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A MULTI-STAGE DECISION SUPPORT MODEL FOR COORDINATED SUSTAINABLE PRODUCT AND SUPPLY CHAIN DESIGN

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ABSTRACT OF DISSERTATION

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The Graduate School
University of Kentucky
2011

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A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By
Haritha Metta

Lexington, Kentucky

Director: Dr. Fazleena Badurdeen, Assistant Professor of Mechanical Engineering
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A MULTI-STAGE DECISION SUPPORT MODEL FOR COORDINATED SUSTAINABLE PRODUCT AND SUPPLY CHAIN DESIGN

In this research, a decision support model for coordinating sustainable product and supply chain design decisions is developed using a multi-stage hierarchical approach. The model evaluates alternate product designs and their corresponding supply chain configurations to identify the best product design and the corresponding supply chain configuration that maximizes the economic, environmental and societal benefits. The model considers a total life-cycle approach and incorporates closed-loop flow among multiple product life-cycles. In the first stage, a mixed integer linear programming model is developed to select for each product design an optimal supply chain configuration that maximizes the profit. In the subsequent stages, the economic, environmental and societal multiple life-cycle analysis models are developed which assess the economic, environment and the societal performance of each product design and its optimal supply chain configuration to identify the best product design with highest sustainability benefits.

The decision support model is applied for an example problem to illustrate the procedure for identifying the best sustainable design. Later, the model is applied for a real-time refrigerator case to identify the best refrigerator design that maximizes economic, environmental and societal benefits. Further, sensitivity analysis is performed on the optimization model to study the closed-loop supply chain behavior under various situations. The results indicated that both product and supply chain design criteria significantly influence the performance of the supply chain. The results provided insights into closed-loop supply chain models and their behavior under various situations. Decision support models such as above can help a company identify the best designs that bring highest sustainability benefits, can provide a manager with holistic view and the impact of their design decisions on the supply chain performance and also provide areas for improvement.

KEYWORDS: Coordinated Design, Closed-loop Supply Chains,
Economic Optimization, Mixed Integer Linear Programming,
Multiple Life-cycle Analysis

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20 January 2011

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I dedicate my dissertation to my parents and my husband.

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1. CHAPTER ONE: INTRODUCTION

1.1 Overview

The increasing worldwide resource consumption coupled with its impact on the environmental and eco-systems have forced organizations to embrace sustainable practices within their business operations. For the business to be sustainable, the entire supply chain (SC) must be sustainable. During the recent years there has been growing awareness of the need for promoting sustainability within SCs among both academic and industry practitioners. This is evidenced by increasing number of articles and even comprehensive literature reviews (Croom et al., 2009) published in the area of Sustainable Supply Chain Management (SSCM). On the other hand, leading companies such as Wal-Mart, Procter & Gamble, IBM, and Hewlett-Packard (HP) launched several sustainability initiatives. Wal-Mart took commitment to goals of zero waste and reliance on 100% renewable energy, Procter & Gamble and IBM assessed sustainability performance of their suppliers, HP has launched several environmental-friendly initiatives in the areas of reducing the carbon footprint of their operations, developing energy-efficient solutions, etc (based on information in Wal-Mart Annual Report, 2010; Proctor & Gamble Sustainability Report, 2010; IBM Corporate Societal Responsibility report, 2009; Hewlett-Packard Global Sustainability Report, 2009). Despite this growing emphasis, yet, there appears to be lack of holistic systematic approaches that effectively integrate all the environmental and societal aspects into current SC practices/models. This is because developing sustainable SC's (SSCs) requires a broader emphasis considering multiple key aspects such as

The triple bottom line (TBL) emphasis: Although most of the current SSCM literature emphasized on the need for considering all the triple bottom line (TBL) aspects of economic prosperity, environmental protection and societal development (Elkington, 1998), as opposed to focusing merely on the economic gains, not much implementation has been found in comprehensively including all the TBL aspects into SSCM practices (Carter and Rogers, 2009). However, to promote SSCs there is a need to consider all the TBL aspects.

Holistic, systems-based approach: Most of the current SSCM practices do not consider holistic integrated approach (De Brito et al., 2010) and are focused on improving individual SC partner's performance such as supplier, manufacturing, distributor etc. However, if benefits (and potential costs) along the TBL aspects are to be considered in the SC's, a holistic and systems-based approach considering the entire SC as a single entity is needed. One way to achieve this holistic view is when considering the SC from a product life-cycle perspective, which consists of four phases: pre-manufacturing, manufacturing, use and post-use. Therefore SSCs must consider the impact of business decisions across all these four life-cycle phases.

6Rs for Sustainability: To develop SSCs a total life-cycle approach must be considered and this requires moving away from viewing the activities in the SC as being in an open-loop that takes materials from cradle-to-grave to adopting a cradle-to-cradle (McDonough and Braungart, 2002) philosophy with near perpetual closed-loop material flow. One of the early approaches that encouraged closed-loop thinking was the use of 3R's of reduce, reuse and recycle (USEPA, 2008); the emphasis however is mostly was on lean and green manufacturing and SCM. However, the 3R's do not emphasize the need to redesign products for dematerialization and disassembly or remanufacturing so components with useful remaining life can be given a new life in the next life-cycle of the same or different product. Thus, sustainable manufacturing and SCM require innovation-based approaches that extend the 3R's further into 6R's by including the capability to recover, redesign, and remanufacture the products over multiple product life-cycles (Joshi et al., 2006; Jawahir, 2008). Badurdeen et al. (2009) described each of the six "R' as follows:

- Reduce: This occurs primarily in first three stages of a product life-cycle: pre-manufacturing, manufacturing, and use. It refers to the reduced use of resources in the pre-manufacturing stage, reduced use of energy and materials in the manufacturing stage, and reduction waste during the use stage (USEPA, 2008).

- Reuse: This occurs primarily in the second and the subsequent life-cycle stages of a product. This refers to the reuse of the product or its components, after its use in the first life-cycle, for subsequent life-cycles to reduce the amount of raw (virgin) material usage involved in producing new products and components (USEPA, 2008).

- Recycle: is the process of transforming material (e.g. glass, metal and paper) that would otherwise be considered as waste into new materials or products (USEPA, 2008).

- Recover: It involves collection of products at the end of their use for subsequent post-use activities. It involves sorting and cleaning the product for its use in subsequent life-cycles. This process may also refer to disassembly of a product, to obtain its components at the end of its use life (Joshi et al., 2006).

- Redesign: is the act of redesigning products to simplify future post-use processes through the application of techniques such as design for environment (DfE) to make the product more sustainable (Joshi et al., 2006).

- Remanufacture: involves the re-processing of already used products for restoring them to a like-new condition, with similar or better performance to that of the original product, through the reuse of as much components and parts without loss of functionality (Joshi et al., 2006).

Badurdeen et al. (2009) presented a definition for SSCM as involving 'the *planning and management of sourcing, procurement, conversion and logistics activities involved during pre-manufacturing, manufacturing, use and post-use phases in the life cycle in closed-loop through multiple life-cycles with seamless information sharing about all product life-cycle phases between companies by explicitly considering the social and environmental implications to achieve a shared vision'*. Figure 1.1 presents the integrated approach to SSCs. While many definitions for SSCM have been presented in literature, in this research the above definition is adapted due to its completeness in integrating all the key aspects required for SSCs.

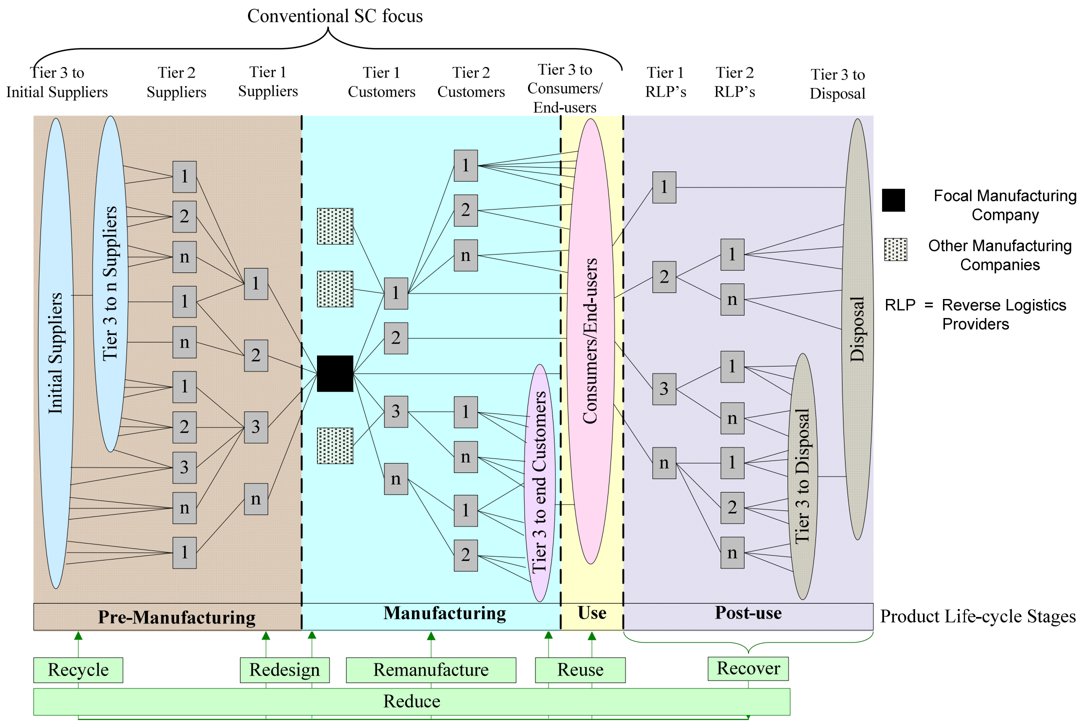


Figure 1.1: Integrated Approach to SSCM (Badurdeen et al., 2009)

The definition emphasizes the need to view the SC and its activities from a much broader framework. This definition also implies that managing SSC's requires more coordination and cooperation between the activities of product and process designers/managers and their SC counterparts that is more integrating among the product, process and SC design activities. For example, designing sustainable products for end-of-life recovery without evaluating the SC's capability/capacity needed to recover and re-channel the products will likely lead to more (TBL) costs than benefits. Similarly, recycling products to reduce environmental impact may not be successful unless process capabilities needed to remanufacture such products, their market potential etc., are evaluated. This implies that all the activities involved within SSCs such as product design (Krishnan and Ulrich, 2001), manufacturing system design, process design, reverse logistics network design (Guide et al., 2003; Guide et al., 2006), closed-loop SC network design (Guide and Wassenhove, 2009), etc., require coordination among product, process and SC design decisions effectively.

Coordinated Design: Integrating Product, Process and SC Design

Changing customer expectations and short product life-cycles, due to rapidly changing technology, have compelled companies to be innovative (Ayag, 2005) and offer product variants and/or new products in much shorter time intervals. However, developing new products alone in response to these trends is not a formula for success. In order to be successful, companies must explicitly consider and assess the process and system capabilities (needed to procure resources, manufacture and distribute the product in a timely manner to meet customer needs) at the product design stage itself. Lack of coordination between these different activities can lead to, for example, material acquisition delays, increased production/delivery lead times, etc., all of which can be stumbling blocks to success. Competitive advantages are likely when companies pursue coordinated design along three different aspects, as described below:

Coordinated Product and Process Design: The importance of concurrent engineering , the process of integrating product and process design decisions, was pointed out as early as 1979 by Hayes and Wheelwright (1979a, 1979b). Progressive companies have adopted the practice and a number of approaches for pursuing concurrent engineering have been presented (Brookes and Backhouse, 1998; Keys et al., 1992).

Coordinated Product and SC Design: Design for SC (Hult and Swan, 2003; Rungtusanatham and Forza, 2005), or the integration of product and SC design decisions is another aspect critical for improving SC performance. Recent trends in globalization and many companies outsourcing design activities caused SCs to become much more complex networks. This has created a need for more coordination and integration of SC partners into the product design process often termed as the New Product Development (NPD) stage. However, despite the early attention drawn to the topic (Lee and Sasser, 1995; Joglekar and Rosenthal, 2003), very little has been published on how to pursue coordinated product and SC design.

Coordinating Process and SC Design: The changing customer needs indicate that merely synchronizing product and process design and/or product and SC design is not sufficient to ensure an organization's success (Rungtusanatham and Forza, 2005). Coordinating process and SC design decisions can bring more cost savings and improved performance to companies.

The process of coordination of product, process and system design decisions was termed by Fine (1998) as 'three-dimensional concurrent engineering (3-DCE)'. Organizations that do not engage in 3-DCE often encounter problems in the later stages of NPD process, often leading to loss of revenue and reputation (Fine, 1998).

1.2 Motivation

This research specifically focuses on coordinating sustainable product and SC design (CSD) decisions, which is analogous to coordinating conventional product and SC design decisions, but with a much broader focus, considering all the key aspects required for SSCs as mentioned earlier. This coordination plays a very important role in improving the SSC performance. In this section, two case study examples of companies are presented to illustrate the importance of performing CSD. The first case example presents how a company has been successful through implementing CSD, while the second case study presents the severe losses incurred by a company due to ignoring the implications of product design decisions on the SC (even in the absence of sustainability considerations).

Kodak Single-Use Camera:

The case of Kodak single-use cameras illustrates a classic example of the application of CSD to design a sustainable product and closed-loop SC. In 1990, Kodak began redesigning their single-use cameras to facilitate recycling and reuse of parts and sub-assemblies. The new design consisted of simple parts most of which were either recycled or reused requiring fewer new parts to be manufactured, thereby reducing the overall resource consumption. The new design thus incorporated all the 6R's previously discussed as necessary for sustainable manufacturing and SCM.

The SC operations of the single-use cameras begin with the procurement of circuit boards, which are manufactured overseas and shipped to the production facility in Rochester, NY. The demand for new cameras is met by a mixture of both new and reused components. The finished cameras are then distributed to various retailers and subsequently sold to customers. After use, customers take the camera to a photofinisher. Kodak and some of its major single-use camera competitors have an agreement as a result of which all single-use cameras collected by photo finishers (i.e. no sorting by brand needed) is sent to one of three collection centers (recovery). The collection centers sort the cameras based on manufacturer and model; Kodak cameras are then transported to the subcontracting facility, where the packaging, front and back covers and batteries are removed. The cameras are then sent to assembly vendors who disassemble and inspect the products. While few parts such as the batteries are replaced, most are reused or recycled after quality inspection. The camera body and internal parts in good condition are reused; other parts such as the plastic outer casing are recycled (after careful separation of metal from plastic). All the reusable and recycled components are sent to the production facility where they are assembled into new products (remanufacturing), packaged and distributed to retailers for resale (based on information in Guide et al., 2003; Kodak Sustainability Report, 2008). Figure 1.2 presents the closed-loop SC for Kodak single-use cameras illustrating the points of application of the 6R's.

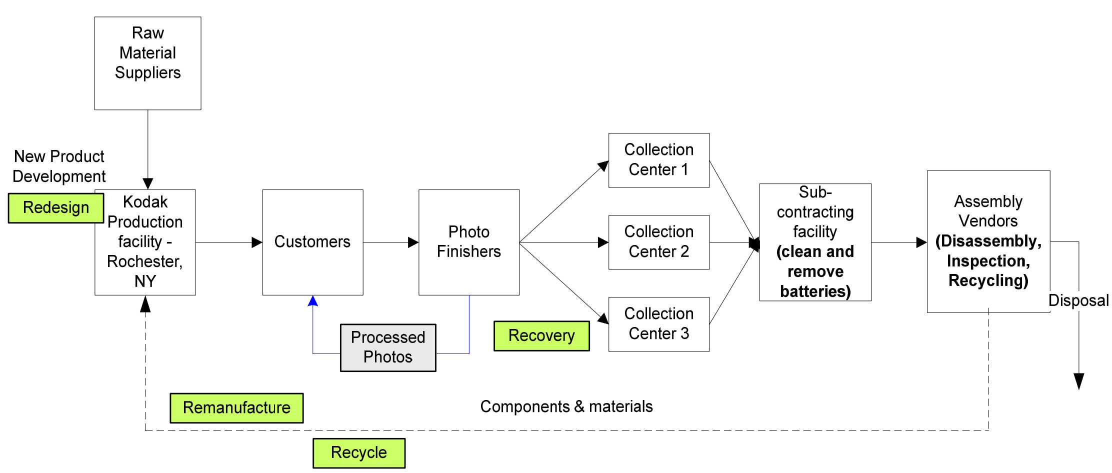


Figure 1.2: Closed-loop SC for Kodak Single-Use Cameras

With the current business model Kodak has been able achieve a recycling rate of 84%, the highest for any consumer product in the USA, and reached the milestone of recycling 1.5 billion single-use cameras (including those from competitors) (Kodak Global Sustainability Report, 2008). Kodak's success with these very sustainable single-use cameras can attributed to adopting CSD methods to simultaneously evaluate and benefit from the SC capabilities while designing the product.

Global Telecommunication Manufacturer:

In contrast to Kodak, many companies have had disastrous experiences by failing to appreciate the linkage between product and SC design decisions. One example is the case of a global telecommunication manufacturer that experienced a problem with one of its central office switches. The switch, whose price ranged $75,000-$200,000 per-unit, required continuous always-on duty cycles, which lead the hard drive to wear-out. This has resulted in double-digit percentage product failures which approximately cost $5,000 (per failure) in just service expenses (excluding parts, travel, and other intangible losses). The current hard drive solution costs $150, and a new replacement drive cost less than $500. The SC refused to purchase the replacement as it is three times the current price, but it however, did not consider the huge service expenses caused due to the double digit failures from the current hard drive solution. The incident cost the company millions of dollars and also led to loss of reputation (Western Digital, 2009). Though this product cannot be classified as a sustainable product, had the company investigated SC design (partners, capabilities/capacities needed) in parallel at the time of designing switches this situation could have been avoided.

1.3 Problem Statement

The importance of coordinating product and SC design decisions in conventional SC's has been pointed out in literature already. When it comes to SSCM there is a need to focus on all the four product life-cycle stages as mentioned earlier and a number of companies (SC partners) are likely be engaged in each of these stages. Given that nearly 80% of the product's cost is determined during its design (Boothroyd et al., 1994) most of the costs (and benefits) incurred across the SC are also dependent upon the decisions made during product design. Thus, in SSC's CSD is imperative if the TBL costs (benefits) are to be minimized (maximized) across the total life-cycle (Metta and Badurdeen, 2009). Further, for SCCs, to successfully achieve closed-loop flow, it is important to not only consider how the design decisions affect the forward loop SC operations (pre-manufacturing, manufacturing, use phases) but also the reverse loop operations (such as recovery, reuse, remanufacturing and recycling). These costs and benefits realized through these operations, in turn, depend on the SC configuration such as number and location of SC partners, and their capabilities and capacities. Successfully CSD helps in identifying the optimal sustainable Product Design and its corresponding SC Configuration (PDSCC) combination - either existing or to be developed - that ensures the desired return of investment and other TBL benefits are achieved (Metta and Badurdeen, 2009).

Quantitative decision-support models for CSD that can evaluate a given set of sustainable product designs at the NPD stage and their impact on SC's can help managers identify the best product designs that will bring highest sustainability benefits to the entire SC. NPD is a multi-stage process as illustrated in Figure 1.3 (Gokhan, 2007). It includes the conceptual design, physical design, detailed design and the final design stages. During the conceptual design stage, hypothetical designs are created by establishing the potential functional features. In the physical design stage, general product features and its design specifications are created. The individual components and sub-assemblies are designed and tested for functionality during the detailed design stage. The design specifications are then confirmed for the selected products and documented during the last stage of NPD. Therefore, the most appropriate stage to evaluate the impact of alternate product designs on their corresponding SC configurations would be during the detailed design stage of NPD. Gokhan (2007) mentioned that each of these four stages does not work in isolation and there exists flow of information between consecutive stages, in terms of feed forward and feedback loops as illustrated in Figure 1.3.

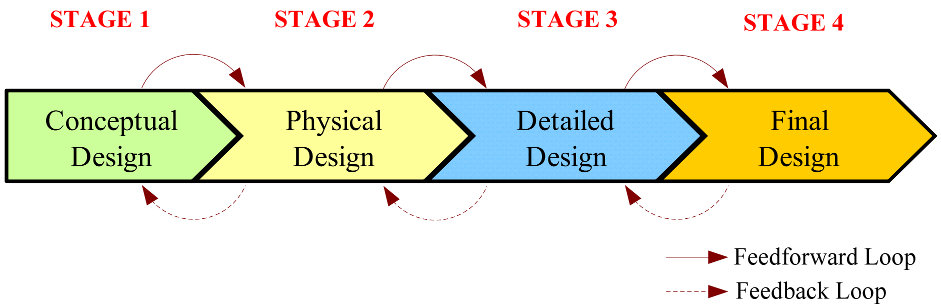


Figure 1.3: Stages in New Product Development (Adapted and Modified from Gokhan, 2007)

1.4 Research Objectives and Contributions

The objective of this research is to develop a decision-support model for CSD that evaluates the impact of alternate product designs on their corresponding SC configuration (number and location of SC partners, their capacities and capacities) to select the best PDSCC combination that maximizes overall sustainability benefits. Integrating/coordinating sustainable product and SC design decisions is a complex task, which involves consideration of all the TBL aspects of sustainability, evaluating the impact of product design across all four product life-cycle stages, and incorporating a closed-loop flow over multiple life-cycles (MLCs) thereby reducing the overall material and resource consumption. This research aims at developing a multi-stage hierarchal approach to pursue this CSD by considering all the relevant aspects.

By using the developed decision support model (termed as CSD model), which includes the Economic Optimization Model (EOM) and the economic, environmental and societal MLC analysis tools, this research primarily aims at identifying the best PDSCC that maximizes economic benefits and minimizes environmental and societal impacts from a given set of alternate designs. In addition, this research aims at addressing several research questions such as:

1) *What are the key factors that influence the selection of optimal SC configuration for each product design?*

   This question addresses what product design and SC design related factors majorly impact the selection of optimal SC configuration and thereby the overall costs/profits. Knowing these factors can provide several opportunities for performance improvement for alternate designs which can contribute to the overall success of a company.

2) *What are the impact/benefits of pursuing a closed-loop flow in SSCs and how does this vary among alternate products?*

   This question investigates the benefits/impact of pursuing a closed-loop flow over MLCs for each PDSCC combination, by comparing their performance with open-loop SC model to address several sub-questions such as:

   a) For what type of products pursing closed-loop flow generates more benefits?
   b) What are the key factors that influence the closed-loop SC performance for a given PDSCC combination?
   c) How many life-cycles a particular product design must have before the benefits of pursuing closed-loop flow are realized?

Most of the previous research in this area focused on several relevant stand-alone areas such as improving only one or two of the TBL aspects, or considering only the reverse logistic operations, focusing on only one product life-cycle, etc. However, none has been performed in CSD that considered the entire SC as a single entity by considering all the key aspects required for SSCs, as in this research. Therefore, this research aims to fill this gap by developing a multi-stage hierarchical approach for performing CSD. Another contribution is that the developed CSD model and associated sub-models are not restricted for a specific product type and can be used for any type of product in any manufacturing industry. Further, this research provides insights on various complexities associated with designing and modeling SSCs and also solutions to address some of these challenges. The developed CSD model is applied for a real-time refrigerator case study.

1.5 Overview of the Dissertation

This dissertation is organized as follows:

Chapter two presents a detailed literature review in the areas of conventional SC models, facility location-allocation models, life-cycle analysis and green SC models, reverse logistic and closed-loop SC models. This is followed by a review of existing literature in coordinated product and SC design models and the limitations of these models from SSC perspective.

The methodology for solving the CSD problem that is the multi-stage hierarchical approach is explained in detail in Chapter three. The complete optimization model formulation and its notations, and the procedures for developing the economic, environmental and societal MLC analysis tools are all explained here.

Chapter four presents the application of the CSD model for an example problem consisting of four alternate product designs (each having 3 different components) at the NPD stage. The step-by-step procedure to apply the CSD model is explained in this Chapter. Also, the results obtained from the CSD model are explained in-detail here.

Chapter five presents an application of the developed CSD model for a real-time refrigerator case. A general description of the company, the problem scope and the product and the SC design related data are provided in this chapter. The CSD problem formulation and the results obtained (the best PDSCC combination with maximum economic benefits and also with minimum environmental and societal impacts) are presented in this chapter. Chapter six presents all the sensitivity analysis performed on the optimization model.

Chapter seven summarizes the findings of this research. Also, future research opportunities and ideas for extending the developed CSD model are discussed here.

2. CHAPTER TWO: LITERATURE REVIEW

This section presents a review of literature in the area of SC design and analysis. A comprehensive review of literature in the areas of the conventional SC models, facility location-allocation models, life-cycle analysis and green SC models, reverse logistic and closed-loop SC models along with their solution methodologies are presented. Following this, a detailed review of literature in coordinated product and SC design is provided. The chapter is concluded by discussing the scope and limitations of existing models from a SSC perspective.

2.1 Conventional SC Models

Initially, most of the work in SCM is focused to optimize an individual SC partner's performance such as suppliers, manufacturers, distributors, retailers ect. Within the manufacturing area, a lot of development has been made in the area of two-stage multi-echelon inventory models since the classic work of Clark and Scraf (1960), who developed a quantitative model to determine the optimal purchasing policy for a multi-echelon inventory problem. Since then several papers were published on SC design in deterministic analytical models (Ishii et al., 1988), stochastic analytical models (Svoronos and Zipkin 1991), economic models (Christy and Grout, 1994) and simulation models (Towill et al., 1992). A comprehensive review of work in multi-stage SC modeling is provided in Beamon (1998). In their paper, they also reviewed the most common performance measures used in SC models. They presented that among the qualitative measures the most important ones are the customer satisfaction, flexibility, information integration, risk management and supplier performance. Among the quantitative measures, the most commonly used ones are the cost and/or customer responsiveness related objectives. The most common decision variables used in SC models are scheduling related, or identifying optimal quantities, optimal number of stages, optimal number of facilities to be opened and allocation of tasks to these facilities etc. to achieve the desired objective. Min and Zhuo (2002) presented the application of simulation techniques to model SC in an extended enterprise. They also provided a review of existing simulation techniques and compared the performance features of a variety of benchmark simulation software. Li et al. (2007) presented a review of literature in the areas of key factors affecting SC performance and the relationships among them, existing simulation models that consider these factors, and dynamic performance optimization methods. They focused in the area of dynamic performance analysis of SCs and provided suggestions on the tool that can help solve such complex dynamic SC models.

Recently, the emerging issues such as outsourcing and globalization of activities in SCs, coupled with changing customer demands, shorter product life-cycles, shrinkage of resources have motivated researchers to design and analyze the SC as a single entity and to investigate global SC issues. Vidal and Goetschalckx (1997) performed literature review on strategic production-distribution models in the areas of applications of optimization methods, modeling issues, case studies and applications. They focused on global logistics models, provided limitations of existing models and identified opportunities for further research. Prasad and Babbar (2000) identified the growing interest and long history of literature in global operational issues, which is supported by an increase in the number of articles published in the leading operations management journals. Meixell and Gargeya (2005) presented a literature review of decision support models for global SC design in the areas of decisions variables, performance metrics, integrated decisions, and the extent to which globalization issues are considered in the models. They concluded that very few models address the practical global SC design issues.

Recently, Goh et al. (2007) developed a multi-objective stochastic optimization model for solving a multi-stage global SC network problem to maximize profit and minimize risk. They considered risks related to supply, demand, exchange, and disruption. They designed an algorithm and presented a solution methodology using the Moreau–Yosida regularization. Li and Xu (2009) developed a multi–tier dynamic global SC network equilibrium model to maximize the profits. Their model considered three tiers of manufacturers, retailers and consumers at different demand markets, as decision-makers. They studied the interactions among different decision-makers, identified optimal and equilibrium conditions and formulated the global SC network as a time-dependent network equilibrium problem.

2.1.1 Facility Location-Allocation Models

In general, facility location/allocation SC models evaluate all the possible SC facilities and their locations to select the optimal number of facilities to be opened at a given location and determine the optimal quantities to be allocated to these facilities. This process of identifying the optimal SC configuration is a critical part of the SC design process. Facility location-allocation has been a well-established area of research. Min et al. (1998) reviewed the existing location routing literature and developed taxonomy for classifying the location-routing research. Most of the initial research in the area of location/allocation models is focused on merely designing the distribution system networks and did not consider the entire SC into consideration. Louwers et al. (1999) developed a mathematical model to solve a facility location-allocation problem for reusing carpet materials through collecting and preprocessing the carpet waste while minimizing the total SC network costs. The model provided a free choice for the preprocessing center locations and incorporates depreciation costs. Melkote and Daskin (2001) developed a Mixed Integer Programming (MIP) approach for a network allocation model that minimizes the sum of transportation, facility location, and the construction costs. Several extensions of the model are provided to be used for real-time applications such as regional planning, energy management. Klose and Drexl (2005) reviewed 199 papers that developed facility location models for distribution system design and provided a review of continuous location models, network location models, MIP models. They reviewed uncapacitated, single-stage, capacitated, multi-stage, multi-product, dynamic, probabilistic, hub location, routing location and multi-objective MIP based location models. Li et al. (2007) presented a short review on distribution center location problems, their sources, and progress over past years. The paper explained basic models and future research directions in this area.

Manzini and Gebennini (2008) developed a Mixed Integer Linear Programming (MILP) optimization models to design and manage dynamic, multi-stage and multi-commodity SC network problems with production plants, distribution centers and customers to find optimal facilities to be opened that will optimize production and inventory levels. Their model is applied to an industrial case study. Thanh et al. (2008) developed a MILP based model for the design and planning of a multi-echelon, multi-commodity production-distribution network with deterministic demands. They considered both strategic and tactical dynamic decisions such as opening, closing or enlargement of facilities, supplier selection, flow along the SC. Klimberg and Ratick (2008) developed location modeling formulations using data envelopment analysis efficiency measures to find optimal facility location-allocation patterns and thereby provided an approach for solving multi objective location problems. Melo et al. (2008) provided a comprehensive review of 120 location-allocation models in SCM and discussed the integration of location decisions with other SC network design related decisions. Ho et al. (2010) reviewed 78 journal articles on the multi-criteria supplier evaluation and selection methods and summarized the most commonly applied approaches, performance criteria and presented the limitations of such approaches. Recently, Afshari et al. (2010) developed a MIP model to solve a distribution network design to minimize total establishment, transportation and inventory costs in multi-commodity, and single period with inventory concerns. The model is applied for a case study to design an automobile distribution network through identifying the optimal locations of warehouses.

2.2 Life-cycle Analysis and Green Supply Chain Models

During past decade, the increasing environmental impact caused by the outsourcing and globalization activities, and the subsequent government legislations and regulatory requirements called for integration of environmental management procedures into the SCM operations. This field referred to as the Green SCM (GSCM) is growing extensively with a significant amount of literature in several areas evolved from monitoring existing environmental practices through proactively considering environmental issues at the NPD stage. It was reported that at least 1,500 articles are published in GSCM in scholarly journals and edited books (Srivastava, 2007).

Some of the early work in greening the SC includes that of Ayres and Kneese (1969) who discussed several environmental issues related to reconciling industrial metabolism and material balancing and roles of production and consumption of SCs. Since then a lot of advancements have been made in the field of environmental impact assessment including the development of Life Cycle Assessment (LCA) concepts and analysis tools (Arena et al., 2003). Miettinen and Hamalainen (1997) presented the application of decision analysis methods and tools in planning of LCA study and in interpretation of results. They explained that the integration of decision analysis and LCA can make LCA a better decision making tool. They illustrated their approach through performing an LCA study on beverage packing systems. Tibben-Lembke (2002) studied the impact of changes in sales over the product's life cycle on the reverse logistics. They observed that a reverse logistic manager faces multiple challenges in each of different product life-cycle stages which mainly depend on whether a product is newly introduced to the market, or an alternative of existing models or just a new model of existing form. They provided suggestion on how logistic managers can consider the product life-cycle in making reverse logistics decisions. Later, Browne et al. (2005) used LCA as a tool to analyze transportation activities in a product SC and applied for a case study of energy use.

A lot of work has been performed in green purchasing. Humphreys et al. (2003) provided a decision support tool that helps companies integrating environmental factors into their supplier selection process. They identified quantitative and qualitative environmental criteria and developed a framework for integrating these criteria into supplier selection process. Rock et al. (2006) performed a case study on Motorola and identified if the environmental standards are complied by its suppliers located in other countries. Lee et al. (2009) developed a model for evaluating green suppliers which can help companies to understand the capabilities of a green supplier and can also evaluate and select the most suitable supplier.

Literature is also available in area of green design includes environmentally conscious design (ECD) (Beamon, 1998), green operations including green manufacturing and remanufacturing, integrating product design (Thierry et al., 1995). Beamon (1999) developed a general procedure towards designing and managing GSCs. They discussed the emerging environmental concerns and presented the need for extended environmental SCs. Their extended environmental SC model includes both forward and reverse loop SC partners and considers corresponding operations. They explained the differences between conventional SCs and the extended models and associated complexities. The paper also presented economic and environmental performance metrics that can be used in extended models. However, their model does not consider the societal aspect of the TBL. Gungor and Gupta (1999) provided a detailed review of work in the environmentally conscious manufacturing and product recovery. Glantschnig (1994) investigated on the challenges faced by green tool design specialists and presents some factors that impact the green design. Zhang et al. (1997) provided a comprehensive review of literature in green design. A significant number of papers in this area considered legislative regulations during the product design stage (Das, 2002). The Supply Chain Council developed the Green Supply Chain Operations Reference (GreenSCOR) in 2003, which is a modification of version 5.0 of the Supply Chain Operations Reference (SCOR) model, by integrating the environmental metrics to the SCOR framework. The GreenSCOR is an integrated green tool that enables companies to track their SC and environmental impacts simultaneously. A review of current GSCM literature is provided in Srivastava (2007).

Recently, Zhu et al. (2008) studied the construct and the scale for evaluating GSCM practice implementation among manufacturers. They collected data from 341 Chinese manufacturers and tested two measurement models of GSCM practice implementation. Their findings indicated that both the first-order and the second-order models for GSCM implementation are reliable and valid. They presented a 21-item measurement scale which can help a company evaluate their strengths and weaknesses in implementing GSCM practices in their firms. Zhou (2009) identified the challenges in implementing the GSCM in special industrial operations. They studied the core aspects required for textile and apparel enterprises for successful implementation of GSCM practices. They identified aspects such as establishment of strategic view, development of a flow system, consideration of environmental based performance, cooperation among partners, and development of performance evaluation and management systems are required for efficient green textile SCs.

Recently, green performance criteria are increasingly being considered in conventional SC models. Reed et al. (2010) reviewed methods for quantifying carbon dioxide emissions and estimated the costs of going green in conventional SC optimization models. Their goal was to provide a foundation that can help researchers in extending current scope of GSC optimization models to include green transportation costs. They presented a set of carbon calculators for common transportation modes and illustrated their operational procedures. Paksoy (2010) developed a multi-period multi-objective optimization model for a GSC. Their SC network considers two echelons, consists of six suppliers, manufacturers and customer zones. The model is formulated as a MILP problem with an objective to identify the optimal SC configuration that minimizes total transportation costs and CO_2 emissions (including manufacturing), penalty cost (due to exceeding emissions limit) within SC. Later, Wang et al. (2011) developed a multi-objective optimization model using a normalized normal constraint method to solve the GSC design problem using a MIP solver CPLEX 9.0 to identify the pareto optimal solutions that minimizes cost and environmental impact. They concluded that their model provides a portfolio of configurations for decision makers and can serve as an effective tool in designing a GSC network. Recently, work is performed on integrating LCA into GSC design in dynamic environments. Nwe et al. (2010) presented an approach for GSC design and management by integrating LCA indicators and performing a dynamic simulation in MATLAB/Simulink. They considered environmental performance metrics as well as profit and customer satisfaction into the SC dynamic model. The model is applied to two metal-working case studies.

2.3 Reverse Logistic and Closed-Loop SC Models

Recently increasing amount of literature emerged in the areas of reverse SCs, reverse logistics, closed-loop SCs models etc. A comprehensive review of quantitative models available for reverse logistics is provided by Fleischmann et al. (1997). Jayaraman et al.

