance and relationship amongst all the factors. Thus, it can be seen that AHP has provided a more robust multi-criteria decision making process. The weights are not simply treated as direct preferences of the designer, instead, the relative importance is also being taken into consideration when generating the weights. Figure 6.7 presents the sets of indicator values with new weights. The new weights are highlighted in bold.

Table 6.7 Sets of Indicator Values with New Weights for Comparison

Symbol	Disassembly	Weights		Indicator Value _{old}		Indicator Value _{new}	
Sp	Shape	γ_{st}	0.1950	6.0000	1.1700	6.0000	1.1700
Dp	Depth	α_{st}	0.2310	1.0000	0.2310	1.0000	0.2310
Sz	Size	δ_{st}	0.1480	4.0000	0.5920	4.0000	0.5920
Loc	Location	β_{st}	0.4260	1.0000	0.4260	1.0000	0.4260
Sp-Acc	Shape	γ_{st}	0.1740	6.0000	1.0440	6.0000	1.0440
Dp-Acc	Depth	α_{st}	0.3350	1.0000	0.3350	1.0000	0.3350
Sz-Acc	Size	δ_{st}	0.2180	4.0000	0.8720	4.0000	0.8720
Loc-Acc	Location	β_{st}	0.2730	1.0000	0.2730	1.0000	0.2730
No_J	No of Joint	β_{Dt}	0.5000	4.0000	2.0000	3.0000	1.5000
J	Type of Joint	α_{Dt}	0.5000	4.0000	2.0000	4.0000	2.0000
Mod	Type of Module	α_{vp}	0.6670	2.0000	1.3340	2.0000	1.3340
ID	Identification of Material	β_{vp}	0.3330	5.0000	1.6650	4.0000	1.3320
Tech	Technology Available	β_t	0.3330	1.0000	0.3330	1.0000	0.3330
Vp	Visual Perceptibility	α_{Ed}	0.1260	2.9990	0.3779	2.6660	0.3359
Acc	Accessibility	β_{Ed}	0.2570	2.5240	0.6487	2.5240	0.6487
Dt	Detachability	γ_{Ed}	0.3910	4.0000	1.5640	3.0000	1.1730
Sd	Sequence of Dismantling	δ_{Ed}	0.2260	2.4190	0.5467	2.4190	0.5467
Ed	Ease of Disassembly	α_t	0.6670	3.1372	2.0925	2.7043	1.8038
				DAI _{old1} =	2.4255	DAI _{new1} =	2.1368

Table 6.8 shows the disassembly sub-indices of the housing sub-assembly before the value and weight changes.

Table 6.8 Disassembly Sub-index of the Different Cases

	Original Value	New Value	Change
Original Weight	2.3658	2.1159	0.2499
New Weight	2.4255	2.1368	0.2887
Change	-0.0597	-0.0209	

From the results, changing the indicator value will yield a better improvement in the disassembly sub-index of the housing sub-assembly. There is a 0.2499 and 0.2887 improvement respective in the case of using the original and

new weight with the different values. However, it can also be seen in the case when the preferences are changed, there is a worse performance in EoL in both cases with the original value and the new value. With the changes in both weight and indicators, this index methodology has provided a way for the designers to calculate the net improvement in the EoL performance so that a decision as to whether or not, the new design is feasible and more sustainable, can be made.

6.6 Summary

In this case study, the framework and EoL methodology were applied to the design of a power tool. Two variations were carried out and compared with the original one. The case study has shown that this index can be used to assist the designer in forecasting the EoL performance of the design and also the alternative design for comparison purposes.

CHAPTER 7

DISCUSSIONS

The literature survey at Chapter 2 has revealed that information management and communication is required for more effective and efficient implementation of design for EoL (DfEoL) in sustainable product development. The incorporation of web-based technology to realize the framework is also essential for globalised product development teams. The work of this thesis aims to design a framework for the purpose of assessing the EoL performance of a product during design stage. Included are a system design for realization of this framework, and an EoL Index Methodology that quantifies the factors affecting the EoL holistically.

This is a novel framework that attempts to facilitate the communication and information flow between the designers and EoL engineers. It is strategically placed between the design and EoL stage, providing the means to enable effective and timely feedback from the EoL stage to the design stage. Players at both stages can access the system anytime and anywhere over the web.

7.1 Major Features of this Framework

The major features of this framework are summarized as following:

- 1) Bridging the information gap between the design stage and EoL stage

The contributions and involvement by the EoL Engineers in the design stage is one of the novel key features of the framework. It enables the EoL Engineers to provide up-to-date data related to EoL requirements and feedback a product's EoL performance to the designer in a systematic and timely manner. Through such a mechanism, designers and EoL Engineers can share their information and communicate with each other to improve the process of DfEoL. In future, this framework can be extended to the other stages as well, such as product service advisory.

- 2) Development of the EoL index methodology

The assessment of EoL performance at Design stage using information transformed from data at EoL stage is achieved through the development of an EoL index methodology. The EoL index methodology is an important part of the framework. It provides the means to holistically quantify various aspects of EoL information from the EoL stage so that the EoL performance of design alternatives can be assessed. In this methodology, the data provided by the EoL engineers are organized in a set of EoL metrics. A rating method is used to quantify these metrics into indicators. The indicators are weighted based on priority considerations, and normalized into an index value that reflects the relative performance of a design alternative at the EoL stage.

