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MODELING AND OPTIMIZATION TO EVALUATE SUSTAINABILITY PERFORMANCE OF CUSTOMIZABLE PRODUCT SERVICE SYSTEMS

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ABSTRACT OF THESIS

MODELING AND OPTIMIZATION TO EVALUATE SUSTAINABILITY PERFORMANCE OF CUSTOMIZABLE PRODUCT SERVICE SYSTEMS

The aim of this thesis is to present a new methodology to evaluate and optimize sustainability of customizable product-service systems while ensuring economic, environmental and societal constraints are also satisfied. Activities across the total product lifecycle are considered to develop a model that evaluates closed-loop flow, while being monitored through the growth, maturity and decline stages of the product to provide a comprehensive analysis. A novel method to evaluate the customer satisfaction is also presented. The research considers a modular product where customization can be achieved by selecting from alternatives while ensuring the compatibility between these alternatives. A manufacturer will be able to use the tool developed to optimize the business models developed by maximizing their profitability, satisfying regulatory and customer requirements, and evaluating the metrics that determine the sustainability of the product. The tool primarily uses a Microsoft Excel based platform for calculation and analysis while using ILOG OPL software for optimization. The sensitivity analysis provides examples of the variety of information that can be generated through the model according to the interests of the user. The results demonstrate the usefulness of the tool as a 'sustainable product configurator' which can be integrated with conventional product configurators after further refinement.

KEYWORDS: Product Service Systems, Sustainability, Optimization, Configurators, Mass customization

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THESIS

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MODELING AND OPTIMIZATION TO EVALUATE SUSTAINABILITY PERFORMANCE OF CUSTOMIZABLE PRODUCT SERVICE SYSTEMS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Manufacturing
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University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky

2011

Dedicated to my family

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1 INTRODUCTION

The survival and growth of organizations today cannot depend solely only on financial profitability. Increased consumer awareness and stricter regulations and controls require the consideration of environmental and societal sustainability in addition to previously emphasized economic sustainability. Furthermore, today's customers demand that their individual needs be met with high quality products and services, quick response and a reasonable cost (Zhou et. al., 2007, Xuanyuan et. al., 2008). These requirements and demands, challenge producers not only to be innovative and flexible (Ma et. al., 2006), but also adapt sustainable manufacturing practices.

The Sustainable Manufacturing Initiative of the United States Department of Commerce (USDOC) has defined sustainable manufacturing as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" (USDOC, 2009). The National Council for Advanced Manufacturing (NACFAM, 2010) further explains that this definition includes both the developing of sustainable products and sustainable manufacturing of all products and states that they hope to address them both. Meanwhile environmental regulations in the European Union (EU), such as the EU directive for Waste Electrical and Electronic Equipment (WEEE), had imposed regulations on manufacturers regarding taking back products and increasing the recycling and remanufacturing percentages to 50 – 80% by 2006 (Ma et. al., 2006). The German motor industry similarly has plans to reach 95% recycling (by weight) by 2015 while the Singapore Green Plan 2012 has targets to increase recycling to 60% (Ma et. al., 2006). It is evident therefore that when manufacturing products, consideration of the impact of both products and processes on the post-use stage is vital. Therefore, creating sustainable systems through a closed-loop flow (extending the lifetime of products through post-use processing) in place of the conventional practice of disposal at end-of-life, is necessary.

In order to offer customers more sustainable solutions manufacturers must transition from the conventional “selling products for ownership” model (Badurdeen and Liyanage, 2010) to novel approaches that enable better closed-loop flow, whether it be standard or mass customized products. One such approach is a Product Service System (PSS) that combines a product and service with the intention of providing a superior service instead of merely offering a product for use. Even a standard product can be used by different customers in varied forms, calling for the ‘service’ component of a PSS to be individually customized (Badurdeen and Liyanage, 2010). Thus a PSS is a customized offering where some co-creation will be required, characterizing a typical mass customization application (Piller, 2003). As PSS may require manufacturers to retain product ownership, this form of mass customized solution provides more opportunities to develop more sustainable products that take account of economic, environmental and societal impacts (Badurdeen and Liyanage, 2010) during the total lifecycle of the product. Manzini & Vezzoli (2003) defined sustainable or eco-efficient PSS as ones that reorient the unsustainable practices in production and consumption through PSS. The focus in this research is to evaluate and optimize the sustainability performance of a customizable PSS.

Customizable PSS, just as any other mass customized solutions, provide the customer with an opportunity to configure products to their individual needs; similar assessments on their sustainability ratings are necessary when it comes to making them sustainable solutions. However their assessment process is less straightforward than with standard, mass manufactured products. In the latter case, the product configuration, including the bill of materials, as well as the manufacturing processes and sequence, can be evaluated beforehand and chosen to achieve the desired key performance indicators (KPIs). To the contrary, when it comes to a customizable PSS, customers often get to co-design their product, selecting the specific configuration that meets their individual needs. Therefore, as opposed to ensuring that a certain product is designed and manufactured sustainably, a customizable PSS requires manufacturers to develop the capability to ensure that every permissible product variant, which can be co-designed by customers, can be assessed for their sustainability performance. To help customers make a more sustainability-informed decision, it might also become necessary in the near future to incorporate this capability into product configurators; such a feature will allow customers to pick and choose between various alternate product modules/features during customization that may positively/negatively affect economic, environmental and societal sustainability. This means that, it is necessary to incorporate the optimization capability to select and present the modules with the highest sustainability benefits to the customer.

Therefore, developing and evaluating sustainable PSS solutions require incorporating the concepts of mass customization, product optimization, given modular product architectures as shown in Figure 1-1.

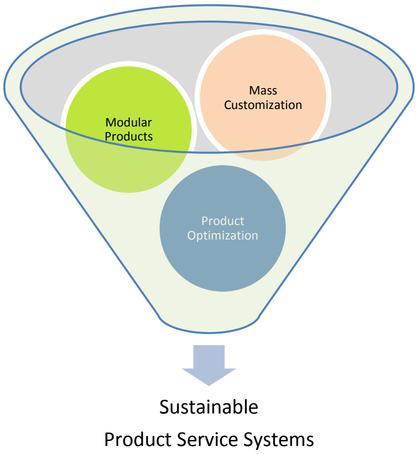


Figure 1-1 Ingredients of a Sustainable PSS

However, no comprehensive analytical models are available to evaluate customizable products or PSS (or for that matter even standard products) from a total lifecycle perspective for sustainability. In a preliminary effort to fill that void, this research demonstrates a methodology to determine optimal PSS configurations (assuming a modular product with selectable options) that will maximize profit while satisfying environmental and societal requirements and constraints. It is approached by first developing a tool for identifying the sustainable product configuration (Product model) and then extending it to sequentially incorporate what happens if products were simply returned at end-of-use (i.e. product with recovery or Product-R model) and incorporating the service aspect while the OEM retains ownership to develop the PSS model. In the models, the total lifecycle is taken into account by considering parameters from the four product lifecycle stages of pre-manufacturing, manufacturing, use and post-use. One approach to develop sustainable products, manufacturing processes and systems is the 6R methodology (Joshi et al, 2006). This methodology extends the green concept of reduce, reuse and recycle to include recover, redesign and remanufacture, and was used as the basis to incorporate and account the impacts of multi lifecycle flow. The model developed considered the Triple Bottom Line (TBL) aspects of Economy, Environment and Society, all four lifecycle stages while also incorporating the 6R methodology. This integrated approach to developing sustainable product is shown in Figure 1-2.

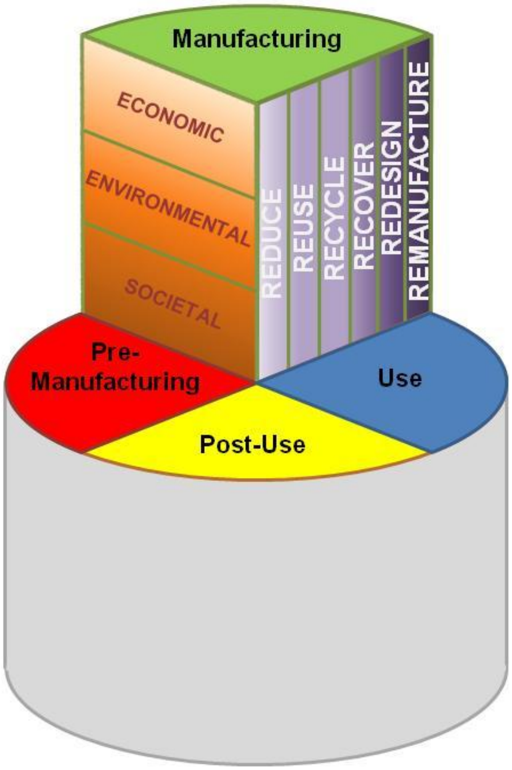


Figure 1-2 Integrated approach to developing sustainable products (Badurdeen et.al 2009)

The tool is expected to help evaluate the sustainability performance by answering the following questions for the different business models (Product, Product-R and PSS).

1. What is the best business model overall?
2. Are there periods in the demand cycle where one model outperforms the other models?
3. Which configurations provide the optimal economic, societal and environmental sustainability for each of the three business models and how do they compare?

Three Mixed Integer Linear Programs (MILPs) were formulated and solved using ILOG OPL optimization software. A simple example was used to demonstrate the application of the models.

The remaining sections of the thesis are organized in the following manner. Chapter 2 provides a literature review on mass customization, product service systems and product optimization. Chapter 3 describes the methodology followed in formulating the three business models. An example is used to demonstrate the application of the models in Chapter 4 and the results are discussed and analyzed in Chapter 5. Chapter 5 also discusses the results of the sensitivity analysis conducted. Observations made in this research and future research potentials are discussed in Chapter 6.

2 LITERATURE REVIEW

This chapter introduces the concepts of mass customization, product optimization, and PSS and discusses literature to provide the state-of-art practices. It also discusses the benefits and challenges of PSS and attempts to show how PSS provide a baseline framework, from which analytical models can be developed that helps design sustainable products that consider the total lifecycle given modular product architectures.

2.1 Mass Customization

Sustainable production and consumption provides the foundation for sustainable development (Khumboon et al., 2008). In order to create sustainable product designs and configurations, there is a necessity for integrating the environmental and societal aspects to the previously considered economic-oriented models that base their designs on costs, mechanical properties of materials and components, and process requirements (Zhou et. al., 2009). Manufacturers should consider objectives such as using materials with low environmental pollution, reducing use of rare and scarce materials, choosing materials that enable clean production, avoiding hazardous and toxic materials, using easily recyclable or degradable materials, and using materials that consume less energy in production (Zhou et. al., 2009). Mass customization (MC) provides a foundation to integrate the TBL aspects of sustainability, delivering exactly what the customer requires (societal), thereby prolonging usage and unnecessary discarding thus reducing landfill (environmental), while also being profitable (economical).

When it comes to mass customized products, customers have been found willing to pay a slightly higher price (Sanders, 2001) since the customer is able to co-design the product and obtain the functionality that they require (Zhou et. al., 2007). This makes MC a potential model to share (between the customer and the OEM) part of the higher upfront costs of sustainable offerings in return for lower costs (of purchase and maintenance) later during the lifecycle of the product.

Standardized and modularized component architecture supports assemble-to-order manufacturing (Zhou et. al., 2007) that makes MC efficient and competitive with mass production. Standardization is achieved by having access to a predefined library of components that is designed to be configured as required (Ostrosi, & Tié Bi, 2010). Modular product families creates the foundation for generating efficient product configurations (Zhou et. al., 2007). These modules can be designed, manufactured, bought in advance and assembled-to-order later (Li et. al., 2006). Product and process modularization helps increase the flexibility of manufacturing, knowledge accumulation and reusability (Ma et. al., 2006). It also increases product variety, higher customer satisfaction, competitive advantages, conformity to environmental regulations (Ma et. al., 2006, Ostrosi, & Tié Bi, 2010). A MC product is assembled by conforming to the interrelations between components and satisfying pre-determined specifications and constraints (Ostrosi, & Tié Bi, 2010, Li et. al., 2006) such as cost, lead time, and balanced inventory (Xuanyuan et. al., 2008).

MC has the potential to change the traditional push market system (where the OEM manufactures without an order from the customer) into a pull-based system (Zhaoliang et. al., 2010) (where the product is manufactured once an order is placed). Although MC provides a variety of benefits and supports the creation of sustainable products, in order to move towards sustainable development the concept of sustainable consumption and thus dematerialization should be considered. PSS provide an excellent framework of integrating MC with dematerialization.

2.2 Product Service Systems

2.2.1 Definition and Features

PSS is one form of customized solutions; it involves moving away from designing and selling products to selling an integrated combination of products and services. PSS extend the functionality of products by incorporating additional services which can then reduce impact on the environment and increase customer satisfaction [Khumboon et al., (2008), Baines et al., (2007)]. In other words, PSS can be “economically profitable, environmentally efficient, and socially responsible” provided the supporting infrastructure and networks are available (Khumboon et al., 2008).

PSS can be divided into three accepted categories (Khumboon et al., (2008), Baines et al., (2007). These include,

1) Product-oriented PSS, which involves selling the product and may include guarantees/warrantees, after sale services, training and consulting. Most consumer products sold through retail stores or online would fall under this category. Examples of PSS that include an additional service element that is uncommon include, ecologically grown vegetables by Odin Holland (Manzini & Vezzoli, 2002) where the customer receives package with assorted fruits and vegetables weekly, the Allegrini home delivery of detergents (Manzini & Vezzoli, 2003) and the Kluber mobile chemical laboratory (Manzini & Vezzoli, 2003) that offers consulting on the performance and environmental impact of lubricants used in their client’s industrial machines.

2) Use-oriented PSS where the manufacturer sells the use of a product and the customer does not own the product (Zhou et. al., 2007), which may also be in the form of leasing or sharing. Examples would include the selling of flooring service by DuPont Flooring Systems (USA) and Diddi & Gori (Baines et al., 2007, Manzini & Vezzoli, 2003), where flooring is provided for offices, trade fairs or exhibitions, car sharing by AutoShare and Mobility [Baines et al., (2007), Manzini & Vezzoli, (2002)], Managed Print Services by Xerox and Canon [Baines et al., (2007), Maxwell & van der Vorst, (2003)] where printing services are provided on a usage basis and the pay-per-wash laundry service provided by Electrolux [Baines et al., (2007), Maxwell & van der Vorst, (2003)]

3) Result-oriented PSS where the result is sold, such as the selling washed clothes instead of selling the washing machine usually offered by dry cleaners, lighting systems by

Parkersell (UK) (Baines et al., 2007) where illumination was provided and the solar heat service by AMG (Manzini & Vezzoli, 2002) where heat was sold in the form of hot water for dressing rooms.

2.2.2 **Benefits and Limitations**

The general expectation by authors researching PSS is that they would have less environmental impact than selling only the product (Baines et al., 2007). Extending product life through a closed-loop system (Khumboon et al., 2008), and systematically processing the products to minimize disposal in the post-use stage, helps achieve this expectation unlike when the responsibilities lie with the customer. Case studies by Maxwell et al., (2006) have shown environmental benefit from PSS across a variety of industrial sectors ranging from furniture, consumer products to healthcare. OEM ownership of the product encourages maintaining optimal condition during usage, extension of lifetime, and the quality and quantity of recycling (Manzini & Vezzoli, 2003), to increase financial returns (forcing better environmental and potentially societal performance).

The function of the product or service is what brings value to the customer (Khumboon et al., 2008) since they are interested in what they are able to achieve through it (Manzini & Vezzoli, 2003). In a use-oriented PSS, the requirement is met by “selling satisfaction” (Manzini & Vezzoli, 2003) and the customer pays for the products usage but is free from other responsibilities and costs connected with its purchase (Baines et al., 2007). Instead the producer takes responsibility for maintenance, operation and disposal (Khumboon et al., 2008). Thus the customer benefits by receiving increased quality of life (Khumboon et al., 2008), through higher product quality and lower commitments for service and maintenance (Baines et al., 2007). Enhanced value is also generated through customizability since even a standard product when coupled with service can provide high individualization (Komoto et al., 2005) while when coupled with MC can provide even further individualization.

For the producer, PSS provide competitive advantage through leading by service (i.e. providing solutions rather than products) against others who may simply provide lower priced products (Baines et al., 2007). Retention of ownership (Baines et al., 2007) can provide added security, reusability of parts and also improvement of their innovation capability by having access to key data about customer usage (Khumboon et al., 2008). A successful example of this is the Rolls-Royce 'Total Care package', which offers airlines with gas turbines on a 'power-by-the-hour' basis while retaining ownership of it (Baines et al., 2007). Collection of data on product performance and customer usage in packages such as this could be used to create better maintenance schedules. This would help improve efficiency while simultaneously reducing cost while also helping future design improvements (Baines et al., 2007). At the same time the service element is difficult to duplicate by others providing a competitive advantage. Other benefits include new and prolonged business opportunities, corporate reputation, brand loyalty and preferred supplier status (Maxwell & van der Vorst, 2003, Manzini & Vezzoli, 2003).

Companies have found that economic and environmental benefits were simultaneously achieved (Maxwell & van der Vorst, 2003, Manzini & Vezzoli, 2003) when product functionality was improved and products became both cleaner and cheaper. Dematerialization (providing value while minimizing material use) which can be another output of a PSS has helped reduce depleting resources and waste. This is achieved by decoupling the use of materials for production from profitability and functionality, thereby reducing material consumption without impacting the latter. Reduction of Xerox's material usage by 72000 tons with a savings of $27 million (Maxwell & van der Vorst, 2003) is a good example of this. It could be argued that reducing material and product usage may have a negative societal effect in the form of loss of employment in traditional manufacturing fields but according to Maxwell & van der Vorst (2003) this could be offset through increased employment opportunities in sales and service areas.

There are certain requirements that producers have to understand for successful implementation of a PSS. Up to 80% of the environmental, societal and economic impacts are determined during the product conception and design stages and, in order to develop effective PSS, organizations and stakeholders in control of this stage should be consulted with (Maxwell & van der Vorst, 2003). Thus first is that they need to involve the customer early in the process when building the PSS so that customer expectations are met (Baines et al., 2007). Next they need to adopt a systems approach by considering all major lifecycle stages, create partnerships with organizations and new stakeholders who will help in building the infrastructure (Baines et al., 2007). Methods of assessing the satisfaction of individuals are also required since satisfaction is a complex concept and varies depending on attitudes, behavior, lifestyle and social pattern of individuals and organizations (Khumboon et al., 2008).

Although the benefits of PSS are numerous there are a number of barriers to its implementation. Thus the use of PSS in industry is limited (Baines et al., 2007). These can be divided into two main categories of cultural and corporate barriers (Baines et al., 2007); cultural barriers are psychological constraints and situations where ownership is an important factor (Omann, 2003) and a cultural shift is required to value the output of the product rather than owning the product (Baines et al., 2007). Baines et al., (2007) also referred that communal societies in Scandinavia, Netherlands and Switzerland seem to be more open to accepting the benefits of PSS over the desire for products. In cultures where ownership is important, PSS solutions may have to be applied first in business to business (B2B) arenas to prove the benefits in the mindset of the general public. It should be noted however that savings and convenience gained by customers may also have unwanted consequences known as rebound effects (Manzini & Vezzoli, 2003). These may include spending saved time and money in unsustainable activities and careless usage of product due to lack of ownership (Manzini & Vezzoli, 2003). Thus educating the customers and creating the values and attitudes of sustainability may have to be simultaneously conducted.

Corporate barriers to PSS begin with manufacturers being skeptical to whether there will be economic benefit (Komoto et al., 2005). While there is a change in how profit is generated, lack of knowledge on how to price the new system with respect to usage, fear of new risks that may be encountered and lack of experience for restructuring the organization to meet the needs of a PSS (Baines et al., 2007) are all factors that can become corporate barriers. On the other hand, as most producers consider service as a secondary activity to manufacturing, there is a difficulty in identifying the value of functional services; the requirement of third parties to provide the infrastructure with whom profit must be shared is another concern. The reason for the inability to alleviate these fears and concerns is the lack of tools for modeling, evaluating and comparing the traditional model of selling products only with the PSS [Komoto et al., (2005), Omann, (2003)]. It is evident therefore that quantitative methods are required to model and prove the advantage, or not, of developing a PSS system for their products (Baines et al., 2007). A new method of quantitatively analyzing sustainability performance and economic profitability will be presented in this thesis together with a methodology of determining the customer satisfaction of a product-service solution.

2.2.3 **Models, Tools and Methodologies of Application**

Khumboon et al., (2008) provided a comprehensive review of existing PSS design methods and evaluation tools; a summary is presented in Table 2-1. They also referred to many ways PSS solutions can be applied such as eco-design, product customization, added services, take-back systems, remanufacturing and recycling. Baines et al., (2007) provided a state-of-art review of PSS research, compiling literature between the years of 1995 and 2006 while describing the potential benefits and barriers for implementation as well as a summary of tools and methods. They found that most of the researchers are from the environmental, ecology, sustainability and economics disciplines with minimal contributions from manufacturing and engineering sectors. Currently found PSS are not fully implemented from a lifecycle point of view due to inadequate supporting methods and tools (Khumboon et al., 2008). Only a few examples of complete PSS that take the whole lifecycle into account are found; the social aspect of sustainability is seldom addressed in literature (Khumboon et al., 2008). There is also no integration of tools due difficultly of combining qualitative (social aspects) and quantitative (environmental, economic) outcomes (Khumboon et al., 2008).

Table 2-1 Summary of Methodologies and Tools (Adapted and modified from Khumboon et al., 2008)

Methodology	Main tools used	Key learning
Designing Eco-efficient Services (DES) methodology	SWOT, ViP, Backcasting, Stakeholder analysis, Blueprinting, META, QFD, Eco-purchase, LCA, EVR, Green communication, Financial tools	Importance of business coalitions for success of implementation of new system
Kathalys method	SWOT, ViP, Strategic problem analysis, sustainable road mapping, Focus group discussion, Simplified LCA	Involvement amongst partners is key to success of projects
Methodology for PSS (MEPSS)	Stakeholder mapping, SWOT, System Map, Scenario building, Simplified LCA, Customer acceptance analysis, E2 vector, system profit screening	Successful in Environmental and economic aspects in case studies
Sustainable Product and Service Development (SPSD) methodology	Checklist of basic functionality, environmental, societal and economic criteria, tools used in MEPSS and other methods	The methodology was practically useful and effective

Komoto et al., (2005) analyzed PSS with lifecycle simulation (using discrete event simulation which deals with stochastic behavior of components, users and other stakeholders) which enabled them to compare environmental and economic performance of alternative PSS.

Maxwell and van der Vorst, (2003) introduced the sustainable product and service development (SPSD) methodology which extended cleaner production system by incorporating the TBL aspects of environment, economy and society from product conception to end-of-life through a checklist. This was however only a qualitative assessment. Maxwell et al., (2006) implemented the SPSD approach across ten sectors (involving 59 companies), with nine proving to be commercially applicable. Five proved to improve all areas of the TBL while all nine benefited in at least one area of the TBL. It is visible that benefits of PSS extend to all sectors including customers, producers, government and the environment (Baines et al., 2007).

Researchers have proven that PSS are practical business models that benefit both OEMs and customers alike while assisting the evolution towards sustainable consumption. Integration with MC can provide a highly individualized and sustainable product solution. However both OEMs and customers may be interested in determining the optimal product solution that satisfies their economic requirements while also being environmentally benign and socially responsible. Therefore product optimization is another key ingredient that needs to be integrated with MC and PSS in order to design a sustainable PSS.

2.3 Product Optimization

Product optimization involves selecting the optimal material, physical shape or configuration that provides one or more benefits (i.e. lowest cost, highest customer satisfaction, lowest environment impact, highest mechanical performance etc.). Zhou et al., (2009) researched how to optimize material selection to develop sustainable products. They analyzed environmental effects by conducting a life cycle analysis (LCA) and then proceeded to optimize mechanical, economic and environmental properties through the use of genetic algorithms (GA) and artificial neural networks (ANN). The approach was used to determine the material with the highest total fitness value for a drink container. As discussed by them, material interactions (both physical and chemical), manufacturability, post-use processing capabilities may also have to be considered to provide a comprehensive analysis. Zhou et al., (2008) researched maximizing the ratio between the overall utility (where the customer preference was measured) and costs from the perspectives of both the customer and manufacturer. A GA was used to solve the combinatorial optimization problem that determined the configuration that provided the lowest purchase cost while providing the highest satisfaction for a configurable notebook computer. The utility of the components was determined by assessing the desirability of product quality by evaluating hypothetical test products. Zhou et al., (2008) also referred to research that had been conducted to maximize the company's value, customer-engineering interaction, and to maximize the shared surplus model (through product portfolio planning).

Ostrosi and Bi, (2010) proposed possible physical solutions of a chair and used fuzzy models to capture the subjective nature of the design and determined the optimal solution that satisfied the customer's needs using a p-medium problem solution. Xuanyuan et al., (2008) and Li et al., (2006) used multi-objective GAs (MOGAs) where a Pareto-optimal solution set (a set of optimal solutions instead of one) was generated. Xuanyuan et al., (2008) considered both dynamic attributes that varied due to decisions during the configuration process (i.e. balanced inventory) and static attributes that remained constant during the process (i.e. lead time) in their research. Zhaoliang et al., (2010) conducted a MOGA-based product configuration optimization based on assembly sequencing and considered cost, lead time, inventory and assembly sequence. De Weck and Suh, (2003) discussed the optimal number of product platforms to maximize the profit of the product family.

Most of these research found in product optimization has focused on the design, manufacturing and use aspects of a product where the material or physical shape has been analyzed for mechanical, economical or environmental performance. While the methodologies were robust and generated valuable results, they seldom address the societal aspect and all four lifecycle stages from pre-manufacturing to post-use. Closed-loop flow of material was not found and methodologies available were unable to provide a holistic assessment by combining all the aspects of the TBL. Research on the optimization of configurable products is also rare although research on product configurators is mature.

Product configuration systems can be found in computer, telecommunication and automotive industries (Li et. al., 2006). However most existing literature use constraints and expert knowledge to identify feasible configurations (Zhou et. al., 2007). They focus mainly on the engineering and environmental perspective, ignoring the societal perspective (Zhou et. al., 2007). It can also be found that single objective optimization is most widely addressed in literature (Xuanyuan et. al., 2008, Zhaoliang et. al., 2010).

Determining the optimal configuration of a mass customized product involves dealing with conflicting criteria and objectives (Xuanyuan et. al., 2008) such as efficiency, cost and lead time (Zhaoliang et. al., 2010). Having hundreds of components adds to the complexity of having to consider compatibility and optimization complications (Xuanyuan et. al., 2008). Loosely constraining can also cause combination explosion giving a huge number of possible configurations (Li et. al., 2006). Although the goal is to find the solution that satisfies the manufacturers, customers and also the constraints (Li et. al., 2006), in some instances it may be better to determine a valid set of solutions rather than a single optimal solution (Xuanyuan et. al., 2008). This is due to the fact that determining the best solution requires the combining of all objectives, and this requires the assigning of relative weights, which could be subjective. However given a set of solutions the user would be able to determine more accurately the solution that best fits their need (Xuanyuan et. al., 2008). The tool developed in this thesis integrated the capability of limiting the solution set to only feasible ones to avoid the problem of combination explosion and also provide an optimal solution set if the user preferred it in place of a single solution.