(1999) developed a closed-loop logistic model based on a MILP approach considering remanufacturing. Their model selects the optimal number of remanufacturing facilities to be opened, their locations, and the optimal quantities to be transported to each of these facilities to minimize the total logistic costs. Their model besides from finding optimal remanufacturing locations was also analyzed to identify factors that impact the design of closed-loop logistic system with remanufacturing. Fleischmann et al. (2000) investigated the design of the reverse logistic networks that recover the used products. They identified the basic characteristics of product recovery networks and classified the product recovery networks into three types such as recycling, remanufacturing and reuse networks.

Hu et al. (2002) developed a discrete-time linear analytical model for a multi-time-step, multi-type hazardous-waste reverse logistics system to minimize the total reverse logistic costs. Their optimization model solved the classical hazardous-waste treatment problem by considered coordination among the critical reverse logistic management activities and by implementing a systematic management strategy. Later, Guide et al. (2003) used a contingency approach to identify factors that impact the production planning and control in closed-loop SCs with product recovery. They studied three different cases and developed a framework that presents the common activities involved in all remanufacturing operations. Dobos and Richter (2004) investigated a production-recycling system by analyzing two different models, the first one studied the economic order quantity-related costs and minimized the relevant costs, while the second model is a generalized version of the first model with cost function linear to other costs and identified the strategy that generates the optimal solution by studying these two models. Later, Dobos and Richter (2006) extended their models to consider the retuned product quality and studied whether the supplier or the user must conduct the quality inspection, and identified the most effective quality control approach for their cases.

Nukala and Gupta (2005) developed a fuzzy Analytical Hierarchy Process (AHP) method to select the recovery facilities in a closed-loop SC model. Their approach uses triangular fuzzy numbers for pair-wise comparisons, extent analysis method for the synthetic extent value of the fuzzy pair-wise comparisons, and principle of comparison of fuzzy numbers to derive the weight vectors. Kim et al. (2006) developed and validated a mathematical model for remanufacturing the reusable parts in reverse logistics environment where manufacturer can either order new parts from suppliers or use 'as new' parts from refurbishing or remanufacturing subcontractor to satisfy his demand. The model identifies the optimal number of parts to be processed at each remanufacturing facility and the number of parts to be purchased from subcontractor to maximize the total cost savings. Min et al. (2006) developed a mixed-integer, nonlinear programming model and a genetic algorithm to identify the optimal solution that minimized cost for the closed-loop SC network design problem with both spatial and temporal consolidation of returned products. Their model was applied to an example in which products are returned from online and retail sales. Later, Guide et al. (2006) developed a network flow with delay models to identify the drivers of reverse SC design through considering the marginal value of time. Further, they examined the impact of industry clockspeed on the selection of an efficient and a responsive return network.

Solvang et al. (2007) proposed a closed-loop SC framework for overall optimization of eco-efficiency. They presented a need for including waste treatment and purification processes in current closed-loop SC models. Kara et al. (2007) developed a decision support simulation tool/model for a reverse logistics network that collects end-of-life appliances in the Sydney Metropolitan Area. They presented that their model calculates the collection cost in a predictable manner. Wojanowski et al. (2007) provided an analytical framework for designing a firm's collection facility network considering deposit-refund and determining the sales price that maximize the firm's profit under a given deposit-refund. They identified that returned product value is a key factor that determines the nature of collection in an industry. Aras et al. (2008) developed a mixed-integer nonlinear programming model and a tabu search based heuristic for identifying the optimal locations for collection centers and the best incentive values for returns of different quality levels. Lu et al. (2008) developed a multi-objective optimization model for reverse logistics network that minimizes total cost of environmental impact. However, their model considers only the waste recycling factors and transportation related factors into the environmental impact computations.

Yang et al. (2009) developed a mathematical model and a genetic local search algorithm for the facility location-allocation problem in closed-loop SCs to optimize the total cost. In their model, they considered both forward logistics and reverse logistics, and variable demand. Agrawal and Toktay (2009) presented case studies of several companies that currently engage in closed-loop SC activities including Interface, Inc., Army, and MedShare International and the issues they are facing while managing these operations. They further identified common research areas that can influence the successful design and management of such models. They finally proposed that a multi-disciplinary approach is needed to solve the managerial issues within closed-loop SCs. A comprehensive review of closed-loop SC research from the past 15 years is provided in Guide and Wassenhove (2009).

As observed from the review of closed-loop SC models and from location-allocation models, while a variety of tools were used to formulate the closed-loop SC location-allocation problem, Linear Programming (LP), MIP and MILP were found to be the most commonly used methodologies (Fleischmann et al. 2001) followed by dynamic programming (Inderfurth and van der Laan, 2001). Geng et al. (2009) developed a mathematical programming model for a distribution reverse logistic system integrating GSCM. To reduce the complexity, they adapted a heuristic methodology in which sub-problems with reduced sets of decision variables are solved iteratively to find optimal solutions. Shi et al., (2009) developed a MILP model to minimize the total cost for a reverse logistics network comprising of returned medical waste. The model is tested for an example problem in which the medical waste was returned from hospitals to a given medical materials producer. Fernandes et al. (2010) examined a real-time closed-loop SC model that manufactures lead batteries, the distribution partners and its recovery at the end-of-life. They developed a MILP model that identifies the optimal closed-loop SC partners to minimize total costs. The model considered various costs such as the cost of opening warehouses, the cost of the raw material, transportation costs etc. Kara and Onut (2010) developed a two-stage stochastic model using a MIP approach to identify the facility locations and transportation quantities for reverse SC network under uncertainty.

However, they considered only recycling and collection facilities. De Brito et al. (2010) studied the causes for lack of integration of sustainability into issues in SCM and operational management research and suggested on how to overcome it. They mentioned that integrating sustainability requires multi-objective studies and must transcend multiple disciplines and both of the above are very difficult tasks to pursue.

2.4 Coordinated Product and SC Design Models

Despite the importance of the issue, very limited literature is available in coordinating product and SC design decisions even without sustainability considerations (Rungtusanatham and Forza, 2005; Metta and Badurdeen, 2009). Most of the initial work focused on supplier integration into the product design stage. Choudhury (2007) developed a methodology using a goal programming approach for integrated product design and supplier selection problem through implementing lean principles and selected the optimal supplier network. They considered importance of communication to the extended enterprise network and created an analytical model to map causes of communication among suppliers. They studied the effect of part count reduction strategy and redesigned the product architecture to minimize the part count and observed that this method can improve the leanness of a supplier network. They applied their model for a power drill case. Krikke et al. (2003) developed a quantitative model to coordinate the decisions between product and logistic network design for application to a refrigerator case study. However, their model was limited to optimizing the reverse flow operations and not the entire SC. Fixson (2004) developed a product architecture framework as a mechanism to coordinate decisions across product, process and SC design. The framework, however, is limited to considering only the product architecture with little or no consideration of SC design aspects.

Recently, Gokhan (2007) developed a design for SC optimization model that simultaneously considers product and SC design decisions at the product design phase. The model selects the product's components from a set of alternative designs. This paper considers the SC performance criteria and the associated price levels to maximize the profit. However, the model is limited to the choice of product design alternatives and selecting suppliers (i.e. only upstream SC partner selection). Another limitation is that their model focuses only on economic optimization with no consideration of environmental and societal aspects, important from a SSC perspective. Sanders (2009) investigated the relationship between the product design and SC design for a specific product manufactured by Philips Healthcare and developed a quantitative model that compares different product and SC designs subject to a range of parameter settings. Their model can serve as a decision support tool for evaluating future product designs. However, they do not consider a closed-loop flow and all the sustainability aspects needed for SSCs.

Recently, Chiu and Okudan (2010) presented a graph theory-based optimization method to integrate product and SC design decisions at the product design stage. They evaluated the impact of supplier selection process on both manufacturing and external enterprise performance. They incorporated these sub-performance measures into the SC performance and applied their model for a bicycle case study. However, they do not consider the entire SC partners and sustainability issues in their model. Table 2.1 presents a summary of the current literature relevant to the CSD problem including their scope/coverage.

Table 2.1: Literature Summary in Coordinated Sustainable Product and SC Design

Author(s)	Description	Scope/Coverage
Krikke et al. (2003)	Developed quantitative optimization model to coordinate product and logistic network design decisions	Does not optimize overall SC performance
Rungtusanatham and Forza (2005a)	Discussed need for coordinating product, process and SC design decisions. Reviewed papers that provide insights into performance implications of such coordination	Literature Review
Forza et al. (2005b)	Presented a review of papers that developed methods to facilitate the coordination between product, process and SC design	
Fixson (2005)	Developed product architecture framework to coordinate product, process and SC design decisions	Does not consider the SC configuration aspects in the framework
Gokhan (2007)	Developed an optimization model that simultaneously considers product and SC design decisions in the product design phase	Does not consider overall SC performance Does not consider all the TBL aspects

2.5 Limitations of Existing Models from SSC Perspective

All of the models/approaches discussed earlier, are limited to considering only a single or two life-cycle stages at a time (either premanufacturing and manufacturing or only post-use). However, for SSCM an integrated approach to involving all the four life-cycle stages must be considered.

Another major drawback of current SC models is the narrowed focus on cost minimization (Lebreton and Tuma, 2006). The definition of sustainability has been evolving over past years, while some companies consider sustainability as the extension/prolonging of use phase, for others sustainability primarily means environmental stewardship (Srivastava, 2007). For some firms, sustainability means conducting actions related to social responsibility. However, in actual sense sustainability must consider all the TBL aspects simultaneously. On the other hand, most of the work that has been performed in sustainability, in general has avoided much focus on the financial portion of sustainability and concentrated on the individual aspects of environment and social responsibility. But to achieve TBL, emphasis must be given to all the three aspects simultaneously.

Another drawback is that most of the models consider a single time period. However, to observe the true benefits/impacts of pursuing a closed-loop flow there is a need to run the SC models over multi-time periods to capture the true performance over multiple product life-cycles. This is because, as opposed to conventional SC models, for closed-loop SC models additional reverse loop related costs are incurred during the initial years. However, the benefits of these reverse loop operations are observed only after few years (depending on when the used products are collected, processed and are made ready for their next life). These values depend on several varying uncertainties such as return time, return quality and quantity, which must be determined. Therefore, several reverse loop modeling issues must be considered while developing closed-loop SC models for durable products for MLCs.

Another challenge is with quantifying the performance of a CSD model that considers all the economic, environmental and societal aspects of sustainability. While the economic aspect can be measured through economic value added, profit/loss metrics, there is no such integrated approach to quantify environmental and societal performance. Although LCA was one of the most comprehensive tools used for assessing environmental impact, integrating the complete LCA into existing SC models seems like a cumbersome task. Hence, most of the literature uses CO_2 emissions, energy consumption, carbon footprint etc. to quantify the environmental impact (krikke et al. 2003); however a total integrated approach is missing in current models. Another limitation is in the area of social sustainability. Very limited or none is available and among the available literature, a majority is from the area of CSR which emphasizes on a need for addressing societal impacts. Further, they provide guidelines/principles (such as ISO 26000 guidelines, IBM supplier conduct principles/guidelines) that could potentially enable companies to be socially responsible (Kastenhofer and Rammel, 2005). However, a systematic study is lacking in this subject with respect to sustainability. Very little or none reported any form of measures or performance tracking systems that can measure, monitor societal impact. The current practices in majority of companies are limited to metrics at operational level (such as employee numbers, accident rate, absenteeism rate, supplier and employee training and development). Very few metrics exist at the strategic level.

Another difficulty is that even though appropriate metrics are identified for each of the TBL aspects, simultaneously quantifying them in CSD models is a challenge. The units of measuring economic, environmental and societal metrics can vary. Even within environmental and societal metrics, there is no single unit that can quantify the environmental or societal performance. For example, the emissions are usually measured in units of pounds, Kilograms, while energy is measured in units of BTU or KWh etc. Therefore, there is need to identify an approach to formulate the objective function to present all the economic, environmental and societal functions in a meaningful format.

3. CHAPTER THREE: METHODOLOGY

In this chapter, the methodology to solve the CSD problem is presented. Following the problem definition, the CSD modeling challenges are provided. Later, the multi-stage hierarchical approach for the CSD model is presented. This is followed by a detailed description of the optimization model (economic) and the procedures to perform the economic, environmental and societal MLC analysis. A description of the complete mathematical model and its notations, and the TBL MLC analysis models developed to solve the CSD problem are included here.

3.1 Problem Definition

This research aims at developing a decision-support model for CSD problem (CSD model) that evaluates the TBL impact of each alternate product designs at the NPD stage on their corresponding SC configurations to select the best PDSCC combination that maximizes economic benefits and minimizes environmental and societal impacts.

CSD involves identifying important product design related aspects such as the materials, functionality, components, interfaces, etc., and evaluating their impact on the corresponding SC configuration (such as the number and location of SC partners, their capabilities, and their capacities) to ensure that the desired performance is met by the company. For example, the type of material chosen for a product design can impact its SC configuration across all four product life-cycle stages, as each material can have different processing cost, can be sourced from different suppliers, can have varied assembly requirements, performance, recovery, reuse, remanufacturing and recycling probabilities all of which influence the SC configuration to a great extent. Therefore, CSD involves integrating both product design and SC design-related criteria, as shown in Figure 3.1, to determine the best PDSCC combination that helps achieve the desired TBL objectives.

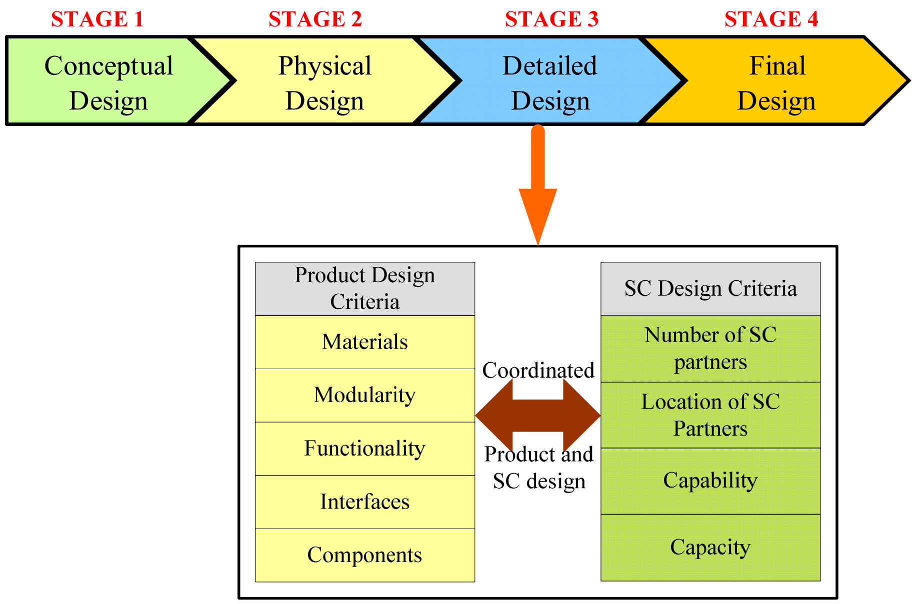


Figure 3.1: Coordinating Product Design and SC Design Decisions

Figure 3.2 presents the flowchart for the developed CSD model. The CSD model evaluates alternate product designs and their corresponding SC configurations using the sub models: EOM, Economic MLC analysis, Environmental MLC analysis and Societal MLC analysis to identify the best PDSCC combination that maximizes all the TBL benefits. The procedure and methodology for the CSD model and its sub models is explained later in this chapter.

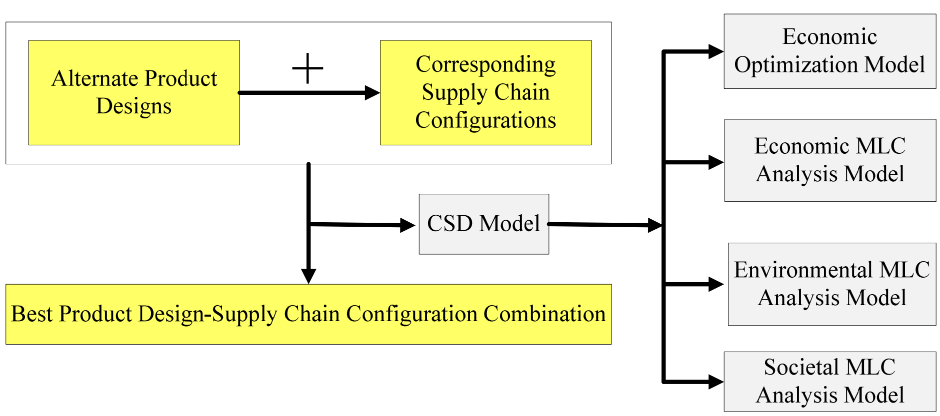


Figure 3.2: Flowchart of CSD Model

3.2 CSD Modeling Issues and Challenges

Designing and managing SSCs, while incorporating all the key aspects (mentioned in Introduction chapter) is much more challenging as compared to that of designing conventional open-loop SCs which focus on merely economic benefits. Several issues must be considered which can be broadly categorized into (a) modeling the reverse loop SC, (b) multiple life-cycle consideration and, (c) quantification of environmental and societal performance. The issues related to each of the three categories are explained below:

3.2.1 Modeling the Reverse Loop SC

All the SC operations involved from raw material processing to delivering the final product to the customer are considered as forward loop SC operations (Guide et al., 2003). The focus of the conventional SC models is limited to first three product life-cycle stages including pre-manufacturing, manufacturing and use, and their aim is only to deliver the final product to the customer. Therefore, the conventional SC models consider only the forward loop SC operations. In order to promote SSCs, there is a need to consider an additional post-use stage along with the three stages considered in the conventional SC models. It is during this post-use stage that the returned products from the customers are recovered, to be either refurbished, remanufactured or recycled based on their condition, and thereby are ready to be used for another life. All the operations performed by the SC from the end of the use stage to the point where the returned products are available for use in their next life are considered as reverse loop SC operations. This reverse loop SC performs operations including but not limited to collection, recovery, refurbish, disassembly, remanufacture, and recycle etc. based on the returned product's condition. Therefore, a closed-loop SC is formed when both forward and reverse loop operations are considered within a SC. Several factors influence the reverse loop SC operations. These factors are illustrated in Figure 3.3 and discussed in detail in the following sections.

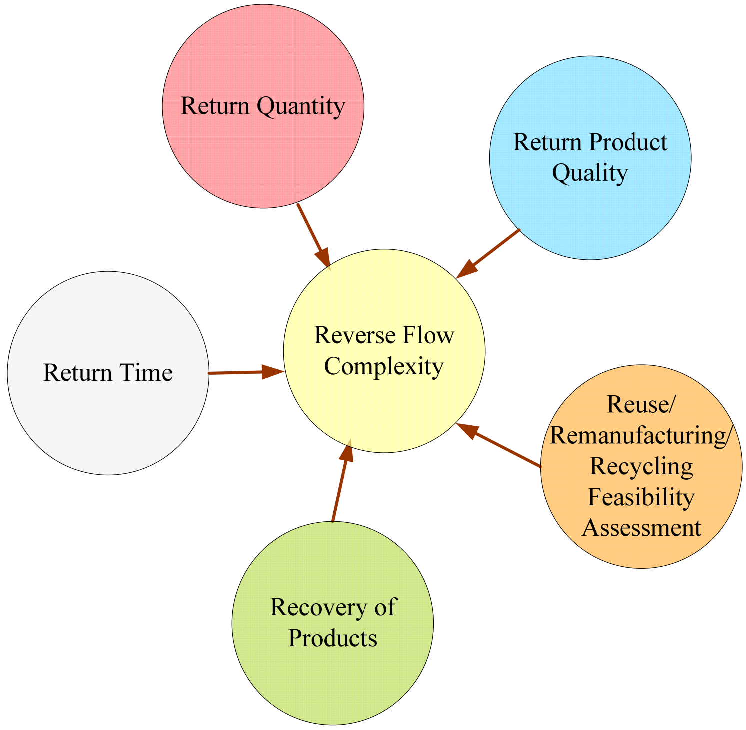


Figure 3.3: Factors affecting the Reverse Flow Operations

3.2.2 Recovery of Products

The first step in reverse flow management is recovering the used products from customers. A major challenge many companies face at this point is estimating recovery quantity for the products for each time period (day, month, year, etc.). Generally, this task is challenging beacuse for most products, customers are not required to return them to the manufacturer at the end of use. However, it can be less challenging for others. A classic example is the case of Kodak single-use cameras. The company collects the used cameras from customers through photofinishers, performs the reverse loop operations such as refurbishing, recycling of the cameras and their components. Kodak is able to achieve a high and predictable recovery of its cameras due to: (a) its strong ties with photofinishers and (b) incentives paid to the photofinishers to transport the used cameras back to collection centers. This capability has contributed to the company's success in reverse flow operations. However, the situation will be very different for other products where the infrastructure for product recovery is not as established. Also, factors such as product size and design complexity play a major role in the ability to recover products. For example, in setting up collection centers, for say refrigerators, transportation options for product return, incentives to be paid, storage/handling capacity/capability needed, etc., must be considered. Therefore, establishing realistic recovery rates is not straightforward. However, if regulations exist on minimum quantity to be recovery (for example, such as those set forth in the European Union's End of Life Vehicle Directive – EOLV, 2002) that must be achieved, those rates can be used as the threshold values. Else, minimal recovery rates for which the additional reverse flow expenses (capital and recurring) are justifiable must be determined.

3.2.3 Return Quantity and Return Time

Secondly, the uncertainties involved in return timing is another factor that must be considered in reverse loop SC modeling. The quantity of products returned as well as when they are returned are important to determine the production mix for forward flow in the SC. Again with the case of the Kodak, because the product life-cycle is relatively short, it might be possible to estimate return timing (i.e.: when customers will bring the cameras to photofinishers) somewhat reasonably. However, for longer life products such as refrigerators, the return timing is much more difficult to estimate; the use patterns are highly variable, affecting the time of returns.

3.2.4 Return Product Quality

Returned product quality is important to assess the feasibility of a product to be passed on to its next life and to determine the right type of operation (refurbish, remanufacture or recycling) to be performed and therefore is another factor that must be considered in modeling SSCs. The quality can vary between different products, based on their design criteria, manufacturing conditions and use patterns. Even for products of similar type, the quality can vary between them based on how they were used, their exposure to atmospheric conditions etc. Hence, each product must be individually inspected for its quality. This process becomes extremely complicated for complex products like refrigerators or automobiles where a large number of components and sub-assemblies are involved; most often a simple GO/NO-GO type of visual inspection for flaws would not be sufficient to identify if components are reusable, recyclable or remanufacturable. Another drawback is lack of comprehensive set of criteria that can assess a product for its reusability or whether components can be remanufactured or recycled.

3.2.5 Assessing Reuse, Remanufacturing and Recycling Feasibility

As mentioned earlier, there is no straightforward method currently available to assess a product or its component for reusability, remanufacturability or recyclability. One way to address this issue is to establish measurable and quantifiable criteria to assess each unit (product or a component) to check for feasibility of second life use. For example, product design criteria such as ease of upgradeability, aesthetic quality, and availability of service agreements have been suggested to assess reusability of products (Jaafar et al., 2007). Remanufacturability of components could be evaluated based on the ease of component access for cleaning and inspection, ease of handling components, availability of technology to restore the component, and ease of usage of the component in other models (Sundin, 2004). Similarly, criteria such as ease of separation of materials could be used to evaluate the recyclability of components. When integrating these design criteria into CSD models it must be noted that each component in a product could have different features/materials and therefore each of them must be assessed independently.

3.3 Multiple Life-cycle Consideration

Closed-loop SSC's require re-channeling the products recovered at the end of the use phase back to pre-manufacturing, manufacturing or use phases to be used in subsequent lives. As illustrated in Figure 1.1, applying the 6R's provides a platform to achieve such closed-loop material flow and reduce the overall resource consumption. However, as the complexity of the product increases applying the 6R's is more difficult and will depend on factors such as cost of redesign, market potential for redesigned products, SC network configuration and network changes, etc.

However, if the product is not designed for MLCs it is not possible to achieve continuous flow of material to realize the true benefits of CSD such as reduced material consumption, lower energy usage, reduced emissions, better quality of life for customers, etc. Moreover, these benefits will be derived better in the long-run depending on the life-cycle of the product. This is because initially the company (or the SC collectively) incurs the reverse loop capital expenses which will have a certain payback period. Thus, depending on the product use pattern and post use activities the minimum time period that a product must exist in market for it to generate higher benefits in a closed-loop SC system as compared to an open-loop SC can vary. For example, if a product is used for say 2 years, the company must wait for atleast 2 years to make the product available for next life. However, for products with a longer use phase, such as refrigerators (typically between 8 to 12 years) it takes much longer to obtain the used products and make them available for second life. This means for a typical refrigerator manufacturer, the demand in the first 8-12 years is satisfied by only new products. Hence, for such companies, it takes much longer to enjoy the benefits of considering closed-loop flow.

The Kodak single-use camera is a classic example of a company achieving the true benefits of CSD. The democratic Chronicle in 2009 reported that the cameras can have up to nine lives. As a result, the company was able to achieve reduction in material and energy consumption over multiple product generations. By the time the fifth generation of the camera has reached, the company required nearly 78% less raw material and consumed only 38% of the energy as that of the first generation product (Field, 2000) as illustrated in Figure 3.4. While it has been relatively easy for Kodak to perform CSD (due to the nature of the product and the SC), it would be more challenging for other companies to achieve these same benefits.

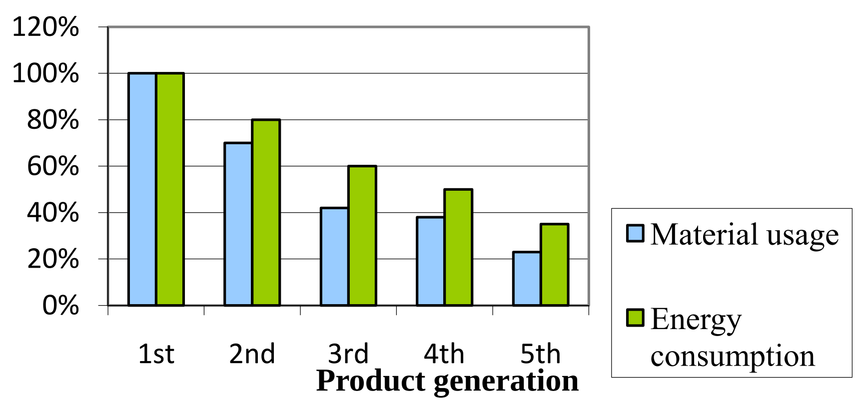


Figure 3.4: Reduction in Material and Energy Consumption for Kodak Single-use Cameras (Field, 2000)

3.4 Quantifying Environmental and Societal Performance

While the importance of pursuing TBL benefits is well recognized, not many SC models in literature consider all the TBL aspects simultaneously. This is partly is due to the issues mentioned in the literature review chapter, which relates to the difficulties of quantifying environmental and societal impacts of SC operations. Another challenge relates to how well economic, environmental and societal benefits (once quantified) can be integrated and optimized in a single model. There have been several studies suggesting that is it is not best to measure environmental and societal impacts in monetary terms because that could undermine their importance if viewed as reducing economic gains. Even if all TBL aspects were somehow converted using a common denominator for aggregation and optimization in CSD models, the question of what TBL aspect is more important and by how much more arises. Therefore in this research, to address this complexity a hierarchical approach to evaluate product designs and corresponding SC designs with respect to each of the TBL aspects is developed.

3.5 CSD Model Framework: Hierarchical Approach

The hierarchical approach evaluates alternate product designs and corresponding SC configurations with respect to each of the TBL aspects, one after another. In order to identify which of the TBL must be considered first, second and third, literature in the area of drivers for sustainability was studied. Jaffar et al. (2007) provided two possible scenarios for drivers of sustainability. The first scenario presents the economy as the driver and society being the driven whereas the second presents the society being the driver and the economy as the driven. In both cases, the environment was considered as the medium. As mentioned earlier, quantifying economic benefits is relatively easy and straightforward (either maximize profit or minimize cost) as compared to quantifying environmental and societal performance. While considerable work exists in environmental performance metrics very little or none exist in performance metrics that can assess the societal impact of an SC. As considering the environment or societal aspects in the first levels of hierarchy requires well established metrics to evaluate SC performance, and as there is no proper data in this field, the second scenario presented by Jaffar et al. (2007) could not be considered.

Based on foregoing discussion, and given that economic benefits are imperative for a company to stay in business, the first scenario presented by Jaffar et al. (2007) is considered in this research. Thus, the hierarchical approach was developed with economic performance at the first level, followed by environmental and societal performance at the second and third levels. Thus, the economic optimization model is formulated and solved to identify for each alternate product design an optimal SC configuration that maximizes the profit. At the end of the economic optimization, for each alternate product design a corresponding optimal SC configuration is selected. Then, for every PDSCC, an economic MLC analysis is performed to select the best PDSCC combinations with maximum cumulative profit over total period. In the subsequent stage, the environmental MLC analysis is conducted on the above selected PDSCCs to identify the best combinations with minimal environmental impact. In the final stage, the societal MLC analysis is performed to assess the societal performance of selected PDSCC combinations (best with respect to economic and environmental performance) to select the best PDSCC combination with maximum societal performance. Figure 3.5 illustrates the hierarchical approach developed for the CSD model.

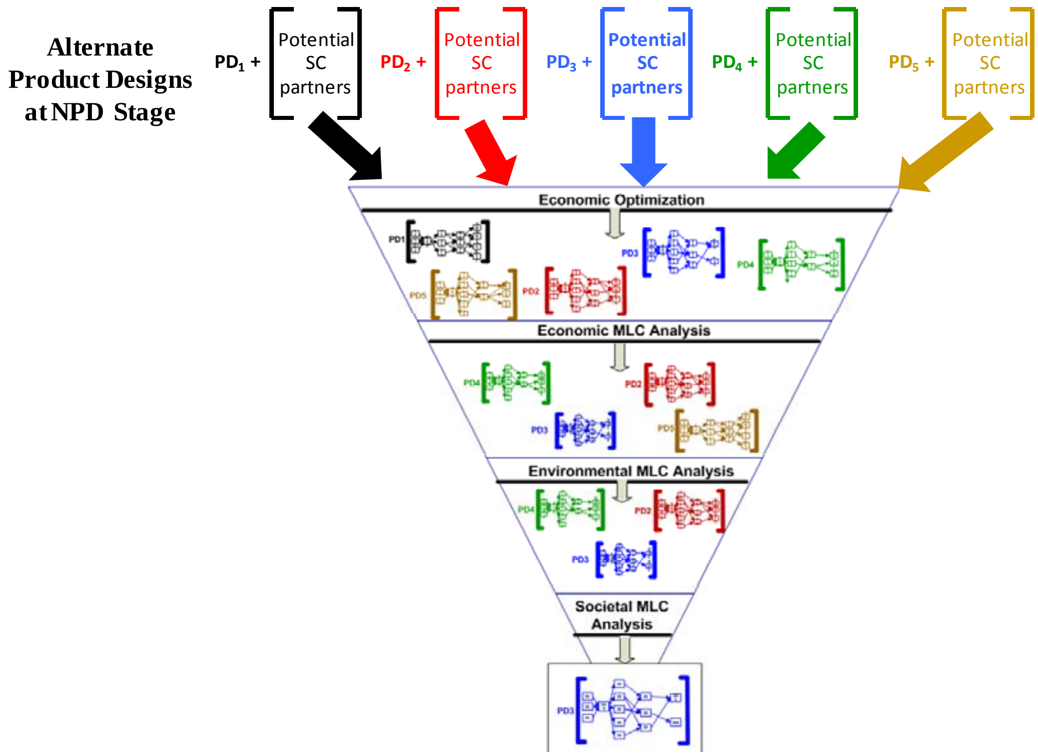


Figure 3.5: Hierarchal Approach to CSD Modeling

The advantage to following such a hierarchical approach is that the huge complexity involved in modeling and optimization for the total SC with respect to all TBL aspects simultaneously is avoided. Also, optimization at the first level of modeling will enable selecting PDSCC combinations (based on economic performance) that are assessed in the subsequent levels for environmental and societal impacts; this will avoid the need for optimization at these later levels, which is beneficial in this case, as the lower level analyses could explicitly focus on MLC performance which is difficult to conduct through optimization models.

3.5.1 CSD Model Formulation

An important aspect that must be considered during modeling of the CSD problem is the uncertainties involved in the SC. As discussed earlier, several uncertainties such as delays in material acquisitions, machine breakdowns, demand variations, reverse flow-related variations are present in SC operations. Stochastic models can effectively capture such variations. However, developing stochastic optimization models for a problem with a large scope such as SC can become very difficult as it requires determining the influencing factors over a long period; while some of these factors have predictable patterns, for others such as recovery rates, return quality etc. the influencing factors and their patterns are still not identified. Hence, a deterministic model is considered in this research.

The period (T) of analysis for the CSD model must be greater than the total product's life-cycle (L) in order to comprehensively capture and assess sustainability benefits in the closed-loop flow. The first step is to estimate the annual demand during time period (T). Forecasting the demand particularly for new products is very challenging due to lack of past data. However, to some extent, the nature of the product could help in determining the level of uncertainly associated with its demand. One way to predict demand is to observe the historical trend for similar product types and their life-cycles in the market. Anderson and Zeithaml (1984) suggested that all products go through four phases including Introduction, Growth, Maturity and Decline during their total life-cycle. During the introductory period, the new product is introduced in the market and the price of the product is high (covering the costs), while the demand is low (as the product is gaining its attention in the market), typically following the price-elasticity of demand. During the growth phase, more customers are aware of the product and the demand increases. This stage is typically characterized by increased sales due to repeat customers. During the maturity stage for most products, demand stabilizes to a steady-state condition. Subsequently the demand decreases signaling the decline phase where the product eventually becomes obsolete. The length of these product life-cycle phases varies for different products. Therefore the different phases of a product life-cycle provide a reasonable estimate for the annual demand over the period (T). As the growth stage is relatively short with highly variable demand, only the introductory, steady-state and decline periods are considered in the CSD model for period (T).

Figure 3.6 illustrates that during the introductory period $(t_1 - t_{s1})$ the demand is price-elastic. During the steady-state period $(t_{s1} - t_{sf})$ the market is mature and demand is assumed to be constant. During the decline period $(t_{sf} - t_f)$ both the price and demand are assumed to decrease. Therefore, as illustrated in the Figure 3.6, a linear approximation of annual average demand based on the time period is assumed for the purposes of the CSD model.

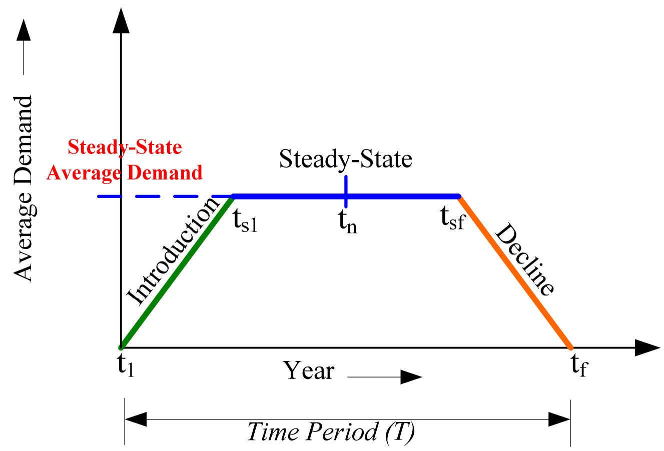


Figure 3.6: Demand Variation over Time Period (T)

To develop the CSD model based on the hierarchal approach first the EOM that selects for each product design an optimal SC configuration that maximizes profit must be formulated. This problem is similar to the well-known location-allocation problem except that in this case involves a lot more constraints that relates to the post-use stage SC network and uncertainties associated. While there are several tools for solving this type of SC models, MILP is observed to be most widely used tool due to its ability to solve NP-hard problems within a reasonable computation time (Gokhan, 2007). Hence in this research, the EOM is formulated as a MILP problem and solved using the IBM ILOG CPLEX optimization software.

The next stages in the hierarchy involve developing models to perform MLC analysis. For each PDSCC combination, the Economic MLC Analysis (MLC_{Eco}), Environmental MLC Analysis (MLC_{Env}), Societal MLC Analysis (MLC_{Soc}) models are developed using Microsoft Excel Spreadsheet Application and run for period (T). As discussed earlier, it is very challenging to perform MLC analysis in the optimization model because combining both optimization and MLC analysis in an optimization model makes the model too complex to solve within a reasonable computation time. Another reason is that, although a single metric can be used for measuring economic benefit, there is no single metric that could comprehensively measure the environment or societal performance of PDSCC combinations. Therefore, multiple performance metrics are used in MLC_{Env} and MLC_{Soc} models in this research. Also, the MS Excel based model provides an easy-to-use tool.