This EoL index considers the various options of EoL and takes into account a wide range of factors affecting EoL. The various determinants of EoL performance are hierarchically broken down into measurable factors. A

bottom up modular approach is adopted in aggregating the EoL index. The application of Analytic Hierarchy Process (AHP) in determining the importance of the various factors according to the designer's preferences allows a more robust multi-criteria decision making process. By using AHP, the relative importances between the factors are accounted for and eventual weights can be generated. This EoL index provides a mean for the designers to consolidate all the factors that affect the EoL of a product together for assessment of EoL performance. The modularity aspect of this index allows the addition and exclusion of any factors related to the product design under study.

This EoL index provides designers a simple, timely, and quantitative tool to know how a product would perform at EoL. With such knowledge, designers can make informed design decisions that will improve the product's life cycle performance and competitiveness.

In addition, as the model for AHP is fixed for the factor hierarchy, that is, the relationships between the factors are fixed, and thus it does not take into account the future uncertainties for EoL. Instead, the changes in EoL are to be reflected on the EoL scale tables. The EoL engineers will maintain and update the information on the EoL scale tables. When there is any advancement in the technology that enhances the EoL processes, the EoL engineers can log on to the system to change the indicator values of the EoL scale tables. Eg, when there is an improvement in the technology for disassembly making joints with screws easier to disassemble, the indicator value of screw will decrease to represent the lower cost of disassembling screws brought by the improvement in the technology.

3) Use of Ontology

Another important feature of this framework is the use of ontology to standardise the concepts, terminology and nomenclature used between the designers and EoL Engineers. An ontology representing the product structure is developed. In the process, technical issues related to information management, relevancy and data validity are addressed. In order to provide a smooth mapping between the D-BOM and the ontology, each class and the relationship between classes in ontology is defined to correspond to each of the components and the joining relationships between them.

4) Semantic web service based system design

A system design based on semantic web services technology is proposed. This is a platform for designers and EoL engineers to build on other customised systems specific for their needs. The distributed and interoperability nature of the system would support worldwide access. This is in line with the trend of globalized product life cycle where design and EoL stages are at different geographical locations. The system architecture designed in this work is based on the IMSS platform. Its feasibility has proven through the few segments of prototyping. Due to the nature and focus of this research work, the development of the system is not within the scope of this thesis and hence the full system was not implemented.

7.2 Merits and Demerits of this Framework

As previously mentioned, this DELII system is for both the design and EoL stages and is designed for access by both designers and EoL Engineers. Thus, this is not a

system solely for designers (eg. Computer Aided Design Systems), nor it is a system to decide the EoL options for the product already designed. It relies on the input of the EoL engineers to assist the designers to assess the product EoL at the design stage. In this approach, the EoL information used is based on the current EoL capabilities and practices at the point of assessment. This is an improvement over the previous works[106] as they rely on historical data, e.g., recycling profiles of materials, into the design system for assessment and design advisory.

The approach of this DELII framework makes it pro-active rather than reactive. The EoL performance is already assessed before the design is frozen for manufacturing. This is a difference between this work and the widely published ELDA[100, 101, 156] which uses the technical characteristics of the eventual design to select the EoL option. ELDA is more of an EoL advisory tool whereas DELII is more of design advisory tool.

As a design advisory tool, it is defined as a tool to aid the designer in assessing the EoL performance of a product at design stage in complementary to the other design tools. It is not a framework for tradeoff decisions between EoL performance and other design considerations such as manufacturability, cost and disassembly though they are taken into consideration indirectly through the factors included in the EoL index.

The factors included in this index are more holistic. They encompass a wider range of considerations from disposal to the various other EoL options. In the few reported previous studies, indices are focused on particular area of EoL eg disassembly[112], recycling[157] or remanufacturing[116] only.

In a practical environment for application, there are some issues that affect the effectiveness of this work. The DELII framework hopes to achieve improved

design advisory for DfEoL using most up-to-date information from the EoL stage. However, a time lag normally exists between the design of a product and the EoL of the product depending on the intended life span of the product. As such, there are still some uncertainties in this EoL performance assessment. These uncertainties can be minimized by ensuring that the EoL information is given based on the best available EoL capability and practices during design. Expert knowledge from the EoL stage is instrumental and vital to the effectiveness of DELII framework.

This is a data intensive framework. It is resource demanding to capture the EoL information and fill up the EoL scale indices at the initial set-up stage. Additionally, there would be other factors that would need to be modeled and captured in order to better represent a product's EoL performance based on the characteristics of the product in consideration. Continuous efforts are required to build up the system with more knowledge and accuracy.

It is envisaged that the implementation of the ontology at the starting phase would also be tedious. There is a need to balance between developing precise and generic concepts. Automatic generation of the ontology for a product structure requires the D-BOM list to be precise and exact. There is no intelligence built in to cater for errors or unknowns in the current design.