Integrating lifecycle analysis (LCA) and optimization for modular products has shown significant advantages as far as sustainability is concerned (Ma et. al., 2006). However there is difficulty in conducting lifecycle analysis with current technologies due to the limitations of lifecycle inventories (Zhou et. al., 2009, Ma et. al., 2006), and computational limitations (Ma et. al., 2006). Furthermore most lifecycle modeling methods do not integrate the inter-relationships between environmental and economic aspects with the design and configurations, technicalities, and customer requirements (Ma et. al., 2006). Systems such as Enterprise Resource Management (ERM), Supply Chain Management (SCM), and Manufacturing Execution Systems (MES) couple many technological and economic aspects of manufacturing organizations but they also fail to adequately address the multi-dimensional aspect of sustainability (Ma et. al., 2006).

2.4 Summary

It is evident that substantial amount of research studies are available in the areas of MC, PSS and product optimization and although they have been conducted in isolation they complement one another and have the potential of creating sustainable PSS for modular products once integrated. The review also showed that although the economic and environmental aspects of sustainability are often addressed, the societal aspect has been often neglected. Most lifecycle assessments conducted terminate at the end of the use stage, while design for post-use processing is seldom addressed. Most assessments found are also of the qualitative nature, causing difficulty in integration of assessments between lifecycle stages or between aspects of the TBL.

This research develops a quantitative optimization model, that builds upon currently available methodologies while addressing the shortcomings found presently. It also provides a holistic approach by considering the TBL throughout the four lifecycle stages, a closed-loop flow of material through the use of the 6R approach analyzing the product service systems throughout the total demand lifecycle.

3 METHODOLOGY

The objective of the research is to develop a decision support tool that can help select and evaluate the most sustainable product (Product), product with recovery (Product–R) and product service system (PSS) design that ensures economic, environmental and societal sustainability goals are satisfied while considering activities across all four lifecycle stages. It is assumed that the product in consideration has multiple variants for a number of modules and optimization is achieved by selecting the best alternative for each component. This chapter describes the approach followed to develop the three optimization models.

A series of steps were followed in developing the tool. Initially the closed-loop material flow structure was defined. Thereafter the metrics required for economic, environmental and societal product sustainability evaluation were identified; metrics to measure product sustainability impacts on all lifecycle stages were selected to provide a total lifecycle assessment. The interactions and interdependencies between the metrics and the flow of material through the lifecycle stages were then identified using the 6R methodology as a guideline. A methodology to assess customer satisfaction was then developed. Next, a mathematical model based on a mixed integer linear program was formulated to identify the optimal configuration for the Product model, solved using the ILOG OPL optimization software and then extended to evaluate the Product-R and a PSS models. Finally testing and evaluation was conducted through an example where multiple periods and sensitivities were analyzed. Figure 3-1 presents steps followed and a detailed outline will be presented in the following sections of this chapter.

3.1 Defining Closed-loop Material Flow Structure

To simplify the modeling, the pre-manufacturing stage combined two processes, first processing of virgin materials and second manufacturing of components. We assume that the OEM considered in the model only handles the final assembly (considered as the manufacturing stage in this study) and then ships the final product to customers. At end-

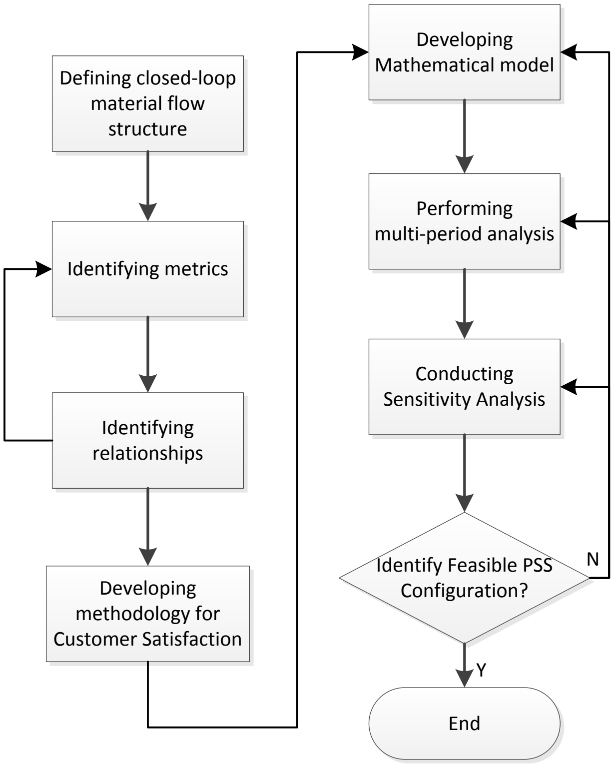


Figure 3-1 Steps followed in developing the Decision Support Tool

of-life the product is collected by the OEM, or third party collectors assigned by the OEM (for the PSS and Product-R models), and sorted. The reusable products are refurbished and sold to a separate market at a lower price (typically around 60%-80% of the normal price). The remaining products are disassembled and reusable parts separated and used by the OEM for remanufacturing. The remaining parts are then sorted for recycling or disposed through land-filling or incineration.

Recycled or shredded material can usually be mixed with virgin material to a certain percentage (referred to as the virgin material index (VMI) in this study) while still retaining the desired properties of the component or product. The percentage will vary depending on the material and will have to be varied for different applications accordingly. If the amount of recycled material available exceeds the permitted amount it may have to be sent for use in different applications. The component purchasing cost may be influenced by the amount of recycled material that the OEM is ready to accept when considering a multi lifecycle perspective. The purchase cost may increase or decrease depending whether the recycling is cost effective or not. Virgin material scarcity or shortage and interest in increasing the OEM's sustainability ratings too, could lead to interest in recycled material usage. However, in this research it is assumed that raw material is abundant and that recycling is cost effective for simplicity. If such assumption is not made details about the organizations sustainability policies must be analyzed with respect to the product or component, supply chain disruptions and regulatory policies be scrutinized, and a considerable amount of data with respect to recycling will have to be gathered. When recovery of products is pursued by the OEM, product redesign for easier disassembly, upgradability and use of less hazardous materials must be adopted to ease post-use processing. Also for the PSS model, product modifications for enhanced lifetime leading to increased mean time before failure (MTBF) would lower maintenance costs and benefit the OEM as such costs are incurred on a per use basis. Figure 3-2, further illustrates the activities described above. Q represents the volume sold by the OEM while X_1 represents percentage of products (of those sold) that could be recovered. X_2 is the percentage of recovered products that is suitable for refurbishment. X_3 percent of recovered products will be used for re-manufacturing as parts while X_4 will be sent for recycling. The remaining percentage would be either land-filled (X_5) or incinerated (X_6). Of X_4 percent that is sent for recycling only a limited amount can be reused in the system due to the limitation set by the VMI and reuse of components. If QX_7 is smaller than $Q(1-X_1X_3)*VMI$ then the total amount can be recycled in the system while if it is greater it will be limited by this quantity and the remaining amount $Q(X_1X_4 - (1-X_1X_3)*VMI)$ would have to be sent for different applications.

3.2 Metrics for Evaluation of Product and Product Service Systems Sustainability

The metrics repository developed in a separate research project on sustainable manufacturing at the University of Kentucky [see Lu et al., (2010)] were used to identify appropriate metrics for the economic, environmental and societal assessment of this research. The repository consisted of a large number of metrics and they were carefully studied, selected and adapted to provide the capability to assess the service aspect of a

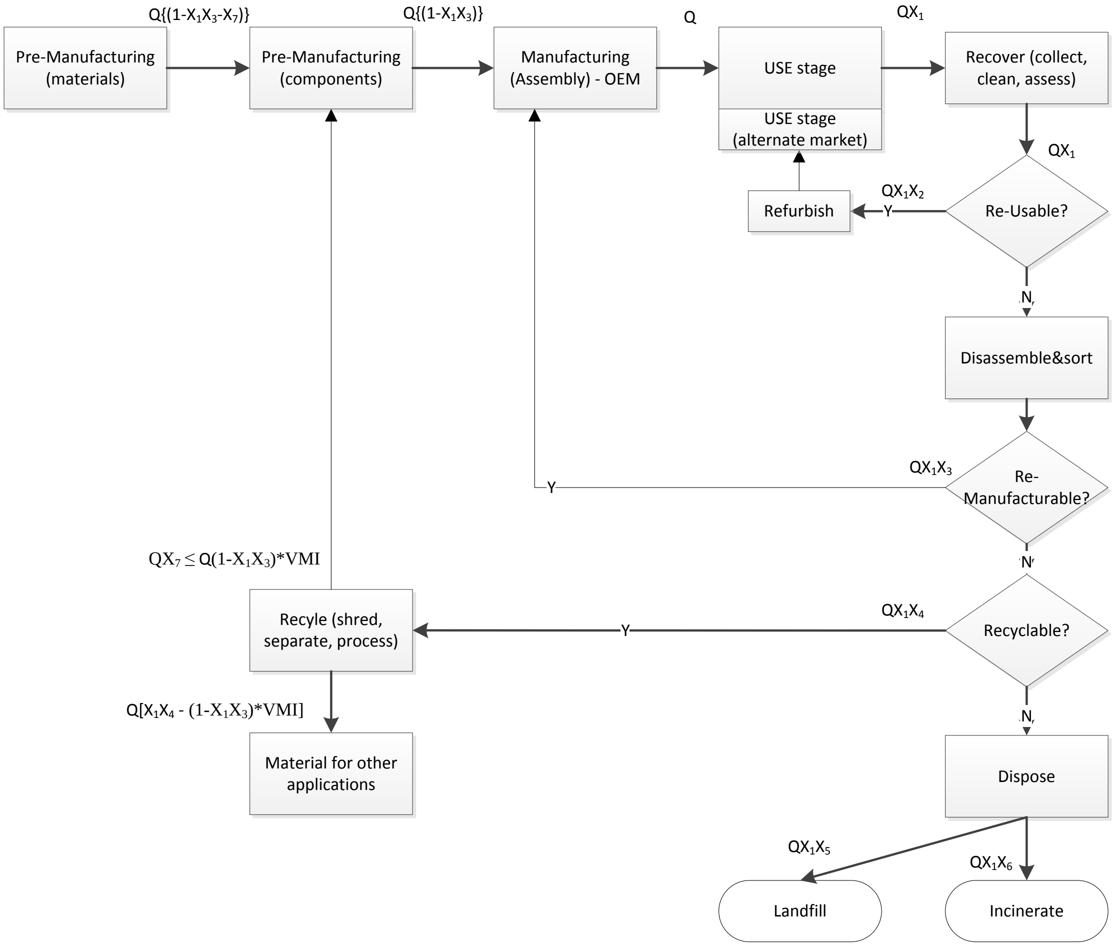


Figure 3-2 Flow chart for Material Flow from a Total Lifecycle Perspective

PSS system. A number of new metrics that were not included in the previously mentioned project were also added to this list in order to assist in assessing a PSS (i.e. average usage, contract period, market price etc.). Several iterations between the list of metrics and the relationship map of the metrics (explained in Section 3.2) was required to make a comprehensive assessment possible. Most metrics were adapted to measure performance at a component level while others were adapted to measure a product level. Although gathering data at a component level may be difficult, it is necessary due to the fact that the objective of the tool is to compare and assess the impact of changes in modular variants in the product. It should be noted however that this tool does not require collection of data at the basic component level (i.e. a crankshaft, piston etc.) and only requires it at a modular component level (i.e. the whole engine, tires, gear box etc.). This will provide the opportunity of at least gathering this data at a crude or approximate level providing the opportunity of comparison and assessment. Gathering data at the component level for the use stage may become the most challenging, for example, to ascertain injury rates and may have to be based on user feedback or expert opinion on which component may be at fault for the injury. Once the list of metrics under the triple bottom line (TBL) was finalized, the lifecycle stage that they would relate to was identified to assist in data collection for a case study. The list of metrics selected for the research, the unit of measurement and the lifecycle stage they relate to are given in Table 3-1 through Table 3-3.

Table 3-1 Economic Performance Measures

	Metric	Unit	PM	M	U	PU
Economic	Average usage (i.e. miles, hrs, pages etc)	/yr			★	
	Assembly cost (labor)	$/unit		★		
	Consumable cost (average)	$/Usage			★	
	Contract Period	yrs			★	
	Disassembly cost	$/unit				★
	Disposal cost of component	$/component				★
	Energy cost	$/KWh	★	★	★	★
	Interest rates	/yr	★	★	★	★
	Life time of product/component	yrs			★	
	Average maintenance cost	$/event			★	
	Market price	$			★	
	Mean time/usage before failure for component	yrs/usage			★	
	Overhead cost (labor)	$/yr		★		
	Purchase cost	$		★		
	Profit percentage	%			★	
	Market Demand (Average)	units/yr			★	
	Quantity Recoverable (after -end of Lifetime)	units/yr				★
	Recyling Cost of component (with profit included)	$/component				★
	Recovery Cost	$/unit				★
	Recovered material value	$/component				★
	Recovered component value	$/component				★
	Refurbished (reuse) value	$/unit				★
	Refurbishing cost	$/unit				★
	Recycled material value	$/component				★
	Storage packing and transportation cost (labor)	$/unit		★		

Table 3-2 Environmental Performance Measures

	Metric	Unit	PM	M	U	PU
Environmental	Assembly Energy	KWh/unit		★		
	Disposal energy	KWh/component				★
	Disassembly energy	KWh/unit				★
	Energy used in PM stage by component	KWh/component	★			
	Energy used in Use stage by component (Fixed)	KWh/yr			★	
	Energy used in Use stage by component (variable)	KWh/usage			★	
	Hazardous material in component	g	★	★	★	★
	Hazardous material for processing (PM & M)	g	★	★		
	Hazardous material for assembly	g		★		
	Material type	-	★	★	★	★
	Material processing energy	KWh/unit	★			
	Overhead energy	KWh/yr		★		
	Recoverable %	-				★
	Recovery Energy	KWh/unit				★
	Refurbishing energy	KWh/unit				★
	Recycling energy	KWh/component				★
	Recovered material percentage (For Reuse, Reman, recycle)	-				★
	Storage packing and transportation energy	KWh/unit		★		
	Weight of material	g		★	★	★
	Carbon footprint of component in PM stage	/component	★			
	Carbon footprint of component in Use stage	/component			★	

Table 3-3 Societal Performance Measures

	Metric	Unit	PM	M	U	PU
Societal	Customer satisfaction index				★	
	Injury rate for pre-manufacturing stage	/component × 10^3	★			
	Injury rate for manufacturing stage	/component × 10^3		★		
	Injury rate for use stage by component	/component × 10^3			★	
	Injury rate for post-use life cycle stage	/component × 10^3				★
	Landfill generated at pre-manufacturing stage	g/component	★			
	Landfill generated at manufacturing stage	g/component		★		
	Landfill generated at use stage	g/component			★	
	Landfill generated at post-use stage	g/component				★

3.3 Relationships between Metrics

To comprehensively evaluate a Product (or Product-R, PSS) model, the impact of a change made in one lifecycle stage of a product on other lifecycle stage(s) must be identified. Environmental, economic and societal factors often have interactions and dependencies both within and between them. Figure 3-3 shows some of the more significant relationships that were taken into account in this research. The ovals represent the metrics identified, the lines an interaction or contribution within the TBL factors while the dashed lines represent interactions between them or information flows to the metrics. Certain metrics may require the support of an LCA tool to calculate the values and the information required for these LCA tools are shown within the green dashed rectangle on the bottom left hand side of Figure 3-3. It should be noted, however, that the relationships between the data provided to the LCA tool and its output were not captured in the mathematical model. The nature of the relationship is highly product-specific; for example the manner in which changing a material of a component affects emissions depends on whether the product is, say a bicycle or an automobile. Therefore to maintain generalizability such relationships were not included in the mathematical model. Instead they are assumed to be included externally by separate calculations such as through LCA tools. Capturing the relationships in the mathematical model must be addressed in further expanding these models.

Economic, environmental and societal metrics are combined and reorganized into a more informative form, and together with additional information regarding the product and the customer, is exported into the mathematical model. The model will determine the optimal configuration that maximizes OEM profit subject to environmental and societal impact constraints and generates results of the KPIs that both the OEM and customer are concerned with.

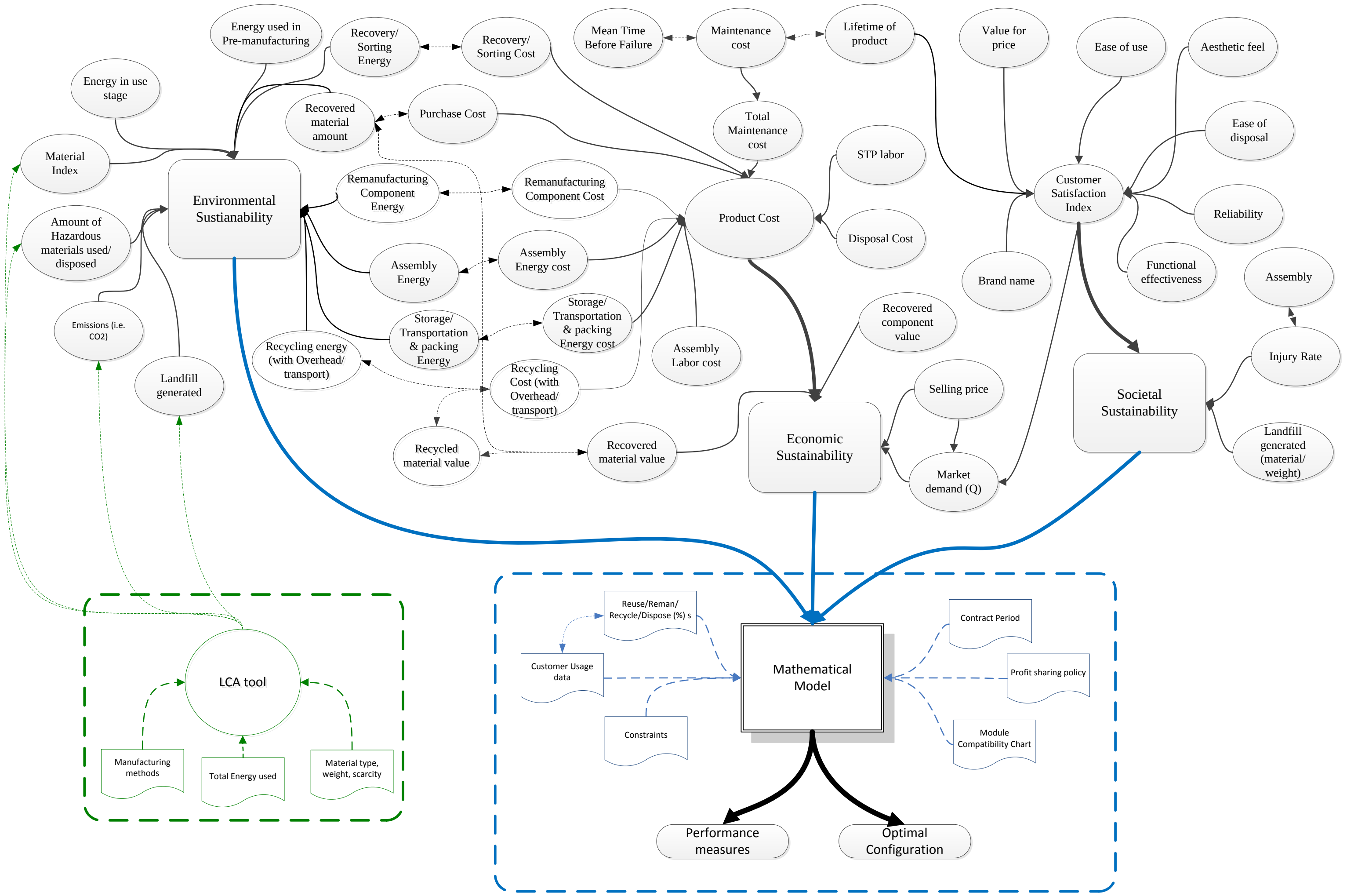


Figure 3-3 Interactions between TBL Performance Measures, the LCA tool and the Mathematical Model

3.4 Customer Satisfaction Index (CSI)

The customer satisfaction of a product-service solution determines its success in the market. Therefore in order to incorporate this aspect, factors that would contribute towards customer satisfaction were investigated and a list of characteristics built upon research by De Silva, (2005) who evaluated consumer products. Here characteristics that would help distinguish the performance between the variants available for each module were selected and organized so that a survey or expert analysis could be conducted on it to evaluate the overall satisfaction of the product.

Assume that the product consists of customizable modules (A, B, C, etc.) that have variants (denoted by A_i, B_i, C_i, respectively) that can be selected from and a fixed module M that cannot be customized. Selecting one variant from each of the customizable modules and assembling them together with the fixed module will form a complete product. Each of the variants and the fixed module will be assessed with respect to the characteristics identified as shown in Table 3-4. These are rated on a scale of 1 to 5 (with 5 being the best) depending on how much it contributes to the particular characteristic of the product. A rating of 0 will be applied to instances where the criteria are not applicable for the particular module. The rating given to each variant is denoted by $F(x)$.

Table 3-4 Assessing Characteristics for Customer Satisfaction

Characteristic	A				B				C				…	M
	A_1	A_2	…	A_i	B_1	B_2	…	Bi	C_1	C_2	…	C_i	…	
Ease of use	5	2		2	1	4		5	0	0		0		2
Aesthetic feel														
Reliability														
Durability														
Functional effectiveness														
Value for price														
Efficiency														
Weight														
Ease of disposal														
Brand name														

α, β, φ and **Ω** represent the rating assigned to each module A,B,C and M respectively, to capture the importance of each of them with respect to customer satisfaction [denoted by $F(y)$]. θ_i (where i = 1 to 10), captures the relative importance of each characteristic in terms of satisfying the product specifications and customer satisfaction [denoted by $F(z)$]. Although the values could be assessed through an ordinary survey or rating given by experts, more accurate assessments for the values for α, β, φ, **Ω** and θ_i, can be obtained through a survey conducted using a methodology such as the Analytic Hierarchy Process (AHP) (Saaty, 1980), which uses pair-wise comparisons. The CSI for each module with respect to each characteristic ($\mathrm{CSI_c}$) can then be calculated by the formula,

$$\mathbf{CSI_c = F(x) \times F(y) \times F(z)} \qquad -(\mathbf{1})$$

The overall CSI value for the jth variant of the ith module ($\mathrm{CSI_{ij_i}}$) is calculated by taking the column total for each module, where n is the number of characteristics assessed for customer satisfaction.

$$\mathrm{CSI_{ij_i}} = \sum_{c=1}^{n} \mathrm{CSI_c} \qquad - \ (\mathbf{2})$$

The product's CSI value will be calculated by adding the value for each of the variants chosen for each module of the product. A minimum CSI value or a benchmark CSI value can be determined by assessing a known product through the same survey and these results could be used in the mathematical model to establish minimum requirements a product must satisfy.

3.5 Assumptions for Model Formulation

The mathematical model was formulated as a mixed integer linear program to maximize the total profit of the OEM subject to economic, environmental and societal constraints. This model was coded and solved in ILOG OPL optimization software. The assumptions that were made during the development of the model are listed below.

1. The product has a set of customizable modules with a number of variants for each; it will be produced by selecting one variant for each module. The non-customizable features of the product are collectively considered as one fixed module (no variants).
2. The assembly time is independent of the variants chosen.
3. Average sales is known or forecasted for the period of analysis.
4. Metrics considered can be pre-determined and calculated to a per component level (If non-linearity exists it can be modeled to a mathematical expression).
5. Reused component efficiency and durability are comparable to those of new components.
6. Storage, packing, and transportation costs per product are fixed for the period and are proportional to the quantity sold.
7. Overhead costs are constant.
8. Remanufacturing and manufacturing costs are equal (since OEM only handles final assembly).
9. Alternate markets are available for products even after the products obsolescence in the main market at a lower price (The PSS and Product-R options are not offered there)
10. For the PSS model, the OEM will retain product ownership; they will bear all maintenance costs, (possibly also consumables and energy costs), and recovers it at end-of-lifetime. These costs are assumed fixed for the period of analysis.
11. Average reusable percentage and remanufacturable percentage for every product and component respectively can be determined and fixed for the period in consideration
12. OEM sells product directly to consumer.
13. Recycling centers and costs are predetermined.

14. There is no limitation for the usage during a given year for the PSS model. The product will last its predicted lifetime if maintained according to specifications and usage.

The objective of the OEM is to maximize the overall profit which is calculated by taking the product of the profit per unit and number of units sold. For the Product model the profit per unit will be the difference between the selling price of the product and the total cost of production, while for the Product-R and PSS models the Total PSS Cost will also have to be deducted. The Total PSS Cost is the difference between the total cost incurred by post-use processing of products and the revenue generated through selling them. However it should be mentioned that it is likely that the OEM will consider post-use processing only if it is profitable and thus the Total PSS cost is most likely a negative value and actually increases the profit. The quantity sold is dependent on the average market demand, while being sensitive to the satisfaction of the product and the selling price (for the Product and Product-R models) or price per usage (for the PSS model).

The model has the following constraints that it has to satisfy. The customer satisfaction index has minimum value that should be achieved while the energy usage, injury rates, carbon footprint, landfill, hazardous material and material index all have maximum values that should not be exceeded. Furthermore the model should choose one variant from each of the customizable modules in order to assemble a complete product. The next section will provide a detailed description what these values are and how they are determined.

3.6 Mathematical Model

Suppose, the product consists of m number of modular components with the ith module having j number of functionally similar options represented by j_i. The difference between the options could for example, be in material used, efficiencies, production costs, manufacturing methods or weight. We include a fixed module M (this may consist of several subassemblies) to account for all components of the product that is fixed. Table 3-5 lists the notations used in the formulation of the mathematical model.

Table 3-5 Notations

Notation	Description
PC	*Production cost*
SP	*Selling price*
ENCU	*Energy cost during use stage*
MC	*Maintenance cost*
CC	*Consumable cost*
DC	*Disposal cost*
PSSAP	*Price Adjustment for PSS model*
PSSC	*Cost associated with post-use stage for PSS*
CSI	*Customer satisfaction index*
TEN	*Total energy used during all LC stages*
TIJ	*Total injury caused during all LC stages*
TLF	*Total landfill generated during all LC stages*
TCF	*Total carbon footprint for all LC stages*
THM	*Total hazardous material used in all LC stages*
TMI	*Total material index for all LC stages*
ij_i	*Subscript - corresponds to* i^{th} *module and* j_i^{th} *option*
M	*Subscript - corresponds to fixed module*
F	*Subscript - corresponds to other fixed parameters connected to the whole product*
max	*Subscript - corresponds to maximum amount permitted*
min	*Subscript - corresponds to minimum amount permitted*

The total production cost for the OEM will include the production costs of the variable and fixed modules, fixed production costs, and purchase costs of parts and subassemblies. Variable costs will include assembly labor and assembly energy costs, and storage, transportation and packing (STP) costs. Overheads would be considered as fixed costs. The total production cost (TPC) can be denoted as follows;

$$\mathrm{TPC} = \sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PC_{ij_i} X_{ij_i}} + \quad \mathrm{PC_M} + \mathrm{PC_F} \qquad -(\mathbf{3})$$

Where,

$$\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{X_{ij_i}} = 1\,;\ (\forall\, \mathrm{i} = 1 \rightarrow \mathrm{m})$$

$\mathrm{X_{ij_i}}$ denotes a binary variable and this condition ensures that only one option in each module can be chosen for a product.