Figure 3.7 illustrates the CSD model framework including the sub-models EOM, MLC_{Eco}, MLC_{Env}, and MLC_{Soc} and their application at each stage of the hierarchical approach. The sub-models perform the following operations:

EOM: This model identifies for each product design an SC configuration that maximizes profit. As this is a deterministic optimization model, the time frame t_n in the time period (T) for which this model is developed must be determined. The steady-state period $(t_{s1} \leq t_n \leq t_{sf})$, where the demand remains constant is the most appropriate period for the EOM formulation.

MLC_{Eco}: This model quantifies the economic benefit of each PDSCC combination over period (T) to select best combinations based on their cumulative profit.

MLC_{Env}: This model quantifies the environmental performance of the best PDSCC combinations selected above over the period T to identify best combinations with maximum environmental performance.

MLC_{Soc}: This model assesses societal performance of the best PDSCC combinations selected at the economic and environmental analysis stages to select the best combination with highest societal performance over the period T.

Based on number of alternate designs, either all the PDSCCs or only a few that perform best at each stage can be carried forward to the next stage in MLC analysis.

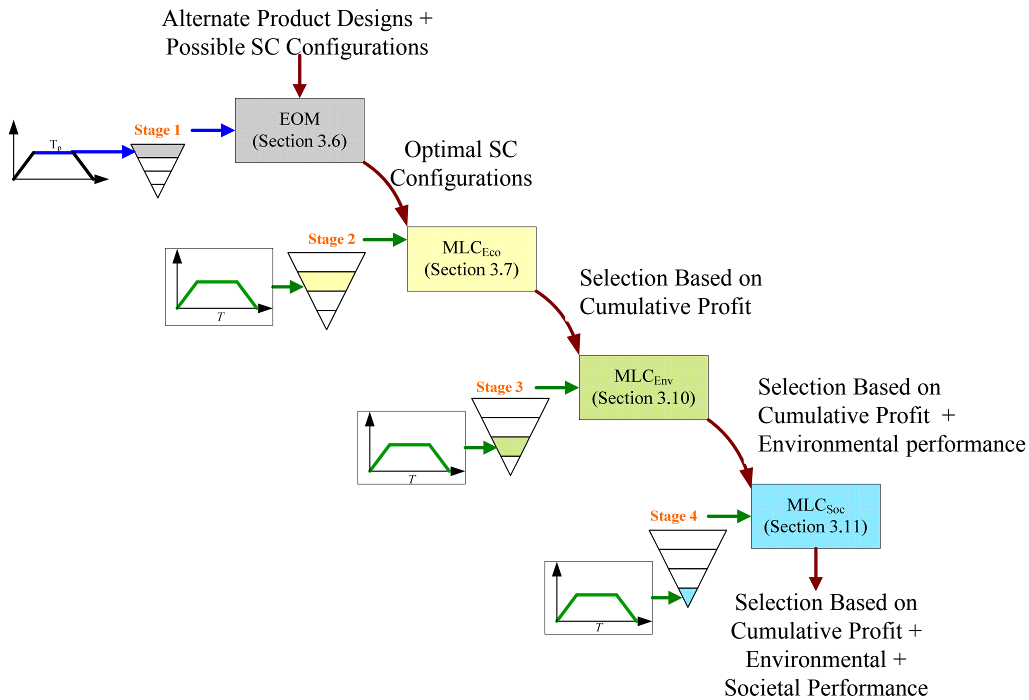


Figure 3.7: CSD Model Framework

A detailed description of the methodology for developing each of the sub-models EOM, MLC$_{Eco}$, MLC$_{Env}$, MLC$_{Soc}$ is presented in the following sections.

3.6 Economic Optimization Model (EOM)

The EOM is developed for the steady-state conditions $(t_{s1} \leq t_n \leq t_{sf})$. The model assumptions, a description of the SC system considered, the mathematical notations and formulation are presented below.

3.6.1 Model assumptions

A SC is a network of companies that provide a good or service (Lambert, 2008). Based on the nature of the business a company is engaged in, the SC configurations can vary. SCs can also vary based on the number of tiers considered. As the number of tiers increases the SC complexity increases. Each SC configuration is unique and it becomes essential to define the boundary of the SC problem considered. Hence, in this section all the assumptions considered for the EOM are presented.

The focus of the EOM is to maximize the Original Equipment Manufacturer (OEM) profit by considering the entire SC as a single entity. That is the reverse loop set-up costs are incurred by the OEM. While distributors and retailers are not explicitly considered in the SC model, a set of customer locations, disposal, collection, remanufacturing and recycling locations are considered. The model is formulated to evaluate all possible reverse loop SC partners to select from among them those that help maximize the objective function. However, no supplier selection is performed. A detailed description of the SC model is presented in the next section.

3.6.2 SC System Description

The EOM evaluates alternate product designs at the NPD stage. The components for each of the product designs vary with respect to type of design, type of material etc. Depending on the complexity of the product, either all components or few critical components are considered in the EOM. The objective of the EOM is to select for each product design the optimal SC configuration that maximizes the profit.

The SC model considered in this research is explained through an example as discussed below. Consider a product design (P) which requires (c) components, where each of the components is sourced from a different supplier (S_c). Consider the SC operations across the product life-cycle stages for the product to be as presented below:

Components/Parts Acquisition

Each component (C) is supplied by different supplier (S_c) and (assume that each supplier can supply only one component) are transported to the OEM for their assembly. The transportation costs are computed from the freight revenue per ton-mile data which is obtained from Department's Bureau of Transportation Statistics and is presented in Table 3.1. The supplier cost for acquiring the component, the distances from supplier locations to the OEM and corresponding transportation costs are all considered in the model.

Table 3.1: Cost for Different Modes of Transportation

Mode	Average Cost (Cents/Ton-Mile)
Barge/Ship	0.72
Truck	26.6

Manufacturing

The OEM assembles the components to produce the products that are then distributed to customers. The OEM could hold inventory of three categories (a) new components from suppliers (b) refurbished products from past life-cycles and, (c) remanufactured components. In the model it is assumed that the total demand is satisfied by a mixture of products made from (a) all new components, (b) one or more remanufactured components or (c) refurbished products from past life-cycles. Always a specific percentage of refurbished products and remanufactured components are used to satisfy current life-cycle demand. Through this percentage value a company can allocate the proportion of past refurbished products or remanufactured components that can be used to satisfy the current demand. In each time period, the OEM assesses current inventory and based on the annual demand acquires the additional quantity required from suppliers. Several costs are incurred by the OEM in performing the assembly and holding operations including capital, assembly, and holding costs all of which are considered.

Use

The annual steady-state demand for products is distributed to various customer locations. A limited number of centralized locations are considered for customers. The number of locations can be decreased or increased depending on the concentration or dispersion of customers for that product. Delivery charges from this point onwards are assumed to be paid by the customers.

Collection

At the end of use, products are collected by the collection centers. Since all the products may not be collected at end of use (due to issues mentioned in reverse flow modeling section) a recovery rate is used to indicate the percentage of collected. The collection centers can be geographically dispersed and have different processing and capital costs as well as capacities and capabilities. All the collection centers perform the sorting operations on the product designs as described below.

Sorting Operations

The operations performed are: (a) evaluate the products to select those reusable, perform refurbishing operations and transport them to OEM for use in next life, (b) disassemble non-reusable products, evaluate and select components for remanufacturing operations; if not evaluate component feasibility for recycling and transport to corresponding recycling plants. Components not remanufactured or recycled are disposed at a specific location. Figure 3.8 illustrates the decision making process at each collection center.

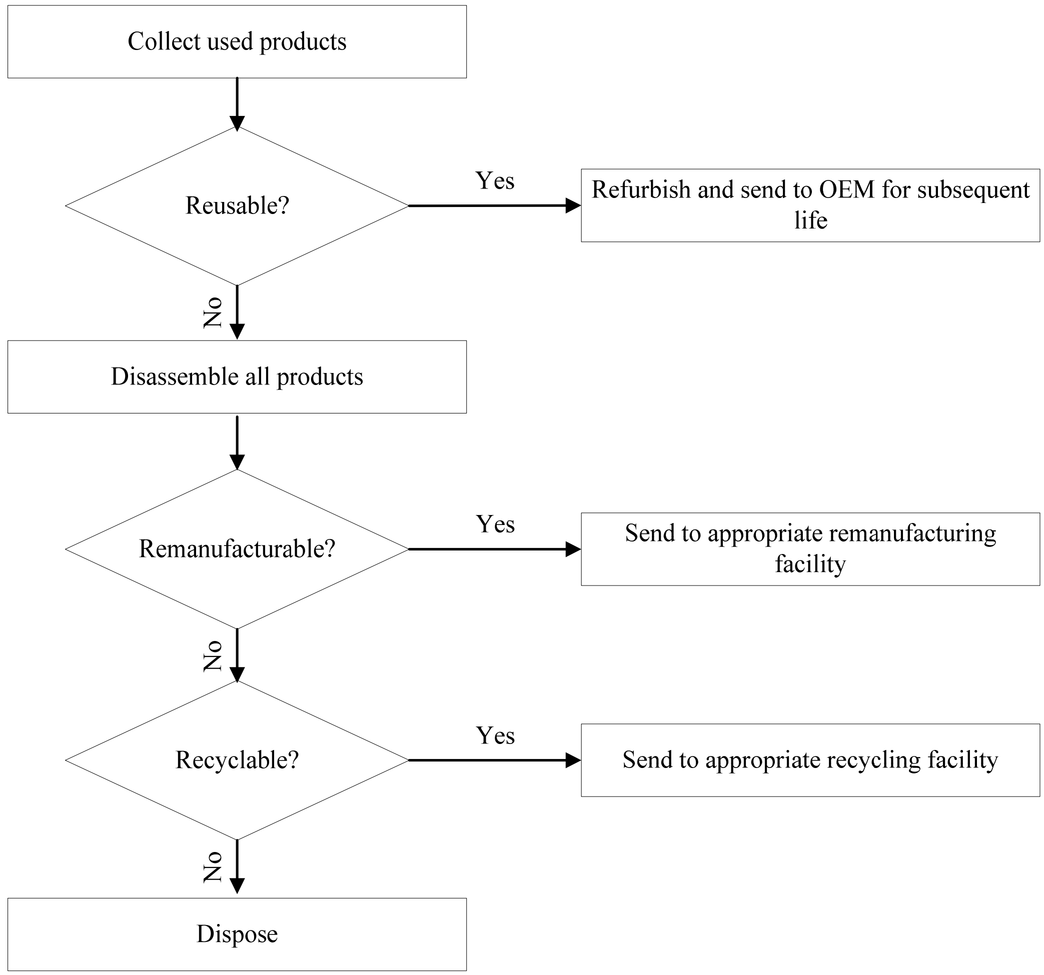


Figure 3.8: Decision Making Process at Collection Center

Criteria for Assessing the Feasibility for Alternate Product Designs

At collection centers, each product is evaluated to identify its potential for reuse, remanufacturing, recycling. Feasibility for these operations is assessed based on a set of criteria established from literature on design characteristics that are favored in a product for reuse (Jaffar et al., 2007), remanufactured (Sundin, 2004), or recycled (De Silva et al., 2009). These criteria are discussed below:

Reuse:

- Ease of upgradeability: As the name explains, the ease with which a product or any of its major components can be enhanced for better performance plays a major role in deciding whether a product can be reused or not. Hence, the product must be designed in a way that the components can be easily replaced.

- Aesthetic quality: Along with functional quality, the reusability of any product also depends on the aesthetic quality. This quality is integral to a product's utility as it increases the customer satisfaction levels.

- Ease of availability of service: Another factor that influences product reusability is the availability of services to maintain and repair a product, and how easy it is for the customers to get these services.

Remanufacturing:

The criteria are selected from the work of Sundin (2004) who identified the most important product design aspects that can determine its remanufacturing ability:

- Ease of access: The remanufacturing process includes several steps such as inspection, cleaning, reprocessing and testing of components. Performing these operations requires access to different areas of the product and/or components. Therefore, ease of access is considered as one of the factors that determine the remanufacturability of a product.

- Ease of handling: Another important factor that influences the remanufactuability of a component the ease at which the component can be handled including ease of lifting and carrying the components, ease of storing the components without any fire hazards, ease of operating a component without exposing employees to hazardous gases. Therefore, ease of handling is considered as one of the factors.

- Availability of technology: This factor implies that if technology is obsolete components cannot be remanufactured.

- Ease of usage in other models: The property of interchangeability and its importance has already been studied in literature. If a component can be used in other models with little or no modification, greater demand exists for such components. Moreover, interchangeable components can be easily assembled into new products and make it easier to repair existing products.

Recycling:

The unit of assessment for recycling is different from that for remanufacturing and reuse. This is because products are assessed for their reuse, whereas individual components are assessed for their remanufacturing feasibility and the materials in each component of a given product design are assessed if they are recyclable or not. Therefore, it becomes very exhaustive to assess every material used in each component to check if it can be recycled. Therefore, the scope of recycling assessment in this research is limited to evaluating critical components of the product to check feasibility to extract major material from those critical components. Ease of extracting the major material is the only criterion considered for recycling assessment.

Table 3.2 summarizes the reuse, remanufacturing and recycling criteria used in this research and their units of analysis. Some of these design criteria vary not only with respect to each alternate design but also with respect to their use patterns, for example European customers might use a product different to how South American customers use it. This variation too is important for reverse flow evaluation and is captured in the EOM. These criteria are represented by α.

Table 3.2: Criteria Impacting Reuse, Remanufacture, Recycle Feasibilities

Design Criteria	Reuse (Product Level)	Remanufacture (Component Level)	Recycle (Material Level)
Ease of upgradability (U_p)	X		
Aesthetic quality (Q_e)	X, α		
Ease of access (A_s)		X	
Ease of handling (H_l)		X, α	
Ease of extracting major component (E_c)			X, α
Availability of technology (T_l)		X	
Availability of service agreements (S_a)	X		
Ease of usage in other models (I_m)		X, α	

<u>Evaluation of Alternate Product Designs</u>

For each product design, the probabilities for criteria in Table 3.2 were established based on individual design aspects. These criteria vary for different products, and might exist in the form of quantifiable numbers, or may be derived from subjective estimates. In this research, a simple method is established to evaluate the product designs based on a rating system in the absence of quantifiable measures. Each criterion in Table 3.2 is rated from 0 to 10, 0 being very low and 10 being very high. It must be noted that for some criteria there exist multiple ratings depending on number of use patterns. For recycling, only two possibilities were considered, to simplify the process; (a) 1, if it is easy to extract major material in components (b) 0, otherwise.

The reuse and remanufacturing ratings between 0-10 are converted into probabilities in the following manner. Each design criteria that impact the reuse and remanufacturing capabilities are given equal importance. Hence, for each reuse design criteria the rating is divided by (10×3) to convert it into a probability. Similarly, as there are four different remanufacturing criteria each of them are divided by (10×4) for obtaining the probability values. These probabilities are compared with the reuse and remanufacturing threshold limits to select the products or components for refurbishing and remanufacturing, respectively. Again, the threshold limits for each product design varies based on its individual features and the company objectives.

Using the above method, collection centers evaluate each product design to select reusable products and non-reusable products. Later, refurbishing operations are performed on reusable products and the rest are disassembled. The refurbished products are sent back to OEM for their next life. For the disassembled products, each critical component is evaluated to check for its feasibility to be remanufactured or recycled and are sent to remanufacturing and recycling centers, respectively. The rest of the components are disposed at a cost. The refurbishing and disassembly costs at collection centers, distances from collection center to the OEM and disposal locations with associated transportation costs are all considered in the model.

Remanufacturing

All the components chosen for remanufacturing are sent to remanufacturing centers. Similar to collection centers, the remanufacturing centers can be at different locations, can have different capital and processing costs, capabilities and capacities. The EOM determines remanufacturing centers that must be opened and the quantity of components that must be sent to each center so that the profit is maximized. The remanufactured components are sent back to OEM for use in new products. The transportation costs from possible remanufacturing centers to OEM are also considered.

Recycling

All the components chosen for recycling at the collection centers are sent to recycling centers for their subsequent operations. The EOM selects the recycling centers that must be opened and the quantity of components that must be sent to each center so that the profit is maximized based on associated fixed, transportation and processing costs, capabilities and capacities.

Figure 3.9 illustrates the closed-loop SSC with S different suppliers, B different use locations, CC different collection plants, Y different remanufacturing plants, E different recycling plants, and a disposal location D_p as considered in this research. The reverse loop flows are shown in dashed lines. Each SC partner could either work with materials, components or products based on their nature of operation. For example, the suppliers supply the components, while the OEM manufactures products, whereas the collection center could work with both products and components depending on operations. Therefore at each SC partner, the unit of measurement – materials, components or products – varies and adds to the complexity of the model and is illustrated through a corresponding superscript. Similarly, the type of units transported between each SC partner too varies. Between some partners only components are transported, while products or materials are transported between others. This flow of units between SC partners, too, is illustrated through different sets of lines.

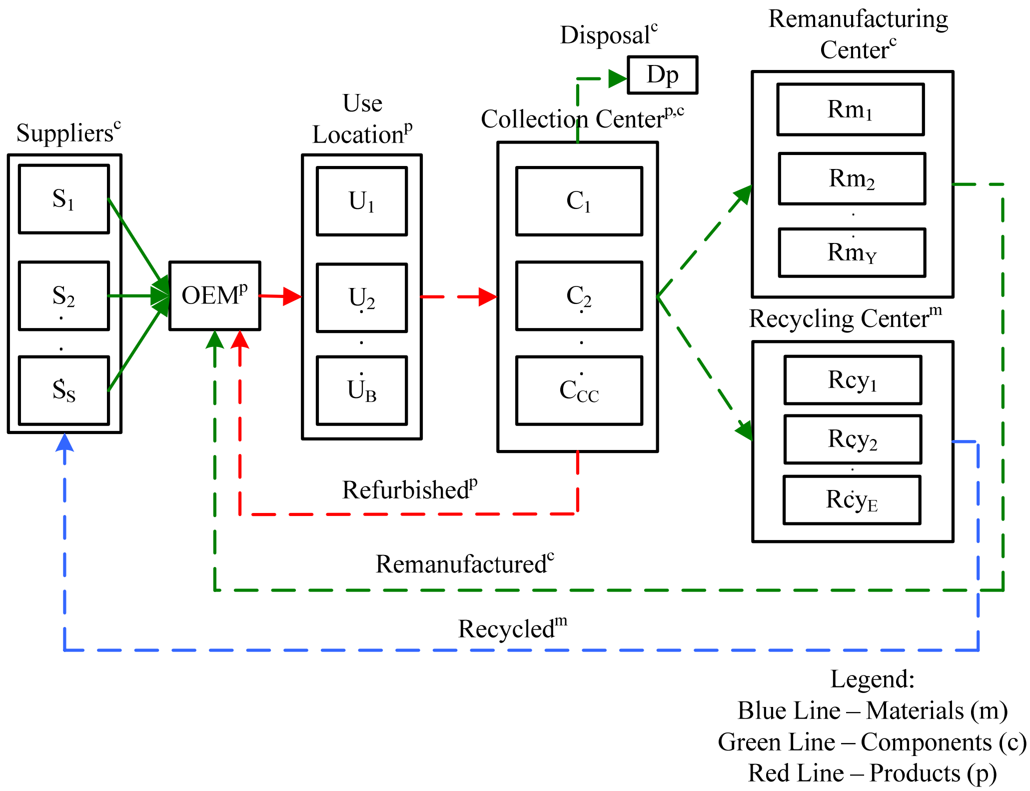


Figure 3.9: SSC Model for the CSD Problem

Therefore to summarize, each of the 6Rs is applied in the EOM's SC model as follows:

- Redesign: Addressed through NPD output by providing the alternate product designs
- Recovery: The process of collection of used products from customers (performed by the collection centers)
- Reuse: Products are refurbished by collection centers and sent to OEM for reuse
- Remanufacture: All the remanufacturing operations are performed at remanufacturing plants
- Recycle: The extraction of major material from components (performed by recycling plants)
- Reduce: This concept is applied at every step to reduce the overall resource consumption

3.6.3 EOM Development

In this section, the EOM problem formulation for the closed-loop SC model is presented. This model aims to maximize total annual profit during the steady-state demand, by selecting the optimal number of collection, remanufacturing and recycling facilities to be opened, and computes the quantities to be transferred between each SC partner across the closed-loop SC. The model assesses the current refurbished and remanufactured component inventory levels to acquire the new components required to satisfy the demand. All the parameters and decision variables used in the model are listed below:

List of Parameters:

- s = Set of suppliers from 1 to S
- g = Set of components from 1 to G
- b = Set of use locations from 1 to B
- cc = Set of collection centers from 1 to CC
- d: Set of remanufacturing centers from 1 to Y
- e: Set of recycle centers from 1 to E
- N = Total number of components sum $(1,2,3 \dots G)$
- t_n = Steady-state time period (year) at which the model is run
- p = Product design
- D_g: Total steady-state demand for component g
- DD_b: Steady-state demand distribution for use location b
- $S_{sg} = \begin{cases} 1 & \text{if Supplier } s \text{ supplies a component } g \\ 0 & \text{otherwise} \end{cases}$
- C_{sg}: Per-unit cost of component g at respective supplier s
- TC_{sg}: Transportation cost per-unit of component g from supplier s to OEM
- A: Per-unit assembly cost at OEM
- H: Per-unit holding cost at OEM
- FC_{OEM}: Annualized capital cost for OEM
- Rf_g: Refurbished quantity available from past life-cycles for component g
- Rm_g: Remanufactured quantity available from past life-cycles for component g

- a: Probability of refurbished quantity satisfying current demand
- b: Probability of remanufactured quantity satisfying current demand
- ND_g: New demand for component g
- α: Recovery probability
- ∂: Reuse threshold for product design
- Ru_b: Reuse probability for use location b
- $\emptyset_g$: Remanufacturing threshold for component g
- Rm_{bg}: Remanufacturing probability for component g at use location b
- Rcy_g: Recycling probability for component g
- $Rcy_{bg} = \begin{cases} 1 & \text{if major material of component } g \text{ at use location } b \text{ is recyclable} \\ 0 & \text{otherwise} \end{cases}$
- FC_{cc}: Annualized capital cost for collection center cc
- PC_{cc}: Processing cost per-unit at collection center cc
- Q_{cc}: Capacity of collection center cc
- TC_{bcc}: Cost per-unit of product transported from use b to collection center cc
- Rf_{bcc}: Quantity of reusable products transported from use location b to collection center cc
- CRf_{cc}: Cost of refurbishing one unit of product at collection center cc
- TC_{cc}: Cost for transporting one unit of refurbished product from collection center cc to OEM
- Dis_{bccg}: Quantity of disassembled components g at collection center cc transported from use location b
- CD_{cc}: Cost of disassembling one unit of product at collection center cc
- TC_{ccdg}: Transportation cost per-unit from collection center cc to remanufacturing center d for component g
- Rm_{bccg}: Quantity of remanufacturable components g transported from use location b to collection center cc
- $CbRm_{dg}$: Capability of remanufacturing center d for processing component g
- Q_{dg}: Capacity of remanufacturing center d available for processing component g

- CRm_{dg}: Cost of remanufacturing one unit of component g at remanufacturing center d
- FC_d: Annualized capital cost for remanufacturing center d
- TC_{dg}: Transportation cost per-unit from remanufacturing center d to OEM for component g
- TC_{cceg}: Transportation cost per-unit from collection center cc to recycling center e for component g
- $CbRcy_{eg}$: Capability of recycling center e for component g
- Q_{eg}: Capacity of recycling center e for component g
- $CRcy_{eg}$: Cost of recycling one unit of component g at recycling center e
- Rcy_{bccg}: Quantity of recyclable components g transported from use location b to collection center cc
- FC_e: Annualized capital cost for recycling center e
- TC_{eg}: Transportation cost per-unit from recycling center e to supplier s supplying the component g
- Dp_{bccg}: Quantity of disposable components g transported from use location b to collection center cc
- TC_{ccg}: Transportation cost from collection center cc to disposal location for one unit of component g
- CP: Cost for making one unit of product p
- θ: Margin (between 0 to 1) (Price = Cost + Margin) per-unit of product
- SP_p: Price of one unit of new product p
- D_p: Price discount for one unit of refurbished/remanufactured product
- SP_{dis}: Price of one unit of refurbished/remanufactured product
- M: Cost for acquiring other components for making one unit of product
- Z: Cost for disposing a unit of component
- Th_{cc}: Capacity threshold multiplication factor for collection center cc for it to be opened

- Th_d: Capacity threshold multiplication factor for remanufacturing center d for it to be opened
- Th_e: Capacity threshold multiplication factor for recycling center e for it to be opened

List of Decision Variables:

- $O_{cc} = \begin{cases} 1, & if\ collection\ center\ cc\ is\ \text{opened} \\ 0, & otherwise \end{cases}$
- $O_d = \begin{cases} 1, & \text{if remanufacturing center } d \text{ is opened} \\ 0, & \text{otherwise} \end{cases}$
- $O_e = \begin{cases} 1, & \text{if recycle center } e \text{ is opened} \\ 0, & \text{otherwise} \end{cases}$
- C_{bcc}: Quantity of products transported from use location b to collection center cc
- CC_{ccdg}: Quantity of components g transported from collection center cc to remanufacturing center d
- CC_{cceg}: Quantity of components g transported from collection center cc to recycling center e

Objective Function:

The objective function of this model is to maximize the total annual profit of the closed-loop SC considered. The total profit is the difference between Total Revenue (TR) and Total Costs (TC) as shown below:

$$Total\ Profit\ =\ Total\ Revenue\ (TR) - Total\ Cost\ \ (TC)$$

Total Revenue (TR) is generated from the sale of a mixture of new and remanufactured components and refurbished products and is given by:

$$\begin{aligned} &Total\ Revenue \\ &\qquad = Revenue\ from\ New\ Products \\ &\qquad +\ Refurbished\ and\ Remanufactured\ Components\ Revenue \end{aligned}$$

The revenue from New products is computed as the quantity of new products sold times the price of unit of new product as:

$$Revenue\ From\ New\ Products = Quantity\ of\ New\ Products\ Sold \times Unit\ Price\ of\ New\ Product$$

The quantity of New Products sold is the difference between total product demand and refurbished and remanufactured demand. As refurbished items are products and remanufactured items are in terms of components, the new demand for each component must be computed. There is no restriction on the number of remanufactured components that can be used along with a new component.

As an example for a component g, the new demand is calculated as the difference between total demand for component g (equal to demand for products, as it is assumed each product requires one component) and the quantity of refurbished components of type g available (equal to number of refurbished products) and the quantity of remanufactured components of type g available (varies for each component). The quantity of refurbished components of type g available is computed as the product of total refurbished components of type g available at the OEM (Rf_g) times the percentage of these that could satisfy the current year's demand (a). The refurbished component quantity remains same for all components. The remanufactured quantity used to satisfy the demand is computed by multiplying the available remanufactured quantity for each component g (Rm_g) with the remanufacturing probability (b). The demand for a new component is computed as follows:

$$Demand\ for\ new\ component\ g = (Total\ demand\ for\ component\ g - Number\ of\ refurbished\ components\ g\ satisfying\ demand - Number\ of\ remanufactured\ components\ g\ satisfying\ demand)$$

Therefore, the *New Demand for each component g* (ND_g) is expressed by

$$\forall \text{ all } g \text{ components } ND_g = \left[D_g - \left(Rf_g \times a\right) - \left(Rm_g \times b\right)\right] \quad (3\text{-}1)$$

The price of a Unit of New product (SP_p) is computed as the sum of the cost incurred in making a unit of product including supplier cost, supplier transportation cost, assembly cost, and the cost of acquiring other components plus the margin. A cost plus pricing strategy is used as shown below:

$$SP_p = \left(\sum_{s=1}^{S}\sum_{g=1}^{G}\left(\left(S_{sg} \times TC_{sg}\right) + \left(S_{sg} \times C_{sg}\right)\right) + A + M\right) \times (1 + \theta) \quad (3\text{-}2)$$

Revenue from New Products is computed from price of new product and the quantity of new products sold. However, in this model, as the new demand is computed individually for components, and as this demand varies for each component, the average unit price of component is computed from SP_p by dividing it with number of component (N). Therefore, total revenue is computed as shown in the following equation:

$$Revenue\ from\ New\ Products = \left(\sum_{g=1}^{G} ND_g\right) \times \left(\frac{\left(\sum_{s=1}^{S}\sum_{g=1}^{G}\left(\left(S_{sg} \times TC_{sg}\right) + \left(S_{sg} \times C_{sg}\right)\right) + A + M\right) \times (1+\theta)}{N}\right) \quad (3\text{-}3)$$

Refurbished and Remanufactured Products Revenue is computed as the sum of revenue generated from refurbished and remanufactured products sold as shown below:

$$\begin{aligned} &Refurbished\ and\ Remanufactured\ Product\ Revenue \\ &= (Quantity\ of\ refurbished\ and\ remanufactured\ products\ sold) \\ &\times (Unit\ price\ of\ refurbished/remanufactured\ product) \end{aligned}$$

The Remanufactured and Refurbished Components Quantity satisfying the current demand is computed as

$$Remanufactured\ and\ Refurbished\ Components\ Quantity\ = \sum_{g=1}^{G}(Rf_g\ \times a) + (Rm_g\ \times b\ ) \tag{3-4}$$

Price of Unit of Refurbished/remanufactured Product (SP_{dis}), which is sold at a discounted price, is computed as the difference between the price of new product minus the discount D_p as

$$SP_{dis} = SP_p \times (1 - D_p) \tag{3-5}$$

From above, the revenue from refurbished and remanufactured products is expressed as

$$Revenue\ from\ Refurbished\ and\ Remanufactured\ Products = \left(\frac{\left(\sum_{s=1}^{S}\sum_{g=1}^{G}\left((S_{sg}\ \times\ TC_{sg}) + (S_{sg}\ \times\ C_{sg})\right) +\ A +\ M\right) \times (1+\theta) \times (1 - D_p)}{N}\right) \times \left(\sum_{g=1}^{G}\left((Rf_g\ \times a) + (Rm_g\ \times b\ )\right)\right) \tag{3-6}$$

Therefore, the Total Revenue is expressed as

$$Total\ Revenue\ (TR) = \left(\sum_{g=1}^{G} ND_g\right) \times \left(\frac{\left(\sum_{s=1}^{S}\sum_{g=1}^{G}\left((S_{sg}\ \times\ TC_{sg}) + (S_{sg}\ \times\ C_{sg})\right) +\ A +\ M\ \right) \times (1+\theta)}{N}\right) + \left(\frac{\left(\sum_{s=1}^{S}\sum_{g=1}^{G}\left((S_{sg}\ \times\ TC_{sg}) + (S_{sg}\ \times\ C_{sg})\right) +\ A +\ M\right) \times (1+\theta) \times (1 - D_p)}{N}\right) \times \left(\sum_{g=1}^{G}\left((Rf_g\ \times a) + (Rm_g\ \times b\ )\right)\right) \tag{3-7}$$

Total cost computations:

The total annual cost incurred during the time period t_n includes several closed-loop SC costs as listed below:

- Total supplier cost for the components,
- Total assembly costs,
- Total holding costs,
- Total cost for acquiring other components,
- Total processing costs at collection, remanufacturing and recycling centers,
- Total transportation costs between SC partners including (suppliers to OEM, use locations to collection centers, collection centers to remanufacturing, recycling, OEM and disposal locations, remanufacturing centers to OEM and recycling centers to respective supplier)
- Total refurbishing costs
- Total disassembly costs
- Total disposal costs
- Total fixed costs for OEM, collection, remanufacturing and recycling centers

Each of the listed costs is explained below:

Total supplier cost is the summation of all the supplier costs incurred for buying all the components and is expressed by

$$Total\ Supplier\ Cost = \sum_{s=1}^{S}\sum_{g=1}^{G}\left(\left(S_{sg} \times C_{sg}\right) \times ND_g\right) \quad (3\text{-}8)$$

Total Assembly Cost is the total cost incurred for assembling all the remanufactured and new components available at OEM to satisfy the demand for period t_n. Since only critical components are considered in the model, the total assembly cost per-unit of product is the sum of per-unit assembly cost and other component acquisition cost (cost required to acquire the components not supplied by the suppliers in this model).

$$Total\ Assembly\ Cost\ =\ \sum_{g=1}^{G}\left(\frac{ND_g + (Rm_g \times b)}{N}\right) \times (A + M) \quad (3\text{-}9)$$

Total Transportation Cost is the cost of transporting a unit of product/component from one SC partner to another. It involves several components as listed in total cost section which are discussed below:

Suppliers to OEM: The total cost incurred for transporting all the components from their respective suppliers to OEM. This value is expressed as

$$Supplier\ to\ OEM\ Transportation\ Cost = \sum_{s=1}^{S}\sum_{g=1}^{G}\left(\left(S_{sg} \times TC_{sg}\right) \times ND_g\right) \quad (3\text{-}10)$$

Use to Collection Center: The summation of the costs for transporting all the products from all use locations to all collection centers expressed by

$$Use\ to\ Collection\ Center\ Transportation\ Costs = \sum_{b=1}^{B}\sum_{cc=1}^{CC}(TC_{bcc} \times C_{bcc}) \quad (3\text{-}11)$$

Collection Centers to Remanufacturing Centers: The total cost incurred for transporting all components from all collection to all remanufacturing centers and is computed by

$$Collection\ to\ Remanufacturing\ Centers\ Transportation\ Costs = \sum_{cc=1}^{CC}\sum_{d=1}^{Y}\sum_{g=1}^{G}\left(TC_{ccdg} \times CC_{ccdg}\right) \quad (3\text{-}12)$$

Collection Centers to Recycling Centers: The summation of costs for transporting all components from all collection to all recycling centers and expressed by

$$Collection\ to\ Recycling\ Centers\ Transportation\ Costs = \sum_{cc=1}^{CC}\sum_{e=1}^{E}\sum_{g=1}^{G}\left(TC_{cceg} \times CC_{cceg}\right) \quad (3\text{-}13)$$

Collection Centers to OEM: The total cost incurred for transporting products from all collection centers to OEM and is expressed by

$$Collection\ Centers\ to\ OEM\ Transportation\ Cost =$$

$$\sum_{b=1}^{B} \sum_{cc=1}^{CC} (Rf_{bcc} \times TC_{cc}) \tag{3-14}$$

Collection Centers to Disposal: The summation of costs incurred for transporting all components from all collection centers to disposal location expressed by

$$Collection\ Centers\ to\ Disposal\ Transportation\ Costs =$$

$$\sum_{g=1}^{G} \sum_{cc=1}^{CC} \left(\left(\sum_{b=1}^{B} Dp_{bccg} \right) \times TC_{ccg} \right) \tag{3-15}$$

Remanufacturing Center to OEM: The total cost for transporting all the components from all the remanufacturing centers to OEM and expressed by

$$Remanufacturing\ Center\ to\ OEM\ Transportation\ Costs =$$

$$\sum_{cc=1}^{CC} \sum_{g=1}^{G} \sum_{d=1}^{Y} \left(CC_{ccdg} \times TC_{dg} \right) \tag{3-16}$$

Recycling Centers to Respective Supplier: The summation of all the costs incurred for transporting all the recycled material from the recycling centers and can be expressed as

$$Recycling\ Centers\ to\ Supplier\ Transportation\ Costs =$$

$$\sum_{cc=1}^{CC} \sum_{g=1}^{G} \sum_{e=1}^{E} \left(CC_{cceg} \times TC_{eg} \right) \tag{3-17}$$

Total Product Cost per-unit is the summation of costs incurred in producing a unit of product. It is the sum of supplier component cost, supplier transportation cost, assembly cost and other component acquisition cost incurred for producing one unit of product and is expressed by

$$Total\ Product\ \text{Cost}\ Per\ Unit =$$

$$\sum_{s=1}^{S}\sum_{g=1}^{G}\Big(\big(S_{sg} \times TC_{sg}\big) + \big(S_{sg} \times C_{sg}\big)\Big) + A + M \tag{3-18}$$