The DELII framework assumed that the relationships between the EoL factors are linear. All the factors are being normalized into a simple scale of 0-10. The rate of change on all the EoL scale tables does not necessarily reflect the same magnitude of influence on the EoL performance. For example, the difference between using a "screw" joint and "snap fit" joint (for type of joints) is quantified to be "1" and this is the same as the difference between using "recycling

technology commercialized but not widely available” and “recycling technology widely available but tedious” (for recyclability). However, the actual extent of impact on EoL might not be the same in the above scenario i.e. some impact might be downplayed, hidden or masked through this. Nonetheless, this assumption is considered to be acceptable given the fact that the DELII framework aims to be a tool for assessing relative performance of the design alternatives in a holistic way. As design alternatives are assessed based on the same scale tables, the comparisons between indices from each design alternative would still be fair and sufficient to judge their relative EoL performance.

7.3 Discussions on Case Study

A case study on a power tool based on real data from an industrial project has been carried out as a proof of concept to demonstrate the DELII framework. Two design variants have been assessed and compared with the original one. The result has shown that this index can be used to assist the designer in forecasting the EoL performance of the design and also the alternative design for comparison purposes. In the first variant (*see 6.5.1.*), the EoL index has shown, in agreement with the real-case investigation, that the new design would perform better at EoL without compromising the gripping ability.

This framework allowed the designer at the beginning of the life of a product to be able to forecast the EoL performance using the current up-to-date EoL data. As for those data that are not available at the point of design such as the condition of the component and degree of cleaning needed, etc, an empirical value can be imputed to generate the EoL index because they do not affect design parameters. In fact, this empirical value can be varied in order to study the effect of usage stage on the

EoL index. The varying indicator value can be input to see how EoL performance is affected due to improper usage and maintenance. The minimum condition for the components to be recommended for recovery can also be determined from the results.

The weakest EoL performance amongst the three aspects, disassembly, disposal and recovery can be identified through the results. In the output graph, the breakdown of the sub-indices will be able to give good comparisons of the different sub-indices within a single component as well as between different components. From there, the indicator which gives the highest value can be traced back. Improvements can then be suggested from the indicator value table.

This framework has provided the designer with an easier way to estimate the EoL performance of the power tool at the design stage. The designer does not need to have a lot of data for the various values of the EoL index to be generated. There is little non-design information that the designer needs to understand and input into the framework for the EoL index calculation. Most of the information used in the calculation is managed by the EoL Engineers. The designer gets a detailed breakdown of the extent of contribution to EoL performance from each aspect of the index. Thus, this case study has also brought out the modular nature of the EoL index methodology where departmentalised analysis can be done. From the results, the designer was able to identify the weakest point of the design in EoL performance. Another point to note is that the various sub-indices are broken down into measurable factors which can be obtained at one of the stages within the product life cycle, normally the design stage or EoL stage. Quantification of the factors is achieved. Furthermore, the normalization of the factors is done by the

EoL Engineers who are experts in the field of knowledge, thus overcoming the lack of EoL knowledge of the designers.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

8.1 Conclusions

Sustainable product development is set to be a prominent characteristic of the manufacturing sector and it is becoming increasingly important as the environmental deteriorates and consumers' awareness of sustainability increases. In particular, the problem of e-waste has pushed for an imperative need of more EoL management in the electrical and electronics sectors. Various factors including legislation, corporate social responsibility, market force and consumer demands, economic incentives, improving environmental performance, and life cycle approach to product development are driving the interest and need for EoL

research. In recent years, LCE approach is widely adopted to holistically manage the product development process to optimise and balance the three “P” bottom-line, that is, to obtain minimal pollution, profits and social progress. At the same time, emerging Information and Web Technologies are also being leveraged to provide and develop tools that can assist product developers to incorporate environmental considerations into the product design easily.

The literature survey has shown that EoL research for design advisory is still in infancy but there is a growing interest in making EoL an integral part of product development life cycle. Past works include methodology and systems for design of EoL, disassembly indices, design of EoL strategy and incorporation of EoL considerations in CAD tools. However, these systems are mainly standalone. They only cater for design stage and make use only of historical EoL data. In the work of this thesis, a novel framework called the Design & EoL Information Integration (DELII) has been designed. This is a framework to facilitate and enhance the communication and information exchanges between the design stage and EoL stage. Within this framework, EoL data are managed and classified, and then the product information are managed through the application of ontology. Subsequently, this information is used in a newly developed EoL index methodology to assist the designer to assess the EoL performance of the design. Finally a system framework is designed for the implementation of the system based on the semantic web services technology.

The contributions and involvement by the EoL stakeholders in this framework is one of the novel key features as the EoL stakeholders are able to provide more up-to-date data to the designer in the design stage through this framework. A feedback mechanism for EoL information flow back to the design

stage is established here. This is a framework which aims to provide foundations and basic requirement for system integration between the design stage and EoL stage. The focus here is not the system development as there is too much work to be done within the scope of this thesis. This is a platform for designers and EoL engineers to build on other customised systems specific for their needs. The framework methodology is to enable designers and EoL stakeholders to share their information and communicate with each other to improve the process of DfEoL. In future, this framework can be extended to the other stages as well, such as product service advisory.

Also, an EoL index methodology is proposed as part of the framework for the purpose of assessing EoL performance of a product design using the EoL information provided in the framework by the EoL engineers. This EoL index gives designers a simple and quantitative way to know how the product will perform at EoL. With such knowledge, design decisions can be made to improve the product. This has fulfilled the objective of transforming data to information and subsequently to knowledge for the designers to understand and assess EoL performance of their product design.