The selling price per unit is usually determined by the value the customer is willing to pay for it although this maybe different when competition is low or the OEM operates a monopoly. In instances where the selling price of each component ($\mathrm{SP_{ij_i}}$) is difficult to be determined the production cost of the component could be used to calculate a reasonable price. Competitors' pricing or the current market price could be used as benchmark for pricing the product and could help determine a maximum selling price ($\mathrm{SP_{max}}$) if the user wants to set it as a constraint. The Selling Price (SP) can be denoted as follows;

$$\mathrm{SP} = \sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{SP_{ij_i} X_{ij_i}} + \ \mathrm{SP_M} \qquad -(\mathbf{4})$$

The total cost incurred by the customer, that is the total cost of ownership (TCO) will include the purchase price (equal to SP), total energy cost during use (TEnC), total maintenance cost (TMC), total consumable cost (TCC) and disposal cost (DC). That is, TCO = SP + TEnC + TMC + TCC + DC.

The total energy cost (TEnC) of the product during use (subject to assumption 4) is,

$$\mathrm{TEnC} = \sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{EnCU}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{EnCU}_{\mathrm{M}} \qquad -(\mathbf{5})$$

The total maintenance cost (TMC) includes labor, transport and common parts that are replaced during a maintenance event for that particular module (some modules may not require maintenance during use and will have $\mathrm{MC}_{\mathrm{ij_i}} = 0$ in that case). This is the estimated total calculated for the contract period and will be included in the price per usage (PPU) or paid by the customer at the time of service.

$$\mathrm{TMC} = \sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{MC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{MC}_{\mathrm{M}} \qquad -(\mathbf{6})$$

The consumable cost varies depending on the configuration of product. An example would be ink cartridges for printers and tires for vehicles where the price to print a page will vary according to the size and design of the cartridge and the wear per mile would depend on parameters such as the diameter, width and material of the tire. Some modules may not have consumables that have to be replaced and in that case $\mathrm{CC}_{\mathrm{ij_i}} = 0$. Total consumables cost,

$$\mathrm{TCC} = \sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{CC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{CC}_{\mathrm{M}} \qquad -(\mathbf{7})$$

The modules vary in material used and thus disposability and cost involved. The fixed disposal cost includes the collection, sorting and disassembly costs. End-of-life Value (EOLV) represents any value that may be present at the end of the products' useful lifetime. The EOLV will vary depending on when the customer decides on disposing it (the value depreciates with the number of years it is used). Disposal Cost,

$$\mathrm{DC} = \sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{DC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{DC}_{\mathrm{M}} + \mathrm{DC}_{\mathrm{F}} - \mathrm{EOLV} \qquad -(\mathbf{8})$$

The PSS and Product-R models have additional criteria to be evaluated. First is that the OEM incurs the cost for recovery, sorting, refurbishing and disassembly, although it may earn revenue through selling the refurbished product, using reusable parts and selling material for recycling. Secondary market price, amount spent on purchasing new components and scrap material value will be used to determine the value of recovered products and components. Consolidating all the costs and revenues for each component we calculate the total PSS cost (TPSSC). For the Product-R model the TPSSC will only be calculated for the products that are recovered. This profit (or cost) may be shared with the customer in the PSS model. The percentage of this profit shared by the OEM is denoted by profit sharing percentage (PSP).

$$\mathrm{TPSSC} = \left(\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PSSC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{PSSC}_{\mathrm{M}} + \mathrm{PSSC}_{\mathrm{F}} \right) \times (1 - \mathrm{PSP}) \qquad -(\mathbf{9})$$

In the PSS model the OEM does not receive payment for the product at delivery. Therefore a price adjustment (to compensate for the time discounted value and current interest rates the OEM has to pay to financial institutions) must be applied when calculating the Price Per Usage (PPU). This is represented as Total PSS Price Adjustment,

$$\mathrm{TPSSPA} = \sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PSSPA}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{PSSPA}_{\mathrm{M}} \qquad -(\mathbf{10})$$

Adding TCO, TPSSI and TPSSC and dividing it by the contract period (CP) and average usage per year (AU) provides a rough estimate of the PPU. TEnC will have to be excluded in this calculation if the customer bears the energy (i.e. electricity, fuel etc.) cost. Therefore,

$$\mathrm{PPU} = \frac{\mathrm{TCO} + (\mathrm{TPSSC} \times \mathrm{PSP}) + \mathrm{TPSSPA}}{\mathrm{CP} \times \mathrm{AU}} \qquad -(\mathbf{11})$$

The profit per product is the difference between the selling price and the total production costs. Therefore, in the Product model, profit per product is given by,

$$\mathrm{P} = \left(\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{SP}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{SP}_{\mathrm{M}}\right) - \left(\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PC}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{PC}_{\mathrm{M}} + \mathrm{PC}_{\mathrm{F}}\right) \qquad -(\mathbf{12a})$$

Because additional expenses are incurred during PSS usage, the profit per product function for the PSS model is given by,

$$\mathrm{P} = \left(\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{SP}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{SP}_{\mathrm{M}}\right) - \left(\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PC}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{PC}_{\mathrm{M}} + \mathrm{PC}_{\mathrm{F}}\right)$$

$$-\left(\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PSSC}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{PSSC}_{\mathrm{M}} + \mathrm{PSSC}_{\mathrm{F}}\right)(1 - \mathrm{PSP}) \qquad -(\mathbf{12b})$$

The revenue of the PSS model could also be calculated through the periodic payment collected according to usage (usage could be time, distance, or number of uses). The average usage could be determined from past data or estimated through a forecast. The rough revenue during the lifetime of the product would be,

PSS revenue = Average Usage (per month) x Price per Usage x Contract period (months)

In the PSS model the OEM provides maintenance and consumables (and possibly energy). Therefore an alternate form of profit per product for the PSS model would be would be,

$$\mathrm{P} = \mathrm{PSS\ revenue}\ - \left(\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \quad \mathrm{PC_M} + \mathrm{PC_F} \right)$$

$$-\mathrm{TEnC} - \mathrm{TMC} - \mathrm{TCC} - \mathrm{TPSSC} \qquad - \ (\mathbf{12c})$$

The profit per product for the Product-R model will be calculated similar to the PSS model (equation 12b), the only difference being in the amount of recovered products and therefore the profit (or cost) involved.

Although a market demand based on historical data can be forecast, it can vary due to a number of reasons. In this model, the total quantity of products sellable is modeled as a function of the CSI and the selling price (or PPU for PSS model). Thus, even though a certain configuration may be profitable as a single product, if its CSI is low and selling price (or PPU) is high, the overall profit maybe low due to its low volume of sales. The total quantity of products sellable (Q) can be denoted as;

$$\mathrm{Q} = \mathrm{Average\ market\ demand}\ +\ f(CSI, SP) \qquad - \ (\mathbf{13})$$

The objective of the OEM is to maximize the overall profit (P*). The overall profit equation for the Product, Product-R and PSS models can be denoted as;

$$\mathrm{P}^{*} = \mathrm{P} \times \mathrm{Q} \qquad -(\mathbf{14})$$

The constraints considered in the optimization model are thresholds for the total cost of ownership (in Product and Product-R models), maximum price per usage (PSS model), minimum CSI, maximum total energy used, maximum total number of injuries occurring lifetime of product, total amount of landfill (liquid or solid residue) generated in lifetime, total carbon footprint of product, total amount of hazardous material used and total material index.

Each option in each variable module will have a separate CSI calculated for it depending on features required by the customer. A minimum satisfaction limit is set to secure the products' reputation in the market. This value can be determined by assessing previous and competitors' products and combining them with recommendations from experts. This constraint is shown in equation (15)

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{CSI}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{CSI}_{\mathrm{M}} \geq \mathrm{CSI}_{\mathrm{min}} \qquad -(\mathbf{15})$$

Total energy consumption includes energy used in the pre-manufacturing (both processing of material and manufacturing of components), manufacturing (for final assembly, storage, packing and transportation), use and post-use stages (recovery/sorting, refurbishing, disassembly, remanufacturing and recycling). Since products or components that are remanufactured and recycled will save energy used in processes necessary to manufacture or process them, that amount must be deducted from this total. An upper limit is set for the total energy consumption as shown by constraint (16). This value will have to be determined through current standards although some organizations set stricter standards internally.

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{TEN}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{TEN}_{\mathrm{M}} + \mathrm{TEN}_{\mathrm{F}} \leq \mathrm{TEN}_{\mathrm{max}} \qquad -(\mathbf{16})$$

Similarly, the total injuries (equation 17), landfill (equation 18), carbon footprint (equation 19) and hazardous material usage (equation 20) are calculated considering all lifecycle stages and the benefits of reusing remanufacturing and recycling.

Injury rates for pre-manufacturing, manufacturing and post-use stages could be based on OSHA reports and customer feedback or market research during the use stage. Accordingly, the constraint on injuries could be represented as;

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{TIJ}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{TIJ}_{\mathrm{M}} + \mathrm{TIJ}_{\mathrm{F}} \leq \mathrm{TIJ}_{\mathrm{max}} \qquad -(\mathbf{17})$$

Directives such as WEEE have imposed regulations on recycling and remanufacturing to reduce the amount of landfill. Companies such as Toyota have internal standards to limit landfill to near zero levels. The maximum limit for landfill could be set according to the standards the OEM is governed by or internal targets and goals; the constraint for landfill is represented by,

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{TLF}_{\mathrm{ij_i}}\mathrm{X}_{\mathrm{ij_i}} + \mathrm{TLF}_{\mathrm{M}} + \mathrm{TLF}_{\mathrm{F}} \leq \mathrm{TLF}_{\mathrm{max}} \qquad -(\mathbf{18})$$

The carbon footprint can be calculated based on energy source(s) and amount used. The carbon footprint can vary significantly depending on geographic location of OEMs and sources of energy used. The constraint on carbon footprint is shown as;

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{TCF_{ij_i}X_{ij_i}} + \mathrm{TCF_M} + \mathrm{TCF_F} \le \mathrm{TCF_{max}} \qquad -(\mathbf{19})$$

Similar equations could be used if SO_x, NO_x and water footprints need to be assessed.

A maximum limit of the total hazardous material (i.e. lead, mercury) used during the total lifecycle of the product could also be determined according to regulatory or internal standards. This limit is represented by,

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{THM_{ij_i}X_{ij_i}} + \mathrm{THM_M} + \mathrm{THM_F} \le \mathrm{THM_{max}} \qquad -(\mathbf{20})$$

Total amount of material used will be the sum of material needed to manufacture the components (if scrap is negligible or recyclable, weight of material in the components could be used). In Product-R and PSS models, the percentage of material remanufactured and recycled is deducted. The calculated result could be used as input data to an LCA tool together with energy consumption and details of hazardous materials to calculate the overall environmental impact and footprints. The total material used will also be used to calculate the material index which is a function of the type, weight and scarcity of the material. The OEM can have a target to limit the amount of material used ($\mathrm{TMI_{max}}$) during the lifecycle of the product which is represented by equation (21).

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{TMI_{ij_i}X_{ij_i}} + \mathrm{TMI_M} \le \mathrm{TMI_{max}} \qquad -(\mathbf{21})$$

It should be understood that determining the right hand side (R.H.S.) values for the constraints may be difficult and may require a considerable amount of effort in reviewing current and proposed standards and developing internal targets and goals. However, in order to take advantage of a tool of this nature these parameters need to be determined at least as approximate values.

Based on the discussion presented for the formulation of the mathematical model can be summarized as follows,

Objective:

Maximize overall profit (P*) where,

$$\mathrm{P}^{*} = \mathrm{P} \times \mathrm{Q} \qquad -(14)$$

For the Product model,

$$\mathrm{P} = \left(\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{SP}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{SP}_{\mathrm{M}}\right) - \left(\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{PC}_{\mathrm{M}} + \mathrm{PC}_{\mathrm{F}}\right) \qquad -(12\mathrm{a})$$

And for the Product-R and PSS models

$$\mathrm{P} = \left(\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{SP}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{SP}_{\mathrm{M}}\right) - \left(\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{PC}_{\mathrm{M}} + \mathrm{PC}_{\mathrm{F}}\right) -$$

$$\left(\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{PSSC}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{PSSC}_{\mathrm{M}} + \mathrm{PSSC}_{\mathrm{F}}\right)(1 - \mathrm{PSP}) \qquad -(12\mathrm{b})$$

$$\mathrm{Q} = \text{Average market demand} + f(CSI, SP) - (11)$$

Subject to:

$$\sum_{i=1}^{m} \sum_{\mathrm{j_i}=1}^{\mathrm{k_i}} \mathrm{CSI}_{\mathrm{ij_i}} \mathrm{X}_{\mathrm{ij_i}} + \mathrm{CSI}_{\mathrm{M}} \geq \mathrm{CSI}_{\mathrm{min}} \qquad -(15)$$

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{TEN_{ij_i}X_{ij_i}} \; + \; \mathrm{TEN_M} + \mathrm{TEN_F} \; \leq \; \mathrm{TEN_{max}} \qquad -(16)$$

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{TIJ_{ij_i}X_{ij_i}} \; + \; \mathrm{TIJ_M} + \mathrm{TIJ_F} \; \leq \; \mathrm{TIJ_{max}} \qquad -(17)$$

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{TLF_{ij_i}X_{ij_i}} \; + \; \mathrm{TLF_M} + \mathrm{TLF_F} \; \leq \; \mathrm{TLF_{max}} \qquad -(18)$$

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{TCF_{ij_i}X_{ij_i}} \; + \; \mathrm{TCF_M} + \mathrm{TCF_F} \; \leq \; \mathrm{TCF_{max}} \qquad -(19)$$

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{THM_{ij_i}X_{ij_i}} \; + \; \mathrm{THM_M} + \mathrm{THM_F} \; \leq \; \mathrm{THM_{max}} \qquad -(20)$$

$$\sum_{i=1}^{m}\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{TMI_{ij_i}X_{ij_i}} \; + \; \mathrm{TMI_M} \; \leq \; \mathrm{TMI_{max}} \qquad -(21)$$

Where,

$$\sum_{\mathrm{j_i=1}}^{\mathrm{k_i}}\mathrm{X_{ij_i}} = 1\,;\ (\forall\, \mathrm{i} = 1 \rightarrow \mathrm{m})\,,\ \mathrm{X_{ij_i}} = 0, 1$$

3.7 Multi-Period Analysis

It is assumed that the product has a demand cycle (Metta, 2011) where there are periods of growth, maturity and decline. The product has a limited lifetime after which they disposed (in the Product model) or recovered (in the Product-R and PSS models). In the first few years after the product is introduced there will be no recovered products. Thereafter, there will be a period where the OEM will be recovering used products and manufacturing (and also remanufacturing) new products. During the final period the OEM will cease the manufacturing of new products and only be involved in recovery and refurbishing of products. The value of the refurbished products and reusable parts may reduce in value due to its obsolescence during this period and similarly there will be an impact on the reuse, remanufacture and recycle rates. In order to capture these characteristics, the model was formulated to incorporate the quantity manufactured, recovered and also the percentages relating to each of the post-use options (i.e. reuse, remanufacture etc.). The model is first used to analyze the period that products are manufactured. Thereafter, depending on the configuration of products manufactured during these years and the policy of the OEM on post-use handling after product obsolescence, the model is used to perform multi-period analysis for the total period, including the years after manufacturing is ceased. Combining and analyzing the collective results will generate a holistic analysis of the product for the total lifecycle for each of the three service models. An example of such analysis will be in presented in Chapter 4 where a case example is discussed; the results are analyzed in Chapter 5.

4 CASE STUDY EXAMPLE

The application of the mathematical model developed in Chapter 3 is demonstrated through a simple hypothetical example in this chapter. The hypothetical product is assumed to consist of three customizable modules (A, B and C) and a fixed module (M). It is assumed that module ‘A’ has 5 variants while modules ‘B’ and ‘C’ have 4 variants each leading to a product structure as shown in Figure 4-1. Considering an actual example of a bicycle these modules could be the frame (with variants of aluminum, steel, titanium and different geometries), seat (leather or canvas), the wheel (material variants of aluminum, steel and size variants with different diameters) with the fixed module being the handle, gear system and brake mechanism.

Product variants will be produced by selecting an alternative for each of the customizable modules. Given the number of alternatives available for the three modules, 5 × 4 × 4 = 80 different product variants can be generated. It is assumed that the product has a demand cycle where demands grows to reach maturity within 2 years, and remains steady for 6 years and then declines over the next 2 years. The product lifetime is assumed to be 5 years. Products are recovered at end-of-use after 5 years in the Product-R and PSS models and those in a reusable state will be refurbished and shipped to a separate market for reuse. Thus the demand cycle lasts for 10 years (OEM will manufacture products for 10 years) while the OEM will provide services and recover products through the end of the 15th year. It is also assumed that refurbished products are sold at 70% of the usual price between the years 6-10 and at 50% of the price thereafter.

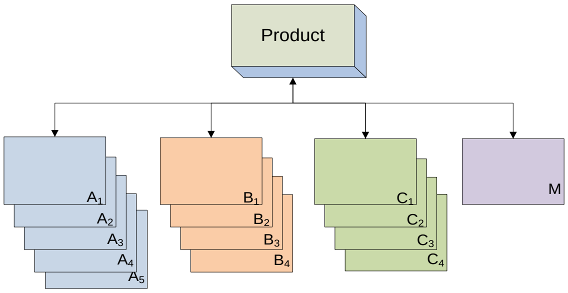
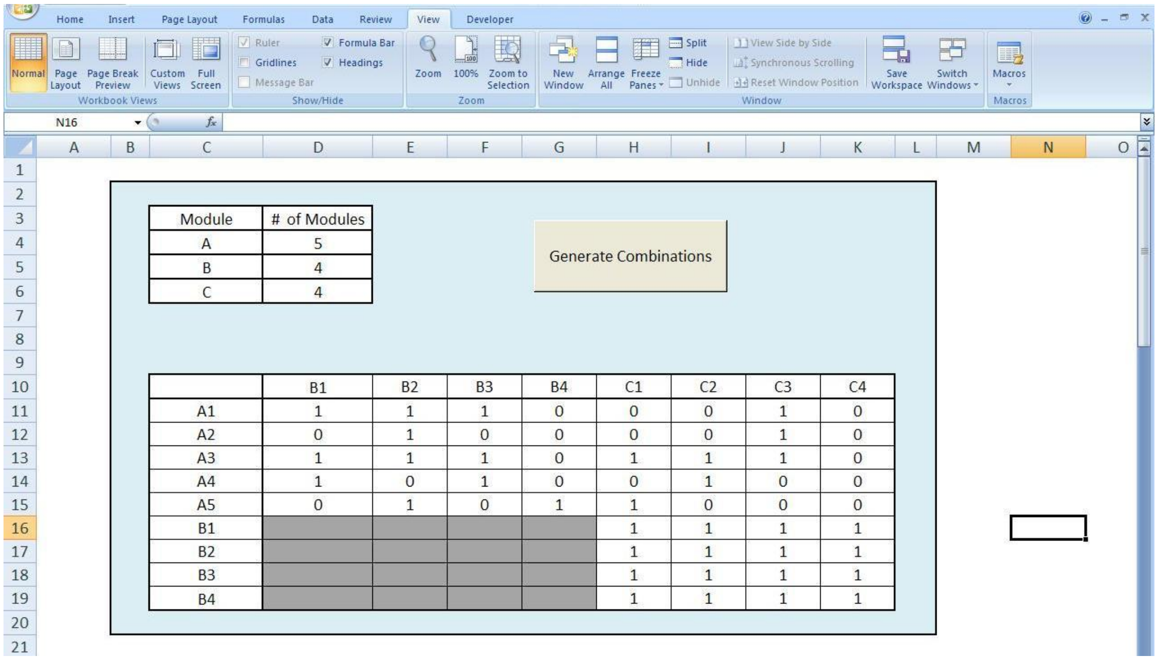


Figure 4-1 Modules of a Product

4.1 Compatibilities between Variants

Not all variants of the modules can be combined to form a product due to incompatibilities in material, efficiencies, texture etc. Thus, a compatibility matrix similar to the one shown in Figure 4-2 is used to represent which of the modules are compatible with each other. The value of 1 in a cell denotes that the combination is allowed and 0 otherwise. A macro was developed to convert the above data into a format usable in OPL.



Module	# of Modules
A	5
B	4
C	4

	B1	B2	B3	B4	C1	C2	C3	C4
A1	1	1	1	0	0	0	1	0
A2	0	1	0	0	0	0	1	0
A3	1	1	1	0	1	1	1	0
A4	1	0	1	0	0	1	0	0
A5	0	1	0	1	1	0	0	0
B1					1	1	1	1
B2					1	1	1	1
B3					1	1	1	1
B4					1	1	1	1

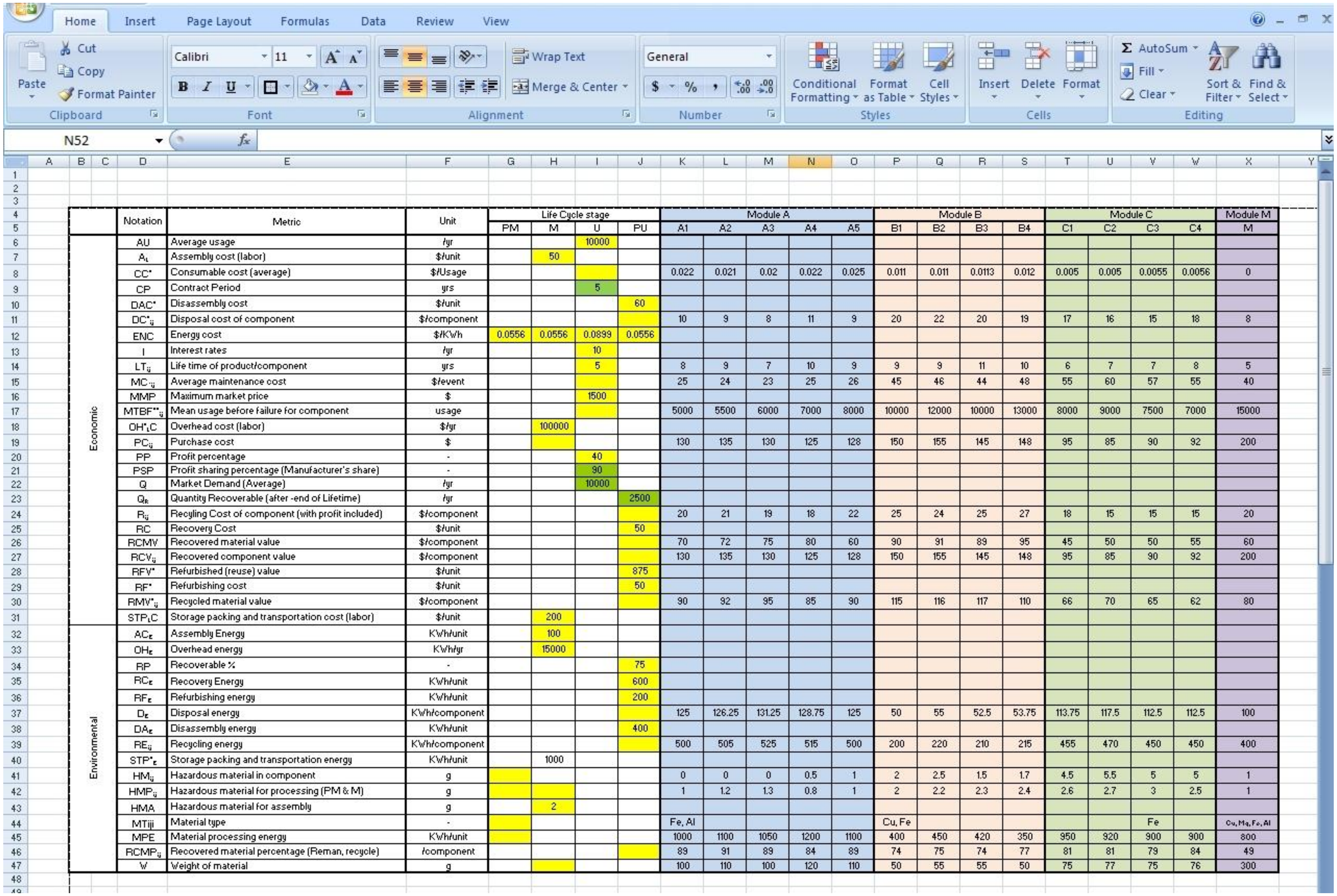
Figure 4-2 Compatibility Matrix and Combination Generating Macro Link

4.2 Interface for Data Input and Output

A Microsoft Excel spreadsheet application is developed as an interface to exchange input and output data with ILOG OPL software in which the optimization model is solved. The interfaces developed are shown in Figure 4-3 and Figure 4-4. All data to compute metrics were entered through this interface and metrics calculated to a per component basis (for the period of contract); that information is then used in equations (3) through (21) in the mathematical model. The data interfaces and metrics values for Economic, Environmental and Societal metrics are shown in Figure 4-5 and Figure 4-6 respectively. The data is finally consolidated as shown in Figure 4-7, together with values for the CSI (discussed later in the chapter) for each module in a form recognizable by the OPL model.