Total OEM Holding Cost is sum of costs spent for storing the refurbished and remanufactured component inventory at OEM and is expressed by

$$Total\ OEM\ Holding\ Cost = \sum_{g=1}^{G}(Rf_g + Rm_g) \times H \tag{3-19}$$

Total Processing Cost at Collection Center is the total cost for processing all the recovered products at all collection centers and is computed as

$$Total\ Processing\ Cost\ at\ Collection\ Center =$$

$$\sum_{b=1}^{B}\sum_{cc=1}^{CC}(PC_{cc} \times C_{bcc}) \tag{3-20}$$

Total Capital Costs is summation of the annualized capital costs incurred for setting up facilities. The capital costs are incurred for OEM, collection, remanufacturing and recycling centers and these costs are expressed by

$$Total\ OEM\ Capital\ Cost = FC_{OEM} \tag{3-21}$$

$$Total\ Collection\ Center\ Capital\ Costs = \sum_{cc=1}^{CC}(FC_{cc} \times O_{cc}) \tag{3-22}$$

$$Total\ Remanufacturing\ Center\ Capital\ Costs = \sum_{d=1}^{Y}(FC_d \times O_d) \tag{3-23}$$

$$Total\ Recycling\ Center\ Capital\ Costs = \sum_{e=1}^{E}(FC_e \times O_e) \tag{3-24}$$

Total Remanufacturing Processing Cost is the summation of cost incurred for remanufacturing all the components at all remanufacturing centers and is expressed by

$$Total\ Remanufacturing\ Processing\ Cost =$$

$$\sum_{cc=1}^{CC}\sum_{g=1}^{G}\sum_{d=1}^{Y}\big(CC_{ccdg} \times CRm_{dg}\big) \tag{3-25}$$

Total Recycling Processing Cost is the sum of costs incurred for recycling all the components at all recycling centers and is expressed as

$$Total\ Recycling\ Processing\ Cost\ = \sum_{cc=1}^{CC}\sum_{g=1}^{G}\sum_{e=1}^{E}\left(CC_{cceg}\ \times\ CRcy_{eg}\right) \qquad (3\text{-}26)$$

Total Disassembly Cost is the total cost incurred for disassembling all the products at all collection centers and is given as

$$Total\ Recycling\ Processing\ Cost = \sum_{b=1}^{B}\sum_{cc=1}^{CC}\sum_{g=1}^{G}\left(\frac{Dis_{bccg}}{N}\ \times\ CD_{cc}\right) \qquad (3\text{-}27)$$

Total Refurbish Cost is the sum of all the costs incurred for refurbishing all products at all collection centers and is expressed by

$$Total\ Refurbish\ Cost\ = \sum_{b=1}^{B}\sum_{cc=1}^{CC}(Rf_{bcc}\ \times\ CRf_{cc}) \qquad (3\text{-}28)$$

Total Disposal Cost is the sum of all costs incurred in disposing all the components at all collection centers to disposal location and is expressed by

$$Total\ Disposal\ Cost =\ \sum_{g=1}^{G}\sum_{cc=1}^{CC}\left(\left(\sum_{b=1}^{B}Dp_{bccg}\right)\times Z\right) \qquad (3\text{-}29)$$

Therefore the total cost is expressed as

$$Total\ Cost\ (TC) =$$

$$\left[\left(\sum_{s=1}^{S}\sum_{g=1}^{G}\left(\left(S_{sg}\ \times\ C_{sg}\right)\times ND_g\right)\ \right)+\left(\sum_{s=1}^{S}\sum_{g=1}^{G}\left(\left(S_{sg}\ \times\ TC_{sg}\right)\times ND_g\right)\right)+\right.$$
$$\left(\sum_{g=1}^{G}\left(\frac{ND_g+\left(Rm_g\times b\right)}{N}\right)\times(A+M)\right)+\left(\sum_{b=1}^{B}\sum_{cc=1}^{CC}(TC_{bcc}\ \times\ C_{bcc})\right)+(FC_{OEM})+$$
$$\left(\sum_{g=1}^{G}(Rf_g+Rm_g)\ \times H\right)+\left(\sum_{b=1}^{B}\sum_{cc=1}^{CC}(PC_{cc}\ \times\ C_{bcc})\right)+\left(\sum_{cc=1}^{CC}(FC_{cc}\times\ O_{cc})\right)+$$

$$(\sum_{d=1}^{Y}(O_d \times FC_d)) + (\sum_{e=1}^{E}(O_e \times FC_e)) + (\sum_{b=1}^{B}\sum_{cc=1}^{CC}(Rf_{bcc} \times TC_{cc})) + \sum_{cc=1}^{CC}\sum_{g=1}^{G}\sum_{d=1}^{Y}(CC_{ccdg} \times CRm_{dg}) + (\sum_{cc=1}^{CC}\sum_{g=1}^{G}\sum_{d=1}^{Y}(CC_{ccdg} \times TC_{dg})) + (\sum_{c=1}^{CC}\sum_{g=1}^{G}\sum_{e=1}^{E}(CC_{cceg} \times CRcy_{eg})) + (\sum_{cc=1}^{CC}\sum_{g=1}^{G}\sum_{e=1}^{E}(CC_{cceg} \times TC_{eg})) + (\sum_{cc=1}^{CC}\sum_{d=1}^{Y}\sum_{g=1}^{G}(TC_{ccdg} \times CC_{ccdg})) + (\sum_{cc=1}^{CC}\sum_{e=1}^{E}\sum_{g=1}^{G}(TC_{cceg} \times CC_{cceg})) + \left(\sum_{b=1}^{B}\sum_{cc=1}^{CC}\sum_{g=1}^{G}\left(\frac{Dis_{bccg}}{N} \times CD_{cc}\right)\right) + (\sum_{b=1}^{B}\sum_{cc=1}^{CC}(Rf_{bcc} \times CRf_{cc})) + \left(\sum_{g=1}^{G}\sum_{cc=1}^{CC}\left(\left(\sum_{b=1}^{B} Dp_{bccg}\right) \times TC_{ccg}\right)\right) + \left(\sum_{g=1}^{G}\sum_{cc=1}^{CC}\left(\left(\sum_{b=1}^{B} Dp_{bccg}\right) \times Z\right)\right)]$$

(3-30)

The reusable, remanufacturable and recyclable components from each use location are selected based on their individual probabilities and threshold values from the following conditions:

Reuse Assessment of products: All products from use locations are evaluated for their suitability for reuse. The products from similar use locations are assumed to have similar characteristics. This is due to the fact that the use patterns vary with respect to geographical region, the atmospheric conditions, social and cultural practices of customers, and technological advancements in that region. Therefore, for reuse assessment,

$$\forall\, b, \quad if\ (Ru_b \geq \partial)\ then\ all\ products\ from\ use\ location\ b\ are\ refurbished$$

Remanufacturing Assessment of components: All the critical components of a product are evaluated for remanufacturability. The components from similar use locations are assumed to have similar characteristics and are evaluated separately. The following condition is used for selecting components for remanufacturing,

$$\forall\, b, g\ \ if\ (Rm_{bg} \geq \emptyset_g)$$
$$then\ all\ components\ of\ type\ g\ from\ use\ location\ b\ are\ remanufactured$$

Recycling Assessment of components: All the recyclable components are evaluated at the collection centers to determine whether the major material from these components can be extracted easily. The components from similar use location again are assumed to have similar characteristics and are evaluated separately. Therefore, the following condition is used for selecting components for recycling,

$$\forall\, b, g$$
$$\left(Rcy_{bg} = \begin{cases} 1 & major\ material\ of\ component\ g\ at\ use\ location\ b\ is\ recycled \\ 0 & otherwise \end{cases} \right)$$

Therefore, the EOM can be expressed as:

Objective Function:

$$Maximize\ Profit = TR - TC$$

Subject to:

Supplier Constraints

$$\sum_{s=1}^{S} S_{sg} = 1 \qquad \forall\, g \qquad (3\text{-}31)$$
$$\sum_{g=1}^{G} S_{sg} = 1 \qquad \forall\, s \qquad (3\text{-}32)$$

Capacity Constraints

$$\sum_{b=1}^{B} C_{bcc} \leq Q_{cc} \qquad \forall\, cc \qquad (3\text{-}33)$$
$$\sum_{b=1}^{B} (DD_b \times \alpha) \leq \sum_{cc=1}^{CC} Q_{cc} \qquad (3\text{-}34)$$
$$C_{bcc} \leq O_{cc} \times (DD_b \times \alpha) \qquad \forall\, cc, b \qquad (3\text{-}35)$$
$$CC_{ccdg} \leq O_d \times \left(\sum_{b=1}^{B} Rm_{bccg}\right) \qquad \forall\, cc, d, g \qquad (3\text{-}36)$$
$$CC_{cceg} \leq O_e \times \left(\sum_{b=1}^{B} Rcy_{bccg}\right) \qquad \forall\, cc, e, g \qquad (3\text{-}37)$$
$$\sum_{b=1}^{B} C_{bcc} \geq Th_{cc} \times Q_{cc} \times O_{cc} \qquad \forall\, cc \qquad (3\text{-}38)$$

Demand Constrains

$$D_g = ND_g + (Rf_g \times a) + (Rm_g \times b) \qquad \forall\, g \qquad (3\text{-}39)$$
$$\sum_{g=1}^{G} \frac{D_g}{N} = \sum_{b=1}^{B} DD_b \qquad (3\text{-}40)$$

$$\sum_{cc=1}^{CC} CC_{ccdg} \leq \left(Q_{dg} \times CbRm_{dg}\right) \quad \forall\, d\,, g \tag{3-41}$$

$$\sum_{cc=1}^{CC} CC_{cceg} \leq \left(Q_{eg} \times CbRcy_{eg}\right) \quad \forall\, e\,, g \tag{3-42}$$

$$\sum_{cc=1}^{CC} \sum_{g=1}^{G} CC_{ccdg} \geq \left(\sum_{g=1}^{G} Q_{dg}\right) \times Th_d \times O_d \quad \forall\, d \tag{3-43}$$

$$\sum_{cc=1}^{CC} \sum_{g=1}^{G} CC_{cceg} \geq \left(\sum_{g=1}^{G} Q_{eg}\right) \times Th_e \times O_e \quad \forall\, e \tag{3-44}$$

Remanufacturing and Recycling Center Constrains

$$\sum_{cc=1}^{CC} C_{bcc} = (DD_b \times \alpha) \quad \forall\, b \tag{3-45}$$

$$\sum_{d=1}^{Y} CC_{ccdg} = \sum_{b=1}^{B} Rm_{bccg} \quad \forall\, cc\,, g \tag{3-46}$$

$$\sum_{e=1}^{E} CC_{cceg} = \sum_{b=1}^{B} Rcy_{bccg} \quad \forall\, cc\,, g \tag{3-47}$$

$$\sum_{cc=1}^{CC} \sum_{b=1}^{B} Dis_{bccg} = \sum_{cc=1}^{CC} \sum_{b=1}^{B} \left(Rm_{bccg} + Rcy_{bccg} + Dp_{bccg}\right) \quad \forall\, g \tag{3-48}$$

$$\sum_{b=1}^{B} \sum_{cc=1}^{CC} C_{bcc} = \sum_{b=1}^{B} \sum_{cc=1}^{CC} \left(Rf_{bcc} + \frac{\sum_{g=1}^{G} Dis_{bccg}}{N}\right) \tag{3-49}$$

Balanced Flow Constraints

$$\alpha <= 1 \tag{3-50}$$

$$\theta \leq 1 \tag{3-51}$$

$$D_p \leq 1 \tag{3-52}$$

$$\partial \leq 1 \tag{3-53}$$

$$Ru_b \leq 1 \tag{3-54}$$

$$\emptyset_g \leq 1 \tag{3-55}$$

$$Rm_{bg} \leq 1 \tag{3-56}$$

$$a \leq 1 \tag{3-57}$$

$$b \leq 1 \tag{3-58}$$

Probability Constraints

$Rcy_g \in \{0,1\}$ (3-59)

$Rcy_{bg} \in \{0,1\}$ (3-60)

} Binary Constraints

Equations (3-31) and (3-32) ensure that each supplier supplies only one component and each component is supplied by a different supplier.

Equations (3-33) ensure that each collection centers have allocated products based on their capacity. Equation (3-34) ensures that all the collection centers together have the capacity to process all the recovered quantity transported from use locations.

Equations (3-35), (3-36) and (3-37) ensure that the products are transported from a given use location to a given collection center only if the collection center is open, similarly components are transported from collection centers to remanufacturing and recycling centers only if they are open and the quantity transported to each collection, remanufacturing and recycling center is less than or equal to total recovered, remanufactured and recycled quantity available. Equations (3-38) ensure that a collection center is open only if the minimum threshold capacity limit is met.

Equations (3-39) and (3-40) ensure that the total demand for each component is satisfied by the sum of new, refurbished and remanufactured components, and the total demand for products must be equal to sum of individual demand market at each geographical region.

Equations (3-41) and (3-42) ensure that if a remanufacturing or recycling center does not have the capability to process a certain component, then the center will not have any capacity, too, and therefore the component is not sent to that location. Further, for each component g, the equations ensure that the total quantity of components transported from all the collection centers to each remanufacturing and recycling center is less than the capacity of that remanufacturing and recycling centers for that component. Equations (3-43) and (3-44) ensure that a remanufacturing center or a recycling center is open only if minimum quantity threshold limit (component quantity that must be transported to a facility for it to be opened) is met.

Equations (3-45) through (3-49) ensure that the flow of units is balanced within the total SC network. It ensures that all the recovered products are processed at collection centers, all the components selected for remanufacturing are processed at remanufacturing centers, all the components selected for recycling are processed at recycling centers, the sum of disassembled components must be equal to sum of remanufactured, recycled and disposed components and the all the quantity that enters the collection centers must leave to corresponding OEM, remanufacturing, recycling and disposal locations.

Equations (3-50) through (3-58) ensure that values such as recovery probability, profit margin, price discount rating, product reuse threshold probability, product reuse probability, component remanufacturing threshold probability, component remanufacturing probability, the probability of refurbished and remanufactured quantity satisfying demand for steady-state period t_n, and the recycling probability for components are all less than or equal to 1.

Equations (3-59) and (3-60) ensures that the recycling thresholds are binary that is in terms of 0 or 1. All the quantities transported between SC partners are initialized as positive integers in the model. All the costs incurred at various SC partners are initialized as floating numbers.

3.7 Economic Multi Life-cycle (MLC_{Eco}) Analysis

The next step in the hierarchical approach is to perform the economic MLC analysis for each PDSCC combination identified by EOM for the period T to select the best combinations that have maximum cumulative profit at the end of T. Therefore, in this section, the assumptions considered for this analysis, the procedure for conducting the economic MLC analysis and a description of the developed tool (MLC_{Eco}) are presented in detail.

3.7.1 Assumptions

In order to perform the MLC analysis, the demand for all the years in period T must be computed. Hence, the demand curve in Figure 3.6 is used as a reference to estimate the demand over time period T. It is assumed that the initial demand at period t_1 and the final demand at period t_f and the price of the product at these two periods t_1 and t_f are known. The demand and product price for rest of the years is computed based on their values at years t_1, t_f and t_n and the demand curve.

3.7.2 Analysis Description

The objective of performing economic MLC analysis is to compute the benefits of pursuing closed-loop flow over MLCs. In order to promote true sustainability, it is not enough to select a product design based on its performance during one period (t_n); it is important to consider the performance throughout the entire period T (from the product's birth until the product becomes obsolete in the market) to capture the true benefits of sustainability achieved through closed-loop flow efforts. Ideally, the optimization model, EOM, should be run for all the years in T to compute the performance of each PDSCC combination over MLCs. However, developing optimization model for MLCs is difficult as it involves several issues such as obtaining a huge amount of both product design and SC design related data, dealing with longer computation time and multiple conflicting objectives etc., all of which makes the model difficult to solve. Hence, in this research the economic optimization is performed at the steady-state period, and the economic MLC analysis is performed for all the years over T. Therefore, the aim of the economic MLC analysis is to compute for each PDSCC combination corresponding SC costs, revenue and thereby the profit for each year over multiple years during T. The output of this analysis is to select best PDSCCs having maximum cumulative profit at the end of T.

The economic MLC analysis is performed separately for each PDSCC combination. It uses the steady-state SC costs results obtained from EOM (presented in Table 3.3), total revenue generated and thereby the total profit obtained during steady-state period T_n. From the steady-state demand and its results, the corresponding annual SC costs, revenue and optimal profit for each year over period T is computed and compared for alternate PDSCC combinations. A detailed description of the demand, selling price for new and refurbished/remanufactured products and components, the transportation quantities, the forward and reverse loop SC costs, the revenue related computations are all presented in this section.

Table 3.3: Steady-state Costs (Input to Economic MLC Analysis)

Total supplier cost
Total transportation cost from suppliers to OEM
Total OEM assembly cost
Total OEM holding cost
Total transportation cost from use locations to collection centers
Total collection centers processing costs
Total refurbishing cost for reusable products
Total cost for transporting refurbished products to OEM
Total cost of disassembly
Total cost for transporting remanufacturable/recyclable components from collection centers to remanufacturing/recycling centers
Total remanufacturing and recycling processing costs
Total cost for transporting disposal components from collection centers to disposal
Total disposal costs
Total cost for transporting remanufactured components to OEM
Total cost for transporting recyclable components to suppliers
Total supplier cost
Total transportation cost from suppliers to OEM
Total OEM assembly cost

Demand Computation

The first step is to compute the product demand for all the years in period T which is done using the demand graph as shown in Figure 3.10. As the demand and the price during t_1, t_f and t_n are known (see assumptions) the demand for rest of the years in the introduction and decline phases are computed by using the slope, intercept and price at t_{s1} and t_{sf}. Therefore, the demand can be expressed by

$$Demand = (Slope\ of\ the\ line \times Price) + Intercept$$

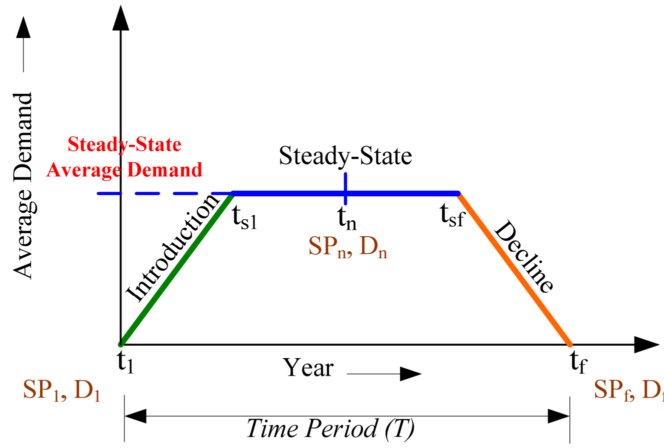


Figure 3.10: Demand Graph for MLC Analysis

Therefore, the slope and the intercept of the introduction and decline lines is given by

$$Slope\ of\ Introduction\ Line\ (m_{IL}) = \left(\frac{D_n - D_1}{SP_n - SP_1}\right)$$

$$Intercept\ of\ Introduction\ Line\ (I_{IL}) = D_1 - (m_{IL} \times SP_1)$$

$$Slope\ of\ Decline\ Line\ (m_{DL}) = \left(\frac{D_f - D_n}{SP_f - SP_n}\right)$$

$$Intercept\ of\ Decline\ Line\ (I_{DL}) == D_f - (m_{DL} \times SP_f)$$

To calculate the demand, the price at each year during *T* must be known. Hence, the next step is to compute the product price for each year in period *T*.

Price Adjustment Factor Computation: The price-elasticity of demand is used to estimate the demand for rest of the years (as demand increases the price of a product decreases) during the introduction phase. However, during the decline phase as the demand decreases the price is also decreased as the product is no longer needed and therefore its price is reduced to attract customers. In reality, the demand and the price of a product could have non-linear relationship, based on product's characteristics, customer buying behavior etc. However, in this model, an approximation is used for purpose of generalization among different products. Therefore, the price values for all the years in time period T are computed using adjustment factors generated based on the discussed pattern. The adjustment factor for steady-state period t_n (Af_n) is considered as 1 as it is the base value. From the prices SP_1 and SP_n the corresponding factor at period t_1 is computed as follows:

$$Price - adjustment\ factor\ at\ year\ t_1\ (Af_1) = \frac{SP_1}{SP_n} \quad (3\text{-}61)$$

Similarly, from the prices at t_f and t_n the corresponding factor at t_f is computed as

$$Price - adjustment\ factor\ at\ year\ t_f\ (Af_f) = \frac{SP_f}{SP_n} \quad (3\text{-}62)$$

Therefore, starting from Af_1 value the factors for other years during introduction period are decreased in equal fractions until the steady-state value Af_n is reached. This is performed to maintain consistency between different years. Similarly, the factors for rest of the years during the decline period are decreased in equal fractions from steady-state value Af_n until Af_f is reached. Therefore, the values for introduction and decline phases are computed as follows:

$$\text{Fractional Value for Introduction Phase} = \left(\frac{Af_1 - Af_n}{t_{s1} - t_1}\right) \quad (3\text{-}63)$$

$$\text{Fractional Value for Decline Phase} = \left(\frac{Af_n - Af_f}{t_f - t_{sf}}\right) \quad (3\text{-}64)$$

From the fractional values and the steady-state price at period t_n, the price for the rest of the years over the demand graph is computed by

$$Price\ for\ year\ \ t_j\ (\ SP_j) = \ \ AF_j\ \times Price\ at\ year\ t_n(\ SP_n)$$
$$\forall\ j = 2,\ \ 3, 4, \ldots 1 + n\ where\ n = T - 2 \quad (3\text{-}65)$$

The price adjustment factors for both new products and for the discounted products are assumed to be similar. Hence, the new product price and the discounted product price are calculated for all the years in the time period T. The price for the new product, is used to estimate the demand for each year and therefore the demand during the introduction and decline phase is computed using the following equations:

$$Demand\ for\ year\ k\ in\ introduction\ phase\ D_k = \ (m_{IL}\ \times\ SP_k)\ +\ I_{IL} \quad k \in \{1, s_1\}$$

(3-66)

$$Demand\ for\ year\ l\ in\ decline\ phase\ D_l = \ (m_{DL}\ \times\ SP_l)\ +\ I_{DL} \qquad l\ \in \{s_f, f\}$$
(3-67)

<u>Transportation Quantities across MLC Years</u>

As the SC costs for each of the MLC years depends on both cost per-unit and the quantity transported, it is important to determine the transportation quantities within the closed-loop SC. The SC quantities are computed differently for forward and reverse flow SC partners due to the nature of operations and hence are presented individually below:

Forward loop Transportation Quantities: The annual demand can be satisfied by a mixture of new, refurbished and remanufactured components with different proportions of each type. This is due to the fact the new demand depends on: (a) the number of refurbished and remanufactured components available (b) and the percentage of these that satisfy the demand.

The refurbished and remanufactured components available are the reusable and remanufactured components returned from the past life-cycles and, these quantities must be determined. As the quantities are proportional to demand, the steady-state values can be used to estimate the quantities for the rest of the years as follows:

The results from the EOM provide the quantity of components that are reused and remanufactured for the steady-state period t_n. By computing a demand ratio (ratio of demand for a given year over steady-state demand), the refurbished and remanufactured quantities for the rest of the years in period T can be projected. Given the complexities explained earlier, the demand ratio is a feasible way to estimate the quantities that depend solely on demand. Therefore, the demand ratio is expressed by

$$Demand\ Ratio\ (Dr_y) = \frac{Demand\ for\ Year\ y\ (D_y)}{Steady\ State\ Demand\ (D_n)}\ \forall\ y = 1,2,3\ldots f \quad (3\text{-}68)$$

The refurbished quantity for a component g resulting from a specific year y can be expressed as

$$Refurbished\ quantity\ for\ component\ g\ from\ year\ y = DR_y \times Refurbished\ quantity\ for\ component\ g\ from\ steady\ state\ year\ n$$

Similarly, the number of remanufactured components available for component g from a specific year y is expressed by

$$Remanufactured\ quantity\ for\ component\ g\ from\ year\ y = DR_y \times Remanufactured\ quantity\ for\ component\ g\ from\ steady\ state\ year\ n$$

Also, the availability of the refurbished and remanufactured components depends on the length of the use stage and the time taken to perform the reverse loop SC operations on the recovered products. As the products sold must be used, before they can be recovered and re-processed, for the first few years, until the past life-cycle components are available for next life, the demand is satisfied by new components only. This is the case in reality too, that is for the first few years all the reverse loop set-up costs are incurred by the company. The company will realize the benefits of performing closed-loop operations, during the long run when the products from previous life-cycles are returned and less new material is used to satisfy the demand.

The percentage of refurbished and remanufactured components used to satisfy the demand: Ideally, all the refurbished and remanufactured components at OEM can be used to satisfy the demand for each year. However, in reality a company may not prefer to sell only refurbished or remanufactured products. It may want to sell a proportion of these products, while still being able to sell new products in the market, thereby staying competitive. While these decisions are company and product specific, for generalization, this aspect is captured in the model through providing an option of giving a percentage value for each of the refurbished and remanufactured components to be used to satisfy each year's demand. Also, the OEM may have refurbished and remanufactured products from multiple years from the past. That is the components from past life-cycles available at the OEM could be returned from any year y in the time period T. This therefore, raises several questions such as (a) Can the returned components from a year y be used to satisfy the demand for any number of years? If yes, is it realistic to consider such a business model? (b) If not, for how long must the company wait before it considers the returns from a specific year y as scarp quantity?

In reality, the returned products from past lives can be used to satisfy the demand for a limited number of years. This is because products returned from previous years could become obsolete quickly. While these decisions depend on the type of the product (such as consumer or a household product) and the company inventory policies, this model considers that all the products returned from a year y can be used for a certain number of years from their return to satisfy the demand and the rest of the years returns are scraped. Most of the scraped components contain valuable metals, and therefore the companies can sell these scrap parts to metal recyclers. For example, most of the automotive dismantlers sell parts with ferrous and aluminum metals with no resale value to recyclers and generate revenue (Toto, 2003). Therefore it is assumed a certain amount of revenue is generated from selling scrap components and this value depends on the type of materials used in a product.

The percentage of refurbished and remanufactured components available to satisfy the annual demand must be determined. In reality, these probabilities are company and product specific. While companies would like to use large quantities of refurbished and remanufactured items for some products, for others they settle for low quantities. Also these percentages could vary based on the year from which the products are returned and the year for which these components are used to satisfy the demand. That is the returns from a specific year y can be used to satisfy demand for any year l , as long as they are available, in the time period T. In general, this value l depends on the length of use phase (v) and time taken to perform reverse loop operations on the return product to make them available for next life (q). Therefore, the returns from year y are first available in year $(y + v + q)$ and can last until year f. This means that it requires dealing with a vast amount of data. This complexity can be considerably reduced by assuming that for all refurbished/remanufactured components returned from a specific year, a constant percentage is used to satisfy the demand, based on availability. Table 3.4 presents an example of these refurbishing and remanufacturing percentages for each year in the time period T and the years (Δ) after which the returned quantities are considered as scrap. It must be noted that not all the years in T are shown, because the refurbished and the remanufactured quantity available at the OEM is computed for only those years during T, for which the returned components are available to satisfy the demand. Since the rest of the years returns $\left[t_{(T-v-q+1)}\ to\ t_{(T)}\right]$ are not available for any of the years these are not considered in the computations.

Table 3.4: Sample Past Returned Quantities and their Percentages

Refurbished/Remanufactured Component Return Year	Percent used in Each Year		Scrap Quantity
	Refurbished	Remanufactured	
t_1 $[rm_1, rf_1]$	A_1	B_1	Quantity remaining after first Δ years of return
$t_{1+1}[rm_{1+1}, rf_{1+1}]$	A_{1+1}	B_{1+1}	
t_{1+2} $[rm_{1+2}, rf_{1+2}]$	A_{1+2}	B_{1+2}	
t_{1+3} $[rm_{1+3}, rf_{1+3}]$	A_{1+3}	B_{1+3}	
.	.	.	
.	.	.	
.	.	.	
$t_{(T-v-q)}[rm_{(T-v-q)}, rf_{(T-v-q)}]$	$A_{(T-v-q)}$	$B_{(T-v-q)}$	

As discussed earlier, until products from first life are available at OEM for their next life, all the demand is satisfied by new products only and the OEM incurs no inventory costs. However, as the products start returning from previous life-cycles, the OEM inventory constantly builds up. In this research, priority is given for refurbished and remanufactured components to satisfy the demand therefore, it becomes necessary to compute for each year in period T, the quantity of refurbished and remanufactured components available at OEM, the number of these that satisfy the demand (computed from percentages given in Table 3.4) for each year and the number of components that are scraped. These quantities could vary for each year depending on the length of use phase (v) and the time consumed in performing the reverse loop operations (q). The computation methods vary for different time periods within period T as discussed below:

Year 1 to $(1 + v)$: All the demand for these years is satisfied by new products. There is no inventory at OEM during all these years. Only new components are used to satisfy the demand.

Year $(1 + v + q)$ to (T): The demand for these years is satisfied by a mixture of new, refurbished and remanufactured products. The OEM inventory for both refurbished and remanufactured components varies for each year, as for year $(1 + v + q)$ the products returned from 1 $[rf_1, rm_1]$ could be available, whereas for year $(1 + v + q + 1)$ components remaining at OEM from year 1 and products returned from year $(1 + 1)$ $[rf_{1+1}, rm_{1+1}]$ can be available and so on. Therefore, for each year increment y in this duration, the products returned from year $(1 + y)$ $[rf_{1+y}, rm_{1+y}]$ are available, and components remaining at OEM (returned from year 1 through$(1 + y - 1)$) can be available. From the past quantities available at OEM and their corresponding percentages shown in Table 3.4, the actual quantities available at each year to satisfy the demand is calculated as illustrated in Table 3.5. When the products are available for the first time from the past year, say t_1, the refurbished and remanufacturing quantity that can satisfy the year $t_{(1+v+q)}$ (year at which each component g from year t_1 is first available) demand is expressed by

$$Refurbished\ quantity\ for\ any\ component\ g\ satisfying\ demand\ for\ year\ t_{(1+v+q)} = Percentage\ of\ components\ used\ for\ that\ year\ (A_1) \times Refurbished\ components\ available\ (rf_1)$$

However, from the year $t_{(1+v+q+1)}$ onwards, the number of refurbished components returned from year t_1 that can satisfy the demand, is based on the left over component quantity at OEM from year t_1 and the refurbished component percentage for year t_1 (A_1). The refurbished component quantity from year t_1, available for year $t_{(1+v+q+1)}$ is given by

$$Refurbished\ quantity\ for\ any\ component\ g\ satisfying\ demand\ for\ year\ t_{(1+v+q+1)} = (Percentage\ of\ components\ used\ for\ that\ year\ (A_1) \times Refurbished\ components\ available\ for\ year\ t_1\ (rf_1)) \times (1 - A_1)$$

Similarly for year $t_{(1+v+q+2)}$, the refurbished component quantity from year t_1, that is available is computed by

$$Refurbished\ quantity\ for\ any\ component\ g\ satisfying\ demand\ for\ year\ t_{(1+v+q+2)}$$
$$= (Percentage\ of\ components\ used\ for\ that\ year\ (A_1)$$
$$\times Refurbished\ components\ available\ for\ year\ t_1\ (rf_1\ )\ )\ \times (1 - A_1)^2$$

Similarly, for year $t_{(1+v+q+n1)}$ ($t_{(1+v+q+n1)} \leq t_T$), the refurbished component quantity from year t_1, available is computed by

$$Refurbished\ quantity\ for\ any\ component\ g\ satisfying\ demand\ for\ year\ t_{(1+v+q+n1)}$$
$$= (Percentage\ of\ components\ used\ for\ that\ year\ (A_1)$$
$$\times Refurbished\ components\ available\ for\ year\ t_1\ (rf_1\ )\ )\ \times (1 - A_1)^{n1}$$

Where $n1$ varies from $1, 2, 3\ \ldots.(T - 1 - v - q)$.

The computations similar to above are used to calculate the number of remanufactured components for each type g returned from year t_1, that can satisfy the demand for years $t_{(1+v+q)}$ through t_T. The number of refurbished and remanufactured components returned from year t_{1+1} to satisfy the demand for years $t_{(1+v+q+1)}$ through t_T are also computed in a similar fashion. The shaded cells in Table 3.5 indicates that no refurbished and remanufactured components returned from those years are available to satisfy the demand. Each calculation is labeled for future computational purposes. It must be noted that these computations are performed for each component g.

Scarp Quantity Computations: All the refurbished and remanufactured components remaining at the OEM after first Δ years of their return are scraped and are removed from Table 3.5. The scrap components generate revenue.

Total Refurbished and Remanufactured Components Quantity satisfying each Year's Demand: Therefore, for each year between t_{1+v+q} through t_T, for each component g, the total refurbished and remanufactured quantity satisfying the demand is computed as the sum of individual quantities satisfying demand (returned from each year t_1 through t_{T-v-q}). Therefore, as an example for year $t_{(1+v+q+2)}$ the total refurbished components and the total remanufactured components satisfying demand can be expressed by

$$Total\ refurbished\ quantity\ for\ each\ component\ type\ g\ =\ (A_1\ \times rf_1)\ \times (1-A_1)^2 + (A_{1+1}\ \times rf_{1+1})\ \times\ (1-\ rf_{1+1}) + (A_{1+2}\ \times rf_{1+2})$$

(3-69)

$$Total\ remanufactured\ quantity\ for\ each\ component\ type\ g = (B_1\ \times rm_1)\ \times\ (1-B_1)^2\ + (B_{1+1}\ \times rm_{1+1})\ \times\ (1-rm_{1+1}) + (B_{1+2}\ \times rm_{1+2})$$

(3-70)

Table 3.5: Sample Computations for Refurbished and Remanufactured Components

Year	For Each Component g Returned from Year (Rf – Refurbished, Rm –Remanufactured)							
	t_1		t_{1+1}		t_{1+2} and so on		Until $t_{(T-v-q)}$	
	Rf	Rm	Rf	Rm	Rf	Rm	Rf	Rm
$t_{(1+v+q)}$	$(A_1 \times rf_1)$ (5.11)	$(B_1 \times rm_1)$ (5.12)						
$t_{(1+v+q+1)}$	$(A_1 \times rf_1) \times (1-A_1)$ (5.21)	$(B_1 \times rm_1) \times (1-B_1)$ (5.22)	$(A_{1+1} \times rf_{1+1})$ (5.23)	$(B_{1+1} \times rm_{1+1})$ (5.24)				
$t_{(1+v+q+2)}$ and so on	$(A_1 \times rf_1) \times (1-A_1)^2$ (5.31)	$(B_1 \times rm_1) \times (1-B_1)^2$ (5.32)	$(A_{1+1} \times rf_{1+1}) \times (1-rf_{1+1})$ (5.33)	$(B_{1+1} \times rm_{1+1}) \times (1-rm_{1+1})$ (5.34)	$(A_{1+2} \times rf_{1+2})$ (5.35)	$(B_{1+2} \times rm_{1+2})$ (5.36)		
Until $t_{(T)}$	$(A_1 \times rf_1) \times (1-A_1)^3$ (5.41)	$(B_1 \times rm_1) \times (1-B_1)^3$ (5.42)	$(A_{1+1} \times rf_{1+1}) \times (1-rf_{1+1})^2$ (5.43)	$(B_{1+1} \times rm_{1+1}) \times (1-rm_{1+1})^2$ (5.44)	$(A_{1+2} \times rf_{1+2}) \times (1-rf_{1+2})$ (5.45)	$(B_{1+2} \times rm_{1+2}) \times (1-rm_{1+2})$ (5.46)	$(A_{T-v-q} \times rf_{T-v-q})$ (5.47)	$(B_{T-v-q} \times rm_{T-v-q})$ (5.48)

New Demand Computations: Therefore, the quantity of new components required to satisfy the demand for each year between t_{1+v+q} to t_T is computed as the difference between the total demand for the component g and the number of refurbished and remanufactured components of type g used to satisfy the demand and is expressed by

$$New\ demand\ for\ component\ g\ =\ Total\ demand\ for\ component\ g\ -$$
$$Total\ refurbished\ quantity\ satisfying\ demand\ for\ component\ g\ -$$
$$Total\ remanufactured\ quantity\ satisfying\ demand\ for\ component\ g$$

Inventory from New Demand: For some years during this time frame there can be situations where all the demand is satisfied by only refurbished and remanufactured components. In this case no new components are used and hence the new demand is zero. Also, there may be situations where more refurbished and remanufactured components are available to satisfy the required demand. For these cases, it is assumed that all the demand is satisfied by the refurbished and remanufactured components and the remaining are added to the OEM inventory.