Finally, a web-distributed system design based on semantic web services technology is being proposed to implement this feedback mechanism and manage the information. The distributed and interoperability nature of the system will allow worldwide access. In conclusion, the thesis has developed a product design advisor for EoL performance based on a proposed novel framework DELII and the EoL index methodology.

8.2 Limitations of the Work

The main limitation of the work is the modelling of the AHP. It is assumed that all the factors are independent of each other and thus can be modelled using a simple AHP. This work has chosen to decompose the factors affecting EoL in a hierarchical tree structure and hence making factors from different branches not related to each other. The factors eventually might be related in certain ways and not only in the direct hierarchical manner. An extension to address this limitation is to use Analytic Network Process to model the relationships amongst the factors. In ANP, there are feedbacks created to represent reinforced relationships.

The other limitation will be the validity of the data in the EoL tables. This work can be extended by devising an automated update system to keep the EoL scale tables as up to date as possible when technology changes. This extent of success of this framework is largely due to the willingness of the EoL engineers to cooperate and update the tables with valid and up-to-date data. There are also constraints in time lag.

8.3 Recommendations for Further Research

The work has provided a platform to integrate product designers and EoL engineers. Further enhancement and applications can be developed on this platform to meet specific needs of various stakeholders over the life cycle of a product. In particular, further efforts in the following *two* areas are recommended.

1. A study on the use of artificial intelligence methods in the EoL Index
2. Service Advisory

A Study on the Use of Artificial Intelligence Methods in the EoL Index

The work of this thesis has employed Analytic Hierarchy Process (AHP) in the generation of weights for various EoL indexing factors. It is envisaged that the EoL Index framework can be further enhanced by further exploration of relevant artificial intelligence (AI) methods. The following two AI approaches are recommended, namely, Case-based Learning [158], and Fuzzy Cognitive Map (FCM) [159].

Case-based learning can be incorporated into the framework to retain past cases and use them as reference cases for analysis of new cases. This would make it possible to give the designers a quick EoL index without going through the entire EoL indexing methodology. This would be particularly useful for product family design where a new model inherits features of other or past models.

Fuzzy Cognitive Map (FCM) is deemed as a possible approach to enhance the capability and robustness of the EoL index. FCM is a tool for representing causal knowledge, reasoning and decision-making of fuzzy sets of factors, especially for soft knowledge domains. The fuzzy graph structures allow random concepts and relationships to be captured, represented and processed systematically. By using FCM, the factors affecting EoL, especially those of non-technical, can be modelled using membership functions before the concept maps of the relationships among the factors are defined and drawn. These causal relationships are indicated either in positive or negative depending on how the factors affect each other. Each sub-index can be defined as a fuzzy concept map based on their affecting factors before connecting with each other to grow into bigger fuzzy concept maps, resulting in bigger knowledge bases. These connections are made possible by fuzzy causal algebra, which governs the causal

propagation and causal combination on a FCM. After combination typically iteratively, the weights of each factor can be determined and be used in the calculation of the EoL index.

Service Advisory

This thesis has focused on the formalisation of EoL stage and also the incorporation of the EoL considerations through the means of an EoL index for the purpose of design advisory. Another part of the IMPSS is the service stage and research efforts can extend into formalising the service stage, to incorporate service stage considerations in design and provide service stage advisory as well. The framework can be used for service design advisory by modelling the factors affecting the service stage to generate a Servicing index for designers to assess the performance of the product during the service stage.

AWARD & LIST OF PUBLICATIONS

Award:

- 1) Best Student Paper Award - 5th International Conference on Design and Manufacture for Sustainable Development (Sustain '07), 10-11 May, Loughborough, UK, 2007.

Hui Mien Lee, Wen Feng Lu, Bin Song, SH. Ramanath and Robert Gay, “End-of-Life (EoL) Index for Design Advisory – Disassembly Sub-Index”, 5th International Conference on Design and Manufacture for Sustainable Development (Sustain '07), 10-11 May, Loughborough, UK, 2007.

Journal Papers:

- 1) Zhiqi Shen, Robert Gay, Chunyan Miao, Tin Wee Tan, Chong Suan Kuay and Hui Mien Lee, “Process Modelling and Automated Execution for Bio-Manufacturing”, International Journal of Information Technology, vol. 12, no. 1, pp. 37-48, 2005.
- 2) Hui Mien Lee, Wen Feng Lu, Bin Song, Zhiqi Shen, Zhonghua Yang and Robert Kheng Leng Gay, “A Framework for Integrated Manufacturing and Product Service System (IMPSS): Integrating Service Operations into Product Life Cycle”, International Journal of Service Operations and Informatics, vol. 2, no. 1, pp. 81-101, 2007.