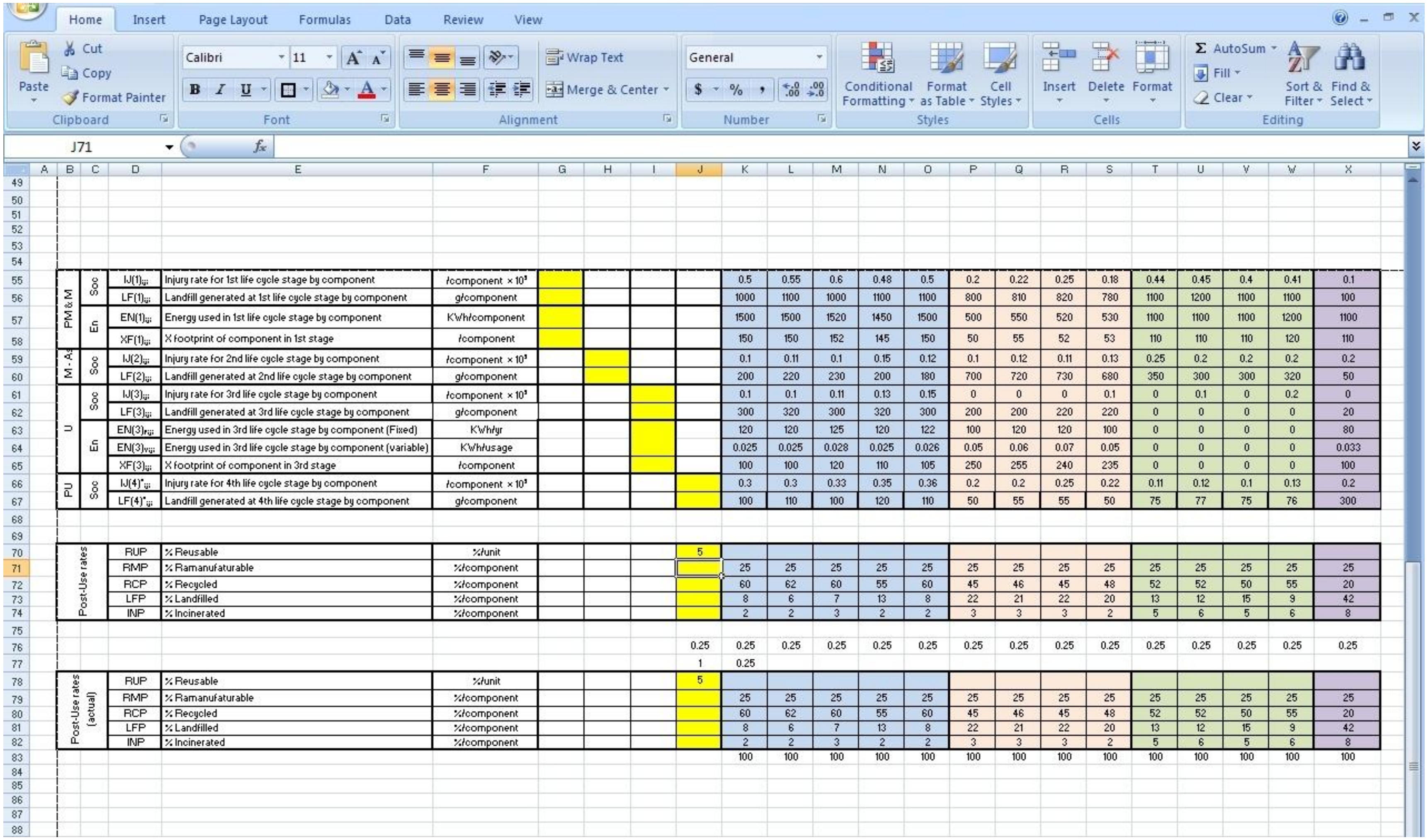
As described the methodology the product follows a demand cycle (in this example it spans a period of 10 years) and also processes used products in the Product-R and PSS models. As the number of new products and used products varies it changes the key parameters in the economic, environmental and societal parameters (i.e. costs, material index, injury rates etc.). Thus for the demand cycle, data was generated for each of the years that the quantity of new product manufactured changed (for the Product model) and each time either the quantity of new or used products changed (for the Product-R and PSS models).

Once data required is generated for the 10 years and conditions that the user wants to evaluate the three models for is established, the data is copied into the form shown in Figure 4-8 and exported to the ILOG OPL optimization software. The software then determines the optimal configuration for each of the three models (Product, Product-R and PSS) for each year of analysis.



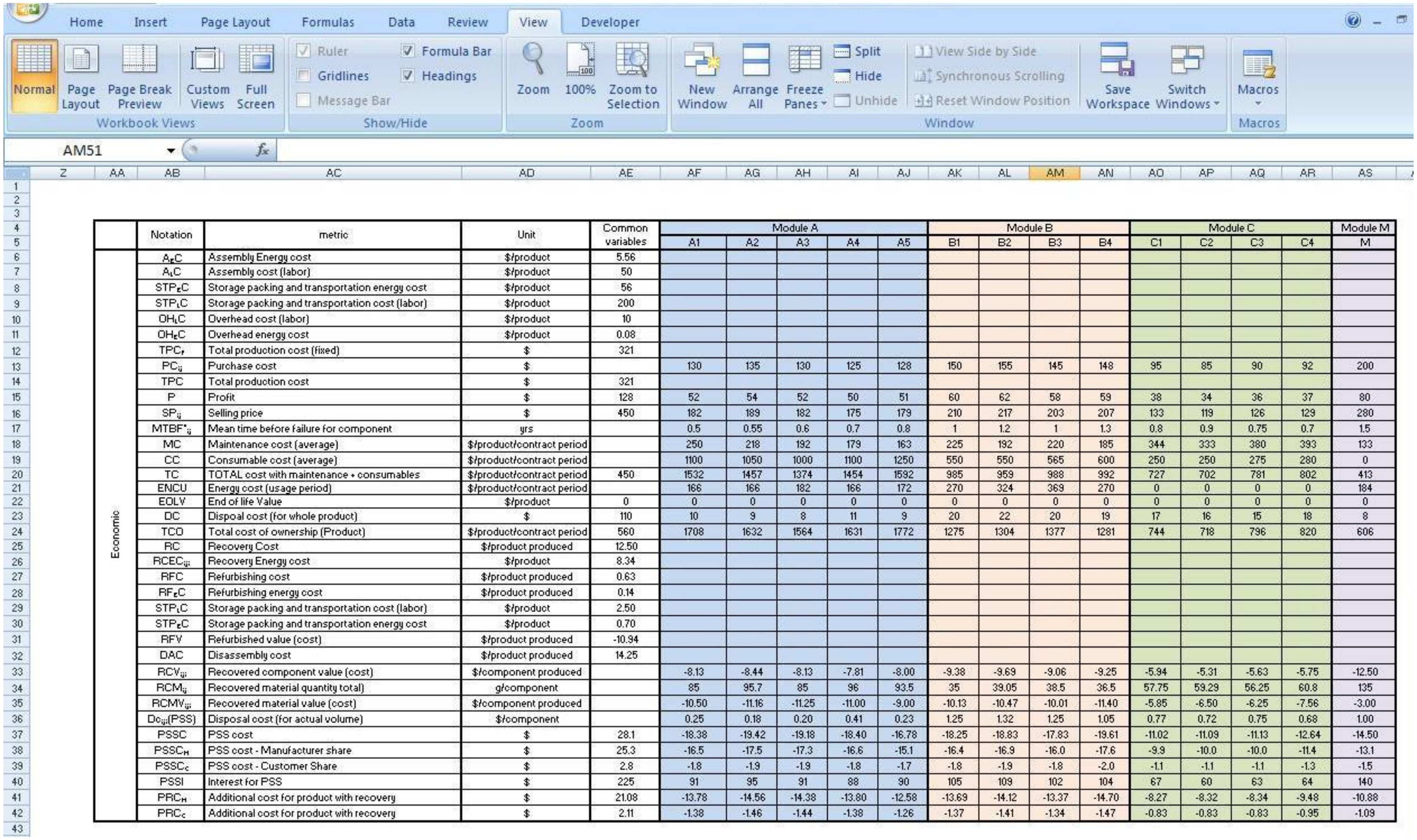
	Notation	Metric	Unit	Life Cycle stage				Module A					Module B				Module C				Module M
				PM	M	U	PU	A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M
Economic	AU	Average usage	/yr			10000															
	A_L	Assembly cost (labor)	$/unit		50																
	CC^*	Consumable cost (average)	$/Usage					0.022	0.021	0.02	0.022	0.025	0.011	0.011	0.0113	0.012	0.005	0.005	0.0055	0.0056	0
	CP	Contract Period	yrs			5															
	DAC^*	Disassembly cost	$/unit				60														
	DC^*_{ij}	Disposal cost of component	$/component					10	9	8	11	9	20	22	20	19	17	16	15	18	8
	ENC	Energy cost	$/KWh	0.0556	0.0556	0.0899	0.0556														
	I	Interest rates	/yr			10															
	LT_{ij}	Life time of product/component	yrs			5		8	9	7	10	9	9	9	11	10	6	7	7	8	5
	MC^*_{ij}	Average maintenance cost	$/event					25	24	23	25	26	45	46	44	48	55	60	57	55	40
	MMP	Maximum market price	$			1500															
	$MTBF^{**}_{ij}$	Mean usage before failure for component	usage					5000	5500	6000	7000	8000	10000	12000	10000	13000	8000	9000	7500	7000	15000
	$OH^*_L C$	Overhead cost (labor)	$/yr		100000																
	PC_{ij}	Purchase cost	$					130	135	130	125	128	150	155	145	148	95	85	90	92	200
	PP	Profit percentage	-			40															
	PSP	Profit sharing percentage (Manufacturer's share)	-			90															
	Q	Market Demand (Average)	/yr			10000															
	Q_R	Quantity Recoverable (after -end of Lifetime)	/yr				2500														
	R_{ij}	Recyling Cost of component (with profit included)	$/component					20	21	19	18	22	25	24	25	27	18	15	15	15	20
	RC	Recovery Cost	$/unit				50														
	RCMV	Recovered material value	$/component					70	72	75	80	60	90	91	89	95	45	50	50	55	60
	RCV_{ij}	Recovered component value	$/component					130	135	130	125	128	150	155	145	148	95	85	90	92	200
	RFV^*	Refurbished (reuse) value	$/unit				875														
	RF^*	Refurbishing cost	$/unit				50														
	RMV^*_{ij}	Recycled material value	$/component					90	92	95	85	90	115	116	117	110	66	70	65	62	80
	$STP_L C$	Storage packing and transportation cost (labor)	$/unit		200																
Environmental	AC_E	Assembly Energy	KWh/unit		100																
	OH_E	Overhead energy	KWh/yr		15000																
	RP	Recoverable %	-				75														
	RC_E	Recovery Energy	KWh/unit				600														
	RF_E	Refurbishing energy	KWh/unit				200														
	D_E	Disposal energy	KWh/component					125	126.25	131.25	128.75	125	50	55	52.5	53.75	113.75	117.5	112.5	112.5	100
	DA_E	Disassembly energy	KWh/unit				400														
	RE_{ij}	Recycling energy	KWh/component					500	505	525	515	500	200	220	210	215	455	470	450	450	400
	STP^*_E	Storage packing and transportation energy	KWh/unit		1000																
	HM_{ij}	Hazardous material in component	g					0	0	0	0.5	1	2	2.5	1.5	1.7	4.5	5.5	5	5	1
	HMP_{ij}	Hazardous material for processing (PM & M)	g					1	1.2	1.3	0.8	1	2	2.2	2.3	2.4	2.6	2.7	3	2.5	1
	HMA	Hazardous material for assembly	g		2																
	MTiji	Material type	-					Fe, Al					Cu, Fe						Fe		Cu, Mg, Fe, Al
	MPE	Material processing energy	KWh/unit					1000	1100	1050	1200	1100	400	450	420	350	950	920	900	900	800
	$RCMP_{ij}$	Recovered material percentage (Reman, recycle)	/component					89	91	89	84	89	74	75	74	77	81	81	79	84	49
	W	Weight of material	g					100	110	100	120	110	50	55	55	50	75	77	75	76	300

Figure 4-3 Data Entry Table for Economic and Environmental Metrics



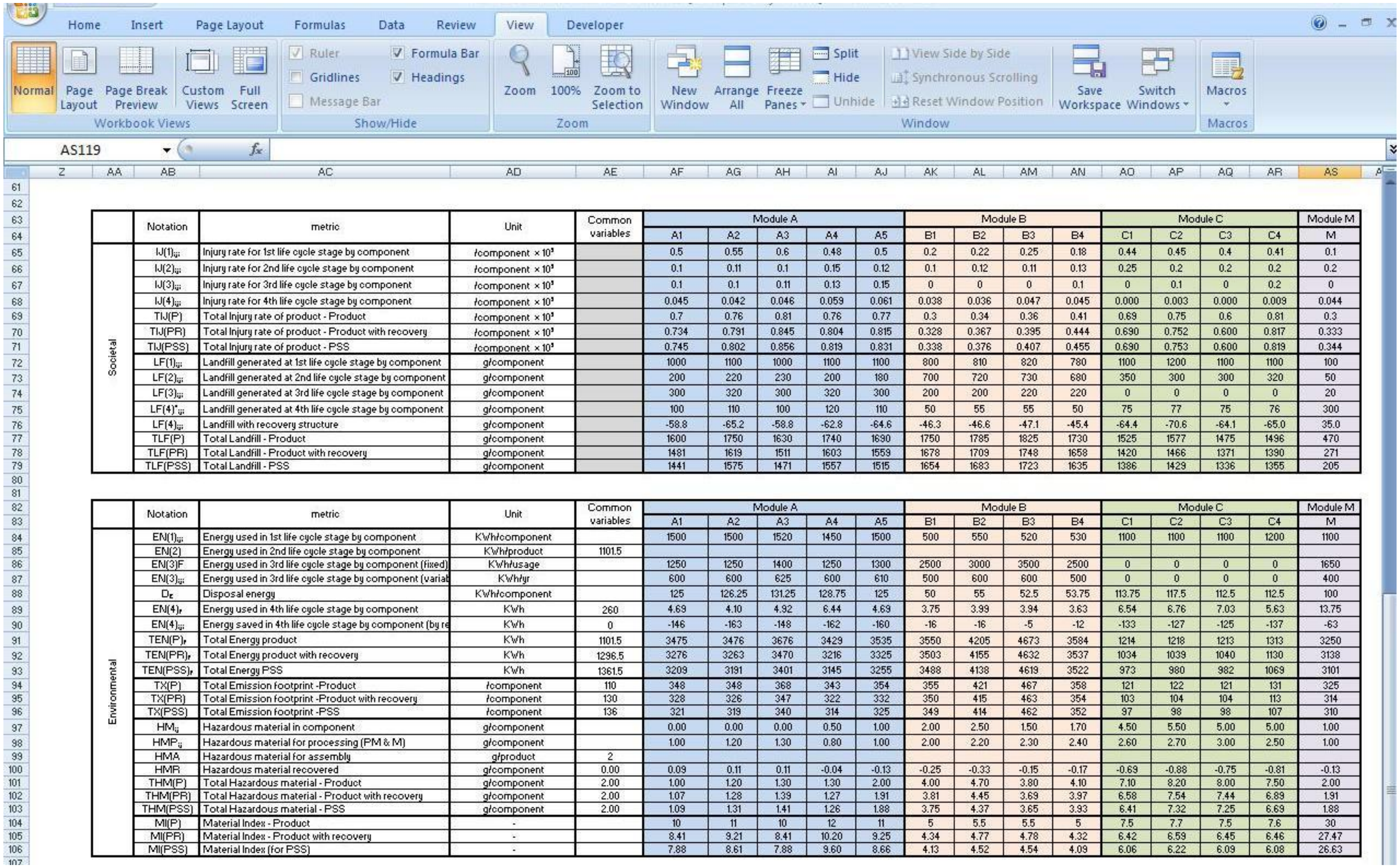
Row	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
55	PM & M	Soc	$IJ(1)_{ij}$	Injury rate for 1st life cycle stage by component	/component $\times 10^3$					0.5	0.55	0.6	0.48	0.5	0.2	0.22	0.25	0.18	0.44	0.45	0.4	0.41	0.1
56			$LF(1)_{ij}$	Landfill generated at 1st life cycle stage by component	g/component					1000	1100	1000	1100	1100	800	810	820	780	1100	1200	1100	1100	100
57		En	$EN(1)_{ij}$	Energy used in 1st life cycle stage by component	KWh/component					1500	1500	1520	1450	1500	500	550	520	530	1100	1100	1100	1200	1100
58			$XF(1)_{ij}$	X footprint of component in 1st stage	/component					150	150	152	145	150	50	55	52	53	110	110	110	120	110
59	M - As	Soc	$IJ(2)_{ij}$	Injury rate for 2nd life cycle stage by component	/component $\times 10^3$					0.1	0.11	0.1	0.15	0.12	0.1	0.12	0.11	0.13	0.25	0.2	0.2	0.2	0.2
60			$LF(2)_{ij}$	Landfill generated at 2nd life cycle stage by component	g/component					200	220	230	200	180	700	720	730	680	350	300	300	320	50
61	U	Soc	$IJ(3)_{ij}$	Injury rate for 3rd life cycle stage by component	/component $\times 10^3$					0.1	0.1	0.11	0.13	0.15	0	0	0	0.1	0	0.1	0	0.2	0
62			$LF(3)_{ij}$	Landfill generated at 3rd life cycle stage by component	g/component					300	320	300	320	300	200	200	220	220	0	0	0	0	20
63		En	$EN(3)_{Fij}$	Energy used in 3rd life cycle stage by component (Fixed)	KWh/yr					120	120	125	120	122	100	120	120	100	0	0	0	0	80
64			$EN(3)_{Vij}$	Energy used in 3rd life cycle stage by component (variable)	KWh/usage					0.025	0.025	0.028	0.025	0.026	0.05	0.06	0.07	0.05	0	0	0	0	0.033
65			$XF(3)_{ij}$	X footprint of component in 3rd stage	/component					100	100	120	110	105	250	255	240	235	0	0	0	0	100
66	PU	Soc	$IJ(4)^*_{ij}$	Injury rate for 4th life cycle stage by component	/component $\times 10^3$					0.3	0.3	0.33	0.35	0.36	0.2	0.2	0.25	0.22	0.11	0.12	0.1	0.13	0.2
67			$LF(4)^*_{ij}$	Landfill generated at 4th life cycle stage by component	g/component					100	110	100	120	110	50	55	55	50	75	77	75	76	300
70	Post-Use rates		RUP	% Reusable	%/unit				5														
71			RMP	% Ramanufaturable	%/component					25	25	25	25	25	25	25	25	25	25	25	25	25	25
72			RCP	% Recycled	%/component					60	62	60	55	60	45	46	45	48	52	52	50	55	20
73			LFP	% Landfilled	%/component					8	6	7	13	8	22	21	22	20	13	12	15	9	42
74			INP	% Incinerated	%/component					2	2	3	2	2	3	3	3	2	5	6	5	6	8
76									0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
77									1	0.25													
78	Post-Use rates (actual)		RUP	% Reusable	%/unit				5														
79			RMP	% Ramanufaturable	%/component					25	25	25	25	25	25	25	25	25	25	25	25	25	25
80			RCP	% Recycled	%/component					60	62	60	55	60	45	46	45	48	52	52	50	55	20
81			LFP	% Landfilled	%/component					8	6	7	13	8	22	21	22	20	13	12	15	9	42
82			INP	% Incinerated	%/component					2	2	3	2	2	3	3	3	2	5	6	5	6	8
83										100	100	100	100	100	100	100	100	100	100	100	100	100	100

Figure 4-4 Data Entry Table for Environmental Metrics and Societal Metrics



	Notation	metric	Unit	Common variables	Module A					Module B				Module C				Module M
					A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M
Economic	A_EC	Assembly Energy cost	$/product	5.56														
	A_LC	Assembly cost (labor)	$/product	50														
	STP_EC	Storage packing and transportation energy cost	$/product	56														
	STP_LC	Storage packing and transportation cost (labor)	$/product	200														
	OH_LC	Overhead cost (labor)	$/product	10														
	OH_EC	Overhead energy cost	$/product	0.08														
	TPC_F	Total production cost (fixed)	$	321														
	PC_{ij}	Purchase cost	$		130	135	130	125	128	150	155	145	148	95	85	90	92	200
	TPC	Total production cost	$	321														
	P	Profit	$	128	52	54	52	50	51	60	62	58	59	38	34	36	37	80
	SP_{ij}	Selling price	$	450	182	189	182	175	179	210	217	203	207	133	119	126	129	280
	$MTBF^*_{ij}$	Mean time before failure for component	yrs		0.5	0.55	0.6	0.7	0.8	1	1.2	1	1.3	0.8	0.9	0.75	0.7	1.5
	MC	Maintenance cost (average)	$/product/contract period		250	218	192	179	163	225	192	220	185	344	333	380	393	133
	CC	Consumable cost (average)	$/product/contract period		1100	1050	1000	1100	1250	550	550	565	600	250	250	275	280	0
	TC	TOTAL cost with maintenance + consumables	$/product/contract period	450	1532	1457	1374	1454	1592	985	959	988	992	727	702	781	802	413
	ENCU	Energy cost (usage period)	$/product/contract period		166	166	182	166	172	270	324	369	270	0	0	0	0	184
	EOLV	End of life Value	$/product	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	DC	Dispoal cost (for whole product)	$	110	10	9	8	11	9	20	22	20	19	17	16	15	18	8
	TCO	Total cost of ownership (Product)	$/product/contract period	560	1708	1632	1564	1631	1772	1275	1304	1377	1281	744	718	796	820	606
	RC	Recovery Cost	$/product produced	12.50														
	$RCEC_{ijk}$	Recovery Energy cost	$/product	8.34														
	RFC	Refurbishing cost	$/product produced	0.63														
	RF_EC	Refurbishing energy cost	$/product produced	0.14														
	STP_LC	Storage packing and transportation cost (labor)	$/product	2.50														
	STP_EC	Storage packing and transportation energy cost	$/product	0.70														
	RFV	Refurbished value (cost)	$/product produced	-10.94														
	DAC	Disassembly cost	$/product produced	14.25														
	RCV_{ijk}	Recovered component value (cost)	$/component produced		-8.13	-8.44	-8.13	-7.81	-8.00	-9.38	-9.69	-9.06	-9.25	-5.94	-5.31	-5.63	-5.75	-12.50
	RCM_{ij}	Recovered material quantity total)	g/component		85	95.7	85	96	93.5	35	39.05	38.5	36.5	57.75	59.29	56.25	60.8	135
	$RCMV_{ijk}$	Recovered material value (cost)	$/component produced		-10.50	-11.16	-11.25	-11.00	-9.00	-10.13	-10.47	-10.01	-11.40	-5.85	-6.50	-6.25	-7.56	-3.00
	Dc_{ijk}(PSS)	Disposal cost (for actual volume)	$/component		0.25	0.18	0.20	0.41	0.23	1.25	1.32	1.25	1.05	0.77	0.72	0.75	0.68	1.00
	PSSC	PSS cost	$	28.1	-18.38	-19.42	-19.18	-18.40	-16.78	-18.25	-18.83	-17.83	-19.61	-11.02	-11.09	-11.13	-12.64	-14.50
	$PSSC_M$	PSS cost - Manufacturer share	$	25.3	-16.5	-17.5	-17.3	-16.6	-15.1	-16.4	-16.9	-16.0	-17.6	-9.9	-10.0	-10.0	-11.4	-13.1
	$PSSC_C$	PSS cost - Customer Share	$	2.8	-1.8	-1.9	-1.9	-1.8	-1.7	-1.8	-1.9	-1.8	-2.0	-1.1	-1.1	-1.1	-1.3	-1.5
	PSSI	Interest for PSS	$	225	91	95	91	88	90	105	109	102	104	67	60	63	64	140
	PRC_M	Additional cost for product with recovery	$	21.08	-13.78	-14.56	-14.38	-13.80	-12.58	-13.69	-14.12	-13.37	-14.70	-8.27	-8.32	-8.34	-9.48	-10.88
	PRC_C	Additional cost for product with recovery	$	2.11	-1.38	-1.46	-1.44	-1.38	-1.26	-1.37	-1.41	-1.34	-1.47	-0.83	-0.83	-0.83	-0.95	-1.09

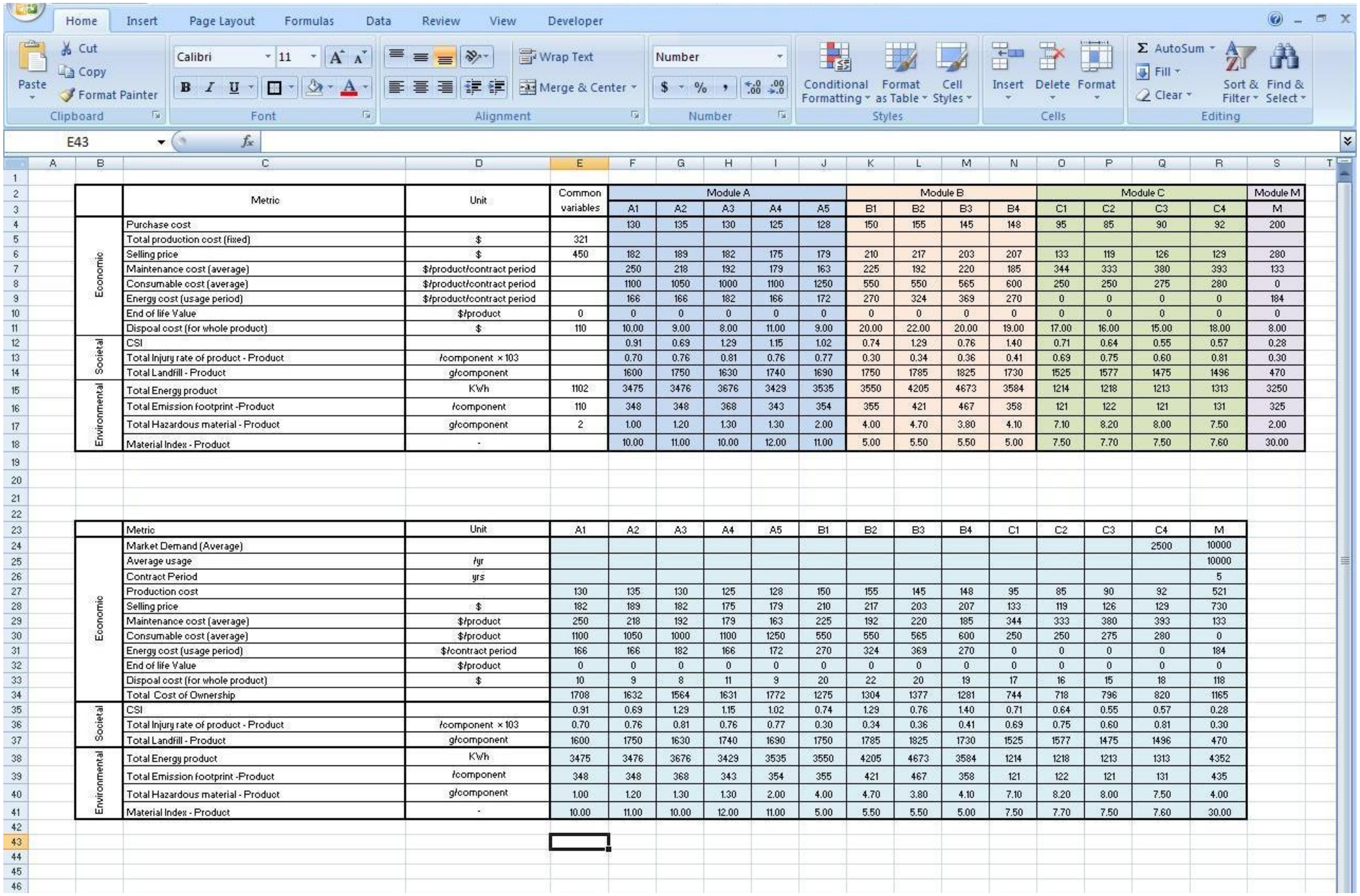
Figure 4-5 Calculation Table for Economic Metrics