Assembly Quantity Computations: All the components must be assembled at the OEM to form the final products. While the refurbished products are already available, the new components and the remanufactured components must be assembled. Therefore, for every year in period t_{1+v+q} to t_T (for each component) the assembly quantity is computed as follows:

$$\begin{aligned} &assembly\ quantity\ for\ component\ g \\ &\qquad = new\ quantity\ for\ component\ g \\ &\qquad + remanufactured\ quantity\ for\ component\ g \end{aligned}$$

The number of components to be assembled remains same for each type of component. This is because of the fact that, each product requires only one component, and all the refurbished products have equal number of different components, and hence the assembly quantity remains same among different components.

$$\begin{aligned} &Total\ assembly\ quantity\ for\ each\ year \\ &\qquad = assembly\ quantity\ for\ component\ g\ for\ that\ year \end{aligned}$$

OEM Inventory Calculations: The inventory levels at OEM must be calculated for each year from t_{1+v+q} to t_T. It includes consideration of all the components returned to OEM from years t_1 through $t_{(T-v-q)}$ and the quantity remaining after satisfying demand for years t_{1+v+q} through t_T. For each year in t_{1+v+q} to t_T, the inventory available at the beginning of the year is used to compute the inventory costs. This assumption is considered as for each year, say t_1 after the reverse loop operation are performed on the recovered products, the respective components are sent to OEM, and until there exists a demand in the upcoming year, the returned components are stored at OEM. Therefore, due to difficulties in computing the exact time the components remain at OEM, an approximation is used. Table 3.6 provides sample computations for determining the inventory at OEM for each of these years (computed using quantities from Table 3.4 and Table 3.5).

Table 3.6: Sample Computations for Past Inventory at OEM

Year	For Each Component g Returned from each Year							
	t_1		t_{1+1}		t_{1+2} and so on		Until $t_{(T-v-q)}$	
	Refurbished	Remanufactured	Refurbished	Remanufactured	Refurbished	Remanufactured	Refurbished	Remanufactured
$t_{(1+v+q)}$	rf_1 (6.11)	rm_1 (6.12)						
$t_{(1+v+q+1)}$	6.11 – 5.11 (6.21)	6.12 – 5.12 (6.22)	rf_{1+1} (6.23)	rm_{1+1} (6.24)				
$t_{(1+v+q+2)}$ and so on	6.21 – 5.21 (6.31)	6.22 – 5.22 (6.32)	6.23 – 5.23 (6.33)	6.24 – 5.24 (6.34)	rf_{1+2} (6.35)	rm_{1+2} (6.36)		
Until $t_{(T)}$	Previous year quantity from (Table 3.6 – Table 3.5) for corresponding year						rf_{T-v-q}	rm_{T-v-q}

The computations indicate that whenever the components are available for the first time (say for year t_{1+v+q}) from previous year (say t_1) all the refurbished and remanufactured quantity returned from the previous year (t_1) (shown in Table 3.4) is considered as OEM inventory. From the next year onwards ($t_{1+v+q+1}$), the OEM inventory at the beginning of each year, is calculated as the difference between the inventory at the beginning of previous year (6.11) and the quantity used during the previous year to satisfy the demand obtained from Table 3.5 (5.11).

Total OEM inventory is the sum of inventory at the OEM (varies for each year in *T*). As an example, for year $t_{(1+v+q+2)}$, the OEM inventory is expressed by

$$OEM\ inventory\ for\ year\ \ t_{(1+v+q+2)}$$
$$= \sum_{g=1}^{G} \left[Sum\ of\ Equations\ (6.31, 6.32, 6.33, 6.34, 6.35, 6.36) in\ Table\ 3 - 6 +\ Inventory\ from\ New\ Demand\ for\ year\ \ t_{(1+v+q+2)} \right]$$

Therefore, all the transportation quantities including new component demand, refurbished, remanufactured and assembly quantities, OEM inventory and scrap quantity are all computed for each year in T from above expressions.

Forward Loop SC Costs

From the forward loop transportation quantities all the forward loop SC costs including supplier and transportation costs from supplier to OEM, as well as assembly and holding costs are all computed. The annualized OEM capital cost is also included. Since the suppliers and OEM costs per-unit remain same, and the SC configuration remains same, the total quantity is multiplied by per-unit cost to obtain the total costs. Therefore, for each year in period T the following costs are computed using the expressions given by

$$Total\ supplier\ component\ cost = \sum_{g=1}^{G} (New\ component\ demand\ for\ component\ g \times\ Supplier\ cost\ for\ component\ g\ )$$

$$Total\ transportation\ cost\ (supplier - OEM) = \sum_{g=1}^{G} (New\ component\ demand\ for\ component\ g \times Transportation\ cost\ for\ component\ g\ from\ respective\ supplier)$$

$$Total\ Assembly\ Cost\ = \ (Total\ assembly\ quantity\ \times per\ unit\ assembly\ cost\ )$$

$$Total\ Holding\ Cost\ = \ (Total\ OEM\ inventory\ \times per\ unit\ holding\ cost\ )$$

Reverse loop Transportation Quantities

All the reverse loop SC transportation quantities (including collection quantity, quantity of component to be refurbished, quantity of components to be remanufactured, quantity disposed, recyclable component quantity, disassembled quantity) change as the demand is varied. However, unlike the forward loop SC quantities these quantities are directly proportional to demand. This is because once the products are sold all the remaining SC parameters remain the same, except for the demand, for each year; while in forward loop there is a need to compute the OEM quantities based on quantity returned from past years and their (varying) percentages, there is no such variation in reverse loop operations. Hence, computing reverse loop quantities is much easier and straightforward process and is performed using demand ratio. Using this ratio for each year, all the reverse loop SC quantities can be calculated by multiplying the steady-state quantities with respective year's ratio.

Reverse Loop SC Costs

Several reverse loop costs are incurred by the SC (listed in Table 3.7).

Table 3.7: Reverse Loop SC Cost Parameters

• Collection center maintenance costs
• Refurbishing cost
• Disassembly cost
• Processing costs - remanufacturing and recycling
• Disposal Cost
• Transportation costs within SC partners (use-collection, collection-OEM, collection-remanufacturing, collection-recycling, collection-disposal, remanufacturing-OEM, recycling- supplier)
• Annualized capital costs for the collection, remanufacturing and recycling centers
• Collection center maintenance costs

As all per-unit reverse loop SC costs remain same (SC configuration same) all the reverse loop SC costs are computed by multiplying the corresponding steady-state SC costs with respective year's ratio for each year in T.

<u>*Revenue Computations:*</u> Once all the SC costs are computed, the revenue generated for each year in T is computed. The revenue is generated from three different sources; new products/components, refurbished and remanufactured products/components and scrap components. The computation of new, refurbished, remanufactured, and scrap component quantities as well as prices were presented earlier. Therefore, the total revenue from each year can be expressed by

$$
\begin{aligned}
Total\ revenue\ from\ each\ year\ =\ & Revenue\ from\ new\ products\ sold\ in\ that\ year \\
& + Revenue\ from\ refurbished\ and\ remanufactured\ products\ sold \\
& + Revenue\ from\ scraped\ components
\end{aligned}
$$

The revenue from new products is expressed as

$$
Revenue\ from\ new\ products\ sold\ in\ that\ year =
$$

$$
\left(\frac{price\ of\ new\ products}{number\ of\ components} \times total\ number\ of\ new\ components\ sold\right)
$$

The revenue from refurbished and remanufactured products is expressed as

$$
Revenue\ from\ refurbished\ and\ remanufactured\ products\ sold =
$$

$$
\left(\frac{price\ of\ refubished/remanufactured\ products}{number\ of\ components} \times total\ number\ of\ refurbished\ and\ remanufactured\ components\ sold\right)
$$

The revenue from scraped components is expressed as

$$
\begin{aligned}
Revenue\ from\ scraped\ components \\
= (\,per\ unit\ revenue\ from\ scrap \\
\times total\ number\ of\ scrap\ components\,)
\end{aligned}
$$

The tabulation of different SC parameters (in notations) across different periods in T are shown in Table 3.8. The highlighted column t_n is the steady-state period and SC parameter values for all other periods are computed from the values in period t_n .

Table 3.8: Sample Table Illustrating SC Parameters Considered in MLC Analysis

SC Parameter		MLC Year					
		t_1	t_{1+1} so on	t_n	t_{n+1}	t_{n+2} so on	t_f
Annual Demand		D_1	D_{1+1}	D_n	D_{n+1}	D_{n+2}	D_f
Forward Loop Costs	SC_1	SC_{1+1}	SC_{1+1}	SC_n	SC_{n+1}	SC_{n+2}	SC_f
	TSO_1	TSO_{1+1}	TSO_{1+1}	TSO_n	TSO_{n+1}	TSO_{n+2}	TSO_f
	AC_1	AC_{1+1}	AC_{1+1}	AC_n	AC_{n+1}	AC_{n+2}	AC_f
	HC_1	HC_{1+1}	HC_{1+1}	HC_n	HC_{n+1}	HC_{n+2}	HC_f
	CO_1	CO_{1+1}	CO_{1+1}	CO_n	CO_{n+1}	CO_{n+2}	CO_f
Reverse Loop Costs	MC_1	MC_{1+1}	MC_{1+1}	MC_n	MC_{n+1}	MC_{n+2}	MC_f
	FC_1	FC_{1+1}	FC_{1+1}	FC_n	FC_{n+1}	FC_{n+2}	FC_f
	TCM_1	TCM_{1+1}	TCM_{1+1}	TCM_n	TCM_{n+1}	TCM_{n+2}	TCM_f
	TCD_1	TCD_{1+1}	TCD_{1+1}	TCD_n	TCD_{n+1}	TCD_{n+2}	TCD_f
	TCY_1	TCY_{1+1}	TCY_{1+1}	TCY_n	TCY_{n+1}	TCY_{n+2}	TCY_f
	DC_1	DC_{1+1}	DC_{1+1}	DC_n	DC_{n+1}	DC_{n+2}	DC_f
	MC_1	MC_{1+1}	MC_{1+1}	MC_n	MC_{n+1}	MC_{n+2}	MC_f
	TMO_1	TMO_{1+1}	TMO_{1+1}	TMO_n	TMO_{n+1}	TMO_{n+2}	TMO_f
	YC_1	YC_{1+1}	YC_{1+1}	YC_n	YC_{n+1}	YC_{n+2}	YC_f
	TYS_1	TYS_{1+1}	TYS_{1+1}	TYS_n	TYS_{n+1}	TYS_{n+2}	TYS_f
	TCO_1	TCO_{1+1}	TCO_{1+1}	TCO_n	TCO_{n+1}	TCO_{n+2}	TCO_f
	TUC_1	TUC_{1+1}	TUC_{1+1}	TUC_n	TUC_{n+1}	TUC_{n+2}	TUC_f
	CC_1	CC_{1+1}	CC_{1+1}	CC_n	CC_{n+1}	CC_{n+2}	CC_f
	CM_1	CM_{1+1}	CM_{1+1}	CM_n	CM_{n+1}	CM_{n+2}	CM_f
	CY_1	CY_{1+1}	CY_{1+1}	CY_n	CY_{n+1}	CY_{n+2}	CY_f
Revenue	PN_1	PN_{1+1}	PN_{1+1}	PN_n	PN_{n+1}	PN_{n+2}	PN_f
	PRf_1	PRf_{1+1}	PRf_{1+1}	PRf_n	PRf_{n+1}	PRf_{n+2}	PRf_f
	S_1	S_{1+1}	S_{1+1}	S_n	S_{n+1}	S_{n+2}	S_f
	P_1	P_{1+1}	P_{1+1}	P_n	P_{n+1}	P_{n+2}	P_f
	D_1	D_{1+1}	SP_{1+1}	SP_n	SP_{n+1}	SP_{n+2}	SP_f

<u>SC Costs Adjustments for MLC Years</u>

All the forward and reverse loop SC costs computed for each year (in the previous section) are based on steady-state values. Ideally, these costs must be computed from data for corresponding year. However, gathering SC costs per-unit for each year for different SC partners is very cumbersome. As the number of years in period *T* increases, the amount of data to be obtained and processed becomes increasingly large. Further, companies may not have all the data for proposed product designs. Usually when business models extend for more than one year in future, as in this case, DCFs or the time value of money must be considered. Therefore, in the economic MLC analysis model all future costs are discounted as needed by

$$Future\ Value = Present\ Value\ (1 + Interest\ Rate)^{Number\ of\ Periods}$$

The above expression is used to calculate the Present Value of all future SC cashflows. The discount rate is considered as opposed to interest rate.

SC Parameter Values for MLC years

SC costs/revenues are first computed in their respective years (shown in Table 3.8). All these values are present values for year t_n. Therefore, based on the year considered, the actual SC costs/revenues for each year are computed as shown in Table 3.9 for period T from their values in period t_n. As the values are corresponding to the steady-state period, the SC costs/revenues for year t_n are similar to those in Table 3.8. The interest rate is represented by IR and discount rate is represented by DR.

Table 3.9: Present Value of SC Parameter Computations for MLC years

SC Parameter		MLC Year: t_1, t_{1+1} and so on until t_n	MLC Year: t_n	MLC Year: t_{n+1}, t_{n+2} and so on until t_f
Annual Demand		$\frac{Corresponding\ Table\ 3.8\ value}{(1+DR)^{(n-year\ considered)}}$	*Corresponding value in Table 3.8*	$Corresponding\ Table\ 3.8\ value \times (1+IR)^{(year\ considered-n)}$
Forward Loop Costs	Total Supplier Cost			
	Total Transportation Cost (Supplier - OEM)			
	Total Assembly Cost			
	Total Holding Cost (OEM)			
	Annualized Capital Cost (OEM)			
Reverse Loop Costs	Total Maintenance Cost (Collection Center)			
	Total Refurbish Cost			
	Total Transportation Cost (Collection - Remanufacturing)			
	Total Transportation Cost (Collection - Disposal)			
	Total Transportation Cost (Collection - Recycle)			
	Total Disassembly Cost			
	Total Remanufacturing Costs			
	Total Transportation Cost (Remanufacturing - OEM)			
	Total Recycle Costs			
	Total Transportation Cost (Recycle - Suppliers)			
	Transportation Costs (Collection - OEM)			
	Total Transportation Cost (Use - Collection)			
	Total Annualized Collection Center Capital Cost			
	Total Annualized Remanufacturing Center Capital Costs			
	Total Annualized Recycle Center Capital Costs			
Revenue	Total Price for New Products			
	Total Price for Refurbished/Remanufactured Products			
	Total Revenue from Scrap			
	Price of a New Product			
	Price of a Refurbished/Remanufactured Product			

SC Costs Incurred for Each Year during MLC years

All the SC costs calculated as shown in Table 3.9, are the actual costs incurred for each year in the MLC analysis. However, while the some of these costs such as forward loop SC costs are incurred for that year, all the reverse loop SC *processing* related costs are incurred v years later, as the products must be used for v years and then are available for reverse loop SC operations. Hence, all the reverse loop processing related costs for each year, for example say t_1 are incurred during the year t_{1+v}. This also implies that for the first few v years, no reverse loop costs are incurred. As the costs are the present value (for the year t_1) and since these costs are incurred during a future year (t_{1+v}) the future values for these costs are computed for each year using equation and a similar interest rate IR.

As the reverse loop facilities such as collection, remanufacturing and recycling must be set-up and be ready before the first year's products are ready for their reverse loop operations, these facilities are assumed to be set-up a year before the first year's products are ready for their reverse loop operations. While it is assumed that all the reverse loop facilities are set-up, installed within 1 year, in reality it might take longer or fewer months for this process. However, this depends on individual company's resources, and the requirements. Therefore, all the reverse loop facility capital costs occur first in year t_{1+v-1} and continue for all years in period T until t_T. There is no reverse loop facility costs incurred for the years t_1 to t_{1+v-1}. Table 3.10 presents the computation for the reverse loop SC processing costs for all the MLC years. It shows that until the year t_{1+v} no reverse loop processing costs are incurred and from year t_{1+v} onwards the costs incurred for each year are from the previous v years. As these costs are incurred v years later, the actual value of these costs is computed using interest rate and present value.

Table 3.10: Sample Computations of Reverse Loop SC (Processing Costs)

<table>
<tr><th rowspan="2">Reverse Loop Processing-Related SC Costs</th><th colspan="5">MLC Year</th></tr>
<tr><th>t_1</th><th>t_{1+1} so on until t_{1+v}</th><th>t_{1+v}</th><th>t_{1+v+1} and so on until t_f</th><th>t_f</th></tr>
<tr><td>Total Maintenance Cost (Collection Center)</td><td>0</td><td>0</td><td rowspan="12">$\left(\begin{array}{c} value\ from\ column\ t_1 \\ in\ Table\ 3.9 \\ \times\ (1+IR)^{(v)} \end{array}\right)$</td><td rowspan="12">$\left(\begin{array}{c} value\ from\ column\ t_{1+1} \\ in\ Table\ 3.9 \\ \times\ (1+IR)^{(v)} \end{array}\right)$ and so on until</td><td rowspan="12">$\left(\begin{array}{c} value\ from\ column\ t_{T-v} \\ in\ Table\ 3.9 \\ \times\ (1+IR)^{(v)} \end{array}\right)$</td></tr>
<tr><td>Total Refurbish Cost</td><td>0</td><td>0</td></tr>
<tr><td>Total Transportation Cost (Collection - Remanufacturing)</td><td>0</td><td>0</td></tr>
<tr><td>Total Transportation Cost (Collection - Disposal)</td><td>0</td><td>0</td></tr>
<tr><td>Total Transportation Cost (Collection - Recycle)</td><td>0</td><td>0</td></tr>
<tr><td>Total Disassembly Cost</td><td>0</td><td>0</td></tr>
<tr><td>Total Remanufacturing Costs</td><td>0</td><td>0</td></tr>
<tr><td>Total Transportation Cost (Remanufacturing - OEM)</td><td>0</td><td>0</td></tr>
<tr><td>Total Recycle Costs</td><td>0</td><td>0</td></tr>
<tr><td>Total Transportation Cost (Recycle - Suppliers)</td><td>0</td><td>0</td></tr>
<tr><td>Transportation Costs (Collection - OEM)</td><td>0</td><td>0</td></tr>
<tr><td>Total Transportation Cost (Use - Collection)</td><td>0</td><td>0</td></tr>
</table>

Table 3.11 shows the computations for reverse loop SC capital costs. As discussed earlier, the capital costs are not incurred until the year $\boldsymbol{t_{1+v-1}}$ and from this year onwards the costs are incurred and these costs remain the same (as shown in Table 3.9).

Table 3.11: Sample Computations for Reverse Loop SC (Capital Costs)

Reverse Loop Capital Costs	MLC Year	
	t_1 until t_{1+v-1}	t_{1+v-1} and so on until t_f
Total Annualized Collection Cost	0	Value from Same Column in Table 3.9
Total Annualized Remanufacturing Center Costs	0	
Total Annualized Recycle Center Costs	0	

Total Cost and Revenue Computations for MLC years: Once the forward loop SC costs and revenue related parameters are computed from Table 3.9 and the reverse loop SC costs are computed as shown in Table 3.10 and Table 3.11, the annual SC costs, annual revenue and annual profit is computed for each year in period *T*. The total annual SC cost and the annual revenue is given by

$$Total\ Cost\ for\ year\ y = Sum\ of\ all\ forward\ and\ reverse\ loop\ SC\ costs\ incurred\ for\ year\ y$$

$$Total\ Revenue\ for\ year\ y = Sum\ of\ revenue\ generated\ from\ (new, refurbished, and\ remanufactured\ products\ or\ components\ sold + scrap)\ in\ year\ y$$

Therefore, the annual profit is expressed by

$$Total\ Annual\ Profit\ for\ year\ y = (Total\ Revenue - Total\ Cost)\ for\ year\ y$$

Table 3.12 presents the complete data considered for economic MLC analysis over T. It includes the demand, the forward and reverse loop SC costs, the revenue and the total annual profit generated from each year over MLCs. In addition, the computations for obtaining these values are also shown.

Table 3.12: Table Presenting Parameters Considered in Economic MLC Analysis

Parameter Set Number	SC Parameter		MLC Years		
			t_1	t_{1+1} and so until t_f	t_f
Annual Demand			All values similar to corresponding year's value in Table 3.9		
Set 1	Forward Loop Costs	Total Supplier Cost			
		Total Transportation Cost (Supplier - OEM)			
		Total Assembly Cost			
		Total Holding Cost (OEM)			
		Annualized Capital Cost (OEM)			
Set 2	Reverse Loop Costs	Total Maintenance Cost (Collection Center)	All values similar to corresponding year's value in Table 3.10		
		Total Refurbish Cost			
		Total Transportation Cost (Collection - Remanufacturing)			
		Total Transportation Cost (Collection - Disposal)			
		Total Transportation Cost (Collection - Recycle)			
		Total Disassembly Cost			
		Total Remanufacturing Cost			
		Total Transportation Cost (Remanufacturing - OEM)			
		Total Recycle Cost			
		Total Transportation Cost (Recycle-Suppliers)			
		Transportation Costs (Collection - OEM)			
		Total Transportation Cost (Use -Collection)			
Set 3		Total Annualized Collection Center Capital Cost	All values similar to corresponding year's value in Table 3.11		
		Total Annualized Remanufacturing Center Capital Cost			
		Total Annualized Recycle Center Capital Cost			
Set 4	Revenue	Total Price for New Products	All values similar to corresponding year's value in Table 3.9		
		Total Price for Refurbished/Remanufactured Products			
		Total Revenue from Scrap			
		Price of a New Product			
		Price of a Refurbished/Remanufactured Product			
Total Cost			Sum of values in Sets (1,2,3) corresponding to each year		
Total Revenue			Sum of values in Set 4 corresponding to each year		
Total Profit			Total Revenue – Total Cost		

3.7.3 Economic MLC Analysis (MLC_{Eco}) Tool

In this section, a description of the tool developed to perform the economic MLC analysis as described in the previous section is provided.

The MLC_{Eco} tool is created in Microsoft Excel Spreadsheet. All the input data required for performing the analysis including the EOM results, the price and demand for the first and the last year of the analysis, the steady-state price and demand, the number of refurbished and remanufactured components available for the steady-state period, the supplier component cost per-unit, the transportation per-unit cost from suppliers to OEM, the assembly and holding cost per-unit, the percentage of refurbished and remanufactured components used to satisfy demand for future years, returned from years t_1 until year t_{T-v-q}, and the interest/discount rate for computing the present value of SC parameters for each of the years in T is captured in the MLC Economic Input Data Sheet illustrated in the Figure 3.11.

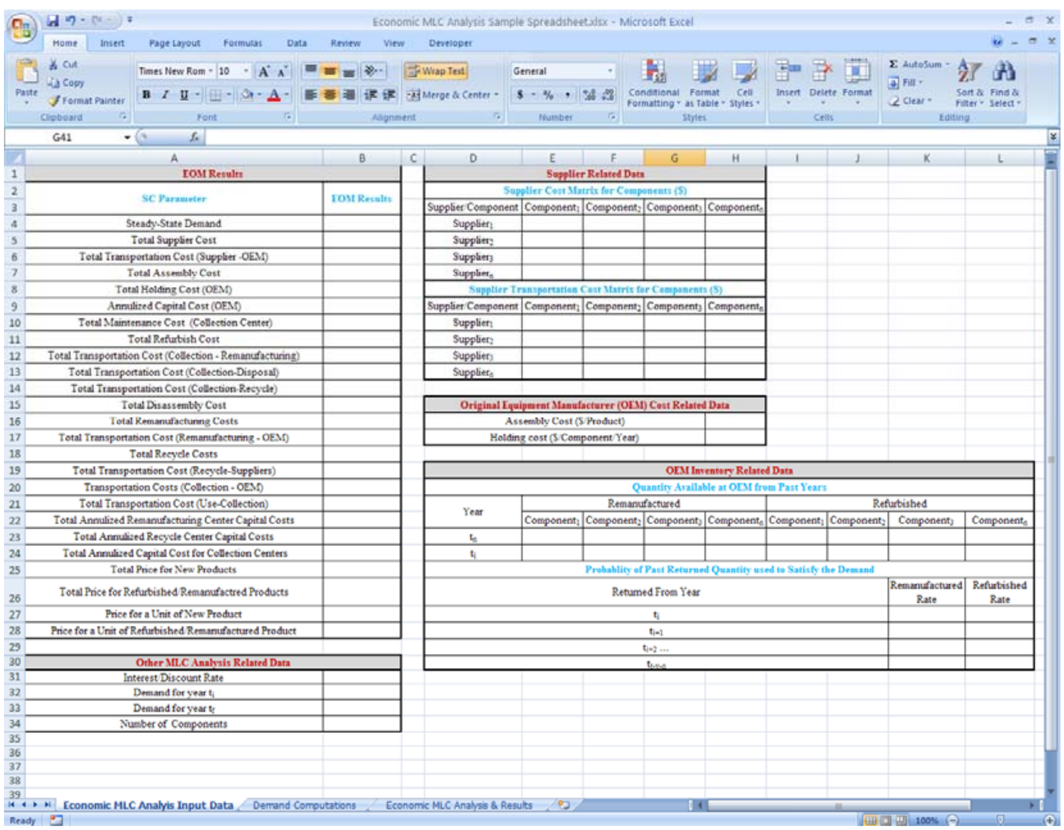


Figure 3.11: Snapshot of 'Economic MLC Analysis Input Data' Sheet

Therefore, from the Input Data the price, demand, and the refurbished and remanufactured component quantity for each year in T is computed in 'Demand Computations' sheet as shown in Figure 3.12. From these values, the SC transportation quantities, OEM inventory, assembly quantity, scrap quantity, new, refurbished and remanufactured quantities, and the present value of SC costs and revenue are computed for each year. From these values, the total SC costs, revenue, and total profit for each year is computed in the 'Economic MLC Analysis and Results' sheet. Figure 3.13 provides a snapshot of 'Economic MLC Analysis and Results' spreadsheet. As there is large amount of data analyzed in this spreadsheet, only the results of the MLC analysis are presented.

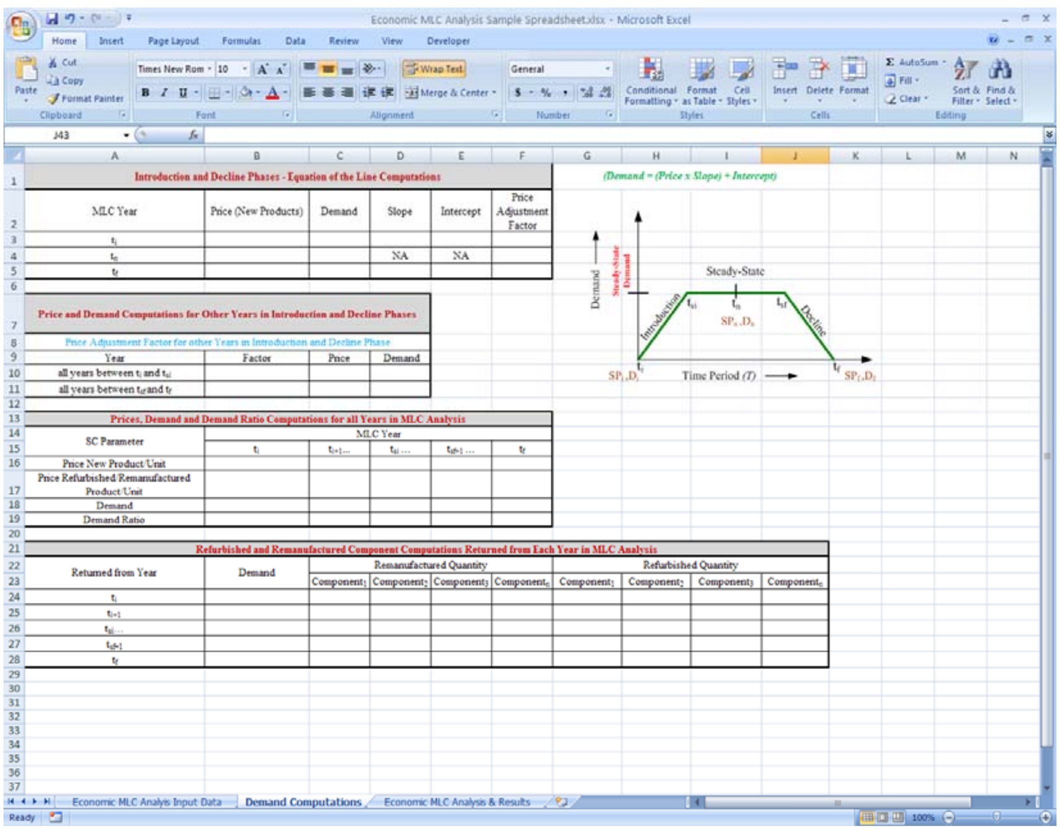
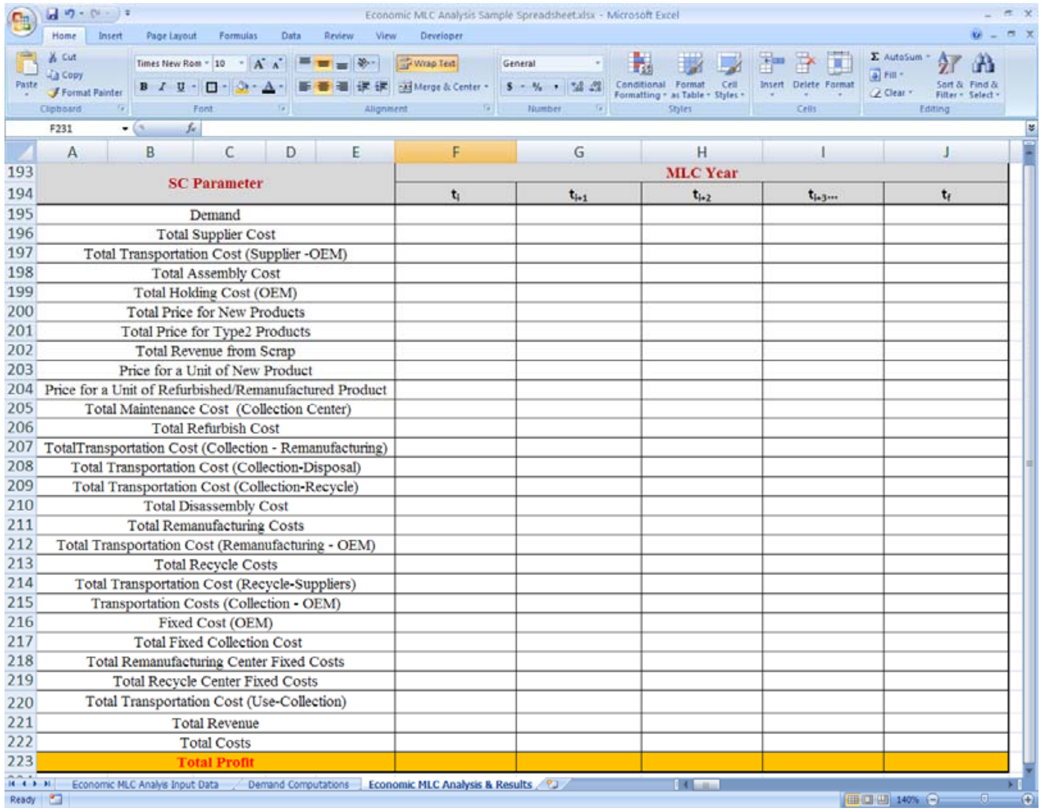


Figure 3.12: Snapshot of 'Demand Computations' Sheet



SC Parameter	MLC Year				
	t_i	t_{i+1}	t_{i+2}	$t_{i+3\cdots}$	t_f
Demand					
Total Supplier Cost					
Total Transportation Cost (Supplier -OEM)					
Total Assembly Cost					
Total Holding Cost (OEM)					
Total Price for New Products					
Total Price for Type2 Products					
Total Revenue from Scrap					
Price for a Unit of New Product					
Price for a Unit of Refurbished/Remanufactured Product					
Total Maintenance Cost (Collection Center)					
Total Refurbish Cost					
TotalTransportation Cost (Collection - Remanufacturing)					
Total Transportation Cost (Collection-Disposal)					
Total Transportation Cost (Collection-Recycle)					
Total Disassembly Cost					
Total Remanufacturing Costs					
Total Transportation Cost (Remanufacturing - OEM)					
Total Recycle Costs					
Total Transportation Cost (Recycle-Suppliers)					
Transportation Costs (Collection - OEM)					
Fixed Cost (OEM)					
Total Fixed Collection Cost					
Total Remanufacturing Center Fixed Costs					
Total Recycle Center Fixed Costs					
Total Transportation Cost (Use-Collection)					
Total Revenue					
Total Costs					
Total Profit					

Figure 3.13: Snapshot of 'Economic MLC Analysis and Results' Sheet

Therefore, the developed MLC_{Eco} tool computes the total profit generated for each year in the period T for each PDSCC combination separately. However, the economic MLC performance of alternate PDSCC combinations, is measured in terms of the cumulative profit at the end of period T. Therefore, for each of the PDSCC combinations, the MLC analysis is performed using the MLC_{Eco} tool, and the best PDSCC combinations are selected based on their cumulative profit as illustrated in Table 3.13. The Table shows the computations for calculating the cumulative profit at the end of T (t_f) for each PDSCC combination.

Table 3.13: Computation of Cumulative Profit for PDSCC combinations

Year	$PDSCC_1$		$PDSCC_2$		$PDSCC_3$ and so on until		$PDSCC_n$	
	Annual Profit	Cumulative Profit	Annual Profit	Cumulative Profit	Annual Profit	Cumulative Profit	Annual Profit	Cumulative Profit
t_1	x_1	x_1	y_1	y_1	z_1	z_1	v_1	v_1
t_{1+1}	x_2	$x_1 + x_2$	y_2	$y_1 + y_2$	z_2	$z_1 + z_2$	v_2	$v_1 + v_2$
t_{1+2} . . .	x_3	$x_1 + x_2 + x_3$ . . .	y_3	$y_1 + y_2 + y_3$ . . .	z_3	$z_1 + z_2 + z_3$ . . .	v_3	$v_1 + v_2 + v_3$ . . .
t_f	x_f	**$(x_1 + x_2 + x_3 \ldots + x_f)$**	y_f	**$(y_1 + y_2 + y_3 \ldots + y_f)$**	z_f	**$(z_1 + z_2 + z_3 \ldots + z_f)$**	v_f	**$(v_1 + v_2 + v_3 \ldots + v_f)$**

3.8 Open-loop SC Model

In this research, a closed-loop SC model is developed to reduce the overall material and resource consumption over MLCs, and thereby aiming to promoting true sustainability within the SC. Most of the conventional SC models are open-loop models (no post-use consideration). In order to realize the actual performance of the closed-loop SC model over MLCs there is a need to compare its performance with the conventional SC model. Therefore, an Open-loop SC model is developed, which considers only forward loop SC partners (Suppliers, OEM, and Use locations). Figure 3.14 illustrates the open-loop SC model with S different suppliers, one OEM, and B different use locations considered in this research. The suppliers provide the components to OEM where the products are assembled to be transported to different use locations.

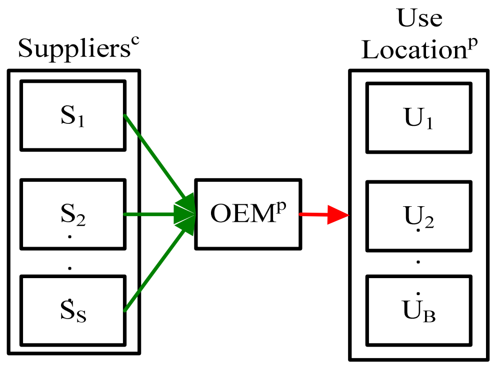


Figure 3.14: Open-loop SC Model

3.8.1 Open-loop MLC Analysis Description

The MLC analysis for an open-loop SC is performed in a similar way as that of the economic MLC analysis for each year in period T. As opposed to considering the EOM results, as in that of the MLC_{Eco} tool, this analysis considers only the steady-state values of price, demand and per-unit cost. The results from EOM cannot be used in this case, as EOM considers a closed-loop SC. As there are no reverse loop SC operations, the open-loop MLC analysis includes only (a) price and demand computations, (b) forward loop SC quantities and their costs (total supplier, total transportation from suppliers to OEM, OEM capital cost, OEM assembly and holding costs) computations, and (c) the revenue computations for each MLC year. Each of these computations is discussed below:

Price and demand Computations

The price and demand computations for the open-loop MLC analysis is performed in a similar way to that of the MLC_{Eco} tool. As there are no refurbished or remanufactured products, in this case, only unit price for new product is considered. Similar price-adjustment factors as that of the economic MLC analysis, are used for computing price of new product per-unit for rest of the years in T. The slope and intercept are calculated for both introduction and decline phases using the first year's, steady-state, and last year's demand and the price per-unit of a new product. Based on the slopes, prices and intercepts for both introduction and decline lines, the demand for all the MLC years is estimated.