- 3) Zhonghua Yang, Jing-Bing Zhang, Robert Gay, Liqun Zhuang and Hui Mien Lee, "Building a Semantic-rich Service-Oriented Manufacturing Environment", International Journal of Information Technology and Web Engineering, vol. 2, no. 3, pp 53-64, 2007
- 4) Hui Mien Lee, Wen Feng Lu, Bin Song and Robert Gay, "EoL Framework for Design Advisory", International Journal of Product Life Cycle Management Special Issue (Submitted)

Conference Papers:

- 1) Hui Mien Lee, Wen Feng Lu and Robert Kheng Leng Gay, "Framework for Integrated Manufacturing and Product Service System (IMPSS)", In Proceedings of 2005 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI'05), Beijing, China, 10-12 Aug, 2005 pp. 186-191.
- 2) Hui Mien Lee, Zhiqi Shen, Robert Kheng Leng Gay, Chunyan Miao, Tin Wee Tan, Chong Suan Kuay and Luying Xiong, "Integrated BioManufacturing Workflow Design and Implementation: From R&D to Diagnostic Kits", In Proceedings of the 31st Annual Conference of the IEEE Industrial Electronics Society (IECON '05), Raleigh, North Carolina, USA, 6-10 Nov, 2005 pp. 2308-2313.
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- 4) Zhonghua Yang, Jing-Bing Zhang, Robert Gay, Liqun Zhuang and Hui Mien Lee, "Building a Semantic-rich Service-Oriented Manufacturing Environment", 6th Web Information System Engineering (WISE 2005), New York City, New York, USA, 20-22 Nov, 2005 , LNCS 3806, pp. 623-632.
- 5) Zhonghua Yang, Robert Gay, Chunyan Miao, Jing-Bing Zhang, Zhiqi Shen and Hui Mien Lee, "Automating Integration of Manufacturing Systems and Services: A Semantic Web Services Approach", In Proceedings of the 31st Annual Conference of the IEEE Industrial Electronics Society (IECON '05), Raleigh, North Carolina, USA, 6-10 November 2005, pp. 2255-2260.
- 6) Hui Mien Lee, Wen Feng Lu, Bin Song and Robert Gay, "The Framework of Information Sharing in End-of-Life for Sustainable Product Development", 4th International IEEE Conference on Industrial Informatics (INDIN '06), Singapore, 16-18 Aug 2006, pp. 73-78.
- 7) Zhiqi Shen, Hui Mien Lee, Chunyan Miao, Meena Sakharkar, Robert Gay and Tin Wee Tan, "Process Integration for Bio-Manufacturing Grid", Grid Computing in Life Science – Proceedings of the 2nd International Workshop on Life Science Grid, LSGrid 2005, 5-6 May pp. 220 – 233, World Scientific, Singapore, 2006.
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APPENDIX A - EXAMPLE OF ONTOLOGY

1) Power Tool used in Case Study

a. RDF/XML Code for Power Tool Ontology

```
<?xml version="1.0"?>
```

```
<!DOCTYPE rdf:RDF [
```

```
  <!ENTITY owl "http://www.w3.org/2002/07/owl#" >
```

```
  <!ENTITY xsd "http://www.w3.org/2001/XMLSchema#" >
```

```
  <!ENTITY rdfs "http://www.w3.org/2000/01/rdf-schema#" >
```

```
  <!ENTITY rdf "http://www.w3.org/1999/02/22-rdf-syntax-ns#" >
```

```
<rdf:RDF xmlns="http://www.owl-ontologies.com/unnamed.owl#" 
```

```
  xml:base="http://www.owl-ontologies.com/unnamed.owl" 
```

```
  xmlns:xsd="http://www.w3.org/2001/XMLSchema#" 
```

```
  xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#" 
```

```
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#" 
```

```
  xmlns:owl="http://www.w3.org/2002/07/owl#">
```

```
  <owl:Ontology rdf:about=""/>
```

```
  <owl:Class rdf:ID="Battery">
```

```
    <rdfs:subClassOf rdf:resource="#Battery_Unit"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="Battery_Charger">
```

```
    <rdfs:subClassOf rdf:resource="#Battery_Unit"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="Battery_Cover">
```

```
    <rdfs:subClassOf rdf:resource="#Battery_Unit"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="Battery_Holder">
```

```
    <rdfs:subClassOf rdf:resource="#Battery_Unit"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="Battery_Unit">
```

```
    <rdfs:subClassOf rdf:resource="#Power_Tool"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="Casing">
```

```
    <rdfs:subClassOf rdf:resource="#Housing_Set"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="Control_Module">
```

```
    <rdfs:subClassOf rdf:resource="#Power_Tool"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="DC_Motor">
```

```
    <rdfs:subClassOf rdf:resource="#Motor"/>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="Drill_Mechanism">
```

```
    <rdfs:subClassOf rdf:resource="#Power_Tool"/>
```

```
    <rdfs:label rdf:datatype="&xsd:string">Drill Mechanism</rdfs:label>
```

```
  </owl:Class>
```

```
  <owl:Class rdf:ID="F_R_Lever">
```

```

    <rdfs:subClassOf rdf:resource="#Control_Module"/>
    <rdfs:label rdf:datatype="&xsd:string">F/R_Lever</rdfs:label>
</owl:Class>
<owl:Class rdf:ID="Flat_Head_Screw">
    <rdfs:subClassOf rdf:resource="#Drill_Mechanism"/>
</owl:Class>
<owl:Class rdf:ID="Gear_Assembly">
    <rdfs:subClassOf rdf:resource="#Drill_Mechanism"/>
</owl:Class>
<owl:Class rdf:ID="Gear_Components">
    <rdfs:subClassOf rdf:resource="#Gear_Assembly"/>
</owl:Class>
<owl:DatatypeProperty rdf:ID="Has_Modules">
    <rdf:type rdf:resource="&owl;FunctionalProperty"/>
    <rdfs:domain rdf:resource="#Power_Tool"/>
    <rdfs:range rdf:resource="&xsd:string"/>
</owl:DatatypeProperty>
<owl:Class rdf:ID="Housing_Set">
    <rdfs:subClassOf rdf:resource="#Control_Module"/>
</owl:Class>
<owl:Class rdf:ID="Keyless_Drill_Chunk">
    <rdfs:subClassOf rdf:resource="#Drill_Mechanism"/>
</owl:Class>
<owl:Class rdf:ID="Label">
    <rdfs:subClassOf rdf:resource="#Housing_Set"/>
</owl:Class>
<owl:Class rdf:ID="Leaf_Spring">
    <rdfs:subClassOf rdf:resource="#Control_Module"/>
</owl:Class>
<owl:DatatypeProperty rdf:ID="Material">
    <rdfs:domain rdf:resource="#Power_Tool"/>
    <rdfs:range rdf:resource="&xsd:string"/>
</owl:DatatypeProperty>
<owl:Class rdf:ID="Motor">
    <rdfs:subClassOf rdf:resource="#Power_Tool"/>
</owl:Class>
<owl:DatatypeProperty rdf:ID="No_of_child">
    <rdf:type rdf:resource="&owl;FunctionalProperty"/>
    <rdfs:domain rdf:resource="#Power_Tool"/>
    <rdfs:range rdf:resource="&xsd:int"/>
</owl:DatatypeProperty>
<owl:Class rdf:ID="Pan_Head_Screw">
    <rdfs:subClassOf rdf:resource="#Drill_Mechanism"/>
</owl:Class>
<owl:Class rdf:ID="Power_Tool">
    <rdfs:label rdf:datatype="&xsd:string">Power Tool</rdfs:label>
</owl:Class>
<owl:Class rdf:ID="Relationship">
    <rdfs:subClassOf rdf:resource="#Power_Tool"/>
</owl:Class>