	Notation	metric	Unit	Common variables	Module A					Module B				Module C				Module M
					A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M
Societal	IJ(1)$_{ijl}$	Injury rate for 1st life cycle stage by component	/component × 10³		0.5	0.55	0.6	0.48	0.5	0.2	0.22	0.25	0.18	0.44	0.45	0.4	0.41	0.1
	IJ(2)$_{ijl}$	Injury rate for 2nd life cycle stage by component	/component × 10³		0.1	0.11	0.1	0.15	0.12	0.1	0.12	0.11	0.13	0.25	0.2	0.2	0.2	0.2
	IJ(3)$_{ijl}$	Injury rate for 3rd life cycle stage by component	/component × 10³		0.1	0.1	0.11	0.13	0.15	0	0	0	0.1	0	0.1	0	0.2	0
	IJ(4)$_{ijl}$	Injury rate for 4th life cycle stage by component	/component × 10³		0.045	0.042	0.046	0.059	0.061	0.038	0.036	0.047	0.045	0.000	0.003	0.000	0.009	0.044
	TIJ(P)	Total Injury rate of product - Product	/component × 10³		0.7	0.76	0.81	0.76	0.77	0.3	0.34	0.36	0.41	0.69	0.75	0.6	0.81	0.3
	TIJ(PR)	Total Injury rate of product - Product with recovery	/component × 10³		0.734	0.791	0.845	0.804	0.815	0.328	0.367	0.395	0.444	0.690	0.752	0.600	0.817	0.333
	TIJ(PSS)	Total Injury rate of product - PSS	/component × 10³		0.745	0.802	0.856	0.819	0.831	0.338	0.376	0.407	0.455	0.690	0.753	0.600	0.819	0.344
	LF(1)$_{ijl}$	Landfill generated at 1st life cycle stage by component	g/component		1000	1100	1000	1100	1100	800	810	820	780	1100	1200	1100	1100	100
	LF(2)$_{ijl}$	Landfill generated at 2nd life cycle stage by component	g/component		200	220	230	200	180	700	720	730	680	350	300	300	320	50
	LF(3)$_{ijl}$	Landfill generated at 3rd life cycle stage by component	g/component		300	320	300	320	300	200	200	220	220	0	0	0	0	20
	LF(4)$^*_{ijl}$	Landfill generated at 4th life cycle stage by component	g/component		100	110	100	120	110	50	55	55	50	75	77	75	76	300
	LF(4)$_{ijl}$	Landfill with recovery structure	g/component		-58.8	-65.2	-58.8	-62.8	-64.6	-46.3	-46.6	-47.1	-45.4	-64.4	-70.6	-64.1	-65.0	35.0
	TLF(P)	Total Landfill - Product	g/component		1600	1750	1630	1740	1690	1750	1785	1825	1730	1525	1577	1475	1496	470
	TLF(PR)	Total Landfill - Product with recovery	g/component		1481	1619	1511	1603	1559	1678	1709	1748	1658	1420	1466	1371	1390	271
	TLF(PSS)	Total Landfill - PSS	g/component		1441	1575	1471	1557	1515	1654	1683	1723	1635	1386	1429	1336	1355	205

	Notation	metric	Unit	Common variables	Module A					Module B				Module C				Module M
					A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M
Environmental	EN(1)$_{ijl}$	Energy used in 1st life cycle stage by component	KWh/component		1500	1500	1520	1450	1500	500	550	520	530	1100	1100	1100	1200	1100
	EN(2)	Energy used in 2nd life cycle stage by component	KWh/product	1101.5														
	EN(3)F	Energy used in 3rd life cycle stage by component (fixed)	KWh/usage		1250	1250	1400	1250	1300	2500	3000	3500	2500	0	0	0	0	1650
	EN(3)$_{ijl}$	Energy used in 3rd life cycle stage by component (variab	KWh/yr		600	600	625	600	610	500	600	600	500	0	0	0	0	400
	D_E	Disposal energy	KWh/component		125	126.25	131.25	128.75	125	50	55	52.5	53.75	113.75	117.5	112.5	112.5	100
	EN(4)$_r$	Energy used in 4th life cycle stage by component	KWh	260	4.69	4.10	4.92	6.44	4.69	3.75	3.99	3.94	3.63	6.54	6.76	7.03	5.63	13.75
	EN(4)$_{ijl}$	Energy saved in 4th life cycle stage by component (by re	KWh	0	-146	-163	-148	-162	-160	-16	-16	-5	-12	-133	-127	-125	-137	-63
	TEN(P)$_r$	Total Energy product	KWh	1101.5	3475	3476	3676	3429	3535	3550	4205	4673	3584	1214	1218	1213	1313	3250
	TEN(PR)$_r$	Total Energy product with recovery	KWh	1296.5	3276	3263	3470	3216	3325	3503	4155	4632	3537	1034	1039	1040	1130	3138
	TEN(PSS)$_r$	Total Energy PSS	KWh	1361.5	3209	3191	3401	3145	3255	3488	4138	4619	3522	973	980	982	1069	3101
	TX(P)	Total Emission footprint -Product	/component	110	348	348	368	343	354	355	421	467	358	121	122	121	131	325
	TX(PR)	Total Emission footprint -Product with recovery	/component	130	328	326	347	322	332	350	415	463	354	103	104	104	113	314
	TX(PSS)	Total Emission footprint -PSS	/component	136	321	319	340	314	325	349	414	462	352	97	98	98	107	310
	HM_{ij}	Hazardous material in component	g/component		0.00	0.00	0.00	0.50	1.00	2.00	2.50	1.50	1.70	4.50	5.50	5.00	5.00	1.00
	HMP_{ij}	Hazardous material for processing (PM & M)	g/component		1.00	1.20	1.30	0.80	1.00	2.00	2.20	2.30	2.40	2.60	2.70	3.00	2.50	1.00
	HMA	Hazardous material for assembly	g/product	2														
	HMR	Hazardous material recovered	g/component	0.00	0.09	0.11	0.11	-0.04	-0.13	-0.25	-0.33	-0.15	-0.17	-0.69	-0.88	-0.75	-0.81	-0.13
	THM(P)	Total Hazardous material - Product	g/component	2.00	1.00	1.20	1.30	1.30	2.00	4.00	4.70	3.80	4.10	7.10	8.20	8.00	7.50	2.00
	THM(PR)	Total Hazardous material - Product with recovery	g/component	2.00	1.07	1.28	1.39	1.27	1.91	3.81	4.45	3.69	3.97	6.58	7.54	7.44	6.89	1.91
	THM(PSS)	Total Hazardous material - PSS	g/component	2.00	1.09	1.31	1.41	1.26	1.88	3.75	4.37	3.65	3.93	6.41	7.32	7.25	6.69	1.88
	MI(P)	Material Index - Product	-		10	11	10	12	11	5	5.5	5.5	5	7.5	7.7	7.5	7.6	30
	MI(PR)	Material Index - Product with recovery	-		8.41	9.21	8.41	10.20	9.25	4.34	4.77	4.78	4.32	6.42	6.59	6.45	6.46	27.47
	MI(PSS)	Material Index (for PSS)	-		7.88	8.61	7.88	9.60	8.66	4.13	4.52	4.54	4.09	6.06	6.22	6.09	6.08	26.63

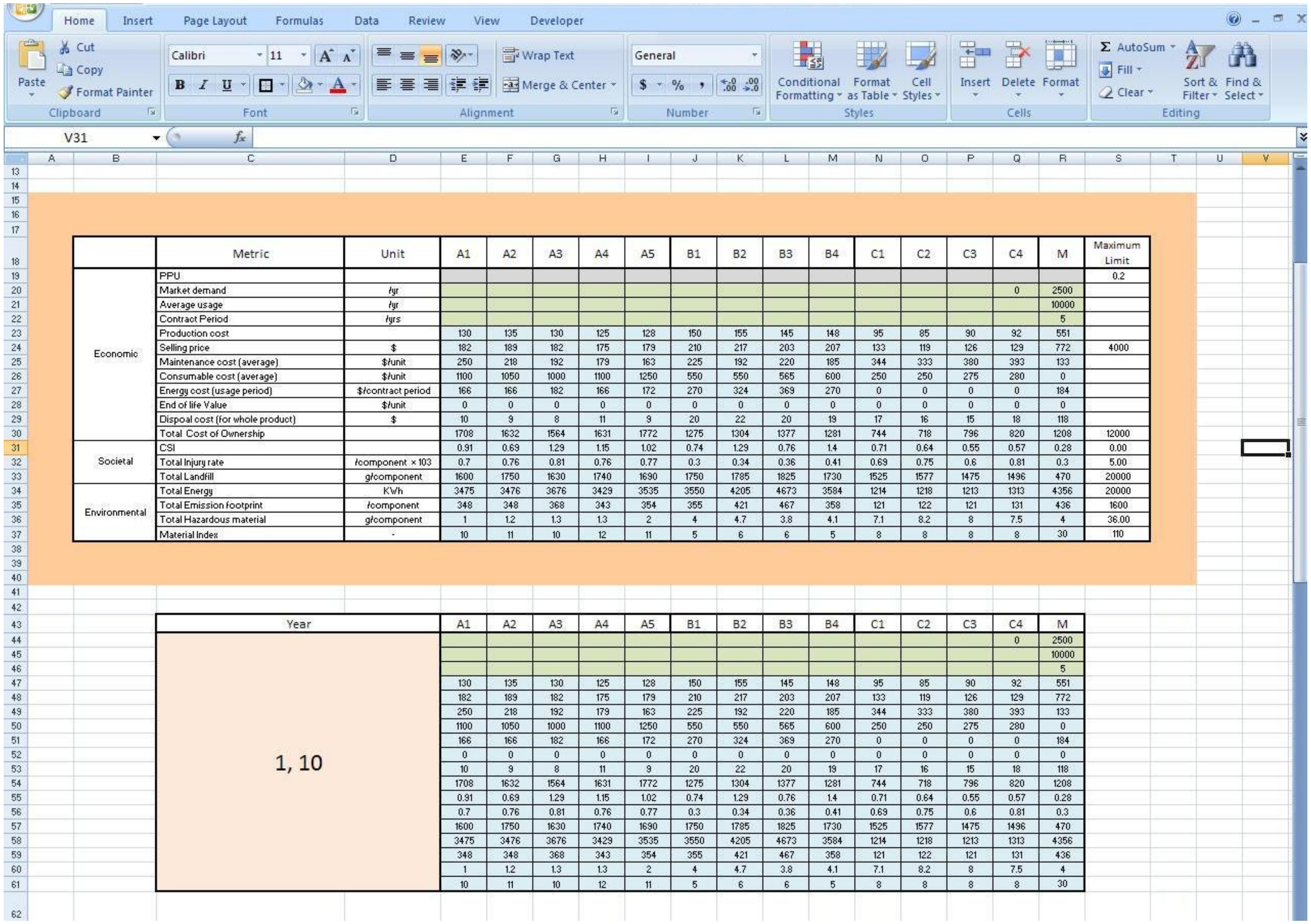
Figure 4-6 Calculation Table for Environmental and Societal Metrics



	Metric	Unit	Common variables	Module A					Module B				Module C				Module M
				A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M
Economic	Purchase cost			130	135	130	125	128	150	155	145	148	95	85	90	92	200
	Total production cost (fixed)	$	321														
	Selling price	$	450	182	189	182	175	179	210	217	203	207	133	119	126	129	280
	Maintenance cost (average)	$/product/contract period		250	218	192	179	163	225	192	220	185	344	333	380	393	133
	Consumable cost (average)	$/product/contract period		1100	1050	1000	1100	1250	550	550	565	600	250	250	275	280	0
	Energy cost (usage period)	$/product/contract period		166	166	182	166	172	270	324	369	270	0	0	0	0	184
	End of life Value	$/product	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dispoal cost (for whole product)	$	110	10.00	9.00	8.00	11.00	9.00	20.00	22.00	20.00	19.00	17.00	16.00	15.00	18.00	8.00
Societal	CSI			0.91	0.69	1.29	1.15	1.02	0.74	1.29	0.76	1.40	0.71	0.64	0.55	0.57	0.28
	Total Injury rate of product - Product	/component × 103		0.70	0.76	0.81	0.76	0.77	0.30	0.34	0.36	0.41	0.69	0.75	0.60	0.81	0.30
	Total Landfill - Product	g/component		1600	1750	1630	1740	1690	1750	1785	1825	1730	1525	1577	1475	1496	470
Environmental	Total Energy product	KWh	1102	3475	3476	3676	3429	3535	3550	4205	4673	3584	1214	1218	1213	1313	3250
	Total Emission footprint -Product	/component	110	348	348	368	343	354	355	421	467	358	121	122	121	131	325
	Total Hazardous material - Product	g/component	2	1.00	1.20	1.30	1.30	2.00	4.00	4.70	3.80	4.10	7.10	8.20	8.00	7.50	2.00
	Material Index - Product	-		10.00	11.00	10.00	12.00	11.00	5.00	5.50	5.50	5.00	7.50	7.70	7.50	7.60	30.00

	Metric	Unit	A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M
Economic	Market Demand (Average)														2500	10000
	Average usage	/yr														10000
	Contract Period	yrs														5
	Production cost		130	135	130	125	128	150	155	145	148	95	85	90	92	521
	Selling price	$	182	189	182	175	179	210	217	203	207	133	119	126	129	730
	Maintenance cost (average)	$/product	250	218	192	179	163	225	192	220	185	344	333	380	393	133
	Consumable cost (average)	$/product	1100	1050	1000	1100	1250	550	550	565	600	250	250	275	280	0
	Energy cost (usage period)	$/contract period	166	166	182	166	172	270	324	369	270	0	0	0	0	184
	End of life Value	$/product	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dispoal cost (for whole product)	$	10	9	8	11	9	20	22	20	19	17	16	15	18	118
	Total Cost of Ownership		1708	1632	1564	1631	1772	1275	1304	1377	1281	744	718	796	820	1165
Societal	CSI		0.91	0.69	1.29	1.15	1.02	0.74	1.29	0.76	1.40	0.71	0.64	0.55	0.57	0.28
	Total Injury rate of product - Product	/component × 103	0.70	0.76	0.81	0.76	0.77	0.30	0.34	0.36	0.41	0.69	0.75	0.60	0.81	0.30
	Total Landfill - Product	g/component	1600	1750	1630	1740	1690	1750	1785	1825	1730	1525	1577	1475	1496	470
Environmental	Total Energy product	KWh	3475	3476	3676	3429	3535	3550	4205	4673	3584	1214	1218	1213	1313	4352
	Total Emission footprint -Product	/component	348	348	368	343	354	355	421	467	358	121	122	121	131	435
	Total Hazardous material - Product	g/component	1.00	1.20	1.30	1.30	2.00	4.00	4.70	3.80	4.10	7.10	8.20	8.00	7.50	4.00
	Material Index - Product	-	10.00	11.00	10.00	12.00	11.00	5.00	5.50	5.50	5.00	7.50	7.70	7.50	7.60	30.00

Figure 4-7 Consolidated Results



	Metric	Unit	A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M	Maximum Limit
Economic	PPU																0.2
	Market demand	/yr													0	2500	
	Average usage	/yr														10000	
	Contract Period	/yrs														5	
	Production cost		130	135	130	125	128	150	155	145	148	95	85	90	92	551	
	Selling price	$	182	189	182	175	179	210	217	203	207	133	119	126	129	772	4000
	Maintenance cost (average)	$/unit	250	218	192	179	163	225	192	220	185	344	333	380	393	133	
	Consumable cost (average)	$/unit	1100	1050	1000	1100	1250	550	550	565	600	250	250	275	280	0	
	Energy cost (usage period)	$/contract period	166	166	182	166	172	270	324	369	270	0	0	0	0	184	
	End of life Value	$/unit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Dispoal cost (for whole product)	$	10	9	8	11	9	20	22	20	19	17	16	15	18	118	
	Total Cost of Ownership		1708	1632	1564	1631	1772	1275	1304	1377	1281	744	718	796	820	1208	12000
Societal	CSI		0.91	0.69	1.29	1.15	1.02	0.74	1.29	0.76	1.4	0.71	0.64	0.55	0.57	0.28	0.00
	Total Injury rate	/component × 103	0.7	0.76	0.81	0.76	0.77	0.3	0.34	0.36	0.41	0.69	0.75	0.6	0.81	0.3	5.00
	Total Landfill	g/component	1600	1750	1630	1740	1690	1750	1785	1825	1730	1525	1577	1475	1496	470	20000
Environmental	Total Energy	KWh	3475	3476	3676	3429	3535	3550	4205	4673	3584	1214	1218	1213	1313	4356	20000
	Total Emission footprint	/component	348	348	368	343	354	355	421	467	358	121	122	121	131	436	1600
	Total Hazardous material	g/component	1	1.2	1.3	1.3	2	4	4.7	3.8	4.1	7.1	8.2	8	7.5	4	36.00
	Material Index	-	10	11	10	12	11	5	6	6	5	8	8	8	8	30	110

Year	A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	M
1, 10													0	2500
														10000
														5
	130	135	130	125	128	150	155	145	148	95	85	90	92	551
	182	189	182	175	179	210	217	203	207	133	119	126	129	772
	250	218	192	179	163	225	192	220	185	344	333	380	393	133
	1100	1050	1000	1100	1250	550	550	565	600	250	250	275	280	0
	166	166	182	166	172	270	324	369	270	0	0	0	0	184
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	9	8	11	9	20	22	20	19	17	16	15	18	118
	1708	1632	1564	1631	1772	1275	1304	1377	1281	744	718	796	820	1208
	0.91	0.69	1.29	1.15	1.02	0.74	1.29	0.76	1.4	0.71	0.64	0.55	0.57	0.28
	0.7	0.76	0.81	0.76	0.77	0.3	0.34	0.36	0.41	0.69	0.75	0.6	0.81	0.3
	1600	1750	1630	1740	1690	1750	1785	1825	1730	1525	1577	1475	1496	470
	3475	3476	3676	3429	3535	3550	4205	4673	3584	1214	1218	1213	1313	4356
	348	348	368	343	354	355	421	467	358	121	122	121	131	436
	1	1.2	1.3	1.3	2	4	4.7	3.8	4.1	7.1	8.2	8	7.5	4
	10	11	10	12	11	5	6	6	5	8	8	8	8	30

Figure 4-8 Data Input Table for the ILOG OPL Software

4.3 Evaluating Customer Satisfaction using CSI

Initially all variants of modules A, B, C and the fixed module M as shown in Table 4-1 were assessed with respect to the characteristics identified by rating them on a scale of 1 to 5 [denoted by $F(x)$] depending on how much it contributes to that characteristic as described in the methodology. The values for α, β, φ, Ω [denoted by $F(y)$] and θ_i [denoted by $F(z)$], were then assessed and normalized. The value corresponding to each characteristic (CSI_c) and the overall CSI value for each module (CSI_{ij_i}) were calculated by equations (1) and (2) and presented as shown in Table 4-2.

In this example the values of $F(x)$, $F(y)$ and $F(z)$ were all generated randomly. However in practice for an actual product, surveys or the AHP could be used as described in the methodology to determine the values. Normalizing α, β, φ, Ω and θ values are optional and was carried out here to calculate a value for the CSI between 0 and 5.

Table 4-1 Customer Satisfaction Characteristics and Evaluation for Case Example

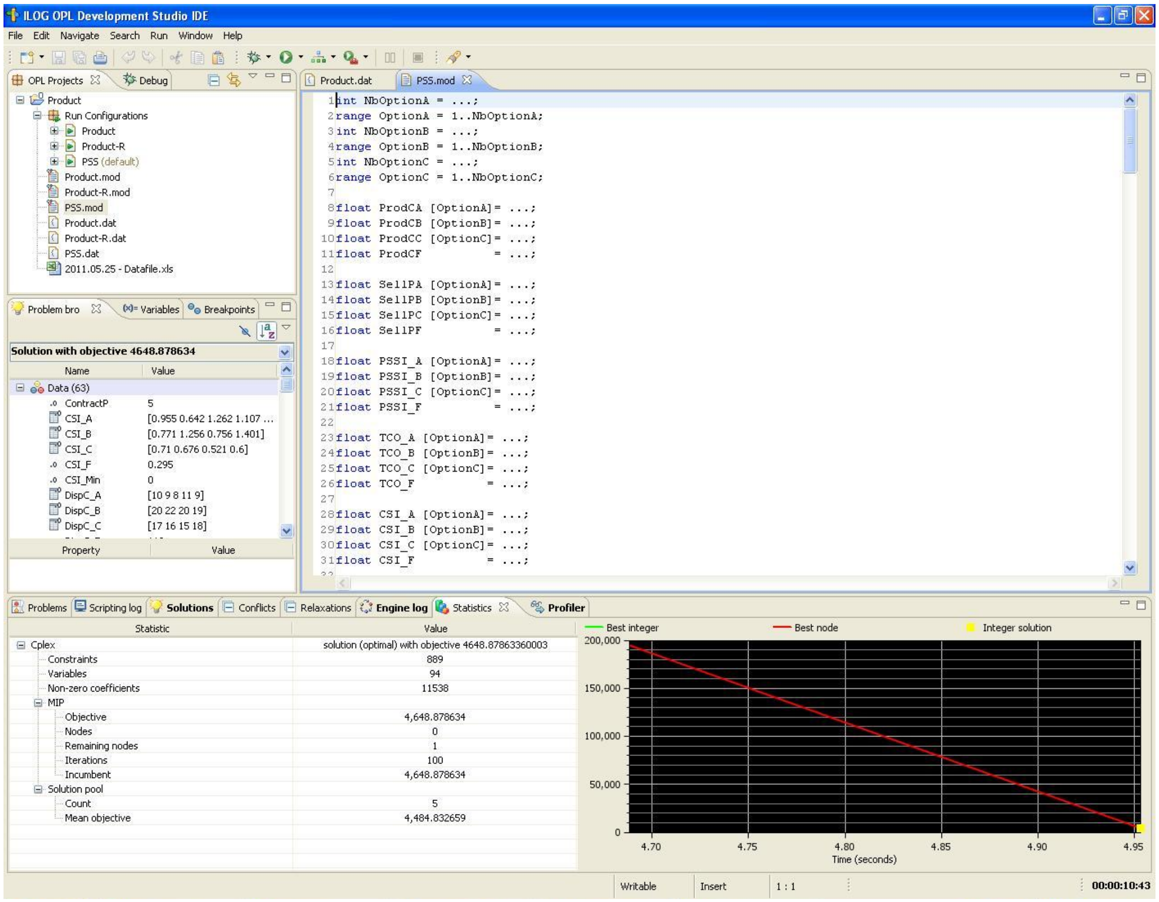
Characteristic	θ1		A					α		B				β		C				ϕ		M	Ω	
	Score	Normalized	A1	A2	A3	A4	A5	Score	Normalized	B1	B2	B3	B4	Score	Normalized	C1	C2	C3	C4	Score	Normalized		Score	Normalized
Ease of use	10	0.139	5	2	4	2	1	3	0.353	1	4	2	5	4	0.471	0	0	0	0	2	0.000	2	1.5	0.176
Aesthetic feel	8	0.111	0	0	0	0	0		0.000	2	5	1	5		0.533	2	4	5	4		0.267	1		0.200
Realiability	10	0.139	4	4	5	5	4		0.286	4	5	4	5		0.381	5	4	4	4		0.190	4		0.143
Durability	8	0.111	5	4	5	5	4		0.286	4	5	4	4		0.381	5	4	5	4		0.190	5		0.143
Functional effectiveness	5	0.069	2	1	5	1	4		0.286	4	5	5	5		0.381	5	5	3	4		0.190	5		0.143
Value for price	6	0.083	1	4	3	4	3		0.600	0	0	0	0		0.000	2	4	1	4		0.400	0		0.000
Efficiency	5	0.069	4	2	4	5	2		0.286	1	4	1	4		0.381	3	3	5	4		0.190	1		0.143
Weight	7	0.097	5	3	5	1	4		0.286	2	3	1	4		0.381	2	3	1	3		0.190	1		0.143
Ease of disposal	6	0.083	4	4	4	4	4		0.286	4	4	4	4		0.381	4	4	4	4		0.190	4		0.143
Brandname	7	0.097	2	1	4	4	5		0.600	0	0	0	0		0.000	4	2	2	1		0.400	0		0.000

Table 4-2 CSI Computations for Modules in Example Product

A* = α × A × θ					B* = β × B × θ				C* = φ × C × θ				M = = Ω × M × θ
A1	A2	A3	A4	A5	B1	B2	B3	B4	C1	C2	C3	C4	
0.245	0.098	0.196	0.098	0.049	0.065	0.261	0.131	0.327	0.000	0.000	0.000	0.000	0.049
0.000	0.000	0.000	0.000	0.000	0.119	0.296	0.059	0.296	0.059	0.119	0.148	0.119	0.022
0.159	0.159	0.198	0.198	0.159	0.212	0.265	0.212	0.265	0.132	0.106	0.106	0.106	0.079
0.159	0.127	0.159	0.159	0.127	0.169	0.212	0.169	0.169	0.106	0.085	0.106	0.085	0.079
0.040	0.020	0.099	0.020	0.079	0.106	0.132	0.132	0.132	0.066	0.066	0.040	0.053	0.050
0.050	0.200	0.150	0.200	0.150	0.000	0.000	0.000	0.000	0.067	0.133	0.033	0.133	0.000
0.079	0.040	0.079	0.099	0.040	0.026	0.106	0.026	0.106	0.040	0.040	0.066	0.053	0.010
0.139	0.083	0.139	0.028	0.111	0.074	0.111	0.037	0.148	0.037	0.056	0.019	0.056	0.014
0.095	0.095	0.095	0.095	0.095	0.127	0.127	0.127	0.127	0.063	0.063	0.063	0.063	0.048
0.117	0.058	0.233	0.233	0.292	0.000	0.000	0.000	0.000	0.156	0.078	0.078	0.039	0.000
1.08	0.88	1.35	1.13	1.10	0.90	1.51	0.89	1.57	0.73	0.74	0.66	0.71	0.35

4.4 Optimization Results

The user interface of the ILOG OPL software is shown in Figure 4-9. It displays the models that are programmed in it, decision variables, results and other output that are of use. The software was run on a desktop computer with an Intel Core 2 Quad processor with a clock speed of 2.66GHz. For each model it took approximately 10.3 seconds to generate the results for each year.



```
int NbOptionA = ...;
range OptionA = 1..NbOptionA;
int NbOptionB = ...;
range OptionB = 1..NbOptionB;
int NbOptionC = ...;
range OptionC = 1..NbOptionC;

float ProdCA [OptionA]= ...;
float ProdCB [OptionB]= ...;
float ProdCC [OptionC]= ...;
float ProdCF          = ...;

float SellPA [OptionA]= ...;
float SellPB [OptionB]= ...;
float SellPC [OptionC]= ...;
float SellPF          = ...;

float PSSI_A [OptionA]= ...;
float PSSI_B [OptionB]= ...;
float PSSI_C [OptionC]= ...;
float PSSI_F          = ...;

float TCO_A [OptionA]= ...;
float TCO_B [OptionB]= ...;
float TCO_C [OptionC]= ...;
float TCO_F          = ...;

float CSI_A [OptionA]= ...;
float CSI_B [OptionB]= ...;
float CSI_C [OptionC]= ...;
float CSI_F          = ...;
```

Solution with objective 4648.878634

Name	Value
Data (63)	
ContractP	5
CSI_A	[0.955 0.642 1.262 1.107 ...
CSI_B	[0.771 1.256 0.756 1.401]
CSI_C	[0.71 0.676 0.521 0.6]
CSI_F	0.295
CSI_Min	0
DispC_A	[10 9 8 11 9]
DispC_B	[20 22 20 19]
DispC_C	[17 16 15 18]

Property	Value

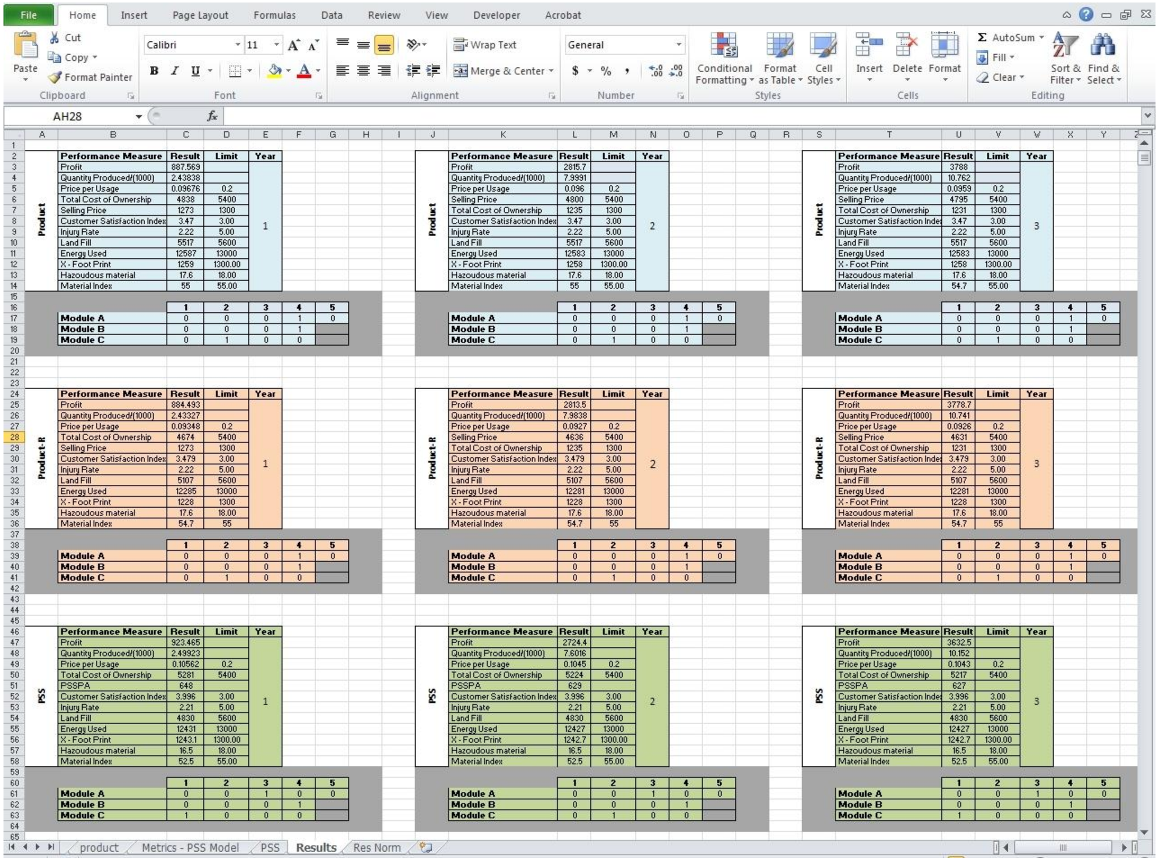
Statistic	Value
Cplex	solution (optimal) with objective 4648.87863360003
Constraints	889
Variables	94
Non-zero coefficients	11538
MIP	
Objective	4,648.878634
Nodes	0
Remaining nodes	1
Iterations	100
Incumbent	4,648.878634
Solution pool	
Count	5
Mean objective	4,484.832659

Figure 4-9 User Interface of ILOG OPL Software

The optimized result will provide the product configuration that will be most profitable to the OEM subject to environmental and societal constraints for each year of analysis. This could be chosen as the default configuration to be marketed for the particular year.