Forward Loop SC Quantities

The forward loop SC parameters considered in this analysis are similar to the parameters considered in the MLC_{Eco} tool. However, in this case, all the demand is satisfied by only new products for all years in period *T*. Each new product has only one component from each supplier. Therefore, for each year, *the number of components transported from each supplier* is equal to the annual demand for that year. Also, as all the components must be assembled at the OEM, *the assembly quantity* is also equal to the annual demand for each year. There are no refurbished or remanufactured components from past years available to satisfy the demand. As a result, the *OEM inventory* is zero for all the years.

Forward Loop SC Costs

The forward loop SC costs are computed using the forward loop quantities and the corresponding per-unit costs. The costs from the steady-state period t_n such as supplier cost per component, transportation cost from each supplier to OEM, assembly cost per product are multiplied by corresponding quantities to obtain the different forward loop SC costs for each of the years in period *T*. As the OEM holding cost is assumed to incur based on its inventory level, which is zero throughout the period, no holding costs are incurred for all the years. The annualized capital cost for the OEM is also considered in this analysis. All the costs are computed in a similar fashion as described in economic MLC analysis section for each year in *T*. Once computed, the present values of these costs are calculated using an interest/discount rate similar to that of the value used in MLC_{Eco} tool. As the results of the MLC_{Eco} must be compared to the results of the open-loop MLC analysis, similar data used for the MLC_{Eco} tool, is used for the open-loop MLC analysis wherever applicable. From the present costs, *the total annual cost* is computed for all the years in period T, which is the sum of costs incurred during each year.

Revenue Computations

The revenue computations for open-loop MC analysis are similar to the economic MLC analysis. However, in this case, all revenue for MLC years is generated only from new products. As no refurbished products or remanufactured components are considered, no revenue is generated from these products. Also, no scrap components are available, due to lack of reverse loop operations; hence no revenue is generated from scrap too. Therefore, the revenue from new products for each year is computed as

$$Total\ Revenue\ in\ year\ t_y = Price\ per-unit\ of\ new\ product\ in\ year\ t_y \times Demand\ t_y$$

As the price per-unit is based on value during steady-state period (t_n), the present value of the total revenue for each year is computed using the procedure explained in economic MLC analysis section.

Total Annual Profit Computations

From the total cost and revenue for each year, the annual profit is computed for all the years in period T using the expression

$$Total\ Annual\ Profit\ for\ year\ t_y = Total\ Revenue\ for\ year\ t_y - Total\ Annual\ Cost\ for\ year\ t_y$$

Table 3.14 presents the different SC parameters considered in the open-loop model.

Table 3.14: List of SC Parameters Considered for Open-loop MLC Analysis

Annual Demand	
Forward Loop Costs	Total Supplier Cost
	Total Transportation Cost (Supplier - OEM)
	Total Assembly Cost
	Annualized Capital Cost (OEM)
Revenue	Price for Unit of New Product
	Total Price for New Products
Total Cost	
Total Revenue	
Total Profit	

3.8.2 Open-loop MLC Analysis (MLC_{Osc}) Tool

An MLC_{Osc} tool is developed in Microsoft Excel Spreadsheet to perform the open-loop MLC analysis as discussed above. The 'Input Data Sheet' for the MLC_{Osc} acquires data including the price and demand for: first year, steady-state period, and the last year of period *T*, all the per-unit costs including component acquisition cost, transportation cost from supplier to OEM, assembly cost, OEM annualized capital cost, the interest/discount rates as shown in Figure 3.15.

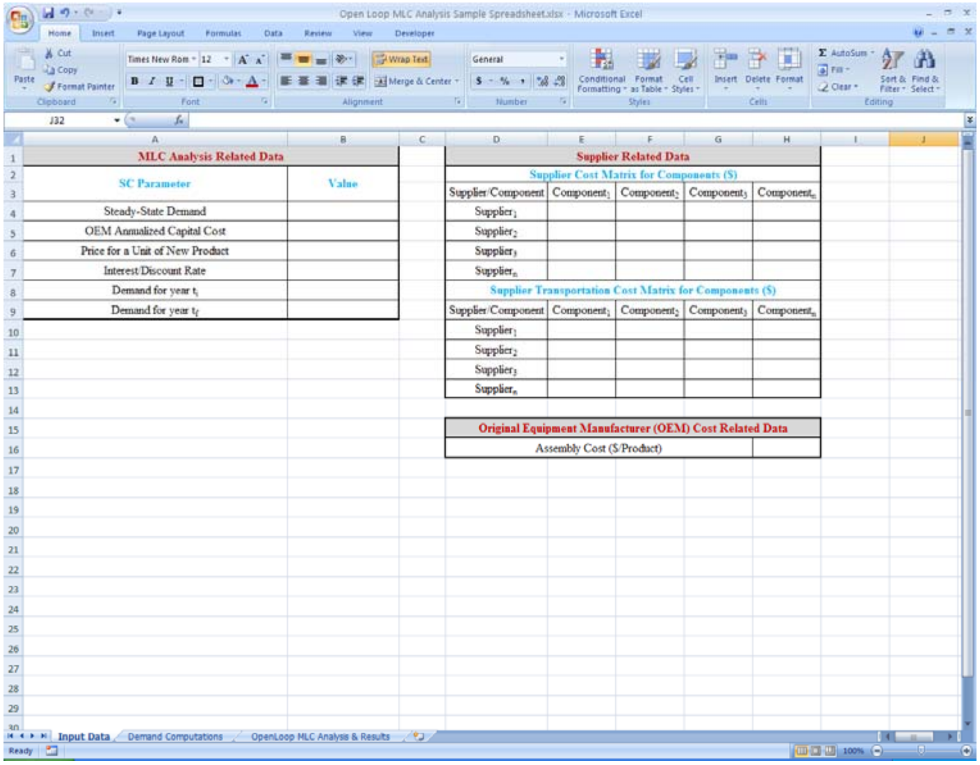


Figure 3.15: Snapshot of MLC_{Osc} Tool 'Input data' Sheet

Based on the Input data, the computations for the price and demand for all years in period T is estimated in the 'Demand Computations' spreadsheet as shown in Figure 3.16.

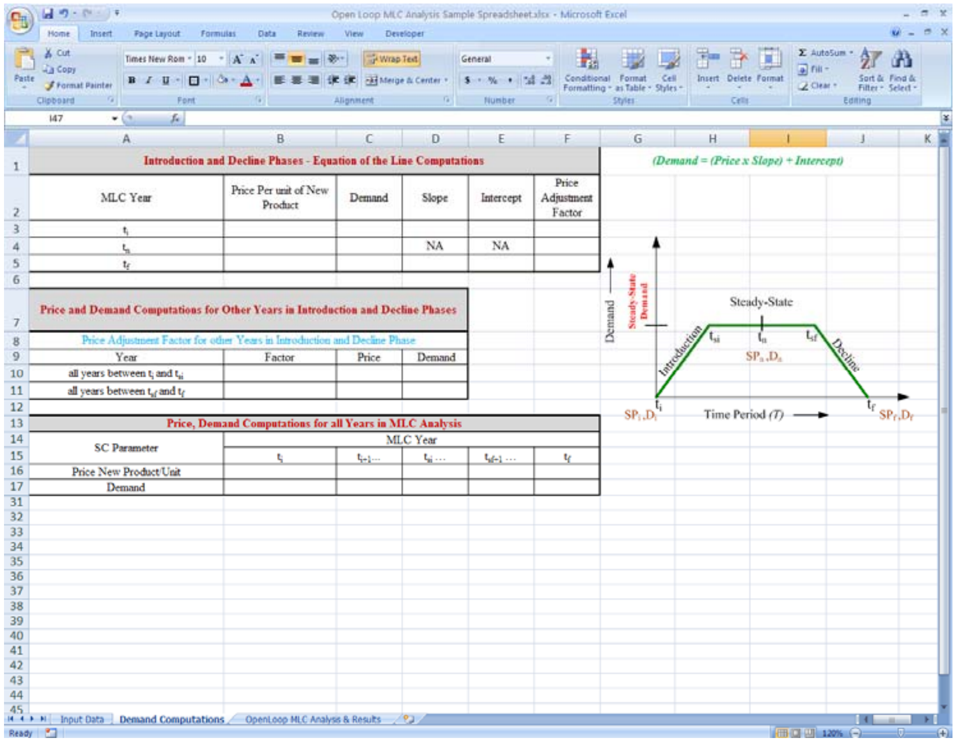
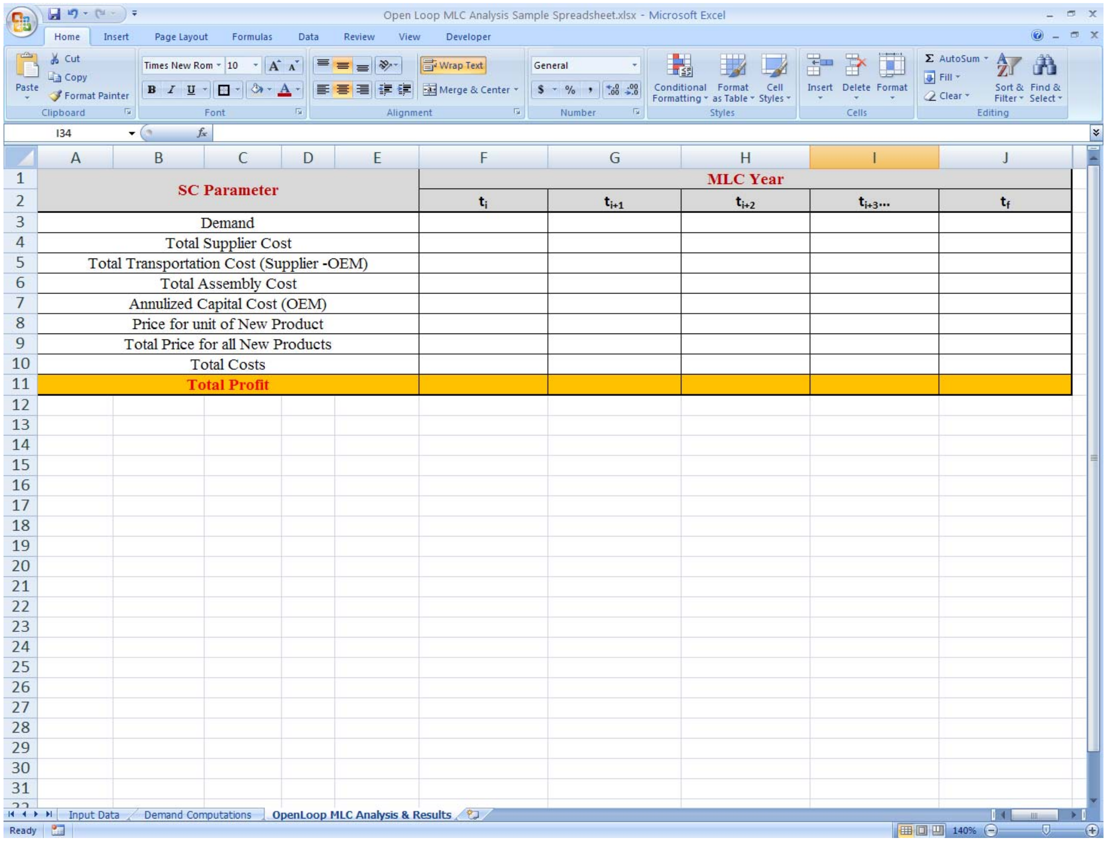


Figure 3.16: Snapshot of MLC_{Osc} Tool 'Demand Computations' Sheet

From the data in the 'Input Data' and the 'Demand Computations' spreadsheets the entire forward loop SC costs and revenue, and thereby the total annual profit for each year in the period T are computed in the 'Open-loop MLC Analysis and Results' spreadsheet. A snapshot of the sheet is shown in Figure 3.17. All the computations are computed based on the above discussed procedure. As the objective of this section is to present the procedure, only sample snapshots of the tools are presented. However, for the example and the case study problem the results generated for these tools are discussed.



SC Parameter	MLC Year				
	t_i	t_{i+1}	t_{i+2}	t_{i+3}...	t_f
Demand					
Total Supplier Cost					
Total Transportation Cost (Supplier -OEM)					
Total Assembly Cost					
Annulized Capital Cost (OEM)					
Price for unit of New Product					
Total Price for all New Products					
Total Costs					
Total Profit					

Figure 3.17: Snapshot of MLC_{Osc} Tool 'Open-loop MLC Analysis & Results' Sheet

For the open-loop model, no optimization is considered. This is reasonable because the EOM only selects reverse loop SC partners, while all the forward loop SC partners remain the same. Hence, irrespective of the optimization, the SC configuration for each product design remains constant, in this case. For each PDSCC at the NPD stage, the open-loop MLC analysis is performed separately to obtain the annual profits for each of the designs over total period *T*. Later, for each PDSCC combination the cumulative profits for each year are computed as described earlier. Therefore, the MLC_{Osc} model is used to compare the performance of open-loop SC with the closed-loop SC.

3.9 PDSCC Economic Performance Comparison

In order to the compare the MLC performance of the closed-loop (MLC_{Eco}) versus the open-loop SC (MLC_{Osc}) models, for each PDSCC combination, the cumulative profits obtained from these tools over period *T* are compared. Following this, the environmental

MLC analysis is performed on the best PDSCC combinations selected from the MLC_{Eco} tool.

3.10 Environmental Multi Life-cycle Analysis

In this section, the environmental MLC analysis performed on the ranked PDSCC combinations is discussed. Following a review of the environmental performance criteria, and the assumptions, a description of the environmental analysis is provided. Later, the environmental MLC analysis (MLC_{Env}) tool developed to identify the best PDSCC combinations that have minimal environmental impact is presented.

3.10.1 Environmental Performance Criteria

Measuring the environmental performance of any SC requires identifying the appropriate metrics. From the past two decades, there has been a growing interest in the area of assessing the environmental performance of business operations and therefore the SCs (Seager et al., 2007). A growing amount of literature is emerging in the field of environmental management systems, environmental-benign manufacturing, LCA analysis, GrSCM. The increasing environmental costs (GEMI, 1998) and corresponding regulatory requirements coupled with increased public awareness, community and public pressure have demanded integration of environmental aspects into current SCs which requires identification of appropriate environmental performance metrics.

During past decade, several metrics have been developed by researchers, by companies and by organizations such as International Organization for Standardization (ISO) to efficiently measure/quantify the environmental performance of a SC. The Global Report Initiative (GRI) provides a range of environmental metrics at an enterprise wide level (GRI, 2006). GEMI (1998) summarized the common metrics used by 41 different companies. Most of these metrics focus on tracking the results/impacts of the environmental practices followed by the SC, such as amount of hazardous waste generated, amount of toxic chemicals released into air, number of environmental violations notices received, water usage, energy usage, number of ozone depleting substances used, amount of fines paid in violation of regulations, amount of renewable energy generated etc. The Committee on Industrial Environmental Performance Metrics

(1999) presented that metrics related to emissions released, energy, water, land, materials, and recycled material usage are commonly used across Automotive, Chemicals, Electronic and Pulp and Paper industry sectors.

Shaw and Grant (2010) presented a review of existing literature in the area of environmental metrics, with an objective to examine the benefits of integrating them into SC framework. In their paper, they presented that almost all the environmental management systems developed so far, worldwide across all the industries, aim mainly at reducing the greenhouse gas emissions, particularly carbon dioxide (CO_2). This is understandable as several legislative regulations exist which aim at reducing the greenhouse gas emissions, particularly CO_2 emissions, and the carbon footprint. For example, the Kyoto agreement bound nations to reduce the carbon emissions by an average of 5.2 percent below the 1990 levels by 2012 (Kyoto Protocol, 1997). Also, the energy and material use is another important measure used by almost all the environmental management systems. DEFRA (2006) identified and categorized key environmental indicators that are important to UK business and one of them is resource use. The resources in a SC include the materials, energy and all other form of resources used by the activities. Also the GRI developed performance indicators for the environmental and logistic sector (GRI, 2006). The major categories of these indicators include materials, energy, emissions. Therefore, based on the above review of SC environmental performance metrics, the CO_2 emissions, the energy and material consumption seem to be the most commonly used metrics for measuring the SC environmental performance.

As in this research, the objective is to develop a generalized environmental MLC analysis tool that can have potential to be used across multiple industries, the metrics that are used across different sectors are considered such as materials consumption, energy usage and amount of CO_2 emissions released are considered for the environmental MLC analysis. As the closed-loop SC network includes several SC partners, the values for each metric must be computed at each partner. Therefore, more number of metrics considered, the higher is the complexity. Hence, in this research the three most common and important environmental metrics are considered and the performance of each PDSCC with respect to each of these metrics is computed and compared.

Environmental Impact of the Closed-loop SC

In the previous section, the metrics such as materials consumption, energy usage and amount of CO_2 emissions are identified. As the environmental MLC analysis must be performed for the closed-loop SC model, which includes several activities performed by different SC partners, there is need to identify the locations at which each of these metrics must be computed. One way to identify this is to consider and analyze various SC activities, as each of these impacts the environment in one or another way. The activities in a closed-loop SC can be categorized into three main sectors: processing, use and transportation (Boustani et al., 2010). *The processing activities* are the operations performed on a product, by different SC partners in the pre-manufacturing, manufacturing, and post-use stages, to make it ready to be used by the customer. As the name explains, all the activities related to transporting a product or any of its components from one SC partner to another are all considered as the SC *transportation activities*. Finally, the activities performed during the use stage of a product are all termed as *use activities*. Therefore, the environmental impact at various SC partners can be computed using the above three activities. For example, all the processing, transportation and use activities consume energy and release CO_2 emissions. Therefore, for each of these activities corresponding energy and emissions released must be computed. Similarly, the material used in this research is computed in terms of number of refurbished and remanufactured components used to satisfy the demand. This metric must be computed at OEM for each year. Therefore, Figure 3.18 illustrates the different closed-loop SC activities and their environmental impact. Typically, the figure illustrates that the closed-loop SC model takes in material and energy and releases CO_2 emissions. The different activities occurring at and in between each SC partner are also shown.

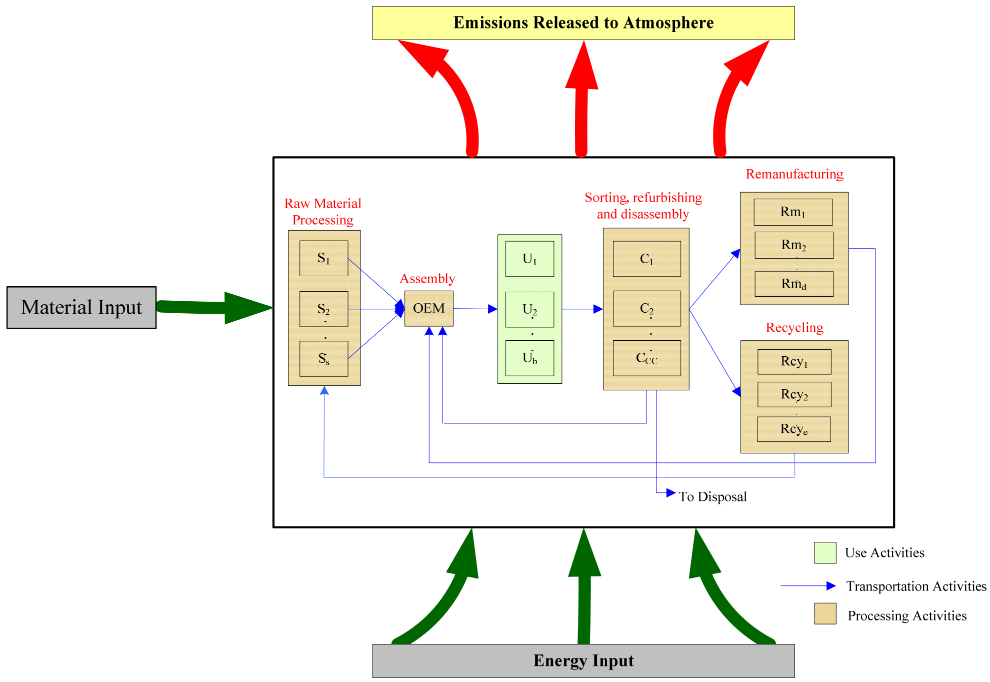


Figure 3.18: Closed-loop SC Activities and their Environmental Impact

Therefore, using the above metrics, the environmental impact for each PDSCC combination is computed.

3.10.2 Assumptions

The environmental analysis uses the results of the economic MLC analysis, that is, the forward and reverse loop SC costs computed in the MLC_{Eco} tool for all years in period *T*, to compute the corresponding MLC energy and emissions released from processing, transportation and use activities. This is a reasonable estimation, as most of the energy used and CO_2 emissions calculators currently available use cost as their basis to compute the environmental impact. A detailed discussion supporting this argument is presented in the analysis description section, where some of these well-recognized calculators are used for computations.

3.10.3 Analysis Description

A detailed description of the environmental MLC analysis is presented in this section. The objective of this analysis is to select the best PDSCC combinations that have minimal environmental impact. The environmental impact of each PDSCC combination is computed in terms of three performance criteria including:

(a) Material Usage (Number of new components used to satisfy the demand)
(b) Energy Consumed (BTU)
(c) CO_2 Emissions (Lb)

As discussed in the assumptions, all the economic MLC analysis results including the forward and reverse loop costs, the refurbished and remanufactured quantities satisfying demand for each MLC year are used as input data to this analysis. The computations for each of the above three metrics is shown below:

Material Usage (Number of new components satisfying demand)

The material usage in this research is defined in terms of the number of new components used to satisfy the demand for a given year. As more refurbished and remanufactured components satisfy the demand, less new components are used. While the refurbished and remanufactured components do not consume any new raw materials, for each new component, a certain amount of raw material is consumed. Therefore more new components from suppliers imply more material usage, hence higher environmental impact. The demand satisfied from new components for each component type g is already computed and available for each year in *T*. Therefore, the total number of new components used is computed by the following expression

$$\textit{Total Number of New Components for a Given Year } t_y = \sum_{g=1}^{G} ND_{gy}$$

From each year the cumulative values are also computed for comparison. However, it must be observed that for any PDSDD combination, until a certain year, t_{1+v+q}, all the demand is satisfied by new components only, as the products sold during the first year must be available for their next life. For example, if all the demand in a year, say t_1, is satisfied by only new components, the number of new components for that year can be expressed by

$$\text{Number of New Components Used in Year } t_1 = \sum_{g=1}^{G}\left(D_{g1}\right)$$

Table 3.15 shows sample computations for 'material usage' for each year in period T.

Table 3.15: Sample Computations for 'Material Usage'

Parameter	Year			
	t_1	$t_{1+1}\ \cdots$	$t_{1+v+q}\cdots$	t_f
Number of New Components Used	$\sum_{g=1}^{G}\left(D_{g1}\right)$	$\sum_{g=1}^{G}\left(D_{g(1+1)}\right)$	$\sum_{g=1}^{G} ND_{g(1+v+q)}$	$\sum_{g=1}^{G} ND_{gf}$
Cumulative Number	$\sum_{g=1}^{G}\left(D_{g1}\right)$	$\sum_{g=1}^{G}\left(D_{g1}\right) + \sum_{g=1}^{G}\left(D_{g(1+1)}\right) + \ldots$	$\sum_{g=1}^{G}\left(D_{g1}\right) + \sum_{g=1}^{G}\left(D_{g(1+1)}\right) + \ldots + \sum_{g=1}^{G} ND_{g(1+v+q)+\ldots}$	$\sum_{g=1}^{G}\left(D_{g1}\right) + \sum_{g=1}^{G}\left(D_{g(1+1)}\right) + \ldots + \sum_{g=1}^{G} ND_{g(1+v+q)+\ldots} + \sum_{g=1}^{G} ND_{gf}$

Energy Consumption (BTU)

In a closed-loop SC, energy is consumed by transportation, processing and use activities. Ideally, the less energy is consumed by the SC, less is the environmental impact. The total energy consumed by each of the above SC activities is computed in this section.

Transportation Energy: The transportation energy is computed based on the transportation costs data from the economic MLC results. The SC transportation costs include the cost incurred for transporting components or products from supplier to OEM, use locations to collection centers, collection centers to OEM, collection center to remanufacturing centers, collection center to recycling centers, remanufacturing centers to OEM, recycling centers to suppliers, collection to disposal locations. Therefore, for each of these costs corresponding energy consumed is computed as follows:

The data for average freight revenue for ton-mile for years between 1960 through 2009 is obtained from Department's Bureau of Transportation Statistics. They covered different modes including air, truck, rail, and ship. As in this research, only ship and truck modes are considered, the data for both these modes is used. While for some years all the data was available, for rest of them there was no data. For the year 2003 all the data was available. Based on this data, the corresponding costs for ton-mile are computed (shown in Table 3.16). Suppose, for example, if we assume that 90% of distance is covered by ship and 10% by truck, the revenue for ton-mile is calculated as follows:

$$\begin{aligned} &Average\ Cost\ Per\ Ton-Mile \\ &\quad = 0.9 \times Revenue\ from\ ship\ \ per\ ton-mile + 0.1 \\ &\quad \times Revenue\ from\ truck\ per\ ton-mile \end{aligned}$$

Similarly, the data for energy consumed in terms of BTU per ton-mile for both truck and ship modes of transportation is obtained (Davis et al., 2009). From this data, the corresponding energy consumption per ton-mile, for the example case, is computed using the expression

$$\begin{aligned} &Average\ Energy\ \ Consumed\ Per\ Ton-Mile\ in\ BTU \\ &\quad = 0.9 \times BTU\ consumption\ from\ ship\ \ per\ ton-mile + 0.1 \\ &\quad \times BTU\ consumption\ from\ truck\ per\ ton-mile \end{aligned}$$

Table 3.16: Sample Transportation Cost and Energy per Ton-Mile Computations

Mode of Transportation	Revenue Per Ton-Mile ($)	Average Cost Per Ton-Mile ($)	Energy Consumed in BTU Per Ton-Mile	Average Energy Consumed in BTU Per Ton-Mile
Truck	0.13	$[(0.9 \times 0.02) + (0.1 \times 0.13)] = \mathbf{0.03}$	3699.41	$[(0.9 \times 562.02) + (0.1 \times 3699.41) = \mathbf{875.75}]$
Ship	0.02		562.02	

In this research, all the transportation costs are assumed to be proportional to the amount of energy consumed. This is because, as more distance is travelled more energy is consumed, and therefore more cost are incurred. For the above example problem, it is considered that for each 0.03 dollars spent on transportation costs, 875.75 BTU of energy is consumed. For all the eight different SC transportation activities, corresponding transportation energy is computed from their MLC_{Eco} costs as shown in Table 3.17. Each of the MLC costs is converted into corresponding energy by multiplying them with factor $\left(\frac{875.75}{0.03}\right)$. Also, the total transportation energy for each MLC year is computed.

Table 3.17: Sample Notations for Transportation Energy

SC Costs	Costs for each year in period *T* ($)			Energy for each year in period *T* (BTU)		
	$t_1 \ldots$	$t_n \ldots$	t_f	t_1	$t_n \ldots$	t_f
Transportation Cost (Supplier - OEM)	C_{11}	C_{1n}	C_{1f}	$C_{11}\left(\times \frac{875.75}{0.03}\right)$	$C_{1n}\left(\times \frac{875.75}{0.03}\right)$	$C_{1f}\left(\times \frac{875.75}{0.03}\right)$
Transportation Cost (Collection - Remanufacturing)	C_{21}	C_{2n}	C_{2f}	$C_{21}\left(\times \frac{875.75}{0.03}\right)$	$C_{2n}\left(\times \frac{875.75}{0.03}\right)$	$C_{2f}\left(\times \frac{875.75}{0.03}\right)$
Transportation Cost (Collection - Disposal)	C_{31}	C_{3n}	C_{3f}	$C_{31}\left(\times \frac{875.75}{0.03}\right)$	$C_{3n}\left(\times \frac{875.75}{0.03}\right)$	$C_{3f}\left(\times \frac{875.75}{0.03}\right)$
Transportation Cost (Collection - Recycle)	C_{41}	C_{4n}	C_{4f}	$C_{41}\left(\times \frac{875.75}{0.03}\right)$	$C_{4n}\left(\times \frac{875.75}{0.03}\right)$	$C_{4f}\left(\times \frac{875.75}{0.03}\right)$
Transportation Cost (Remanufacturing - OEM)	C_{51}	C_{5n}	C_{5f}	$C_{51}\left(\times \frac{875.75}{0.03}\right)$	$C_{5n}\left(\times \frac{875.75}{0.03}\right)$	$C_{5f}\left(\times \frac{875.75}{0.03}\right)$
Transportation Cost (Recycle - Suppliers)	C_{61}	C_{6n}	C_{6f}	$C_{61}\left(\times \frac{875.75}{0.03}\right)$	$C_{6n}\left(\times \frac{875.75}{0.03}\right)$	$C_{6f}\left(\times \frac{875.75}{0.03}\right)$
Transportation Costs (Collection - OEM)	C_{71}	C_{7n}	C_{7f}	$C_{71}\left(\times \frac{875.75}{0.03}\right)$	$C_{7n}\left(\times \frac{875.75}{0.03}\right)$	$C_{7f}\left(\times \frac{875.75}{0.03}\right)$
Transportation Cost (Use - Collection)	C_{81}	C_{8n}	C_{8f}	$C_{81}\left(\times \frac{875.75}{0.03}\right)$	$C_{8n}\left(\times \frac{875.75}{0.03}\right)$	$C_{8f}\left(\times \frac{875.75}{0.03}\right)$
Total Transportation Energy				sum of all above values for corresponding year		

Processing Energy: Seven different processing related activities are involved in the closed-loop SC including the raw material processing, assembly operations, collection center processing, refurbishing operations, disassembly, remanufacturing operations, and recycling operations. Unlike transportation energy, processing energy cannot be considered as proportional to cost. This is because, besides from cost, the processing energy depends on the materials involved, the skill of the workers ect. Therefore, in order to calculate this value, individual energy per kilogram of material consumed for each of the seven different activities is considered. Boustani (2010) provided data on the energy consumed for some of these operations including raw material processing, manufacturing and assembly, disassembly, recycling for a household appliance based on its material composition. Using this data as reference, in this research the energy values for these operations is estimated. For the other data such as collection centers processing, refurbishing, and remanufacturing operations, the energy consumption is estimated. As most of the collection centers sort the products not much energy is consumed, hence, an estimate of 1 Btu/kg is assumed for the collection center processing operations. Similarly, refurbishing and remanufacturing activities in this research involves cleanup of the product or component, which too involves less energy consumption, therefore 1.25 BTU/kg of energy is estimated to be used for these operations. Although the energy consumption data is approximated, these values are still reasonable considering the nature of operations. However, if the actual energy data is available for a given company, these values could be replaced. The energy consumption data (presented in Table 3.18) is based on the weight of the material being processed. While some of the processing activities are performed on the components, others are performed on the product itself (as shown) and therefore the weight varies. Also, the weight can vary among different PDSCC combinations.

The total annual energy consumed for each of these operations is based on the total weight of material, and therefore depends on the material quantity. As the quantity of products/components processed for each of these activities is known from the MLC_{Eco} results, one way to compute the total energy is to compute the amount of energy consumed per product or component for each operation, and multiply this by total units processed. Therefore, the BTU/kg value is converted into corresponding BTU per-unit value using the weights.

Table 3.18: Energy Consumed by Different Processing Activities in a SC

Processing Activity	BTU/Kg	Unit	BTU/Unit
Raw Material Processing	21579.76	Component	$21579.76 \times Weight\ of\ Component$
Assembly	2584.96	Product	$2584.96 \times Weight\ of\ Product$
Collection	1.00	Product	$1.00 \times Weight\ of\ Product$
Refurbishing	1.25	Product	$1.25 \times Weight\ of\ Product$
Disassembly	11.20	Product	$11.20 \times Weight\ of\ Product$
Remanufacturing	1.25	Component	$1.25 \times Weight\ of\ Component$
Recycling	31.88	Component	$31.88 \times Weight\ of\ Component$

Computation of Processing Quantities: The raw material processing quantity (new component) and assembly quantity is already available from MLC_{Eco}. The reverse loop quantities for collection center, refurbishing, disassembly, remanufacturing and recycling activities for the steady-state period are available and these values are used to compute the quantities for rest of the years in *T* using the demand ratio, as explained in MLC_{Eco} section. Each steady-state quantity is multiplied by the demand ratio for a given year, say t_y, to obtain the quantity for year t_y. This can be expressed by

$$Quantity\ for\ Year\ t_y\ = \\ Steady - state\ Quantity\ x\ Demand\ Ratio\ for\ Year\ t_y$$

Therefore, the total processing energy is obtained by multiplying the quantity and the BTU/unit values, for each of the processing activities. Table 3.19 presents sample individual and total processing energy computations for a year t_y in period *T*. Similar computations are performed for rest of the years in period *T*.

Table 3.19: Sample Processing Energy Computations

SC Processing Related Parameter	BTU/Unit	Quantity for Year t_y	Energy for Year t_y (BTU)
Raw Material Processing (Components)	$21579.76 \times$ $Weight\ of\ Component(11)$	$qr_y(12)$	(11 x 12) = 13
Assembly (Products)	$2584.96 \times\ Weight\ of\ Product(21)$	qa_y (22)	(21 x 22) = 23
Collection Center Processing (Products)	$1.00 \times\ Weight\ of\ Product(31)$	$qc_y(32)$	(31 x 32) = 33
Refurbishing (Product)	$1.25 \times\ Weight\ of\ Product$ (41)	$qf_y(42)$	(41 x 42) = 43
Disassembly (Products)	$11.20 \times\ Weight\ of\ Product$ (51)	qs_y (52)	(51 x 52) = 53
Remanufacturing (Components)	$1.25 \times\ Weight\ of\ Component$ (61)	$qm_y(62)$	(61 x 62) = 63
Recycling (Components)	$31.88 \times\ Weight\ of\ Component$ (71)	$qy_y(72)$	(71 x 72) = 73
Total Processing Energy for year t_y			= Sum (13, 23, 33, 43, 53, 63, 73)
$\forall\ y = 1$ to f			

Use Energy: The US Department of Energy (2010) provided a formula for the energy consumed by a product or an appliance as shown below:

$$Daily\ KWh\ Consumed = \frac{(\text{Product Wattage } \times \text{ Hours Used Per Day})}{1000}$$

From this equation, the annual energy consumption in BTU per-unit of product can be expressed by

$$\text{Energy Consumption } \left(\frac{\text{BTU}}{\text{unit}}\right) =$$

$$\left(\frac{\text{Product Wattage } \times \text{ Hours Used Per Day x Days Used Per Year}}{1000}\right) \times\ 3413$$

Therefore, the annual energy consumption for a unit of product can be estimated. Multiplying the BTU/unit with the demand for each year in period T, provides the annual use energy consumed. Therefore, the total energy usage for each year is given by

$$Energy\ use\ during\ year\ t_y = Energy\ Consumed\ per - unit\ (BTU) x\ Demand\ for\ year\ t_y \quad \forall\ y = 1\ to\ f$$

Emissions Released (Lb of CO_2)

In a closed-loop SC, all the transportation, processing and use activities release CO_2 emissions. Lower the emissions, lower is the environmental impact. In this research, emissions are measured in terms of pounds of CO_2 emissions released to air. Therefore, in this section, all the emissions computations related to transportation, processing and use activities are presented.

Transportation Emissions: Each of the eight transportation activities in the closed-loop SC model releases CO_2 emissions. Carbonfund.Org presented the data for CO_2 emissions from different modes of transportation. For the example problem, the CO_2 emissions per ton-mile are computed in Table 3.20.