```

```

<owl:DatatypeProperty rdf:ID="RoHS_Compliant">
  <rdf:type rdf:resource="&owl;FunctionalProperty"/>
  <rdfs:domain rdf:resource="#Power_Tool"/>
  <rdfs:range rdf:resource="&xsd:string"/>
</owl:DatatypeProperty>
<owl:Class rdf:ID="Speed_Change_Assembly">
  <rdfs:subClassOf rdf:resource="#Control_Module"/>
</owl:Class>
<owl:Class rdf:ID="Speed_Components">
  <rdfs:subClassOf rdf:resource="#Speed_Change_Assembly"/>
</owl:Class>
<owl:Class rdf:ID="Switch">
  <rdfs:subClassOf rdf:resource="#Control_Module"/>
</owl:Class>
<owl:Class rdf:ID="Tapping_Screw_Bind">
  <rdfs:subClassOf rdf:resource="#Housing_Set"/>
  <rdfs:label rdf:datatype="&xsd:string">
    Tapping Screw Bind</rdfs:label>
</owl:Class>
<owl:DatatypeProperty rdf:ID="WEEE_Compliant">
  <rdf:type rdf:resource="&owl;FunctionalProperty"/>
  <rdfs:domain rdf:resource="#Power_Tool"/>
  <rdfs:range rdf:resource="&xsd:string"/>
</owl:DatatypeProperty>
</rdf:RDF>

```

b. Concept Map for Power Tool Ontology

2. Concept Map for Integrated Manufacturing and Product Services System (IMPSS) Ontology

3. Concept Map for InkJet Printer Ontology

4.) Concept Map for Life Cycle Assessment (LCA)

APPENDIX B - END-OF-LIFE TABLES

End-of-Life Scale Tables

These tables are examples of how the EoL scale tables of the different factors can be developed and structured according to the expertise of the EoL engineers. As the main purpose of the index is for relative comparison thus most of the factors can be of relative scale.

- 1) Shape – Measure of the regularity of the shape. Divided broadly into regular and irregular shapes. Percentage of irregularity.

Index Value	Criteria -	
0	0%	Square
1	10%	Rectangular, circle
2	20%	
3	30%	
4	40%	
5	50%	
6	60%	
7	70%	
8	80%	
9	90%	
10	100%	Totally irregular shape

- 2) Depth – Measure the depth which is the number of levels that need to be disassembled

Index Value	Criteria
0	1
1	2
2	3
3	4
4	5
5	6
6	7
7	8
8	9
9	10
10	11

- 3) Size – Measure the volume and dimensions as a percentage of product total volume and dimensions

Index Value	Criteria
0	100%
1	90%
2	80%
3	70%
4	60%
5	50%
6	40%
7	30%
8	20%
9	10%
10	0%

- 4) Location – Depth and position with respect to the starting point of disassembly. The disassembly sequence number of the components.