However this does not mean that the customer is deprived of the flexibility of customizing the product, but that the OEM can align the marketing strategy to encourage the purchase of this configuration.

The ILOG OPL software exports the optimized solution into an Excel spreadsheet, as shown in Figure 4-10; the results show the optimal configuration, values for KPIs, the corresponding limits set for each of them, the service model and the year in consideration.



	Performance Measure	Result	Limit	Year
Product	Profit	887.569		1
	Quantity Produced/(1000)	2.43838		
	Price per Usage	0.09676	0.2	
	Total Cost of Ownership	4838	5400	
	Selling Price	1273	1300	
	Customer Satisfaction Index	3.47	3.00	
	Injury Rate	2.22	5.00	
	Land Fill	5517	5600	
	Energy Used	12587	13000	
	X - Foot Print	1259	1300.00	
	Hazoudous material	17.6	18.00	
	Material Index	55	55.00	

	1	2	3	4	5
Module A	0	0	0	1	0
Module B	0	0	0	1	
Module C	0	1	0	0	

	Performance Measure	Result	Limit	Year
Product	Profit	2815.7		2
	Quantity Produced/(1000)	7.9991		
	Price per Usage	0.096	0.2	
	Selling Price	4800	5400	
	Total Cost of Ownership	1235	1300	
	Customer Satisfaction Index	3.47	3.00	
	Injury Rate	2.22	5.00	
	Land Fill	5517	5600	
	Energy Used	12583	13000	
	X - Foot Print	1258	1300.00	
	Hazoudous material	17.6	18.00	
	Material Index	55	55.00	

	1	2	3	4	5
Module A	0	0	0	1	0
Module B	0	0	0	1	
Module C	0	1	0	0	

	Performance Measure	Result	Limit	Year
Product	Profit	3788		3
	Quantity Produced/(1000)	10.762		
	Price per Usage	0.0959	0.2	
	Selling Price	4795	5400	
	Total Cost of Ownership	1231	1300	
	Customer Satisfaction Inde	3.47	3.00	
	Injury Rate	2.22	5.00	
	Land Fill	5517	5600	
	Energy Used	12583	13000	
	X - Foot Print	1258	1300.00	
	Hazoudous material	17.6	18.00	
	Material Index	54.7	55.00	

	1	2	3	4	5
Module A	0	0	0	1	0
Module B	0	0	0	1	
Module C	0	1	0	0	

	Performance Measure	Result	Limit	Year
Product-R	Profit	884.493		1
	Quantity Produced/(1000)	2.43327		
	Price per Usage	0.09348	0.2	
	Total Cost of Ownership	4674	5400	
	Selling Price	1273	1300	
	Customer Satisfaction Index	3.479	3.00	
	Injury Rate	2.22	5.00	
	Land Fill	5107	5600	
	Energy Used	12285	13000	
	X - Foot Print	1228	1300	
	Hazoudous material	17.6	18.00	
	Material Index	54.7	55	

	1	2	3	4	5
Module A	0	0	0	1	0
Module B	0	0	0	1	
Module C	0	1	0	0	

	Performance Measure	Result	Limit	Year
Product-R	Profit	2813.5		2
	Quantity Produced/(1000)	7.9838		
	Price per Usage	0.0927	0.2	
	Selling Price	4636	5400	
	Total Cost of Ownership	1235	1300	
	Customer Satisfaction Index	3.479	3.00	
	Injury Rate	2.22	5.00	
	Land Fill	5107	5600	
	Energy Used	12281	13000	
	X - Foot Print	1228	1300	
	Hazoudous material	17.6	18.00	
	Material Index	54.7	55	

	1	2	3	4	5
Module A	0	0	0	1	0
Module B	0	0	0	1	
Module C	0	1	0	0	

	Performance Measure	Result	Limit	Year
Product-R	Profit	3778.7		3
	Quantity Produced/(1000)	10.741		
	Price per Usage	0.0926	0.2	
	Selling Price	4631	5400	
	Total Cost of Ownership	1231	1300	
	Customer Satisfaction Inde	3.479	3.00	
	Injury Rate	2.22	5.00	
	Land Fill	5107	5600	
	Energy Used	12281	13000	
	X - Foot Print	1228	1300	
	Hazoudous material	17.6	18.00	
	Material Index	54.7	55	

	1	2	3	4	5
Module A	0	0	0	1	0
Module B	0	0	0	1	
Module C	0	1	0	0	

	Performance Measure	Result	Limit	Year
PSS	Profit	923.465		1
	Quantity Produced/(1000)	2.49923		
	Price per Usage	0.10562	0.2	
	Total Cost of Ownership	5281	5400	
	PSSPA	648		
	Customer Satisfaction Index	3.996	3.00	
	Injury Rate	2.21	5.00	
	Land Fill	4830	5600	
	Energy Used	12431	13000	
	X - Foot Print	1243.1	1300.00	
	Hazoudous material	16.5	18.00	
	Material Index	52.5	55.00	

	1	2	3	4	5
Module A	0	0	1	0	0
Module B	0	0	0	1	
Module C	1	0	0	0	

	Performance Measure	Result	Limit	Year
PSS	Profit	2724.4		2
	Quantity Produced/(1000)	7.6016		
	Price per Usage	0.1045	0.2	
	Total Cost of Ownership	5224	5400	
	PSSPA	629		
	Customer Satisfaction Index	3.996	3.00	
	Injury Rate	2.21	5.00	
	Land Fill	4830	5600	
	Energy Used	12427	13000	
	X - Foot Print	1242.7	1300.00	
	Hazoudous material	16.5	18.00	
	Material Index	52.5	55.00	

	1	2	3	4	5
Module A	0	0	1	0	0
Module B	0	0	0	1	
Module C	0	1	0	0	

	Performance Measure	Result	Limit	Year
PSS	Profit	3632.5		3
	Quantity Produced/(1000)	10.152		
	Price per Usage	0.1043	0.2	
	Total Cost of Ownership	5217	5400	
	PSSPA	627		
	Customer Satisfaction Inde	3.996	3.00	
	Injury Rate	2.21	5.00	
	Land Fill	4830	5600	
	Energy Used	12427	13000	
	X - Foot Print	1242.7	1300.00	
	Hazoudous material	16.5	18.00	
	Material Index	52.5	55.00	

	1	2	3	4	5
Module A	0	0	1	0	0
Module B	0	0	0	1	
Module C	1	0	0	0	

Figure 4-10 Interface to Consolidate Output from Optimization

Each block of results requires a separate run, and a set of three results (one for each the Product. Product-R and PSS models) for each year analyzed, can be generated before having to update the data input tables (Figure 4-8). Although it seems that the software has to be run 3 × 10 = 30 times, during some years the system conditions (quantity of new and used products) remained the same and reduced the number of runs required. Once the results for the ten years (for all three models) were generated the results were consolidated into the form shown in Table 4-3.

Table 4-3 Consolidated Optimization Results for the PSS Model

	Performance Measure	Year										Limit
		1	2	3	4	5	6	7	8	9	10	
PSS	Profit	923	2724	3633	3633	3633	3999	4738	5109	4202	2246	-
	Quantity Produced/(1000)	2.50	7.60	10.15	10.15	10.15	10.15	10.24	10.24	7.67	2.45	-
	Price per Usage	0.106	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.107	0.2
	Total Cost of Ownership	5281	5224	5217	5217	5217	5217	5186	5186	5193	5354	5400
	PSSPA	648	629	627	627	627	627	620	620	622	645	-
	Customer Satisfaction Index	3.996	3.996	3.996	3.996	3.996	3.996	4.015	4.015	4.015	3.976	3.00
	Injury Rate	2.21	2.21	2.21	2.21	2.21	2.345	2.684	2.824	3.007	4.9	5.00
	Land Fill	4830	4830	4830	4830	4830	4697	4461	4322	4136	3251	5600
	Energy Used	12431	12427	12427	12427	12427	12358	12241	12180	12098	11942	13000
	X - Foot Print	1243.1	1242.7	1242.7	1242.7	1242.7	1235.8	1224.1	1218	1209.8	1194.2	1300
	Hazoudous material	16.5	16.5	16.5	16.5	16.5	15.63	14.42	13.36	11.95	3.84	18
	Material Index	52.5	52.5	52.5	52.5	52.5	44.66	29.02	21.12	10.59	-74.32	55
	Module A	3	3	3	3	3	3	3	3	3	3	-
	Module B	4	4	4	4	4	4	4	4	4	4	-
	Module C	1	1	1	1	1	1	2	2	2	4	-

4.5 Refining and Extension of Results

Due to space limitations and because a similar approach was followed in further analyzing the results for the Product, Product-R and PSS models, only the procedure for the PSS model is presented here (tables for Product and Product-R model are provided in Appendix A)

It is observed that during the 10 years the product is manufactured, the optimization model identifies three configurations for the PSS model; the most repeated configurations were 3-4-1 and 3-4-2 where the number indicated the alternative chosen for modules A,B,C respectively. Changes in the configuration change reuse, remanufacturing, recycling and disposal percentages, and thus influences post-use processes and structure. The optimization model is not formulated to capture these changes; it was assumed that a single configuration will be marketed (determined by the optimization model) throughout the 10 years. Configuration 3-4-1 was repeated for 6 years while configuration 3-4-2 was repeated for 3 years. Although the number of repeated years for configuration 3-4-2 was lower, the profit earned during these years was higher than that of configuration 3-4-1. Therefore in order to determine which of these two configurations is more profitable overall, the PSS model was re-run for configurations 3-4-1 and 3-4-2 for the 10 years considered.

The Product-R and PSS models required analysis for an extra 5 years beyond the demand cycle because, although manufacturing new products is terminated, post-use processing will continue during this period. This needs to be considered in order to provide a holistic analysis of these two models. To capture the performance during these 5 years the analysis was extended using the same configuration as the initial 10 years. This analysis enables the OEM to compare which of the two configurations attains the best performance overall, assuming that the default configuration remains the same throughout the total 15 years. The results obtained for the two repeating configurations in the PSS model are shown in Table 4-4 and Table 4-5.

Table 4-4 Multi-year Analysis for Configuration 3-4-1

	Performance Measure	Year														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PSS (3-4-1)	Profit	923	2724	3633	3633	3633	3999	4734	5102	4192	2222	743	743	743	557	183
	Quantity Produced/(1000)	2.50	7.60	10.15	10.15	10.15	10.15	10.15	10.15	7.60	2.50	10.15	10.15	10.15	7.6	2.5
	Price per Usage	0.106	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.106	0.079	0.079	0.079	0.079	0.079
	Total Cost of Ownership	5281	5224	5217	5217	5217	5217	5217	5217	5224	5281	3964	3964	3964	3964	3964
	Interst for PSS	1294	1256	1252	1252	1252	1252	1252	1252	1256	1294	0	0	0	0	0
	Customer Satisfaction Index	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
	Injury Rate	2.21	2.21	2.21	2.21	2.21	2.35	2.62	2.75	2.93	4.64	0.87	0.87	0.87	0.87	0.87
	Land Fill	4830	4830	4830	4830	4830	4697	4430	4296	4118	3289	238	238	238	238	238
	Energy Used	12431	12427	12427	12427	12427	12358	12222	12156	12066	11888	1509	1509	1509	1509	1509
	X - Foot Print	1243	1243	1243	1243	1243	1236	1222	1216	1207	1189	151	151	151	151	151
	Hazoudous material	16.50	16.50	16.50	16.50	16.50	15.63	13.88	13.01	11.84	5.43	0.14	0.14	0.14	0.14	0.14
	Material Index	52.50	52.50	52.50	52.50	52.50	44.66	28.94	21.08	10.60	-73.20	-26.18	-26.18	-26.18	-26.18	-26.18

Table 4-5 Multi-year Analysis for Configuration 3-4-2

	Performance Measure	Year														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PSS (3-4-2)	Profit	922	2718	3624	3624	3624	3995	4738	5109	4202	2242	778	778	778	583	192
	Quantity Produced/(1000)	2.52	7.67	10.24	10.24	10.24	10.24	10.24	10.24	7.67	2.52	10.24	10.24	10.24	7.67	2.52
	Price per Usage	0.105	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.105	0.079	0.079	0.079	0.079	0.079
	Total Cost of Ownership	5250	5193	5186	5186	5186	5186	5186	5186	5193	5250	3954	3954	3954	3954	3954
	Interst for PSS	1280	1242	1238	1238	1238	1238	1238	1238	1242	1280	0	0	0	0	0
	Customer Satisfaction Index	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02	4.02
	Injury Rate	2.27	2.27	2.27	2.27	2.27	2.41	2.68	2.82	3.01	4.75	0.89	0.89	0.89	0.89	0.89
	Land Fill	4880	4880	4880	4880	4880	4740	4461	4322	4136	3261	238	238	238	238	238
	Energy Used	12431	12427	12427	12427	12427	12365	12241	12180	12098	11994	1510	1510	1510	1510	1510
	X - Foot Print	1243	1243	1243	1243	1243	1237	1224	1218	1210	1199	151	151	151	151	151
	Hazoudous material	17.60	17.60	17.60	17.60	17.60	16.54	14.42	13.36	11.95	3.60	-0.46	-0.46	-0.46	-0.46	-0.46
	Material Index	52.70	52.70	52.70	52.70	52.70	44.82	29.02	21.12	10.59	-73.62	-26.31	-26.31	-26.31	-26.31	-26.31

A noteworthy result was observed by analyzing the extended results for the PSS model. The configuration 3-4-1 generated a slightly higher average profit per product sold ($443 vs. $441) while the configuration 3-4-2 provided a higher cumulative profit ($37,909,000 vs. $37,764,000) over the fifteen years studied. This could be due to the fact that configuration 3-4-2 was able to sell approximately 1100 products more than configuration 3-4-1 over the 15 years analyzed thus generating a higher revenue. In this study we chose the configuration 3-4-2 as the default configuration since it has the higher cumulative profit, higher CSI, and lower TCO.

Analysis of the Product-R model for the first 10 years also showed two repeating configurations while the Product model provided the same optimal configuration for the entire period. Thus, rerunning the optimization model was only required for the Product-R model. During the extended analysis for the Product-R model it was found that the configuration with the highest cumulative profit also generated the highest profit per product sold.

5 RESULTS AND ANALYSIS

This chapter presents the results obtained by the optimization model and discusses the assessments and inferences that can be drawn. A sensitivity analysis is also conducted. Although hypothetical data was used to develop the preliminary example to validate the model, the example helped identifying areas of concern when the model is used for broader application.

5.1 The Optimization Model

The entire portfolio of 80 products (or PSS) that can be formulated given the modules available, the Landfill generated, energy used and overall profit for each of them are illustrated in Figure 5-1, Figure 5-2 and Figure 5-3 for the Product, Product-R and PSS models, respectively. The point that relates to the configuration chosen by the optimization model is shown within the red circle. Although this presentation is possible for this example since it consists of only 80 variants it will become impossible for larger problems.

As mentioned in the methodology, the demand for the product is dependent on the CSI and either selling price (Product and Product-R models) or PPU (PSS model). In the study it was assumed that each of these parameters could impact the demand by a percentage of ± 5% according to their values. The overall profit for each year is dependent on the 'profit per product' and the demand and the optimization model chooses the configuration that generated the highest product of these two parameters.

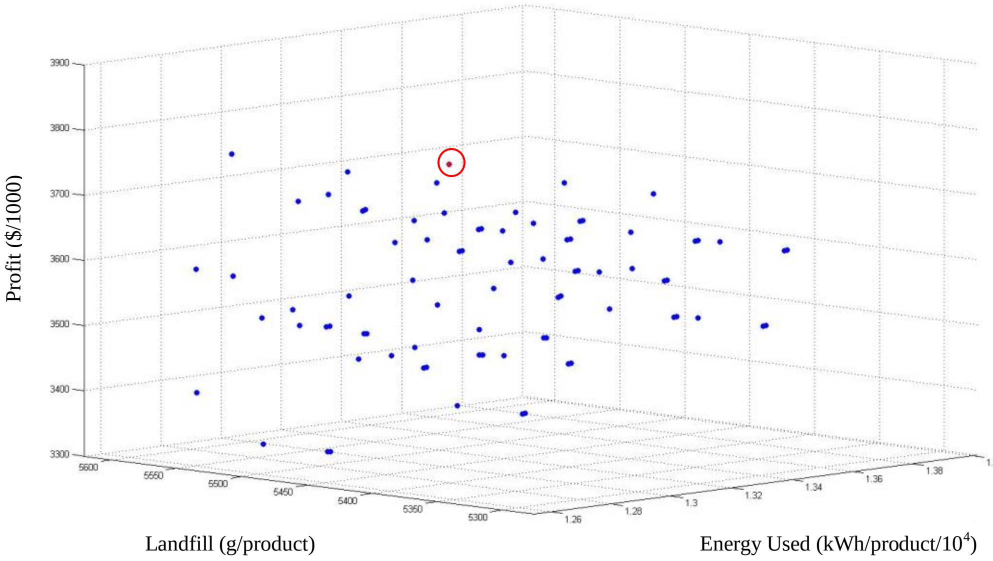


Figure 5-1 Variation of profit with Landfill and energy used for Product model

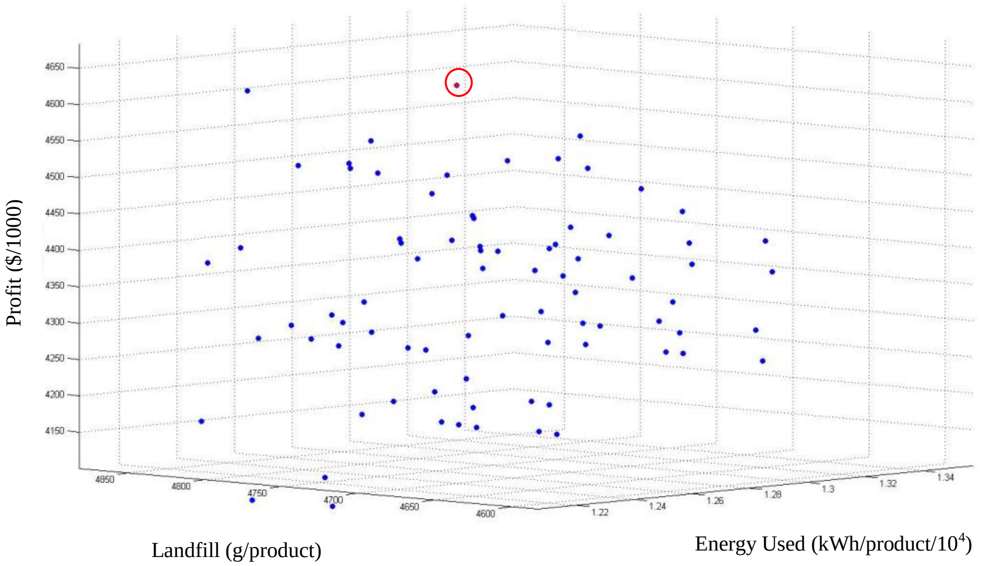


Figure 5-2 Variation of profit with Landfill and energy used for Product-R model

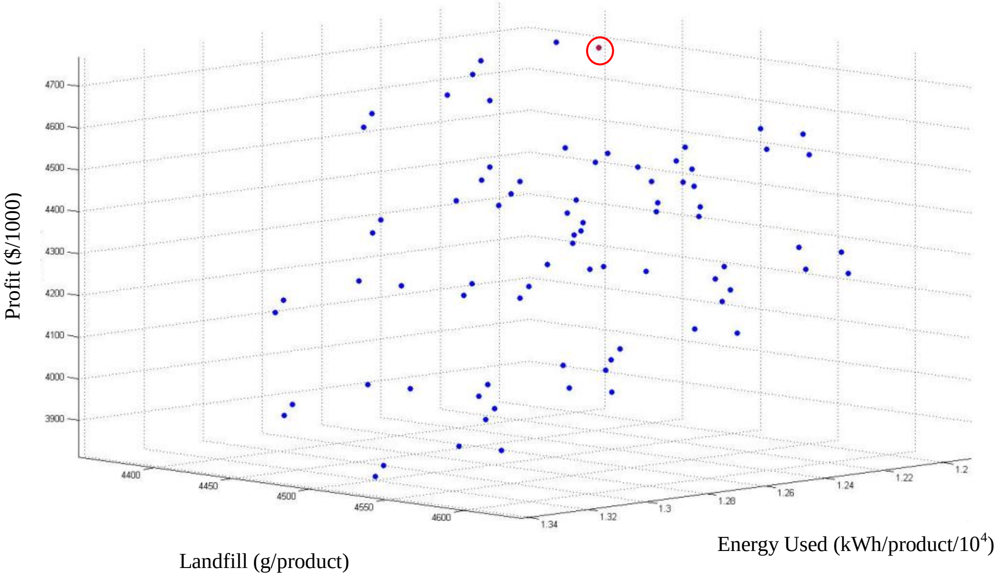


Figure 5-3 Variation of profit with Landfill and energy used for PSS model

Table 5-1 provides a summary of the results obtained through the optimization tool assessed for the total period of fifteen years that the OEM will conduct business with their customers. The average values are assessed over fifteen years while others are either the cumulative over fifteen years (i.e. quantity produced) or the most repeated value over the period studied (i.e. price per usage).

Table 5-1 Summary of Results Obtained

Performance measure	Unit	Product	Product-R	PSS
Configuration		4-4-2	3-4-2	3-4-2
Average Profit	$/product sold	353	414	441
Quantity Produced/(1000)	-	85.4	84.8	81.8
Quantity Sold/(1000)	-	85.4	89.0	85.9
Price per Usage	cents	9.59	9.13	10.37
Total Cost of Ownership	$	4795	4567	5186
Selling Price	$	1231	1238	-
Customer Satisfaction Index	-	3.47	3.63	4.02
Average Injury Rate	/product sold	2.22	2.68	2.85
Average Land Fill	g/product sold	5517	4665	4514
Average Energy Used	KW/product sold	12583	12394	12453
Average Carbon - Foot Print	Kg/product sold	1258	1240	1245
Average Hazoudous material disposed	g/product sold	17.6	15.2	14.6
Average Material Index	/product sold	54.8	29.7	22.7

Table 5-1 shows an increase in the profit for the Product-R and the PSS models (around 17.3% and 24.9% respectively) when compared to the Product model. However this amount is highly dependent on the post-use costs, the reuse, remanufacturing and recyclable percentages and also the value of the post-use components and materials. Thus, whether the PSS and Product-R are actually profitable or the magnitude of the profitability will depend on these parameters for the system studied.

The manufacturing of products is only conducted during the first ten years. The results show that the Product and Product-R model manufactures similar quantities. The demand and thus the quantity produced by the models depend on the CSI values and selling prices (or PPU) of their respective configuration. The Product and Product-R model have similar configurations during the 10 years with a change only in module A. The difference seen in quantity could be due to the difference in the selling prices of module A alternatives, and the fact that the Product-R model has a higher CSI values for its module variants (due to the ease of disposal). The demand of products in the PSS model is sensitive to the price per usage which includes other costs in addition to the selling price. Changes in the usage patterns, payment plans and convenience have effects on the satisfaction of products (CSI value). These differences in the PSS model is seen through the difference in quantity produced when compared to the Product-R and Product models.

In the Product-R model if the customer returns the product to the OEM they would not have to bear the disposal cost. This would be the reason for the reduction of the total cost of ownership (TCO) and the PPU in comparison to the Product model. The reason for PSS to have a higher PPU is the inclusion of the PSS price adjustment (PSSPA) cost which drives the PPU higher than that of the product-R or Product models. The added convenience and the fact that the customer does not have to pay for cost of the product upfront, a higher satisfaction of the product and lower environmental impacts (lower footprints, material index, and hazardous material) may offset this cost and convince the customer to choose this option.

5.2 Analysis of Results

5.2.1 **Economic Analysis**

The PSS model is structured differently from the Product and Product-R models by the fundamental difference being that the OEM is paid on a per usage basis during the contract and does not earn revenue at the delivery of product. Furthermore, the OEM has to provide maintenance, consumables and, at times bare the energy cost which is usually paid by the customer in the Product and Product-R models. In order to make the three service models comparable, the maintenance and consumable costs were deducted from the revenue in the PSS model. The revenue earned by all three models is presented in Figure 5-4 together with the revised revenue for the PSS model (represented by the plot PSS-R). The revenue shown for the PSS model includes the periodic revenue earned through usage of the product, through selling of reused products, costs saved through reusing parts, and revenue through selling material for recycling (As indicated, approximately after the 7th year the OEM can begin to earn higher cumulative revenue through the PSS model than through the other two models). Further analysis of manufacturing and overhead costs of the three models would ensure a more accurate breakeven point.