Table 3.20: CO_2 Emissions per Ton-Mile Computations

Mode of Transportation	CO_2 emissions (Lb per Ton-Mile)	CO_2 emissions (Lb per Ton-Mile)
Truck	0.37	$[(0.9 \times 0.09) + (0.1 \times 0.37)] = \mathbf{0.12}$
Ship	0.09	

It is assumed that the CO_2 emissions released are proportional to transportation costs, and as more distance is travelled more emissions are released. Therefore, for example case, every 0.03 dollar spent 0.12 pounds of CO_2 emissions are released. Just similar to transportation energy computations all the transportation costs for each year in period *T* are multiplied by factor $\frac{0.12}{0.03}$ to obtained corresponding CO_2 emissions. Table 3.21 presents the sample computations for CO_2 emissions released through various SC transportation activities, for the example problem.

Table 3.21: Sample Computations for Transportation CO_2 Emissions

SC Cost	Costs ($)			CO_2 Emissions (Lb)		
	$t_1 \ldots$	$t_n \ldots$	t_f	t_1	$t_n \ldots$	t_f
Transportation Cost (Supplier - OEM)	C_{11}	C_{1n}	C_{1f}	$C_{11}\left(\times \frac{0.12}{0.03}\right)$	$C_{1n}\left(\times \frac{0.12}{0.03}\right)$	$C_{1f}\left(\times \frac{0.12}{0.03}\right)$
Transportation Cost (Collection - Remanufacturing)	C_{21}	C_{2n}	C_{2f}	$C_{21}\left(\times \frac{0.12}{0.03}\right)$	$C_{2n}\left(\times \frac{0.12}{0.03}\right)$	$C_{2f}\left(\times \frac{0.12}{0.03}\right)$
Total Transportation Cost (Collection-Disposal)	C_{31}	C_{3n}	C_{3f}	$C_{31}\left(\times \frac{0.12}{0.03}\right)$	$C_{3n}\left(\times \frac{0.12}{0.03}\right)$	$C_{3f}\left(\times \frac{0.12}{0.03}\right)$
Transportation Cost (Collection - Recycle)	C_{41}	C_{4n}	C_{4f}	$C_{41}\left(\times \frac{0.12}{0.03}\right)$	$C_{4n}\left(\times \frac{0.12}{0.03}\right)$	$C_{4f}\left(\times \frac{0.12}{0.03}\right)$
Transportation Cost (Remanufacturing - OEM)	C_{51}	C_{5n}	C_{5f}	$C_{51}\left(\times \frac{0.12}{0.03}\right)$	$C_{5n}\left(\times \frac{0.12}{0.03}\right)$	$C_{5f}\left(\times \frac{0.12}{0.03}\right)$
Transportation Cost (Recycle - Suppliers)	C_{61}	C_{6n}	C_{6f}	$C_{61}\left(\times \frac{0.12}{0.03}\right)$	$C_{6n}\left(\times \frac{0.12}{0.03}\right)$	$C_{6f}\left(\times \frac{0.12}{0.03}\right)$
Transportation Costs (Collection - OEM)	C_{71}	C_{7n}	C_{7f}	$C_{71}\left(\times \frac{0.12}{0.03}\right)$	$C_{7n}\left(\times \frac{0.12}{0.03}\right)$	$C_{7f}\left(\times \frac{0.12}{0.03}\right)$
Transportation Cost (Use - Collection)	C_{81}	C_{8n}	C_{8f}	$C_{81}\left(\times \frac{0.12}{0.03}\right)$	$C_{8n}\left(\times \frac{0.12}{0.03}\right)$	$C_{8f}\left(\times \frac{0.12}{0.03}\right)$
Total Transportation Emissions				sum of above values for corresponding year		

<u>*Processing Emissions:*</u> All the processing activities release CO_2 emissions. In order to compute the emissions released from each of the seven processing activities the conversion factor provided by the National Energy Foundation (NEF, 2010) is used. While, several carbon footprint calculators are provided, the NEF provides a simple easy-to-use conversion factor which is developed based on the recommended values provided by *Department for Environment, Food and Rural Affairs* (DEFRA) in its Environmental

Reporting Guidelines. These factors are used by UK organizations and several individual companies to compute their carbon footprints. Hence in this research, the factor provided by the NEF is used. They presented that every KWh of energy releases approximately 0.54 Kg of CO_2 emissions. As in this research, energy is measured in BTU and emissions in pounds this value is converted into equivalent factor and therefore, for every BTU of energy consumed by industrial processing operations approximately $3.48e^{-4}$ pounds of CO_2 emissions are released. Therefore, the processing energy values for each year is multiplied by $3.48e^{-4}$ to obtain the pounds of CO_2 emissions released from these operations. Table 3.22 presents sample computations for individual and total processing emissions for all years in period *T*.

<u>*Use Emissions:*</u> All the products when used release CO_2 emissions. The US Environmental protection Agency (USEPA) provided a calculator for estimating the amount of CO_2 emissions released from household appliance and different products. As the model is developed to be used across all the industries, and the USEPA being a well-recognized source of data, in this research the USEPA calculator is used to compute the annual average CO_2 emissions released from each product. The calculator estimates that for every KWh of energy used by a product a pound of CO_2 is emitted in a year. Therefore, as most of the ratings are in KWh, the input data is taken in terms of annual KWh usage and the corresponding pounds of CO_2 emissions released per product is computed. To calculate the total use emissions for each year the emissions/product is multiplied by the annual demand for that year. The computations are illustrated in Table 3.23.

Table 3.22: Sample Processing CO_2 Emissions Computations

SC Processing Related Parameter	BTU/Unit	Quantity for Year t_y	Energy for Year t_y (BTU)	CO_2 emissions for Year t_y (Lbs)
Raw Material Processing (Components)	$21579.76 \times Weight\ of\ Component$ (11)	qr_y (12)	(11 x 12) = 13	13 x 3.48e^{-4}
Assembly (Products)	$2584.96 \times Weight\ of\ Product$ (21)	qa_y (22)	(21 x 22) = 23	23 x 3.48e^{-4}
Collection Center Processing (Products)	$1.00 \times Weight\ of\ Product$ (31)	qc_y (32)	(31 x 32) = 33	33 x 3.48e^{-4}
Refurbishing (Product)	$1.25 \times Weight\ of\ Product$ (41)	qf_y (42)	(41 x 42) = 43	43 x 3.48e^{-4}
Disassembly (Products)	$11.20 \times Weight\ of\ Product$ (51)	qs_y (52)	(51 x 52) = 53	53 x 3.48e^{-4}
Remanufacturing (Components)	$1.25 \times Weight\ of\ Component$ (61)	qm_y (62)	(61 x 62) = 63	63 x 3.48e^{-4}
Recycling (Components)	$31.88 \times Weight\ of\ Component$ (71)	qy_y (72)	(71 x 72) = 73	73 x 3.48e^{-4}
Total Processing Emissions for year t_y				sum of all above
$\forall\ y = 1$ to f				

Table 3.23: Sample Use CO_2 Emissions Computations

SC Parameter	Year in Period *T* ($)		
	$t_1 \ldots$	$t_n \ldots$	t_f
Product KWh/Year	Kwh		
Annual Demand	$D_1 \ldots$	$D_n \ldots$	D_f
Total Annual CO_2 Emissions (Lb)	$D_1 \times kwh$	$D_n \times kwh$	$D_f \times kwh$

3.10.4 MLC_{Env} Tool

The MLC_{Env} tool is developed in Microsoft Excel Spreadsheet. This MLC_{Env} is a part of the MLC_{Eco} tool, and it has the 'Environmental Input Spreadsheet' which takes the annual energy usage data for a product, the reverse loop quantities, the product and component weights for processing computations, and displays other transportation, processing, use related conversion factors used in the model. A snapshot of the spreadsheet is shown in Figure 3.19. The data that must be entered for each PDSCC is shaded while the conversion factors are displayed in red.

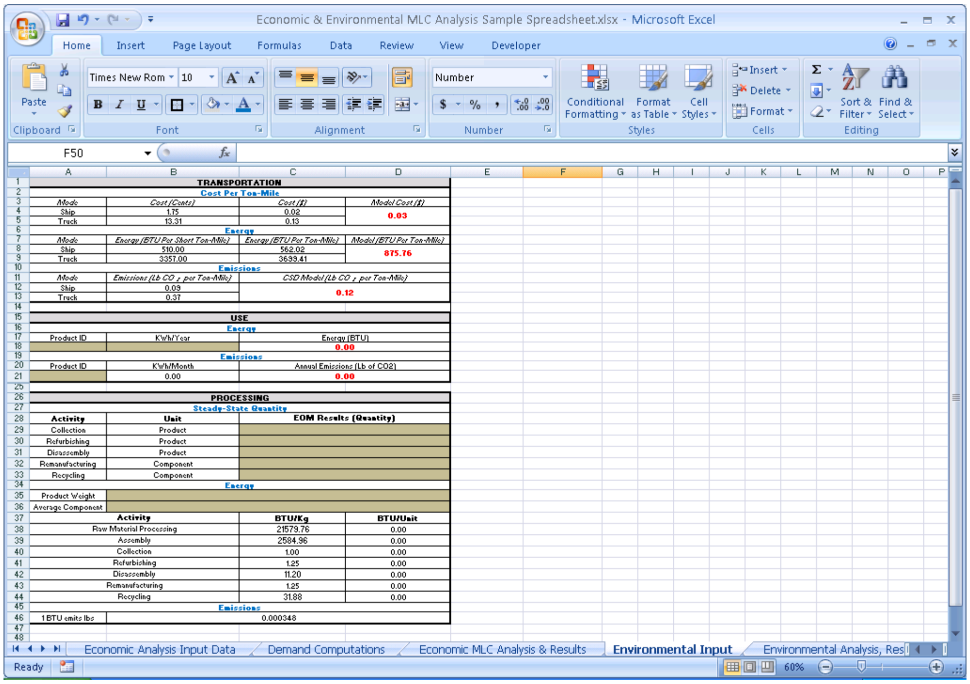


Figure 3.19: Snapshot of 'Environmental Input' Sheet

The sheet 'Environmental Analysis, Results' gathers all the SC costs and refurbished and remanufactured quantity related data from the economic MLC results to perform the analysis by computing the environmental impact for each PDSCC separately as discussed above. Figure 3.20 shows a snapshot of the 'Environmental MLC analysis and Results' sheet and its computations. As the analysis part is described in detail in this section, only the final results are captured.

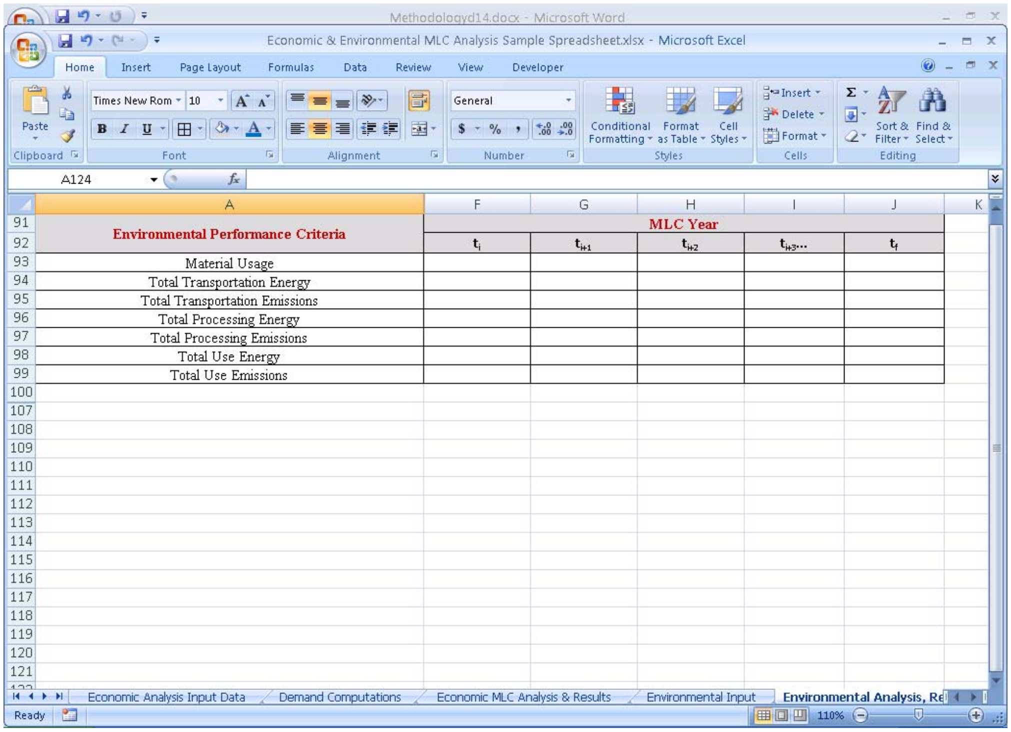


Figure 3.20: Snapshot of 'Environmental Analysis, Results' Sheet

For each of the environmental performance criteria, corresponding cumulative values for all the years in period *T* are computed. Therefore, the MLC_{Env} tool is run for all the PDSCC combinations separately, and the cumulative environmental impact of each of these PDSCC combinations is computed and compared at end of period *T*. Towards the end, the best PDSCC combinations that have minimal environmental impact are selected for the societal MLC analysis.

3.11 Societal Multi Life-cycle Analysis Description

In this section, a description of the societal MLC analysis is presented. Following a review of the societal performance criteria and analysis assumptions, a detailed description of the analysis procedure is presented. Finally, the societal MLC analysis tool (MLC_{Soc}) developed to identify the best PDSCC combination is explained.

3.11.1 Societal Performance Criteria

The field of societal sustainability has been gaining increased recognition during the recent years. Most of the work performed in this area is in the form of developing Corporate Societal Responsibility (CSR) metrics mostly generated by the companies. The ISO developed a set of guidelines for societal responsibility (ISO 26000). This document provides an extensive background on core principles of societal responsibility, guidelines on how to implement social responsibility practices in organizations. Most of the currently used societal metrics include simple measures such as accident rate, heath rate, number of illness complaints, employee diversity, employee training and development related metrics such as hours of training, number of learning activities available, educational development activities including tuition reimbursement ect., employee satisfaction, customer safety with products, employee safety, supplier training and development, customer satisfaction (IBM Supplier Social Conduct Principles, 2009; Apple, 2010). The major challenge in developing societal metrics is that most of these aspects are not quantifiable, due to the nature of the societal aspect and hence most of the companies use simple metrics to overcome this challenge. These metrics can be classified under six different stakeholder sectors including suppliers, employees, financial institutions, customers, community, and NGO/media.

As in this research, the objective is to develop a tool that can evaluate the societal performance of the PDSCC combinations, only the metrics that are relevant to this research are considered. Due to the relevance to this research, metrics within the supplier, employee and customer stakeholder sectors are considered (closed-loop SC model includes, suppliers, employees and customers). Therefore, criteria such as supplier societal-compliance ratio, supplier training and development, employee training and development, and product customization rate are considered for the societal MLC analysis. Each of this metric is defined below:

Supplier societal-compliance ratio: This metric is defined as the number of suppliers complying with societal responsibility policies over total number of suppliers.

Supplier training and development: This metric is measured in terms of average number of training hours spent by a supplier.

Employee training and development: This metric is measured in terms of average number of training hours spent by an employee.

Product Customizability Rate: This metric is measured in terms of the percentage (converted to a number between 0 and 1, hence rate) of components that can be customized in a given product.

Again, as the closed-loop SC network includes several SC partners, each of these criteria must be computed at different partners. Table 3.24 presents the different metrics considered for the societal MLC analysis categorized under three different stakeholder sectors, their formula, and their desired direction to reduce societal impact.

Table 3.24 Societal Performance Criteria and Their Formulas

Stakeholder Sector	Societal Metric	Formula	Desired Direction
Supplier	Supplier societal - compliance ratio	$\frac{Number\ of\ Supplier\ that\ comply\ with\ Policies}{Total\ Number\ of\ Suppliers}$	↑
	Supplier training and development	$Number\ of\ Training\ Hours\ per\ Supplier\ *$	↑
Employee	Employee training and development	$Number\ of\ Training\ Hours\ per\ Employee*$	↑
Customer	Product customizability Rate	$Percentage\ of\ Product\ that\ can\ be\ Customizable$	↑
*Values are Annual Averages			

Societal Impact of the Closed-loop SC

In this section, the location at which the metrics must be computed is presented. As the names of the stakeholders indicate, all the supplier and employee related metrics are computed at the suppliers and employees respectively. In the model, employees are present at each SC partner except for suppliers and use. However, the customer related metric ‘product customizability rate’ is a product related metric, and hence it remains constant for a given product throughout its life-cycle. Hence, the metric is measured at the product design stage. Figure 3.21 illustrates the different closed-loop SC partners and their societal performance criteria considered in this research.

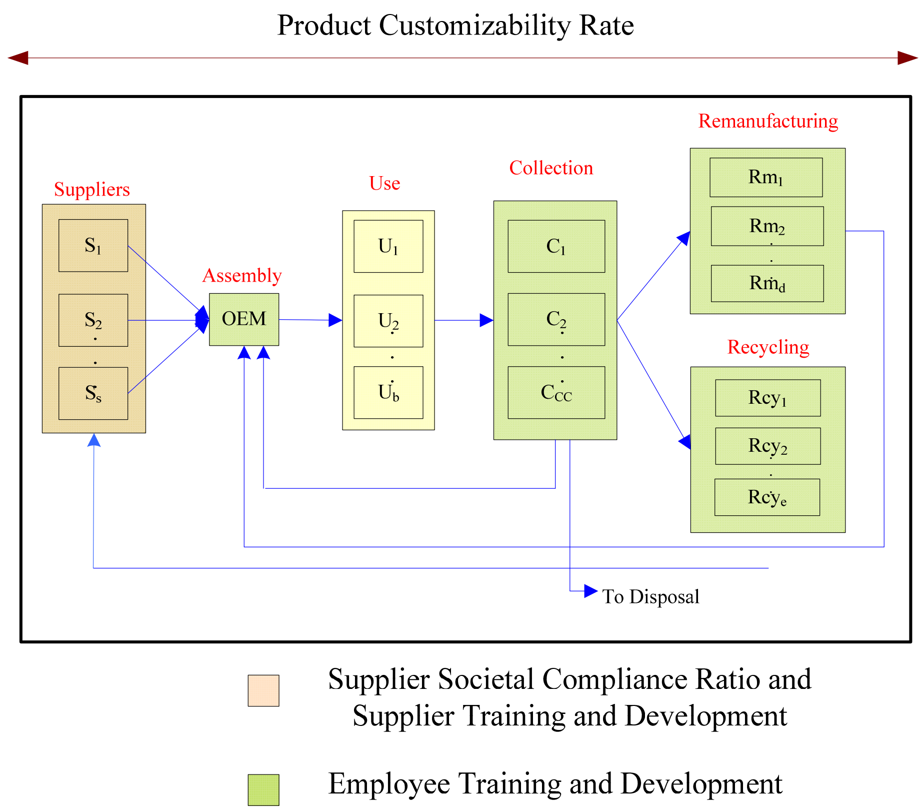


Figure 3.21: Closed-loop SC Societal Performance Criteria

3.11.2 Assumptions

All the analysis is performed based on the steady-state data. The data for the training hours per supplier and employee are estimated annual averages and are assumed to remain constant during the steady-state period (t_{s1} to t_{sf}). The demand ratio computed in the MLC_{Eco} tool, is used to compute these values during the introduction and decline period.

3.11.3 Analysis Description

The objective of this analysis is to select the best PDSCC combinations that have minimal societal impact. Each of the performance criteria is computed as follows:

Supplier societal-compliance ratio: For each of the suppliers, the data on whether they are complaint with societal responsibility policies is identified by the following expression during the steady-state period:

$$if \begin{cases} S_g = 1 \;\; then\ the\ supplier\ is\ compliant \\ S_g = 0 \;\; Else \end{cases} \forall\ g = 1 \ldots G$$

It is assumed that the supplier societal-compliance ratio remains constant during the steady-state period (t_{s1} to t_{sf}). This assumption is made due to the huge complexity involved in gathering the data for all the years in period *T*. However, for the Introduction and Decline phases the steady-state value is multiplied by corresponding year's demand ratio computed in the MLC_{Eco} tool, to obtain the values for remaining years. Due to lack of relevant data, and as only demand data is available for all the years this approximation is made. Table 3.25 presents an example of supplier societal-compliance ratio computations for years in period *T*.

Table 3.25 Supplier Societal-compliance Ratio Computations

Supplier Criteria	**MLC Year ($)**		
	$t_1 \ldots$	$t_n \ldots$	t_f
Demand Ratio	$DR_1 \ldots$	$DR_n \ldots$	DR_f
Supplier Societal-compliance Ratio	$cr_n \times DR_1$	cr_n	$cr_n \times DR_f$

Supplier Training and Development: The estimated annual average number of hours the supplier is trained for the steady-state period is considered as an input. Therefore, this value is used to compute the average training hours for all suppliers for the steady-state period. Similar, to the above case, the training hours for the introduction and decline phases is computed by multiplying the steady-state value with the corresponding year's demand ratio to obtain the values for rest of the years. Table 3.26 presents sample computations for the supplier training hours for each year in period *T*.

Table 3.26: Average Supplier Training Hours Computations

Supplier Criteria	MLC Year ($)		
	$t_1 \ldots$	$t_n \ldots$	t_f
Demand Ratio	$DR_1 \ldots$	$DR_n \ldots$	DR_f
Supplier Training Hours	$h_n \times DR_1$	$h_n = Average\ of\ Annual\ Training\ Hours\ per\ Supplier$	$h_n \times DR_f$

Employee Training and Development: The estimated annual average number of hours an employee is trained for the steady-state period is considered as an input. Similar to supplier training hours, the average training hours for all employees for the steady-state period is computed. Also, the training hours for the introduction and decline phases is computed by multiplying the steady-state value with corresponding year's demand ratio to obtain the values for rest of the years in *T*.

Product Customizability Rate: The percentage of product that can be customized is taken as input for this metric. As this is a product related metric this value remains constant over period *T*.

3.11.4 Societal MLC Analysis (MLC_{Soc}) Tool

Similar to economic and environmental MLC analysis, a Microsoft Excel Spreadsheet tool is developed to conduct the societal MLC analysis on the best PDSCCs selected by the MLC_{Eco} and MLC_{Env} tools. The aim of the MLC_{Soc} tool, which is a part of the MLC_{Eco} and MLC_{Env} is to assess the societal impact of each PDSCC combinations separately, to identify the best combination with minimal societal impact.

The 'Societal Input data' spreadsheet takes all the steady-state input values such as supplier societal-compliance, average supplier and employee training hours, product customizability rate and computes the corresponding societal metrics for all the years in period *T*. Figure 3.22 shows a snapshot of the 'Societal Input data' sheet of the MLC_{Soc} tool. The data is entered into the highlighted cells.

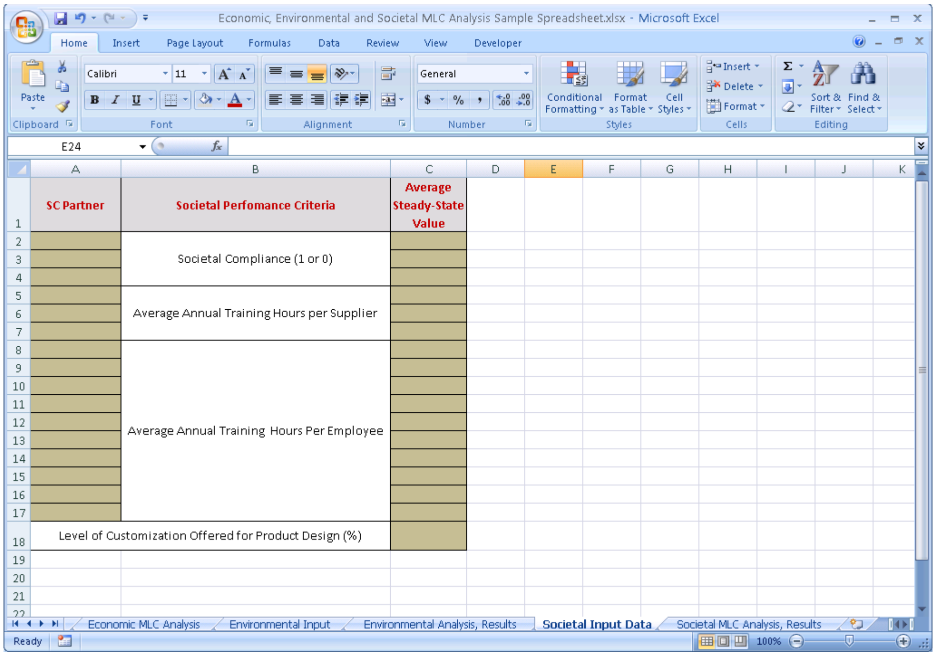


Figure 3.22: Snapshot of the 'Societal Input data' Sheet

Therefore, from the input data, the 'Societal MLC Analysis & Results' sheet performs all the MLC analysis computations. Figure 3.23 illustrates the societal MLC analysis criteria and the results.

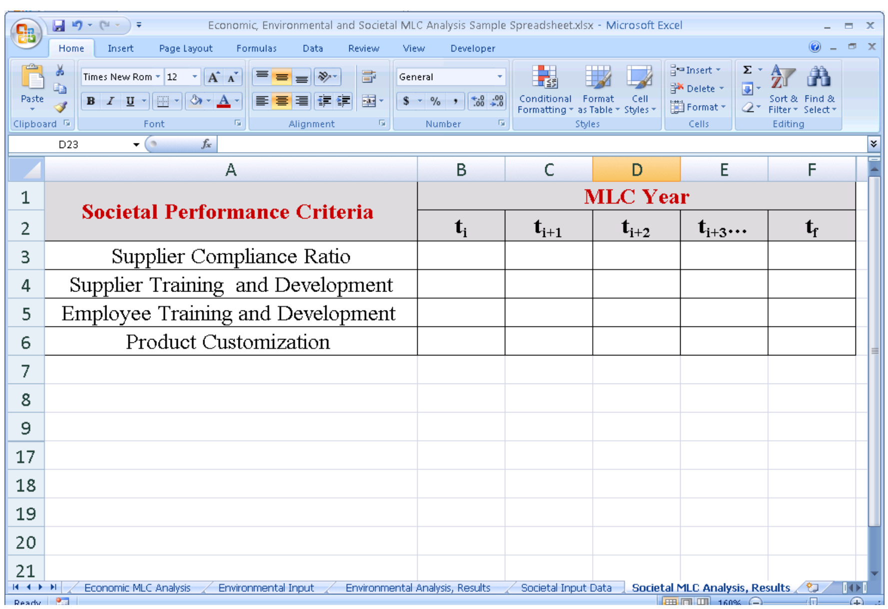


Figure 3.23: Snapshot of the 'Societal Analysis & Results' Sheet

As it can be observed, the economic, environmental and societal MLC analysis spreadsheets are connected to one another and data is transferred from economic MLC analysis to environmental and societal analysis spreadsheets, as needed, for computational purposes. Therefore, for each PDSCC combination, the societal MLC analysis is performed and the cumulative values are computed for each performance criteria over period *T*.

4. CHAPTER FOUR: MODEL APPLICATION, RESULTS AND DISCUSSIONS

To illustrate the working of the CSD model using hierarchical approach, the developed EOM model and the MLC_{Eco}, MLC_{Env} and MLC_{Soc} tools are used to identify the best PDSCC combination that generates highest economic, environmental and societal benefits for an example problem. Following the description of the product design and the supply chain configuration, the four sub-models are formulated and used to identify the best PDSCC with maximum sustainability benefits. All the product and closed-loop SC related data, such as the product design characteristics (reuse, remanufacture and recycling probabilities), steady-state demand, capital costs, distances, processing costs are generated based on realistic estimates.

4.1 Example Problem Description

Four alternate product designs from the NPD stage are considered. While the design consists of several components, for this problem three different critical components are chosen. Each of the three components for the alternate product designs varies with respect to type of design, type of material etc. and is supplied by different supplier. It is considered that few of the product designs already exist in market, while others are hypothetical designs studied at the NPD stage to be launched in future. Table 4.1 presents the weights of the alternate product designs and their components (used to determine the product's/component's transportation cost). The higher the weight the greater is the cost of transporting the product/component for a given distance. The alternate product designs are identified by PD_1, PD_2, PD_3, and PD_4. The variation among the three components for each product design (in terms of their reuse, remanufacturing and recycling ratings and probabilities) is presented in Appendix B.

Table 4.1: Weights of Alternate Product Designs and their Components

Unit	Weight (Lb)			
	PD_1	PD_2	PD_3	PD_4
$Component_1$	50	45	30	60
$Component_2$	25	30	21	29
$Component_3$	43	47	40	46
Product	400	450	370	410

4.2 SC configuration Description

This section presents the SC configuration data for each alternate product design in terms of SC operations performed across the four product life-cycle stages.

Components/Parts Acquisition Data

Each supplier provides one component. Table 4.2 presents the supplier ID for the components and their corresponding cost. As only three components are evaluated individually, the cost for acquiring rest of the components is considered (used for computing the price of the product) and this data is presented in 'others' column. Based on the given location of the supplier, the distances from suppliers to OEM are calculated and this data along with weights in Table 4.1 is used to compute the transportation costs presented in the Appendix A.

Table 4.2: Supplier Related Information for Example Problem

Product ID	Supplier Name			Supplier Component Cost ($/unit)			
	Component t_1	Component t_2	Component t_3	Component t_1	Component t_2	Component t_3	Others
PD_1	S_3	S_1	S_2	350	230	200	400
PD_2	S_1	S_2	S_3	300	270	180	450
PD_3	S_1	S_3	S_2	310	240	300	480
PD_4	S_2	S_1	S_3	380	410	330	500

Manufacturing

The OEM plant assembles the components to form final products to be distributed to various customer locations. The demand for alternate product designs, the OEM annualized capital costs, OEM assembly and holding costs are all presented in the Appendix A.

Use

Table 4.3 presents the distribution of the annual steady-state demand to different customer locations.

Table 4.3: Demand Market: Example Problem

Use Location ID	Demand (in Thousands of Products)			
	PD_1	PD_2	PD_3	PD_4
U_1	25	30	23	28
U_2	25	35	37	20
U_3	25	15	10	22
U_4	25	30	20	10
Total	100	110	90	80

Collection

The average lifespan of products in this problem is assumed to be 4 years and at the end of the use stage, 40% of the total products sold are considered to be recovered. Three possible collection centers are considered in this problem. Table 4.4 presents the potential collection center IDs, annualized capital costs, processing costs, and their capacity information for each alternate product design. All collection centers are assumed to have the capability to perform collecting and sorting operations.

Table 4.4: Collection Center Data for Example Problem

Collection Center ID	Annualized Capital Cost (Millions of $)				Processing Cost ($/Product)				Capacity (Thousands of Product)			
	PD_1	PD_2	PD_3	PD_4	PD_1	PD_2	PD_3	PD_4	PD_1	PD_2	PD_3	PD_4
C_1	1	1.02	0.98	1.80	3	2	2	5	26	30	19	15
C_2	1.1	1.08	1.09	1.82	2	1	4	3	21	21	26	20
C_3	1.03	1.06	1.30	1.85	4	3	5	2	23	29	25	23

The distance from use locations to collection centers and the corresponding transportation costs for the alternate product designs are computed and presented in Appendix C.

Sorting Operations: Collection Centers

The sorting operations are performed as described in the methodology section.

Evaluating Alternate Product Designs: Example Problem

The reuse, remanufacturing and recycling ratings for alternate product designs are used to compute the corresponding probabilities as described in the methodology section and the values are presented in Appendix B. These probabilities are compared with threshold limits for each design separately, to select the products or components for refurbishing, or remanufacturing, or recycling or disposal operations respectively.

The cost for refurbishing and disassembly at each collection center is presented in Appendix A. The distances from collection centers to the OEM and the corresponding transportation costs are presented in Appendix C. The components that can be remanufactured and recycled are sent to the remanufacturing and recycling centers. The rest of the components are disposed at location D_P. The distance and the transportation costs from each collection center to the disposal location are presented in Appendix C.

Remanufacturing

All the components chosen for remanufacturing at the collection centers are sent to remanufacturing centers for their operations. Table 4.5 presents the potential remanufacturing center ID and their annualized capital costs. The capital costs vary for each design for the same centers as each design has different set-up requirements. The remanufacturing costs, capabilities and capacities of potential remanufacturing centers, for each design, are presented in Appendix A.

Table 4.5: Possible Remanufacturing Center Related Data: Example Problem

Remanufacturing Center ID	Annualized Capital Cost (in Millions of $)			
	PD_1	PD_2	PD_3	PD_4
RM_1	2	2.01	1.8	1.85
RM_2	2.02	2.06	1.75	1.7
RM_3	1.8	1.9	1.6	1.9

The Appendix C provides the distances and the transportation costs from collection centers to possible remanufacturing centers. As discussed earlier, the CSD model selects remanufacturing centers that must be opened and the quantity of components that must be sent to each center so that the profit is maximized based on associated capital, transportation and processing costs and their capacities and capabilities. The distances and the associated transportation costs from possible remanufacturing centers back to OEM are shown in Appendix C.

Recycling

All the components chosen for recycling at the collection center are sent to recycling centers for their subsequent operations. Table 4.6 presents the IDs and annualized capital costs for possible recycling centers. The processing costs, capabilities and capacities of possible recycling centers for each design are presented in Appendix A.

Table 4.6: Possible Recycling Center Related Data: Example Problem

Recycle Center ID	Annualized Capital Cost (Millions of $)			
	PD_1	PD_2	PD_3	PD_4
RY_1	2	2.1	1.85	1.8
RY_2	2.1	2.09	1.96	1.9
RY_3	1.8	1.98	1.9	1.99

The Appendix C provides distances and transportation costs from each collection center to potential recycling centers where major material from components is extracted and sent to component suppliers for use in new components. The distances and transportation costs from recycling centers to suppliers are shown in Appendix C.

Therefore, a generalized version of possible closed-loop SC configuration based on the 6R concept of SM, for each of the four alternate product designs is illustrated in Figure 4.1. As the number of potential SC partners is similar for each design, in this case, each SC partner is represented with a suffix i and j where i is the design ID and j is SC partner ID.

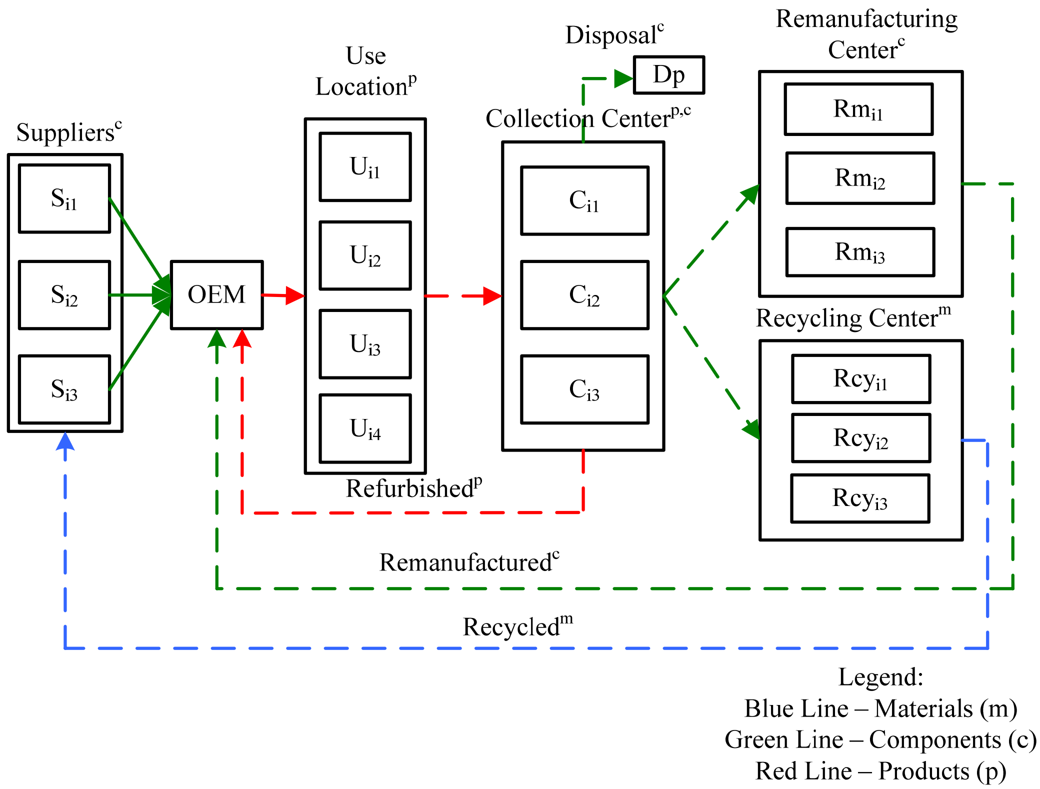


Figure 4.1: Possible Closed-loop SC Configuration (Example problem)

4.3 CSD Model Framework

The demand graph for this problem is illustrated in Figure 4.2. The EOM is run at the steady-state condition in year 6 (t_n). The time horizon for this model is considered as 10 (T) years. The steady-state period ranges from 3 (t_{s1}) to 8 $\left(t_{sf}\right)$ years. The economic, environmental and societal MLC analysis is conducted for all years between 1 to 10 using the tools MLC_{Eco}, MC_{Env}, and MLC_{Soc} tools as described in methodology section.