Index Value	Criteria	
0	0%	Starting point
1	10%	
2	20%	
3	30%	
4	40%	
5	50%	Midway
6	60%	
7	70%	
8	80%	
9	90%	
10	100%	Ending Point

- 5) No of joints – No of joints

Index Value	Criteria
0	0
1	2
2	4
3	6
4	8
5	10
6	12
7	14
8	16
9	18
10	20

6) Type of Joint – Different types of joints

Index Value	Criteria
10	Inseparable Permanent Joints
9	Very hard and costly to separate Permanent Joints
8	Joints that need to use machines to separate
7	Adhesive
6	Welding/ Soldering
5	Wire
4	Screws
3	Snap Fit
2	Clips
1	Velcro Type
0	Loose Fittings Temporary Joints

7) Identification of Material – Scale of Level of Difficulty

Index Value	Criteria
0	100%
1	90%
2	80%
3	70%
4	60%
5	50%
6	40%
7	30%
8	20%
9	10%
10	0%

8) Technology Available – Scale of Level of Technology

Index Value	Criteria
0	100%
1	90%
2	80%
3	70%
4	60%
5	50%
6	40%
7	30%
8	20%
9	10%
10	0%

- 9) Toxicity – Measure of how harmful is the material to the environment and human health

Using the MEEUP methodology indicator

Using Threshold Limit Value as a reference, this indicator measures the toxicity as a percentage of the Threshold Limit Value

Index Value	Criteria	
0	100%	
1	90%	
2	80%	
3	70%	
4	60%	
5	50%	
6	40%	
7	30%	
8	20%	
9	10%	
10	0%	

- 10) Nature – Different types of Broad Categories of Material

Index Value	Criteria
0	Organic Materials
1	Paper
2	Pure metal
3	Alloy
4	Plated metal
5	Glass
6	Nylon
7	Commodity Plastics
8	Engineering Plastics
9	Ceramics
10	Chemical

- 11) Biodegradability – Time to Degrade

Index Value	Criteria	Example
0	100% Biodegradable	<1week
1		<1 month
2		< 1 year
3		< 2 years
4		<5 years
5		<10 years
6		<20 years
7		< 40 years
8		< 60 years
9		< 80 years
10	0 % Non biodegradable	> 100 years

- 12) Distance – Distance to Incineration Plant or Landfill as a percentage to other EoL options

Index Value	Criteria	
0	~0%	Much Lesser
1	20%	
2	40%	
3	60%	
4	80%	
5	100%	Same Distance
6	120%	
7	140%	
8	160%	
9	180%	
10	>200%	Much Further

- 13) Legislation – Scale of Enforcement and Requirement Levels

Index Value	Criteria	
0	100%	
1	90%	Germany Standards
2	80%	Japanese Standards
3	70%	EU Standards
4	60%	
5	50%	US Standards
6	40%	
7	30%	
8	20%	
9	10%	
10	0%	

- 14) Environmental Impact – LCA Combined Impact

Index Value	Criteria	
0	100%	
1	90%	
2	80%	
3	70%	
4	60%	
5	50%	
6	40%	
7	30%	
8	20%	
9	10%	
10	0%	

- 15) Value of Recycled Material – Market price of recycled materials as a percentage of the virgin material

Index Value	Criteria	Example
0	~0%	
1	20%	
2	40%	
3	60%	
4	80%	
5	100%	Market Price
6	120%	
7	140%	
8	160%	
9	180%	
10	>200%	

- 16) Degree of Material Mix – Purity of the Material. Percentage of the highest concentration of compound in the material

Index Value	Criteria
0	100%
1	90%
2	80%
3	70%
4	60%
5	50%
6	40%
7	30%
8	20%
9	10%
10	0%

- 17) Contamination – Using the degree of contamination on surface including oil, paint, adhesives etc. 0%-100% of surface contamination – by naked eye

Index Value	Criteria
0	100%
1	90%
2	80%
3	70%
4	60%
5	50%
6	40%
7	30%
8	20%
9	10%
10	0%

- 18) Recyclability - Using the actual data from recycle fraction, it is a measure of the fraction of the material being recycled

Index Value	Recycle Fraction	Criteria
10	0.0	Inorganic Material – Not recyclable
9	0.1	Organic material for energy recovery and not material recovery
8	0.2	Organic material for energy recovery and material recovery
7	0.3	Recycling technology still in development and not stable
6	0.4	Recycling technology available but not commercialized
5	0.5	Recycling technology commercialized but need improvement
4	0.6	Recycling technology commercialized but not widely available
3	0.7	Recycling technology widely available but tedious
2	0.8	Easily recyclable with established technology but more steps in the recycling process
1	0.9	Easily recyclable with well established technology
0	~1	Recycling is the default EoL method

- 19) Lifespan – Measure of current lifespan as a ratio of total expected number of lifespan

Index Value	Criteria	
0	100%	Total no. of Lifespan
1	90%	
2	80%	
3	70%	
4	60%	
5	50%	Half of the total no. of lifespan
6	40%	
7	30%	
8	20%	
9	10%	
10	0%	First lifespan

- 20) Emissions – Measure of Emissions to the environment using pollution per volume.