For simplicity of analysis it was assumed that the PSS model earns its profit during the same year that the product was sold, similar to the Product-R and Product models (The PSSPA described in the methodology will compensate for the time discounted value). Figure 5-5 shows that the Product model earns a slightly higher cumulative profit (4.4% higher than the PSS model) during the first 5 years. This is due to the Product model obtaining a more profitable configuration because of the condition that requires the default configuration to remain the same throughout the fifteen years of analysis. Similarly between the 6th and 9th years the Product-R model obtains the highest cumulative profitability and beyond the 10th year the PSS attains the best cumulative profit as seen in Figure 5-5. Futures studies may be able to determine the profitability of changing the configuration during the lifecycle by increasing the capability of the model and collection of more extensive data on post-use products.

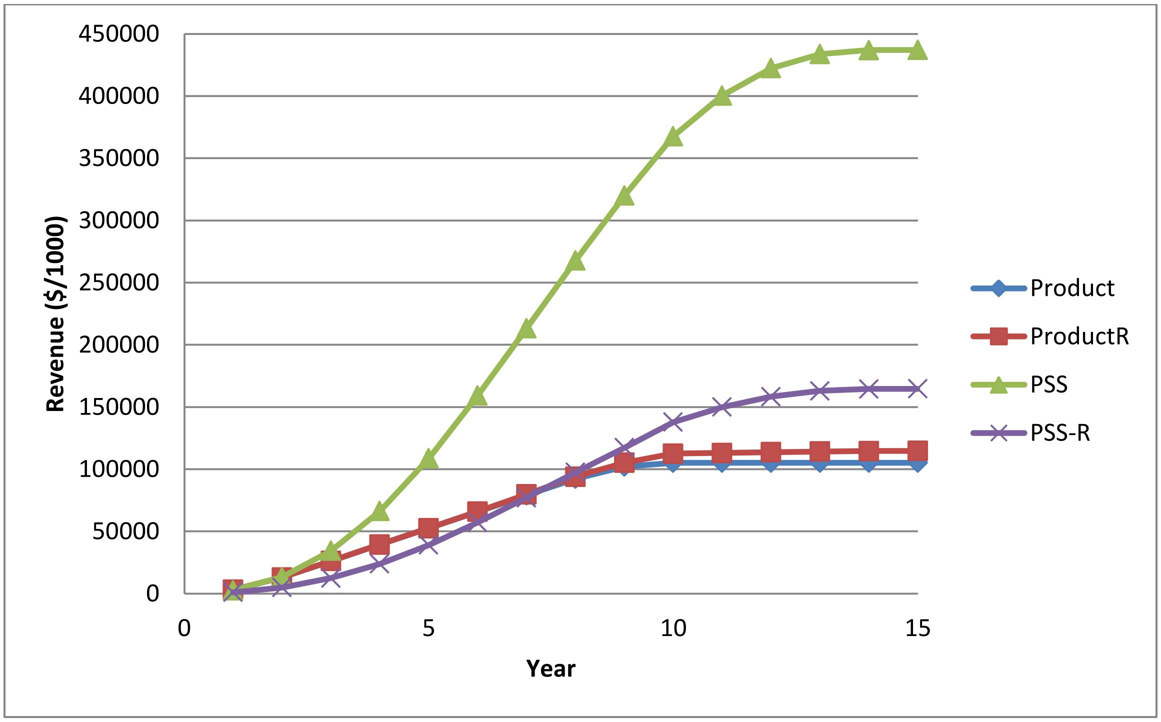


Figure 5-4 Cumulative Revenue for the Three Models

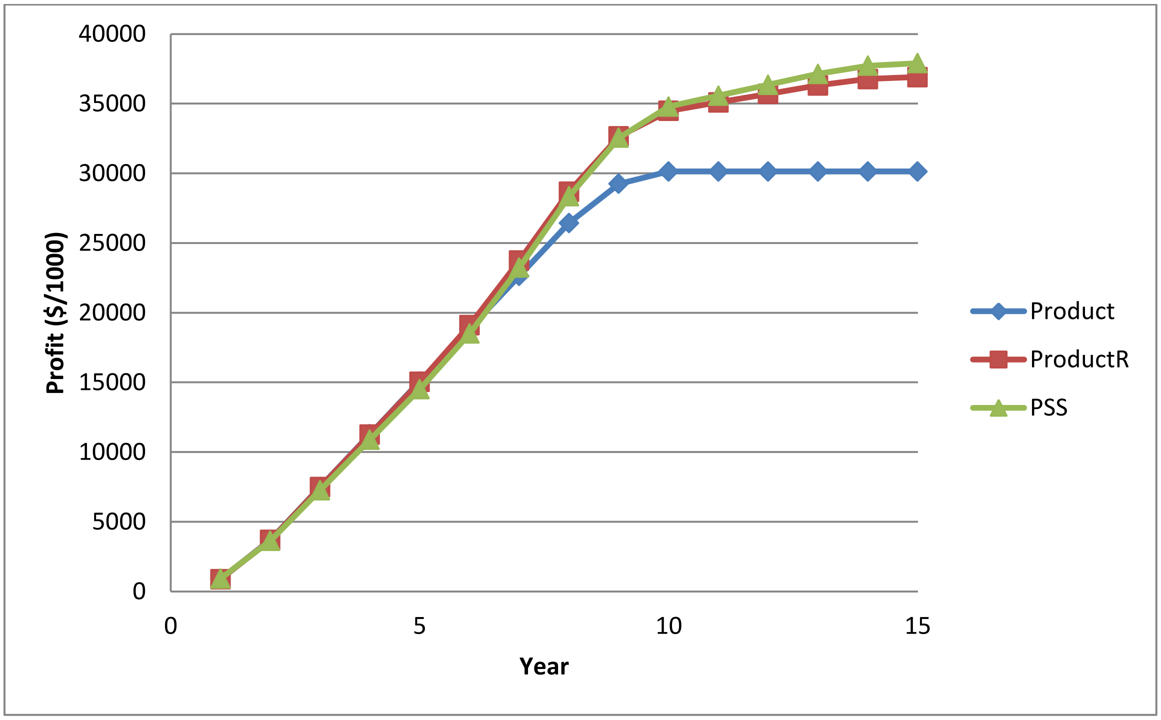


Figure 5-5 Cumulative Profit for Models

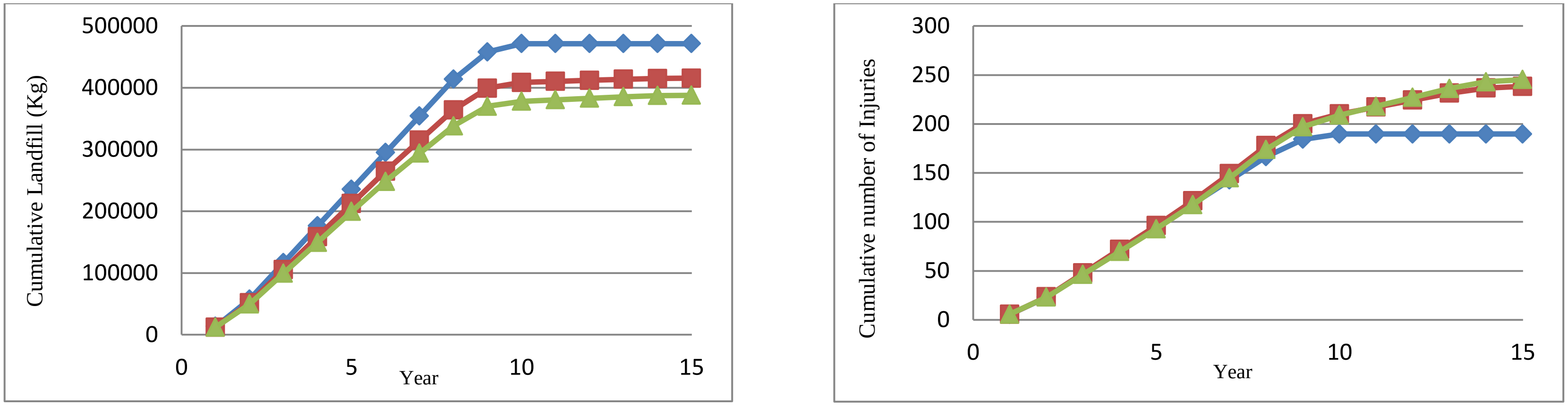
5.2.2 **Societal Sustainability Analysis**

All three service models will consume material and generate landfill as a result of product manufacturing. This is visible in Figure 5-6 (a) where the cumulative landfill is plotted and an increase in seen over the years. The OEM terminates manufacturing of new products following the 10th year and thus the value remains constant thereafter for the Product model while the Product-R and PSS models continue with post-use processing and refurbishing for additional 5 years, generating landfill although significantly less the previous 10 years.

The benefits of dematerialization are seen by lower cumulative landfill rates that are observed in both Product-R and PSS models in comparison to the Product model. The OEM is able to reduce landfill and consumption of virgin materials (through reuse, remanufacturing and recycling of material and components) unlike in the instance where the customer may dispose used products at the end of their lifetime. The difference observed between the Product-R and PSS models is due to the fact that the OEM does not own the product in the Product-R model and thus the recovery rate is highly dependent on customer behavior. This reduces the quantity recovered in the Product-R model in comparison to the PSS model (the study considered a recovery rate of 75% for the Product-R model).

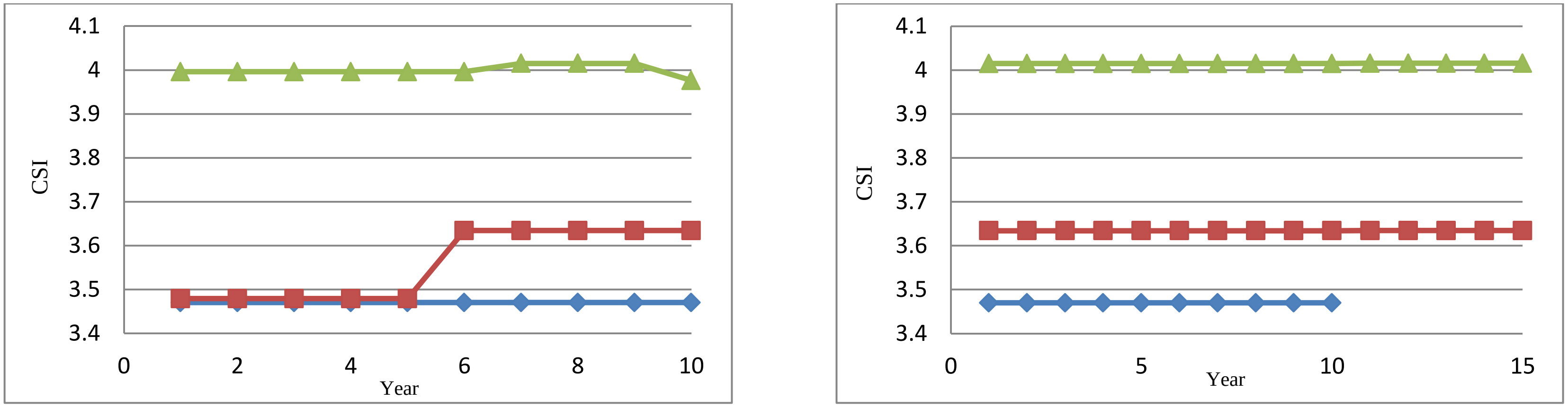
Post-use processing involves the processes of recovery, refurbishing, disassembly, remanufacturing and recycling of products. These processes are subjected to the risk of injuries similar to that of the pre-manufacturing and manufacturing stages of the product. Thus although extending the lifetime of products through post-use processing may reduce the amount of new products produced (and the injuries connected) it contributes to injuries caused due to processing of products. As seen in Figure 5-6 (b) the cumulative injuries of both Product-R and PSS models exceed that of the Product model by the 10th year when the OEM terminates production of new products. This may change depending on the product studied and its lifecycle, but even if the cumulative number of injuries were less than that of the Product model during the first 10 years there is a possibility of the exceeding it between the years 11 to 15 by the other two models. This is because while Product model ceases production after the 10th year, Product-R and PSS models continue with post-use processing of products. However this shouldn’t discourage the OEM since the number of injuries per product sold could be decreased by the Product-R and PSS models beyond that of the Product model if procedures are in place to ensure that post-use processing causes less injuries than that of the pre-manufacturing and manufacturing stages.

Figure 5-6 (c) and (d) show the variation of the CSI before and after the default configurations were standardized for the total lifecycle of the product. The configuration with the higher CSI was chosen as the default not only due to its CSI value but also because it provided a higher cumulative profit as described in Chapter 4.



(a) Variation of cumulative landfill with time

(b) Variation of cumulative injuries with time



(c) Variation CSI with time

(d) Variation CSI with time after standardizing

Figure 5-6 Variation of Societal factors during the total lifecycle of product

5.2.3 Environmental Sustainability Analysis

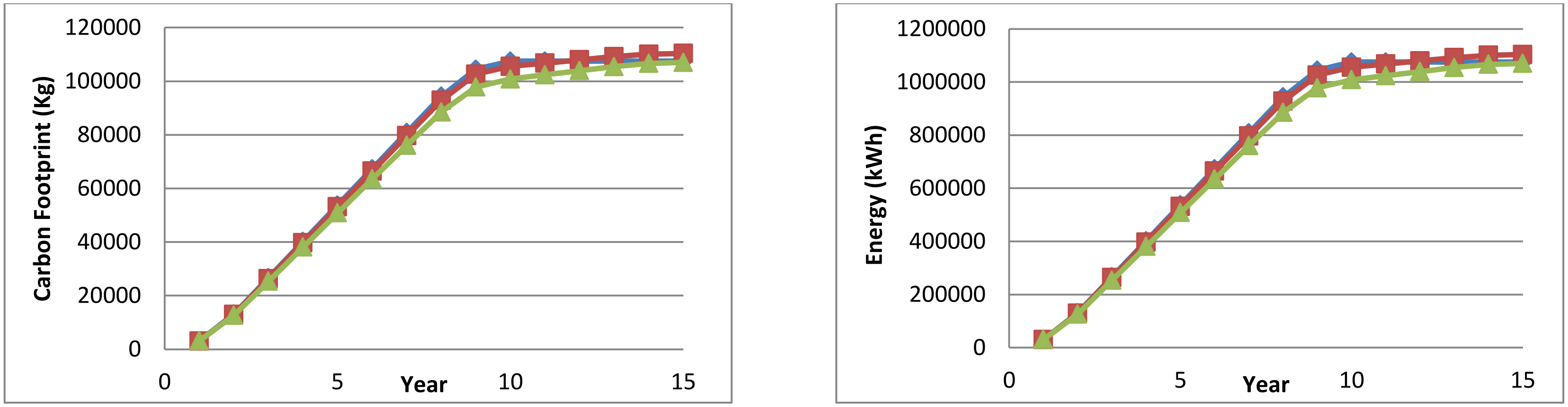
The cumulative energy usage and cumulative carbon footprint follows the same trend for all three models over the 15 years analyzed as seen in Figure 4-6 (a) and (b) respectively. This is due to the fact that the carbon footprint is entirely dependent on the amount of energy used by the system. According to the simple energy calculator provided by National Energy Foundation in the UK (NEF, 2011), the ratio between the kWh used and the amount of carbon (C) emitted in kilograms vary significantly from country to country (as low as 0.027 and 0.077 in Brazil and Belgium, respectively and as high as 0.35 and 0.26 in India and Australia respectively). In this study a ratio of 0.1 was used to calculate the amount of C from the kilo-Watt-hours (kWhs) used.

The PSS and Product-R models would normally be expected to be more energy efficient due to reusing and remanufacturing of products and components (saving the energy used to manufacture them). However, both Product-R and PSS models use energy for post-use processing. The product is considered obsolete following the 10th year and thus production is terminated after this year. The OEM also does not offer the Product-R or the PSS facility to new customers served in the alternate market with refurbished products (due minimal control of product and difficulty in recovery). This reduces the amount of reused products during this period. Thus, although the Product-R and PSS models consume less energy during the first 10 years they reach and exceed the amount consumed by the Product model by the 15th year. However by further analysis it was found that the energy used per unit sold was less for both the Product-R and PSS models (12394 kWh and 12453 kWh, respectively) in comparison to the Product model (12583 kWh). The reason behind this is that although Product-R holds the highest cumulative energy usage it also sells the highest number of products.

Further investigation into the footprints and energy usage of land-filling and incineration may provide more accurate results. In the study the two methods of disposal were not separately addressed although the ratio between the two methods may have an impact on the final results. Consideration may have to be given to recycling since the processing of some materials maybe more harmful to the environment than the processing of virgin materials. The recycling may be justified by scarcity of the material, time or cost factors. On the other hand, the cost involved in recycling or remanufacturing maybe higher than that of virgin material or new parts. In this scenario future costs increases in raw materials, risks of disruptions in the supply of virgin materials or benefits to environment or society may justify the increased costs.

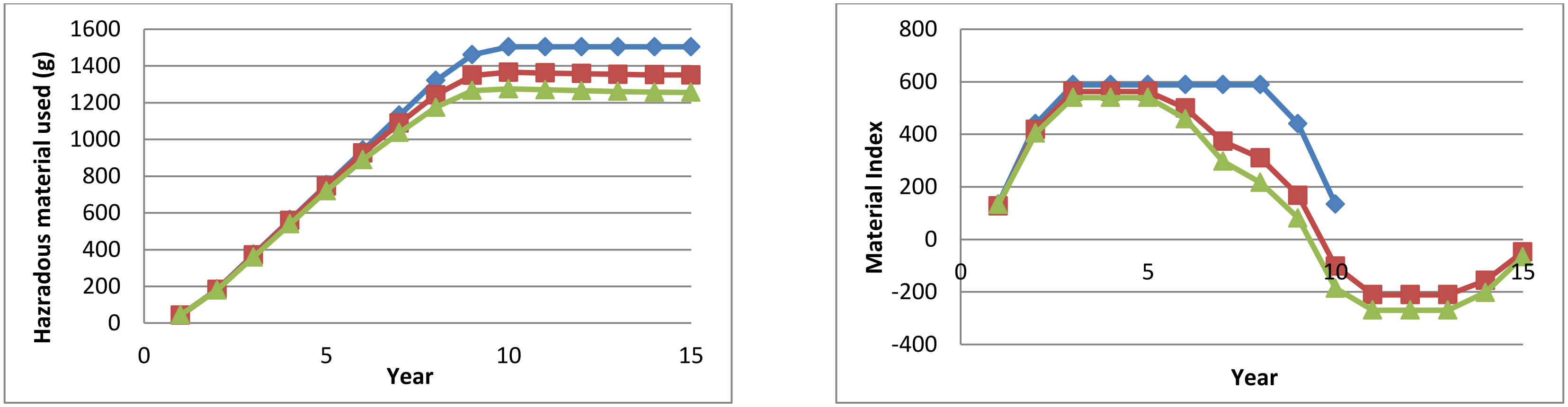
New products are manufactured up to the 10th year and consequently there is an increase in the total amount of hazardous materials consumed as seen in Figure 5-7 (c). However the Product-R and PSS models use less due to the reuse and remanufacturing of products and components. Between the 10th and 15th year there is a slight decrease in the cumulative amount of materials used in the Product-R and PSS models (1.1% and 1.5% respectively), which is due to recycling of material. If recycling of materials uses significantly less hazardous material than is used in the manufacturing of the product (during pre-manufacturing and manufacturing), then the impact of post-use processing on the total amount consumed could be more significant.

The material index is calculated by determining the amount of virgin material that is consumed by the system. Through remanufacturing and recycling, the Product-R and PSS models consume less virgin material than the Product model as seen in Figure 5-7 (d). During the 10th year (which is the final year of production) the Product-R and PSS models recycle more material than is used for manufacturing and thus shows a negative material index (which affects the environment positively). Following the 11th year onwards the PSS and Product-R models continue recycling of materials while not engaging in any manufacturing. This enables the PSS model to have cumulative material index that is less than 50% to that of the Product model by the 15th year.



(a) Variation of Carbon Footprint with time

(b) Variation of Energy usage with time



(c) Variation of Hazardous Material used with time

(d) Variation of Material Index with time

Figure 5-7 Variation of environmental factors during the lifecycle of product

5.3 Sensitivity Analysis

The aim of this research was to optimize and evaluate sustainability of a customizable product-service system. Of the three models analyzed, the PSS model demonstrated significant advantages over the other two models in almost all sustainability criteria. Since this result would encourage an OEM to consider the PSS model, further analysis into the model's sensitivity to system parameters should be conducted to identify which conditions would ensure that the PSS model is profitable and more sustainable. This would help alleviate any concerns that the OEM may have before implementation.

The OEM would be concerned with the amount of refurbishing that has to be conducted since they would have to allocate employees for this process and also consider exploring and promoting the refurbished products in alternate markets. The profitability of reused products will determine whether the investment is justified.

The OEM will also be concerned on how to encourage customers to choose the PSS option. Will sharing the profit gained through post-use processing be an incentive that ensures the profitability of the model? Can different contract periods be offered as per customer request and would the cost to the customer be reasonable?

Changes in the product market due to increased awareness of customers or competition, would cause customers to demand high product satisfaction at a low cost. Therefore, the OEM would be concerned with the sensitivities to these factors on their profitability.

In order to address the above concerns the following sensitivity analyses were conducted.

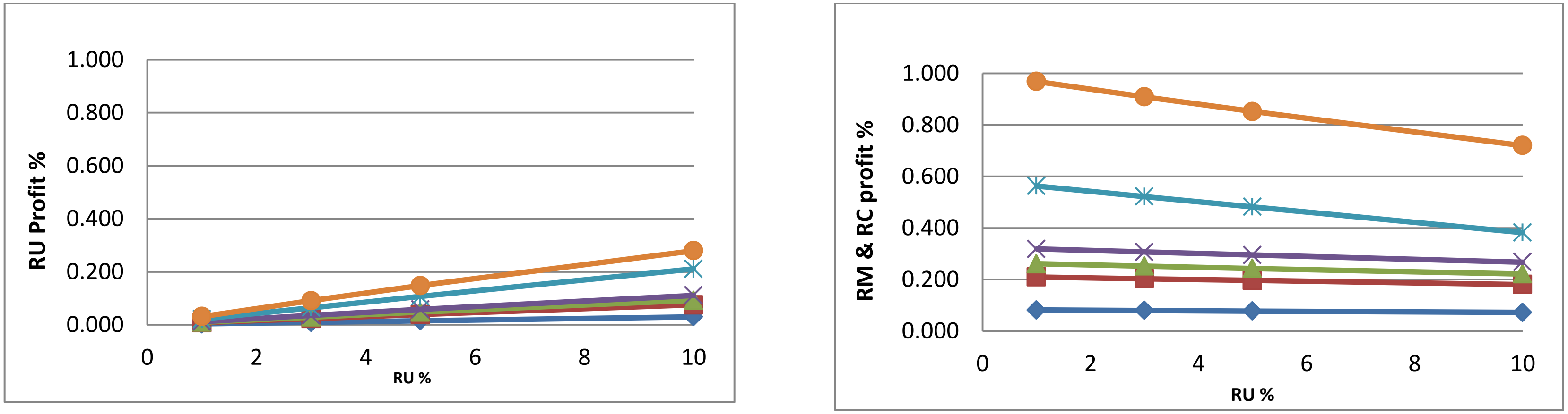
1. Variation of profit with change in percentage of refurbishable products
2. Variation of profit with profit sharing
3. Variation of PPU with contract period
4. Variation of profit with the level of impact by CSI and PPU

5.3.1 **Sensitivity of Profit to the Percentage of Refurbishable Products**

Figure 5-8 (a) shows that the sensitivity of the profit to the reuse percentage increased between the years 6 to 11; between the years 11 to 15 it remained constant. This was caused due to the increase of recovered products (and thus reused products) between the years 6 to 8 and the decrease of newly manufactured products between the years 8 to 10. This increased the contribution the reused products had on the profit. Following the 10th year the OEM's profit was purely based on the recovered products and thus the sensitivity remained constant and higher than the previous years.

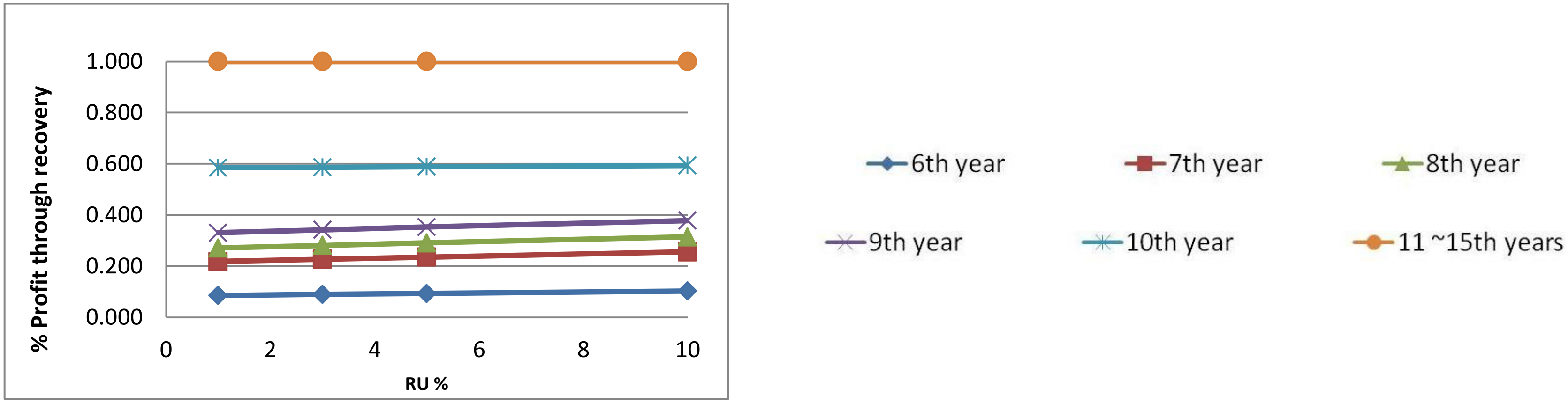
As the quantity of reusable products increased, the quantity of components and materials remanufactured and recycled decreased (total recovered quantity is constant). Similar to Figure 5-8 (a) the sensitivity increased during years 6 to 10, while the sensitivity remained constant during the post use stage of years 11 to 15 and seen in Figure 5-8 (b) for the same reasons explained previously.

Figure 5-8 (c) was generated by superimposing Figure 5-8 (a) and Figure 5-8 (b). This illustrated the overall impact of the RU% on the profit gained through the recovery process. It was visible that the sensitivities to the RU% had decreased, since the profit reduction in remanufacturing and recycling was compensated by the profit increase through reused products. The higher overall sensitivities are seen in years 7 to 9 with the 9th year having the highest sensitivity.