Index Value	Criteria	
0	~0%	
1	20%	
2	40%	
3	60%	
4	80%	
5	100%	Same emission rate
6	120%	
7	140%	
8	160%	
9	180%	
10	>200%	

- 21) Nature of Module – Different type of functional modules

Index Value	Criteria
0	
1	Organic
2	
3	
4	Mechanical
5	
6	
7	Mechatronics
8	Electrical
9	Electronic
10	Chemical

- 22) Material Mix – Percentage of the most dominant material

Index Value	Criteria
0	100%
1	90%
2	80%
3	70%
4	60%
5	50%
6	40%
7	30%
8	20%
9	10%
10	0%

23) Amount of Cleaning Needed – Percentage of product that needs cleaning

Index Value	Criteria
0	0%
1	10%
2	20%
3	30%
4	40%
5	50%
6	60%
7	70%
8	80%
9	90%
10	100%

24) Degree of Weariness – Scale of Level of Weariness

Index Value	Criteria
0	0%
1	10%
2	20%
3	30%
4	40%
5	50%
6	60%
7	70%
8	80%
9	90%
10	100%

25) Cost of Consumables – Cost price of the consumables as a percentage of cost price of consumable in virgin product

Index Value	Criteria	Example
0	~0%	
1	20%	
2	40%	
3	60%	
4	80%	
5	100%	Market Price
6	120%	
7	140%	
8	160%	
9	180%	
10	>200%	

- 26) Cost of Energy – Cost of energy in recovery process as a percentage of cost of energy in process for virgin products

Index Value	Criteria
0	~0%
1	20%
2	40%
3	60%
4	80%
5	100%
6	120%
7	140%
8	160%
9	180%
10	200%

- 27) Market Demand – Market price of the remanufactured parts as a percentage of original parts

Index Value	Criteria	Example
0	~0%	
1	20%	
2	40%	
3	60%	
4	80%	
5	100%	Market Price
6	120%	
7	140%	
8	160%	
9	180%	
10	>200%	

- 28) Age – Age as a percentage of expected lifespan

Index Value	Criteria	
0	~0%	
1	20%	
2	40%	
3	60%	
4	80%	
5	100%	Expected Lifespan
6	120%	
7	140%	
8	160%	
9	180%	
10	>200%	

29) Technical Compatibility – Scale of Technical Compatibility

Index Value	Criteria
0	100%
1	90%
2	80%
3	70%
4	60%
5	50%
6	40%
7	30%
8	20%
9	10%
10	0%

30) Energy Recovery Process – Efficiency of the different types of energy recovery process

Index Value	Criteria	Eg
0	100%	
1	90%	Refuse derived fuel (RDF)
2	80%	Other energy from waste processes
3	70%	Gasification
4	60%	Biomethanisation
5	50%	
6	40%	
7	30%	Pyrolysis
8	20%	
9	10%	
10	0%	

Note that some of the table entries are left empty on purpose. These tables are still being developed and refined as part of the research.

APPENDIX C - INDICATOR QUERY ALGORITHMS

```

When receive_query == true,
check for product level needed;
    If prod_level == component, then eqn == 4
    Else if prod_level == sub-assembly, then eqn == 3
    Else if prod_level == module, then eqn == 2
    Else eqn == 1;
    search (eqn);
When got_eqn == true,
Cal_fun = eqn
If eqn = 1,
    ele [0] =  $\alpha DAI_P$ 
    ele [1] =  $\beta RI_P$ 
    ele [2] =  $\sum_{k=1}^n \gamma MI_T$ 
    ele [3] =  $\sum_{j=1}^m \lambda CI_T$ 
    n = count (product_level = 1)
    m = count (product_level = 5)
If eqn = 2,
    ele [0] =  $\alpha DAI_M$ 
    ele [1] =  $\beta RI_M$ 
    ele [2] =  $\sum_{k=1}^n \gamma SAI_T$ 
    ele [3] =  $\sum_{j=1}^m \lambda CI_T$ 
    n = count (product_level = 2)
    m = count (product_level = 6)
If eqn = 3,
    ele [0] =  $\alpha DAI_{SA}$ 
    ele [1] =  $\beta RI_{SA}$ 
    ele [2] =  $\sum_{k=1}^n \gamma CI_T$ 
    ele [3] = 0
    n = count (product_level = 3)
If eqn = 4
    ele [0] =  $\alpha DI_C$ 
    ele [1] =  $\beta RI_C$ 
    ele [2] = 0
    ele [3] = 0
    n = count (product_level = 4)
EoLsi = ele [0] + ele[1];
While (a < n and ele [2] != 0),
    EoLsi += Value [a];
    a++;
While (a < m and ele [3] != 0),

```

```
EoLsi += Value [a];  
a++;
```

APPENDIX D - SCREENSHOTS OF EXPERT CHOICE FOR WEIGHT GENERATION

1. EoL Index

a. EoL Index Modelling

b. EoL Index Synthesis Results

2. Disassembly

a. Disassembly Modelling

b. Disassembly Synthesis Results

3. Ease of Disassembly

a. Ease of Disassembly Modelling and Synthesis Results

b. Ease of Disassembly Synthesis Results

4. Disposal

a. Disposal Modelling

b. Disposal Synthesis Results

5. Recycling

a. Recycling Modelling

b. Recycling Synthesis Results

6. Recycling Process

a. Recycling Process Modelling

b. Recycling Process Synthesis Results

7. Treatment Process

a. Treatment Process Modelling

b. Treatment Process Synthesis Results

8. Remanufacturing

a. Remanufacturing Modelling

b. Remanufacturing Synthesis Results

9. Remanufacturing Process

a. Remanufacturing Process Modelling

b. Remanufacturing Process Synthesis Results