(a) Effect of RU% on RU Profit%

(b) Effect of RU% on RM + RC Profit%



(c) Effect of RU% on Total Recovery Profit %

Figure 5-8 Variation of Profit with respect to Reuse Percentages

Figure 5-9 shows that the increase of the reusable percentage from 1% to 10% has an impact of only 3.5% on the cumulative profit. Thus in comparison to the Product model even if the reusable percentage is low the PSS model may be profitable provided that remanufacturing and recycling is profitable as in this example (the cumulative profit for the PSS model at 1% RU is $37,328,000 vs. $30,134,000 in the Product model). It can be concluded that in this example it is not warranted that the OEM invest much on refurbishing activities.

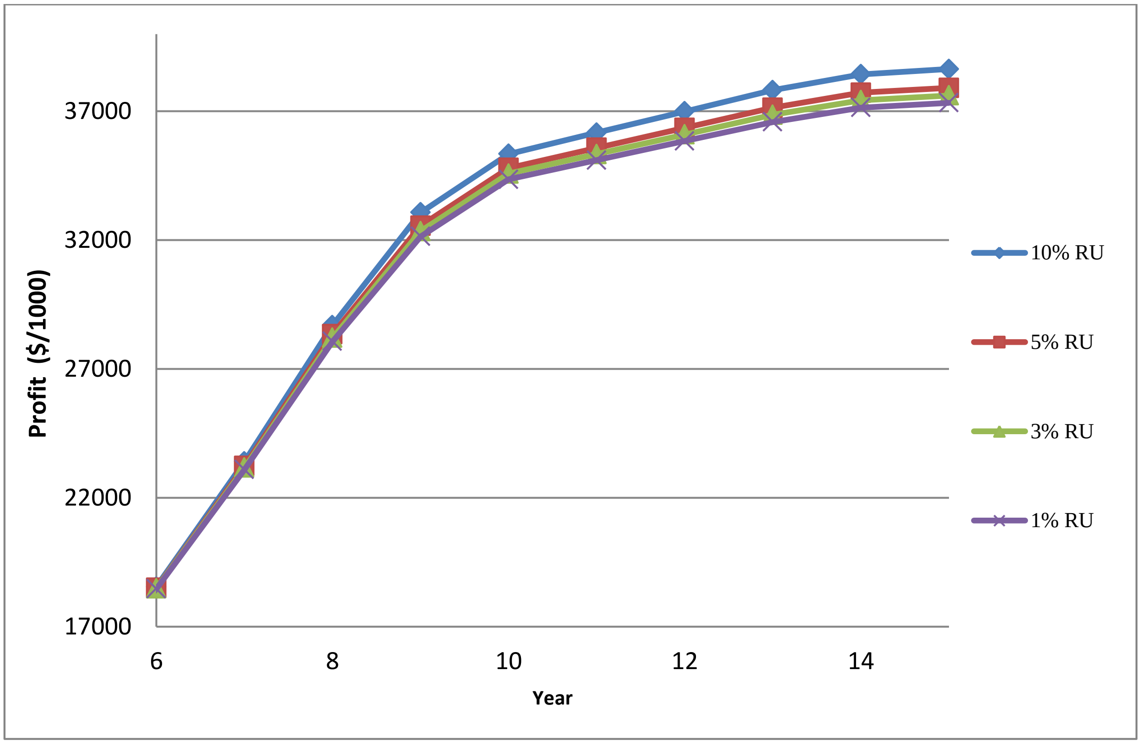


Figure 5-9 Variation of profits with RU percentages

5.3.2 Variation of OEM Profit with Profit Sharing

Figure 5-10 shows the impact on the OEM of sharing the profit gained through the post-use processes with the customer. The profit can only be shared during years 6 to 10 when both recovered products are available and new product are manufactured and sold through the PSS model. Although it may be expected that profit sharing will decrease the

PPU and thereby increase the customer demand, the decrease of the PPU was minimal and therefore only resulted in the decrease in OEM's profit. This is due to the fact that, majority of the cost (>70%) incurred during the lifetime of the product is contributed by the consumable, maintenance and energy costs and the reduction of product cost through sharing of profit has minimal effect on the PPU (as seen in Figure 5-11). The variation observed in the PPU during the years 1 to 10 is due to changes in the quantities produced and the income from post-use processing that is shared with the customer. Between years 11 to 15, the PPU is significantly less due to the fact that products are sold at lower price during this period (due to being outdated) and the fact that the PSS option is not offered (the costs associated with PSS option is not incurred).

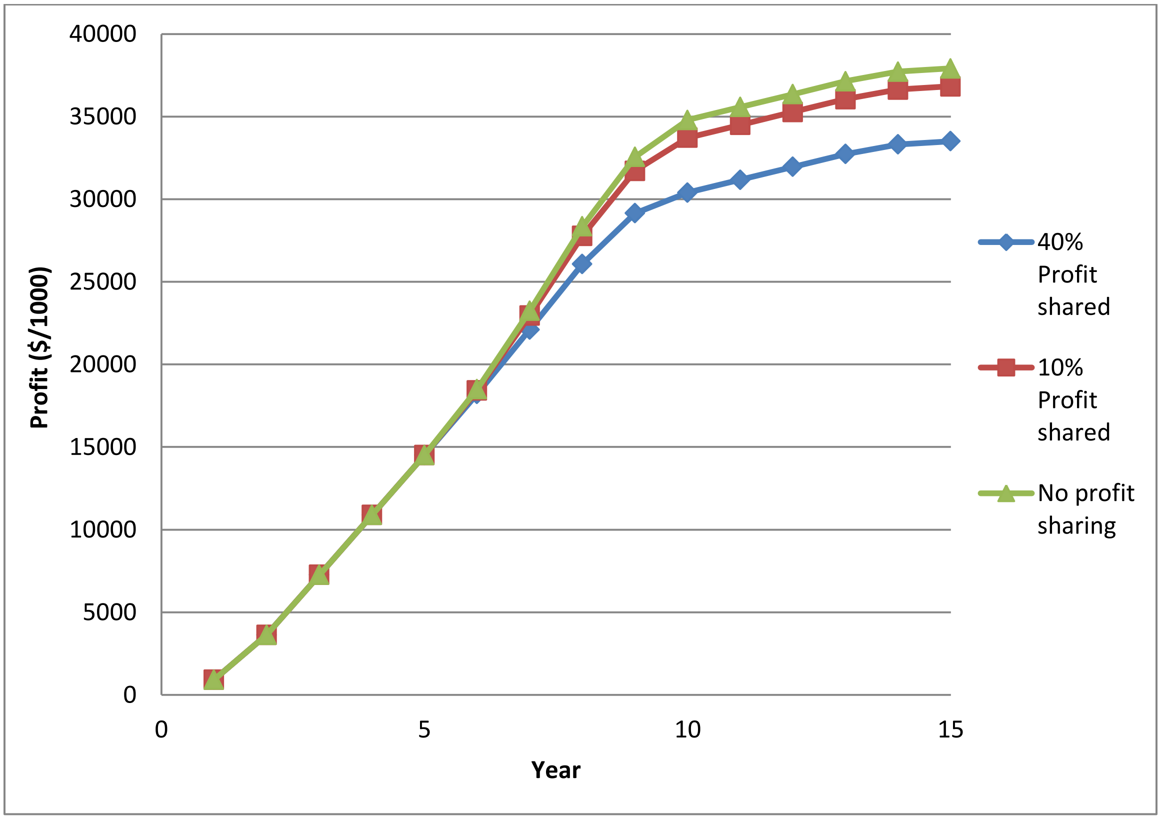


Figure 5-10 Variation of cumulative profit with sharing profit of post-use processing

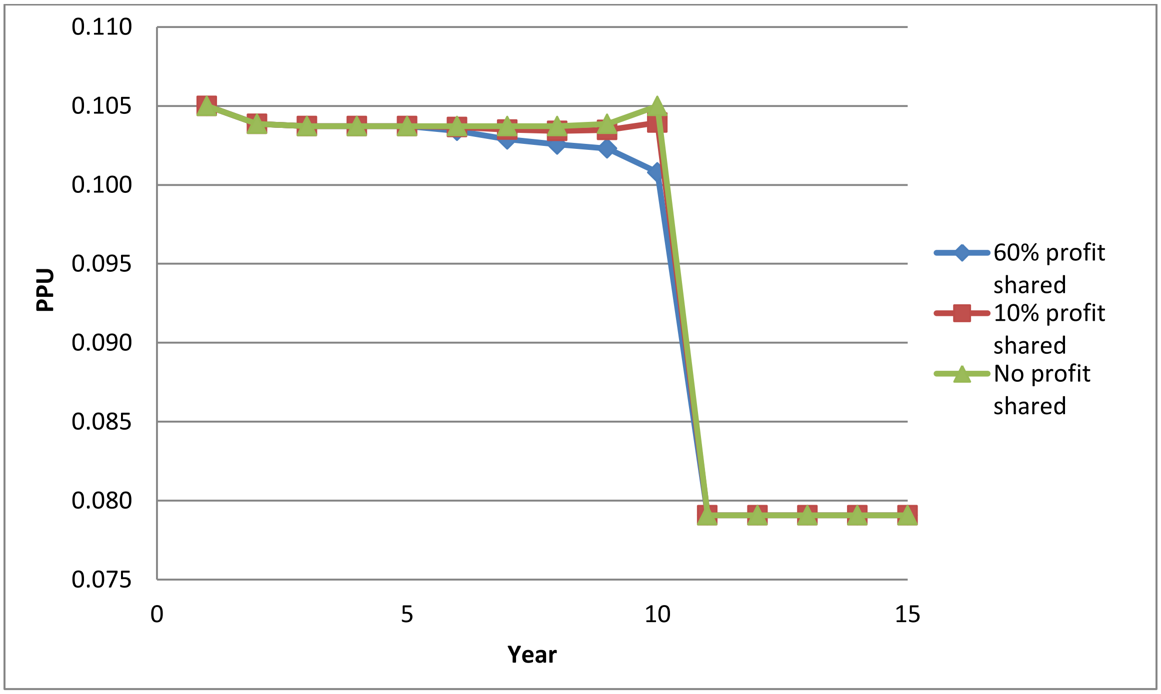


Figure 5-11 Variation of PPU with sharing profit of post-use processing

5.3.3 Variation of PPU with Contract Period

The PPU that the customers may have had to pay, if they requested a contract period less than that of the standard one (5 years) offered, is shown in Figure 5-12. The different in the PPU between choosing a contract period of 2 years versus a period of 5 years is approximately 10% and thus the customers can decide whether this would suit their needs. The reuse, remanufacturing, and recycling rates will change if the product was returned before the end of its useful lifetime and thus further data and a reconfiguration of the PSS model will have to be conducted to determine the effect of variable contract periods on OEM’s profitability.

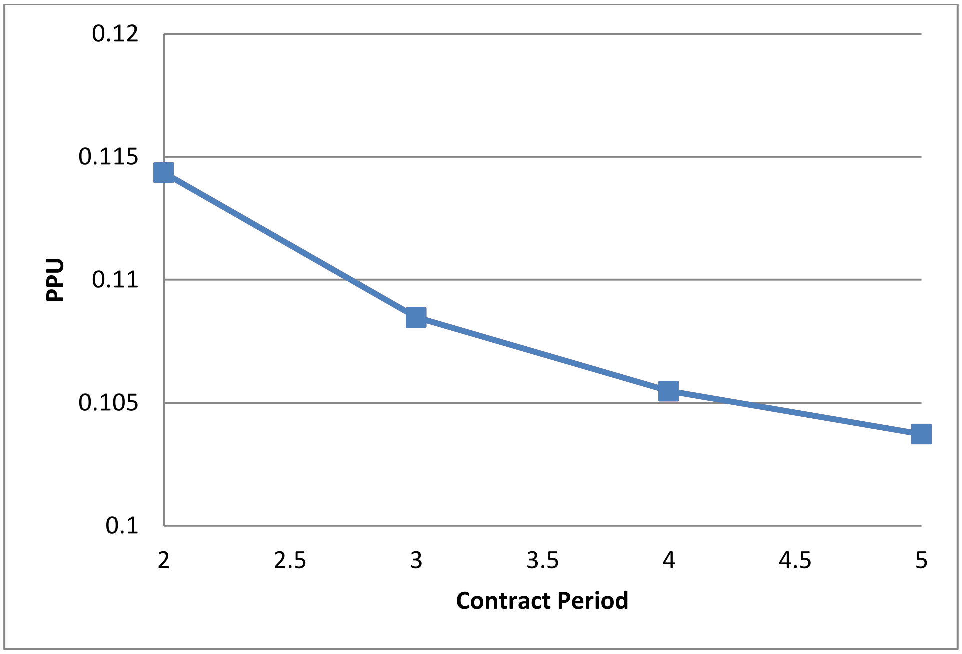


Figure 5-12 Variation of the price per usage with the length of use of product

5.3.4 Variation of Profit with respect to the Sensitivities of CSI and PPU

The equation corresponding to the market demand (or total quantity of products sellable as explained in the methodology) is,

$$\mathrm{Q} = \text{Average market demand } + f(CSI, SP)$$

It can be understood that the level of influence will depend on the function of CSI and selling price (or PPU) in the above equation. In this study the default level of influence of each of these two factors was taken as 5%. This indicates that, for example if the average market demand was 10000 units, each of the factors are able to increase or decrease the demand by 500 units (10000 × 5%). Therefore the actual market demand could vary between 9000 units and 11000 units.

The influence on cumulative profit was investigated by varying the level of impact of both CSI and selling price (or PPU) in the above equation for the market demand. The results obtained are illustrated in Figure 5-13. The 1st percentage shown in the legend corresponds to the level of impact by CSI while the 2nd percentage corresponds to level of impact by the selling price (or the PPU). Both the Product and the Product-R models show a decrease in cumulative profit as the level of impact by CSI decreases. However, for the PSS model the cumulative profit is highest at a CSI level of impact of 3.75% while also showing a variability of as much as 10% in the profit within the conditions analyzed. This would warrant the OEM to investigate further into reasons that may affect the customer satisfaction (i.e. competition, economic situation of the region/country, technology etc.) and to investigate the optimal amount of resources that should be allocated to ensure the satisfaction of the customer.

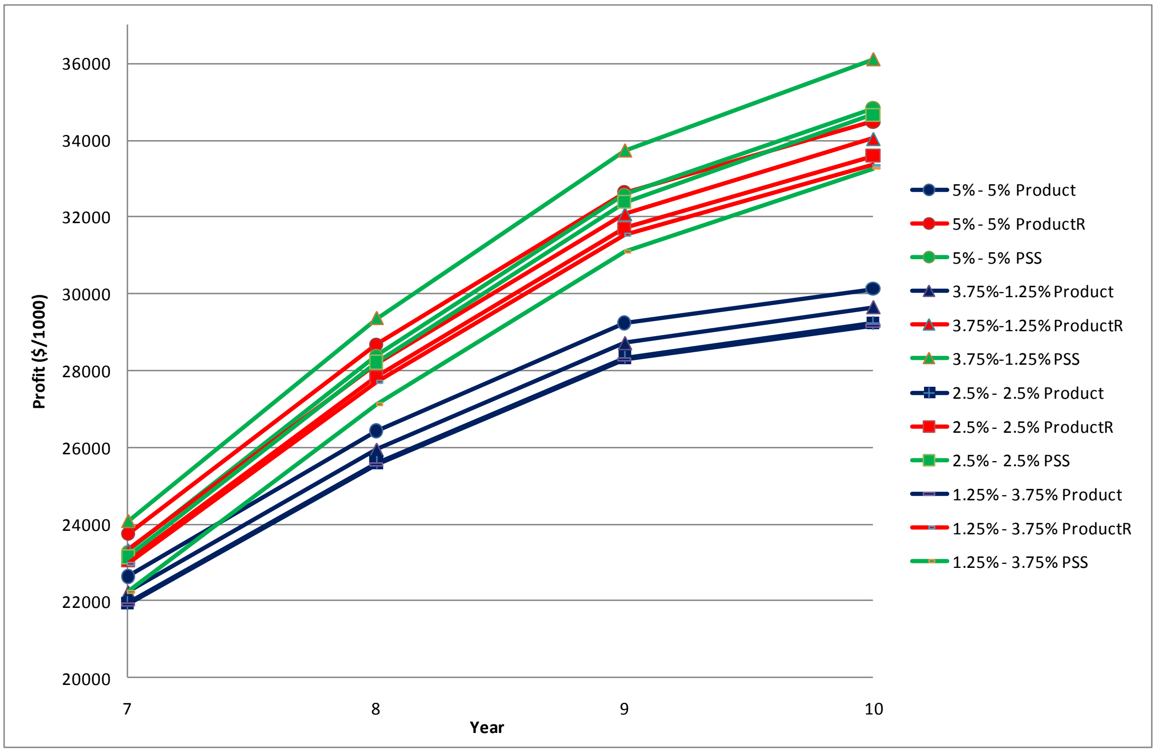


Figure 5-13 – Effects of varying sensitivities to CSI and selling price

The sensitivity of the selling price or PPU on the cumulative profit does not illustrate a visible trend. As discussed earlier the product cost is only a fraction of the cost incurred in the lifetime of the product and this could be the reason that the sensitivity to the selling price is overshadowed by the sensitivity to the CSI.

It was also observed that the configurations that provided the optimal profit for the three models changed depending on the sensitivity of the CSI and selling price. Increases in the capabilities of the model may enable the user to determine whether marketing the same configuration or multiple configurations is more profitable (when considering the cumulative profit over entire product lifecycle of 15 years).

6 CONCLUSIONS AND FUTURE WORK

This research presented a methodology and a tool that would enable an OEM to optimize and evaluate the sustainability performance of a configurable product-service system. Three business models were developed and optimized to maximize the OEM's profitability throughout the total lifecycle of the product, while ensuring societal and environmental sustainability, and meeting customer requirements. Constraints included providing a reasonable purchase price of product (or per usage cost) to the customer, addressing environmental concerns such as carbon footprint and material usage, and societal concerns such as product satisfaction and injury rates of employees. A method of refining variations in the optimal results (when considering multi-period analysis) during the period analyzed and a novel method of evaluating customer satisfaction were also discussed to provide a holistic analysis for the OEM.

The inspiration for the research was that, although PSS is a business model that could help sustainable manufacturing and consumption, current research lacks quantitative models to evaluate them. This research is a preliminary attempt in bridging this gap by providing the formulation of three business models that could collectively be used to evaluate sustainability performance of PSS in relation to traditional products.

The research initiated by choosing metrics that monitored activities across the total lifecycle (from pre-manufacturing to post use) and from all aspects of the TBL. It was also ensured that these metrics encompassed activities that supported the 6R approach and a closed-loop flow of material and products. The optimal product configurations were determined by the ILOG OPL optimization software on which the MILPs were solved on. MILP proved to be a viable methodology since the optimal solution was determined in approximately 10.3 seconds (on a desktop computer with an Intel Core 2 Quad processor with a clock speed of 2.66GHz) having 94 variables and 889 constraints.

The tool also provides the opportunity for the OEM and customer to compare sustainability performances of product-service solutions that they co-design. The capability included in the tool to allow user input on compatibilities (or incompatibilities) between module variants also provides the opportunity to generate a set of optimal solutions that the user can compare, evaluate and choose from. The approach used in this model can also be integrated with further capabilities and databases and be used to enhance conventional mass customization product configurators to make them ‘sustainable’ product configurators.

The optimal configuration and sustainability performance could also depend on various conditions that were not address in this research (For example topography and weather conditions of the area the customers are based in and also their patterns of usage). Furthermore certain options may only be economical or environmentally benign under specific conditions. For example, although energy efficient products or components maybe available, the costs and environmental impacts of these may only be justified if the usage is sufficiently high (For example the use of a hybrid car maybe be justified only if the customer drives a minimum number of miles per year or the cost of the NiMH battery and its environmental effect may exceed the benefits gained).

A limitation in this study is that, design changes in variants of the modules cannot be captured in the optimization model. For example a change in the material used or weight of the material could change the sustainability performance of the product (i.e. energy efficiency, cost, landfill etc.). However an analysis of this nature would have to be product or even material specific and due to the scope of the study and the intention to develop a generalized model this aspect was not captured here. Future studies with the support and integration of a considerable number of analytical models and databases would help develop a tool that could analyze impacts of design changes of this nature.

As consumer awareness regarding sustainability initiatives increase, their choice of purchase may also depend on the environmentally friendly certifications that the product carries (i.e. Energy star, RoHS, ISO etc.) where energy efficiency, emissions and use of hazardous material may be monitored. Further improvements in the model could enable the market demand (and thereby the profit) to reflect such considerations such as these.

Future studies may also investigate the possibility of including interactions between modules that may benefit or hinder the overall performance of the product. Operator training and labor costs could also be included when comparing the three models especially in instances where the OEM provides a results oriented PSS.

As discussed in the case example the ability for the OEM to produce different configurations may increase their flexibility in production and also their competitive advantage. Design improvements in the modules coupled with additional post-use data and enhancements in the models may help achieve this objective in future studies. Enhancements and additions discussed would enable the development of a more comprehensive tool that could further help convince value of sustainable PSS in the mindsets of both the OEMs and customers alike thus paving the way towards sustainable development through sustainable production and consumption.

APPENDIX A: RESULTS FOR PRODUCT AND PRODUCT-R MODELS

Consolidated results

	Performance Measure	Year										Limit
		1	2	3	4	5	6	7	8	9	10	
Product	Profit	888	2816	3788	3788	3788	3788	3788	3788	2816	888	-
	Quantity Produced/(1000)	2.44	8.00	10.76	10.76	10.76	10.76	10.76	10.76	8.00	2.44	-
	Price per Usage	0.097	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.097	0.2
	Total Cost of Ownership	4838	4800	4795	4795	4795	4795	4795	4795	4800	4838	5400
	Selling Price	1273	1235	1231	1231	1231	1231	1231	1231	1235	1273	1300
	Customer Satisfaction Index	3.47	3.47	3.47	3.47	3.47	3.47	3.47	3.47	3.47	3.47	3.00
	Injury Rate	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	5.00
	Land Fill	5517	5517	5517	5517	5517	5517	5517	5517	5517	5517	5600
	Energy Used	12587	12583	12583	12583	12583	12583	12583	12583	12583	12587	13000
	X - Foot Print	1259	1258	1258	1258	1258	1258	1258	1258	1258	1259	1300
	Hazoudous material	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	18
	Material Index	55	55	54.7	54.7	54.7	54.7	54.7	54.7	55	55	55
	Module A	4	4	4	4	4	4	4	4	4	4	-
	Module B	4	4	4	4	4	4	4	4	4	4	-
	Module C	2	2	2	2	2	2	2	2	2	2	-

	Performance Measure	Year										Limit
		1	2	3	4	5	6	7	8	9	10	
Product-R	Profit	884	2813	3779	3779	3779	4068	4649	4939	3964	1834	-
	Quantity Produced/(1000)	2.43	7.98	10.74	10.74	10.74	10.68	10.68	10.68	7.94	2.42	-
	Price per Usage	0.093	0.093	0.093	0.093	0.093	0.091	0.091	0.091	0.091	0.092	0.2
	Total Cost of Ownership	4674	4636	4631	4631	4631	4567	4567	4567	4572	4610	5400
	Selling Price	1273	1235	1231	1231	1231	1238	1238	1238	1242	1280	1300
	Customer Satisfaction Index	3.479	3.479	3.479	3.479	3.479	3.634	3.634	3.634	3.634	3.634	3.00
	Injury Rate	2.22	2.22	2.22	2.22	2.22	2.374	2.58	2.684	2.824	4.129	5.00
	Land Fill	5107	5107	5107	5107	5107	4906	4697	4593	4453	3797	5600
	Energy Used	12285	12281	12281	12281	12281	12480	12388	12342	12282	12204	13000
	X - Foot Print	1228	1228	1228	1228	1228	1248	1238	1235	1228	1219	1300
	Hazoudous material	17.6	17.6	17.6	17.6	17.6	16.81	15.22	14.42	13.36	7.1	18
	Material Index	54.7	54.7	54.7	54.7	54.7	46.79	34.94	29.02	21.12	-42.04	55
	Module A	4	4	4	4	4	3	3	3	3	3	-
	Module B	4	4	4	4	4	4	4	4	4	4	-
	Module C	2	2	2	2	2	2	2	2	2	2	-

Multi-year Analysis for Product-R model

	Performance Measure	Year														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Product-R (4-4-2)	Profit	884	2813	3779	3779	3779	4063	4636	4922	3946	1821	600	600	600	446	136
	Quantity Produced/(1000)	2.43	7.98	10.74	10.74	10.74	10.74	10.74	10.74	7.98	2.43	10.74	10.74	10.74	7.98	2.43
	Price per Usage	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.081	0.081	0.081	0.081	0.081
	Total Cost of Ownership	4674	4636	4631	4631	4631	4631	4631	4631	4636	4674	4025	4025	4025	4025	4025
	Selling Price	1273	1235	1231	1231	1231	1231	1231	1231	1235	1273	625	625	625	625	625
	Customer Satisfaction Index	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48	3.48
	Injury Rate	2.22	2.22	2.22	2.22	2.22	2.33	2.56	2.67	2.83	4.21	0.68	0.68	0.68	0.68	0.68
	Land Fill	5107	5107	5107	5107	5107	4998	4783	4676	4532	3859	166	166	166	166	166
	Energy Used	12285	12281	12281	12281	12281	12226	12116	12061	11989	11783	1130	1130	1130	1130	1130
	X - Foot Print	1228	1228	1228	1228	1228	1223	1211	1207	1199	1177	113	113	113	113	113
	Hazoudous material	17.60	17.60	17.60	17.60	17.60	16.69	14.87	13.96	12.74	5.10	-0.92	-0.92	-0.92	-0.92	-0.92
	Material Index	54.70	54.70	54.70	54.70	54.70	48.58	36.32	30.19	22.02	-43.34	-20.41	-20.41	-20.41	-20.41	-20.41

	Performance Measure	Year														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Product-R (3-4-2)	Profit	884	2813	3778	3778	3778	4068	4649	4939	3964	1834	608	608	608	453	138
	Quantity Produced/(1000)	2.42	7.94	10.68	10.68	10.68	10.68	10.68	10.68	7.94	2.42	10.67	10.67	10.67	7.94	2.42
	Price per Usage	0.092	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.092	0.079	0.079	0.079	0.079	0.079
	Total Cost of Ownership	4610	4572	4567	4567	4567	4567	4567	4567	4572	4610	3954	3954	3954	3954	3954
	Selling Price	1280	1242	1238	1238	1238	1238	1238	1238	1242	1280	625	625	625	625	625
	Customer Satisfaction Index	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
	Injury Rate	2.27	2.27	2.27	2.27	2.27	2.37	2.58	2.68	2.82	4.13	0.66	0.66	0.66	0.66	0.66
	Land Fill	5012	5012	5012	5012	5012	4906	4697	4593	4453	3797	159	159	159	159	159
	Energy Used	12531	12527	12527	12527	12527	12480	12388	12342	12282	12204	1132	1132	1132	1132	1132
	X - Foot Print	1253	1253	1253	1253	1253	1248	1238	1235	1228	1219	113	113	113	113	113
	Hazoudous material	17.60	17.60	17.60	17.60	17.60	16.81	15.22	14.42	13.36	7.10	-0.35	-0.35	-0.35	-0.35	-0.35
	Material Index	52.70	52.70	52.70	52.70	52.70	46.79	34.94	29.02	21.12	-42.04	-19.73	-19.73	-19.73	-19.73	-19.73

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