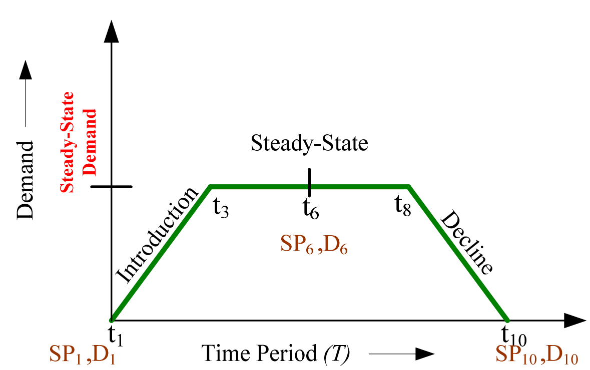


Figure 4.2: Demand Graph (Example Problem)

4.4 Economic Optimization Model (EOM)

The EOM formulated and described in the methodology section is used to identify for each product design a corresponding optimal SC configuration that maximizes profit. The EOM for this problem is run at steady-state condition for year 6. The input data described previously, is entered for each PDSCC combination separately into the EOM. Figure 4.3 illustrates a snapshot of the EOM model run using the IBM ILOG CPLEX optimization software for PD_1.

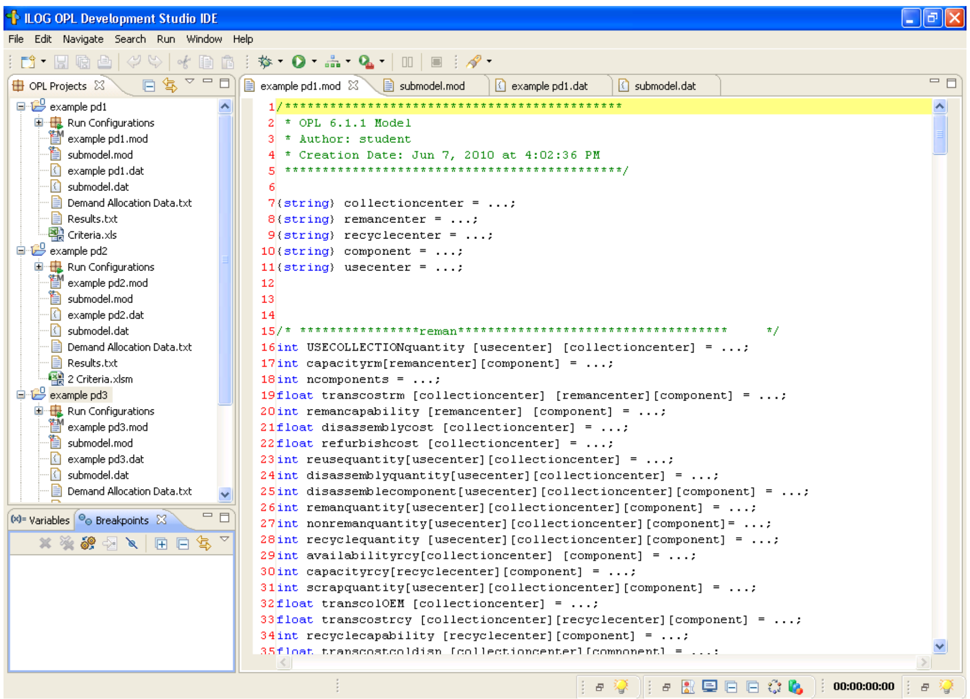


Figure 4.3: Snapshot of the Economic Optimization Model for PD1

4.4.1 Model Assumptions

All the assumptions presented for the EOM earlier are considered for the example problem.

4.4.2 Results

Table 4.7 presents the optimal SC configuration identified by the EOM for each alternate product design. Each SC partner is represented by P_{ij} where P is the SC partner,

i is the product design ID, and j is the partner ID. As the partner can vary for each design, they are identified using the product design and name of the partner.

Table 4.7: Optimal SC Partners for Alternate Product Designs

SC Partner	Product Design (Optimal SC Configuration)			
	PD_1 (SCC_1)	PD_2 (SCC_2)	PD_3 (SCC_3)	PD_4 (SCC_4)
Supplier	S_{11}	S_{21}	S_{31}	S_{41}
	S_{12}	S_{22}	S_{32}	S_{42}
	S_{13}	S_{23}	S_{33}	S_{43}
OEM	OEM			
Use	U_{11}	U_{21}	U_{31}	U_{41}
	U_{12}	U_{22}	U_{32}	U_{42}
	U_{13}	U_{23}	U_{33}	U_{43}
	U_{14}	U_{24}	U_{34}	U_{44}
Collection	C_{11}	C_{21}	C_{31}	C_{41}
	C_{13}	C_{23}	C_{32}	C_{43}
Remanufacturing	RM_{12}	RM_{21}	RM_{31}	RM_{43}
Recycle	RY_{12}	RY_{23}	RY_{33}	RY_{41}
				RY_{42}
Maximum Profit (in Millions of $)	14.65	6.57	10.6	6.65

4.4.3 Summary

For each product design, a corresponding SC configuration is selected by EOM with an objective to maximize the profit. The reverse loop SC partners are selected based on their costs, capabilities, capacities and distances. No selection is performed among suppliers. Hence, all the forward loop SC partners such as suppliers, OEM and use locations that are provided initially are considered in the optimal SC configuration as shown in Table 4.7. The selection of reverse loop partners highly depends on the recovered quantity and hence on steady-state demand. The opening of reverse loop facilities, such as collection, remanufacturing and recycling centers highly depend on the recovered quantity (at the collection center) and the product design aspects. As more products are recovered, more collection centers are opened. However, the collection center that maximizes total profit is given priority. Once the quantity is allocated to this collection center, if there exists more products the next best collection center is opened that maximizes the total profit. Among these recovered products, the quantity that can qualify for reuse, remanufacturing and recycling depends on product design characteristics. The more sustainable a design is, the more chances it has for second life. Therefore, the entire SC performance is optimized for each alternate product design as opposed to individual partner's performance. These types of optimization models that consider entire SC as a single entity can help the companies to choose the optimal closed-loop SC partners for a given design that benefit the overall organizational performance.

The profit during the steady-state period depends mainly on the steady-state demand, and the number of remanufactured components or refurbished products used to satisfy the demand. As more demand is satisfied by refurbished products or remanufactured components, the total forward loop costs are reduced. This implies that more sustainable a product design is, the more products and components can be refurbished or remanufactured, and hence the forward loop costs are less, thereby generating more profits to the company. However, as discussed in previous paragraph, the sustainable products can have more chances of being refurbished at the end-of-life, and its components can have higher chances of being remanufactured or recycled. Hence, the sustainable design as compared to conventional designs can have higher reverse loop costs during the steady-state. However, for measuring true sustainability, it is not enough to make decisions based on a steady-state demand. Although the reverse loop costs are incurred for sustainable designs, in future life-cycles these designs have reduced forward loop costs and can also generate more profit over multiple years in time horizon T all of which must be studied. Therefore, the performance of each design must be studied over MLCs, to quantify the overall SC benefits/impact of performing reverse loop operations.

Hence, from the EOM only the optimal SC configurations for each product design are considered and the decisions on the best PDSCC that maximizes total economic performance is made at the end of economic MLC analysis.

4.5 Economic Multi Life-cycle Analysis

In this section, the economic MLC analysis performed on the example problem is presented. The objective of performing the analysis is to identify and select the best PDSCC combinations that have maximum economic performance at the end of the 10 year period. At the end, the PDSCC combinations are ranked based on their maximum cumulative profit. Secondly, the impact of pursing a closed-loop flow on each of the PDSCC combination is studied in this section. To do so, for each PDSCC combination, the cumulative profits for each of the 10 years obtained from the closed-loop SC model is compared with the cumulative profits from the open-loop SC model.

4.5.1 Analysis Assumptions

All the assumptions considered in methodology section for the economic MLC analysis are considered for this problem, too. In addition, the following aspects are considered: the use stage of the product is 4 years (v); the reverse loop SC operations take 1 year (q); and the economic MLC analysis is performed for a period of 10 years (T) for each PDSCC combination identified by EOM (Table 4.7) separately.

4.5.2 Analysis Description

The economic MLC analysis is performed using the MLC_{Eco} tool described in the methodology section. Each PDSCC combination is analyzed separately.

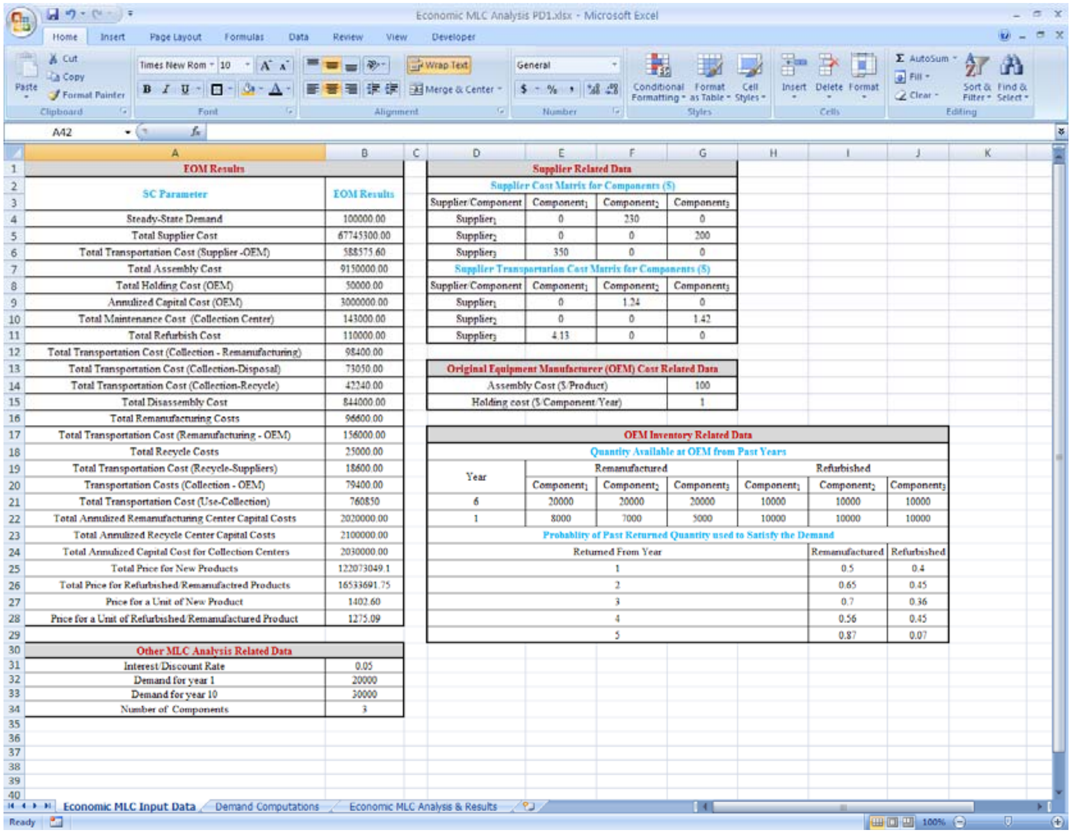
Input Data

For each PDSCC, the data available from EOM such as the EOM results, the steady-state year (year 6) price and demand, the number of refurbished and remanufactured components returned from year 1 sales and are available for year 6 (steady-state year), the number of critical components considered, the 6th year per-unit costs such as the supplier component cost, the transportation cost from suppliers to OEM, the assembly and holding cost is captured in the 'Economic MLC Input Data' sheet.

The additional input data required for the economic MLC analysis such as the demand for the year 1 and 10, probability for refurbished and remanufactured components returned from each past years 1 through 5 and the interest or the discount rate all presented in Table 4.8. As an example, the ‘Economic MLC Input Data’ sheet for PD_1 is illustrated in the Figure 4.4.

Table 4.8: Economic MLC Additional Input Data (Example Problem)

SC Parameter		Product Design ID			
		PD_1	PD_2	PD_3	PD_4
Demand for 1st year		20000	35000	21000	20000
Demand for 10st year		30000	29000	9000	11000
Interest/Discount rate		0.05			
Probability of refurbished components returned from past years satisfying later year's demand	Year 1	0.4	0.7	0.6	0.63
	Year 2	0.45	0.64	0.5	0.65
	Year 3	0.36	0.59	0.3	0.64
	Year 4	0.45	0.64	0.7	0.7
	Year 5	0.07	0.4	0.54	0.59
Probability of remanufactured components returned from past years satisfying later year's demand	Year 1	0.5	0.6	0.55	0.71
	Year 2	0.65	0.58	0.49	0.42
	Year 3	0.7	0.51	0.52	0.64
	Year 4	0.56	0.65	0.61	0.6
	Year 5	0.87	0.57	0.7	0.59



EOM Results	
SC Parameter	EOM Results
Steady-State Demand	100000.00
Total Supplier Cost	67745300.00
Total Transportation Cost (Supplier -OEM)	588575.60
Total Assembly Cost	9150000.00
Total Holding Cost (OEM)	50000.00
Annulized Capital Cost (OEM)	3000000.00
Total Maintenance Cost (Collection Center)	143000.00
Total Refurbish Cost	110000.00
Total Transportation Cost (Collection - Remanufacturing)	98400.00
Total Transportation Cost (Collection-Disposal)	73050.00
Total Transportation Cost (Collection-Recycle)	42240.00
Total Disassembly Cost	844000.00
Total Remanufacturing Costs	96600.00
Total Transportation Cost (Remanufacturing - OEM)	156000.00
Total Recycle Costs	25000.00
Total Transportation Cost (Recycle-Suppliers)	18600.00
Transportation Costs (Collection - OEM)	79400.00
Total Transportation Cost (Use-Collection)	760850
Total Annulized Remanufacturing Center Capital Costs	2020000.00
Total Annulized Recycle Center Capital Costs	2100000.00
Total Annulized Capital Cost for Collection Centers	2030000.00
Total Price for New Products	122073049.1
Total Price for Refurbished/Remanufactred Products	16533691.75
Price for a Unit of New Product	1402.60
Price for a Unit of Refurbished/Remanufactured Product	1275.09

Other MLC Analysis Related Data	
Interest/Discount Rate	0.05
Demand for year 1	20000
Demand for year 10	30000
Number of Components	3

Supplier Related Data			
Supplier Cost Matrix for Components ($)			
Supplier/Component	$Component_1$	$Component_2$	$Component_3$
$Supplier_1$	0	230	0
$Supplier_2$	0	0	200
$Supplier_3$	350	0	0
Supplier Transportation Cost Matrix for Components ($)			
Supplier/Component	$Component_1$	$Component_2$	$Component_3$
$Supplier_1$	0	1.24	0
$Supplier_2$	0	0	1.42
$Supplier_3$	4.13	0	0

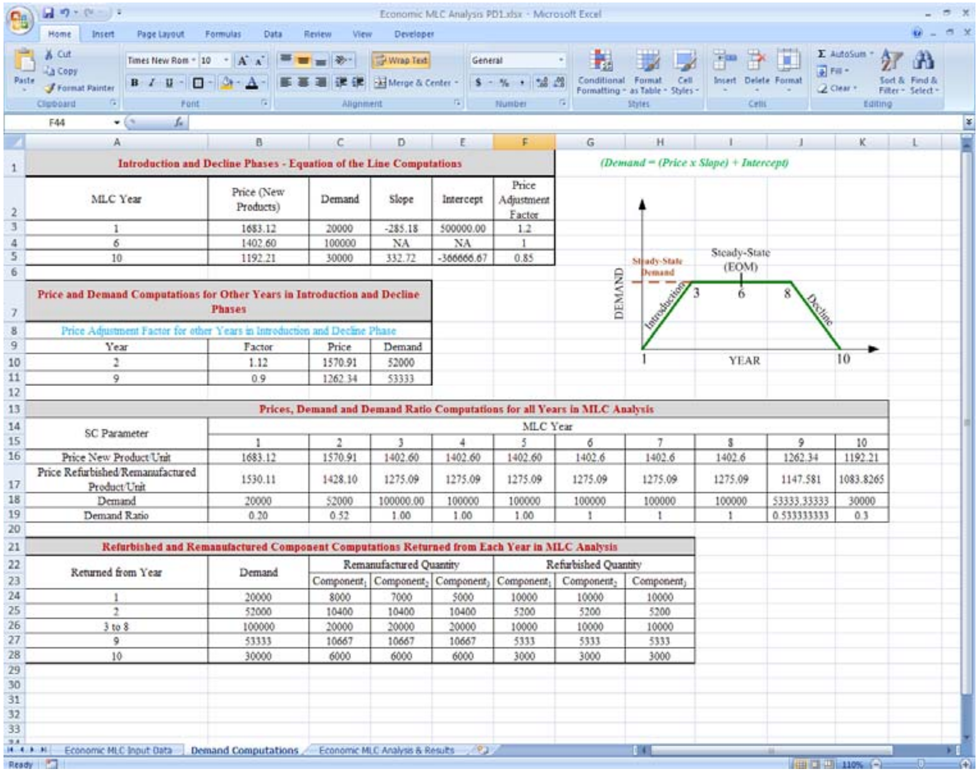
Original Equipment Manufacturer (OEM) Cost Related Data	
Assembly Cost ($/Product)	100
Holding cost ($/Component/Year)	1

OEM Inventory Related Data						
Quantity Available at OEM from Past Years						
Year	Remanufactured			Refurbished		
	$Component_1$	$Component_2$	$Component_3$	$Component_1$	$Component_2$	$Component_3$
6	20000	20000	20000	10000	10000	10000
1	8000	7000	5000	10000	10000	10000

Probablity of Past Returned Quantity used to Satisfy the Demand		
Returned From Year	Remanufactured	Refurbished
1	0.5	0.4
2	0.65	0.45
3	0.7	0.36
4	0.56	0.45
5	0.87	0.07

Figure 4.4: 'Economic MLC Input Data' Sheet for PD_1

Therefore, from the input data, the price, the demand for each of the 10 years, and the refurbished and remanufactured component quantity returned for each year is computed in sheet 'Demand Computations' as shown in Figure 4.5.



Introduction and Decline Phases - Equation of the Line Computations					
MLC Year	Price (New Products)	Demand	Slope	Intercept	Price Adjustment Factor
1	1683.12	20000	-285.18	500000.00	1.2
6	1402.60	100000	NA	NA	1
10	1192.21	30000	332.72	-366666.67	0.85

(Demand = (Price x Slope) + Intercept)

Price and Demand Computations for Other Years in Introduction and Decline Phases			
Price Adjustment Factor for other Years in Introduction and Decline Phase			
Year	Factor	Price	Demand
2	1.12	1570.91	52000
9	0.9	1262.34	53333

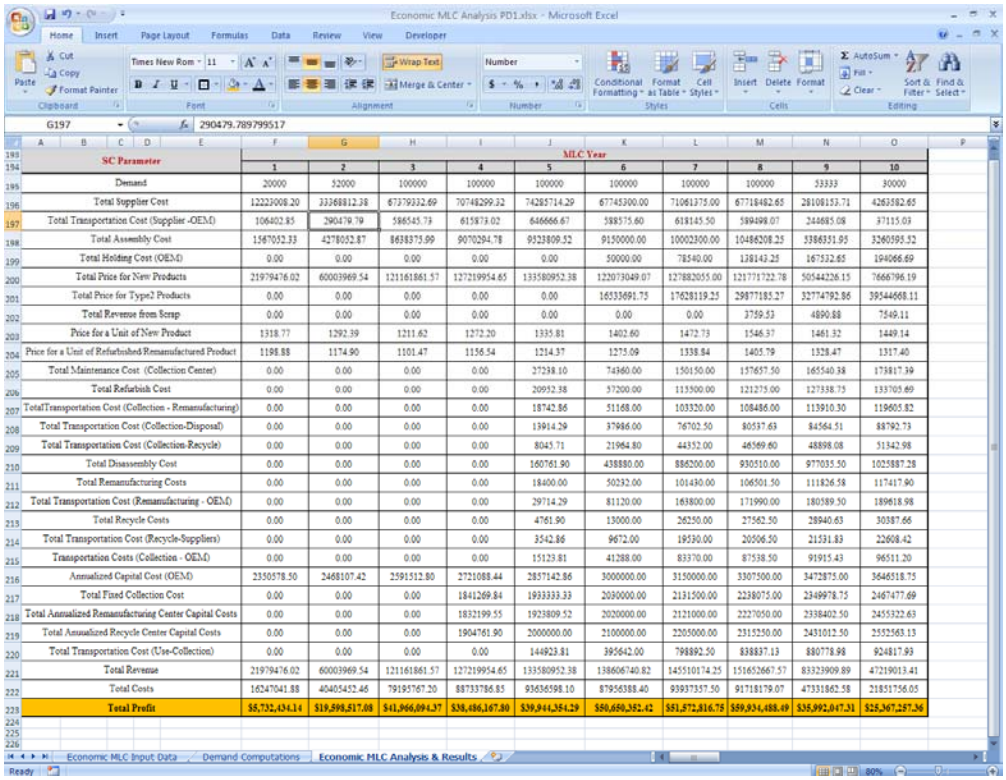
Prices, Demand and Demand Ratio Computations for all Years in MLC Analysis										
SC Parameter	MLC Year									
	1	2	3	4	5	6	7	8	9	10
Price New Product/Unit	1683.12	1570.91	1402.60	1402.60	1402.60	1402.6	1402.6	1402.6	1262.34	1192.21
Price Refurbished/Remanufactured Product/Unit	1530.11	1428.10	1275.09	1275.09	1275.09	1275.09	1275.09	1275.09	1147.581	1083.8265
Demand	20000	52000	100000.00	100000	100000	100000	100000	100000	53333.33333	30000
Demand Ratio	0.20	0.52	1.00	1.00	1.00	1	1	1	0.533333333	0.3

Refurbished and Remanufactured Component Computations Returned from Each Year in MLC Analysis							
Returned from Year	Demand	Remanufactured Quantity			Refurbished Quantity		
		$Component_1$	$Component_2$	$Component_3$	$Component_1$	$Component_2$	$Component_3$
1	20000	8000	7000	5000	10000	10000	10000
2	52000	10400	10400	10400	5200	5200	5200
3 to 8	100000	20000	20000	20000	10000	10000	10000
9	53333	10667	10667	10667	5333	5333	5333
10	30000	6000	6000	6000	3000	3000	3000

Figure 4.5: 'Demand Computations' Sheet for PD_1

4.5.3 Results

For each PDSCC combination, the MLC_{Eco} tool uses the input data and demand computations, to calculate the annual quantities, annual costs, annual prices, annual revenue and annual profit for the 10 year period. All of these computations are performed in the 'Economic MLC Analysis and Results' sheet of the tool. As an example, the results obtained for PD_1 are shown (Figure 4.6).



SC Parameter	MLC Year 1	2	3	4	5	6	7	8	9	10
Demand	20000	52000	100000	100000	100000	100000	100000	100000	53333	30000
Total Supplier Cost	12223008.20	33368812.38	67379332.69	70748299.32	74285714.29	67745300.00	71061375.00	67718482.65	28108153.71	4263582.65
Total Transportation Cost (Supplier -OEM)	106402.85	290479.79	586545.73	615873.02	646666.67	588575.60	618145.50	589498.07	244685.08	37115.03
Total Assembly Cost	1567052.33	4278052.87	8638375.99	9070294.78	9523809.52	9150000.00	10002300.00	10486208.25	5386351.95	3260595.52
Total Holding Cost (OEM)	0.00	0.00	0.00	0.00	0.00	50000.00	78540.00	138143.25	167532.65	194066.69
Total Price for New Products	21979476.02	60003969.54	121161861.57	127219954.65	133580952.38	122073049.07	127882055.00	121771722.78	50544226.15	7666796.19
Total Price for Type2 Products	0.00	0.00	0.00	0.00	0.00	16533691.75	17628119.25	29877185.27	32774792.86	39544668.11
Total Revenue from Scrap	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3759.53	4890.88	7549.11
Price for a Unit of New Product	1318.77	1292.39	1211.62	1272.20	1335.81	1402.60	1472.73	1546.37	1461.32	1449.14
Price for a Unit of Refurbished/Remanufactured Product	1198.88	1174.90	1101.47	1156.54	1214.37	1275.09	1338.84	1405.79	1328.47	1317.40
Total Maintenance Cost (Collection Center)	0.00	0.00	0.00	0.00	27238.10	74360.00	150150.00	157657.50	165540.38	173817.39
Total Refurbish Cost	0.00	0.00	0.00	0.00	20952.38	57200.00	113500.00	121275.00	127338.75	133705.69
TotalTransportation Cost (Collection - Remanufacturing)	0.00	0.00	0.00	0.00	18742.86	51168.00	103320.00	108486.00	113910.30	119605.82
Total Transportation Cost (Collection-Disposal)	0.00	0.00	0.00	0.00	13914.29	37986.00	76702.50	80537.63	84564.51	88792.73
Total Transportation Cost (Collection-Recycle)	0.00	0.00	0.00	0.00	8045.71	21964.80	44352.00	46569.60	48898.08	51342.98
Total Disassembly Cost	0.00	0.00	0.00	0.00	160761.90	438880.00	886200.00	930510.00	977035.50	1025887.28
Total Remanufacturing Costs	0.00	0.00	0.00	0.00	18400.00	50232.00	101430.00	106501.50	111826.58	117417.90
Total Transportation Cost (Remanufacturing - OEM)	0.00	0.00	0.00	0.00	29714.29	81120.00	163800.00	171990.00	180589.50	189618.98
Total Recycle Costs	0.00	0.00	0.00	0.00	4761.90	13000.00	26250.00	27562.50	28940.63	30387.66
Total Transportation Cost (Recycle-Suppliers)	0.00	0.00	0.00	0.00	3542.86	9672.00	19530.00	20506.50	21531.83	22608.42
Transportation Costs (Collection - OEM)	0.00	0.00	0.00	0.00	15123.81	41288.00	83370.00	87538.50	91915.43	96511.20
Annualized Capital Cost (OEM)	2350578.50	2468107.42	2591512.80	2721088.44	2857142.86	3000000.00	3150000.00	3307500.00	3472875.00	3646518.75
Total Fixed Collection Cost	0.00	0.00	0.00	1841269.84	1933333.33	2030000.00	2131500.00	2238075.00	2349978.75	2467477.69
Total Annualized Remanufacturing Center Capital Costs	0.00	0.00	0.00	1832199.55	1923809.52	2020000.00	2121000.00	2227050.00	2338402.50	2455322.63
Total Annualized Recycle Center Capital Costs	0.00	0.00	0.00	1904761.90	2000000.00	2100000.00	2205000.00	2315250.00	2431012.50	2552563.13
Total Transportation Cost (Use-Collection)	0.00	0.00	0.00	0.00	144923.81	395642.00	798892.50	838837.13	880778.98	924817.93
Total Revenue	21979476.02	60003969.54	121161861.57	127219954.65	133580952.38	138606740.82	145510174.25	151652667.57	83323909.89	47219013.41
Total Costs	16247041.88	40405452.46	79195767.20	88733786.85	93636598.10	87956388.40	93937357.50	91718179.07	47331862.58	21851756.05
Total Profit	**$5,732,434.14**	**$19,598,517.08**	**$41,966,094.37**	**$38,486,167.80**	**$39,944,354.29**	**$50,650,352.42**	**$51,572,816.75**	**$59,934,488.49**	**$35,992,047.31**	**$25,367,257.36**

Figure 4.6: 'Economic MLC Analysis and Results' Sheet for PD_1

Due to huge amount of data involved, only the results of the economic MLC analysis are shown in this spreadsheet. However, all the computations explained in the methodology section are performed to obtain the results.

For the rest of the PDSCC combinations, the economic MLC analysis is performed and results are obtained in a similar manner. Table 4.9 summarized the results for all the PDSCC combinations. It presents the cumulative profits for each year in a 10 year time period. As the cumulative profit at the end of the 10^{th} year is considered for evaluating the economic performance of each PDSCC combination, the combinations are ranked based on the cumulative profit at the end of 10^{th} year.

Table 4.9: Summary of Economic MLC Analysis Results (Example Problem)

PDSCC	Annual Cumulative Profit (in Millions of $)										Rank
	1	2	3	4	5	6	7	8	9	10	
$PD_1 - SCC_1$	5.73	25.33	67.29	105.78	145.72	196.37	247.95	307.88	343.87	**369.24**	**3**
$PD_2 - SCC_2$	13.08	40.85	92.11	140.43	190.68	245.64	312.82	390.61	441.81	**469.49**	**1**
$PD_3 - SCC_3$	7.60	29.44	74.17	115.90	158.90	210.04	264.84	323.73	358.77	**382.81**	**2**
$PD_4 - SCC_4$	7.98	29.33	72.17	108.77	146.59	191.45	239.76	293.76	317.51	**324.27**	**4**

The hierarchical approach in the methodology section identifies the best PDSCC combinations that have maximum economic performance at the end of the economic MLC analysis stage, and only those combinations are sent to the subsequent stages. The reason for do so is that, if there are numerous designs at the NPD stage, this approach helps a company in narrowing down the PDSCC combination to select the best combination that has maximum economic, environmental and societal performance. However, as there are only four designs for this problem, all the PDSCC combinations are ranked according to their maximum profit potential and sent to next stage. Hence, for this problem, no PDSCC combination is eliminated, yet.

4.6 Economic MLC Analysis for Open-loop SC Model

The impact of pursing a closed-loop flow for each PDSCC combination is studied in this section. As the closed-loop results are already obtained, the open-loop SC is run using the MLC_{Osc} tool for each PDSCC combination separately, to obtain the profits for each of the 10 years in an open-loop flow.

4.6.1 Analysis Assumptions

All the assumptions considered for the MLC_{Osc} tool are considered in this model. The open-loop MLC analysis is performed for a period of 10 years (T) for each PDSCC combination identified by EOM separately.

4.6.2 Analysis Description

The open-loop MLC analysis on each PDSCC combination is performed separately by the MLC_{Osc} tool as described in methodology section.

Input Data

For each PDSCC combination, the price and demand steady-state period (year 6), and the demand for the year 1 and 10 in this case, the steady-state cost data including supplier component cost, transportation cost from supplier to OEM, the assembly cost, and the OEM annualized capital costs and the interest/discount rate are all acquired by the 'Input Data' sheet. This data is available from the input data sheet of the MLC_{Eco} tool. As an example, the sheet for PD_1 is shown in Figure 4.7.

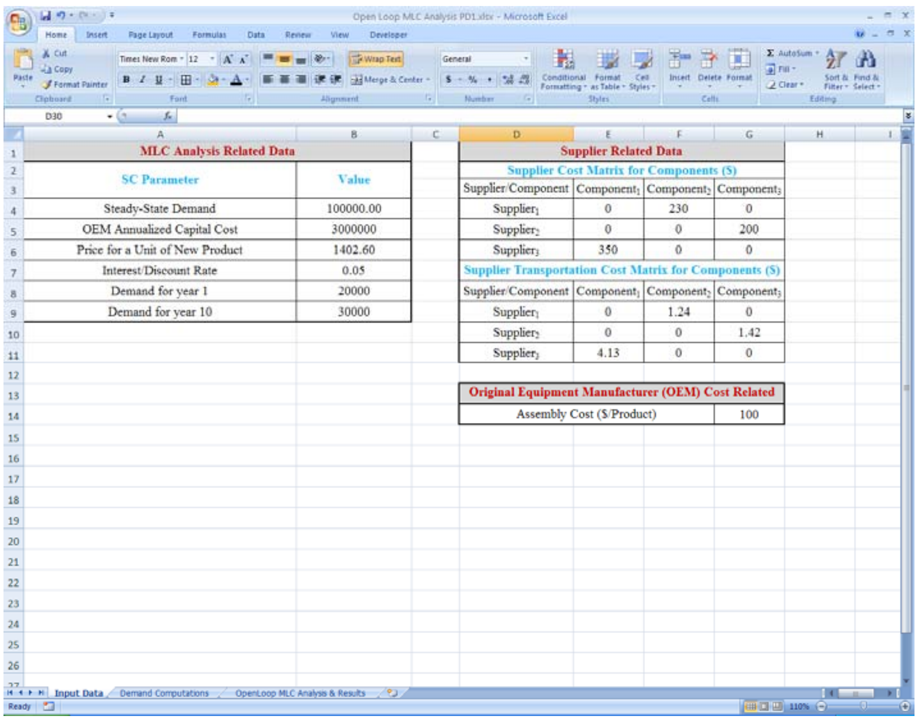
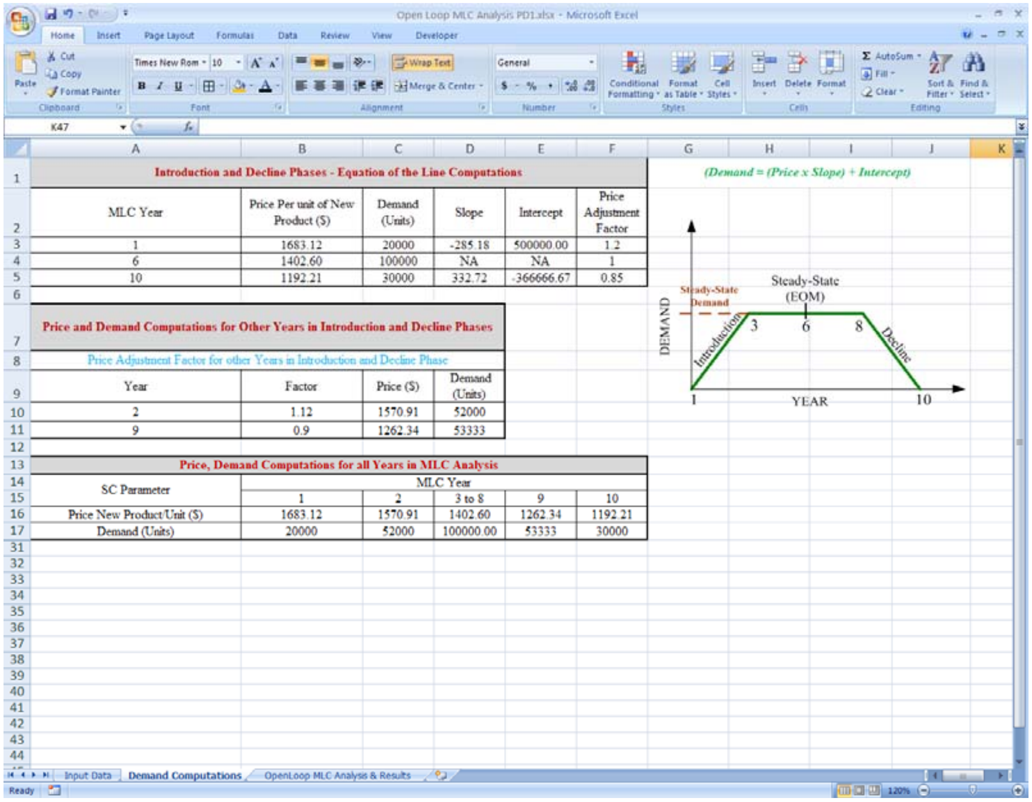


Figure 4.7: MLC_{Osc} 'Input Data' Sheet for PD_1

From the price, cost and the demand related data, the price and the demand for each of the 10 years is computed in sheet 'Demand Computations' sheet. An example of this sheet is shown in Figure 4.8 for design PD_1.



Introduction and Decline Phases - Equation of the Line Computations

MLC Year	Price Per unit of New Product ($)	Demand (Units)	Slope	Intercept	Price Adjustment Factor
1	1683.12	20000	-285.18	500000.00	1.2
6	1402.60	100000	NA	NA	1
10	1192.21	30000	332.72	-366666.67	0.85

Price and Demand Computations for Other Years in Introduction and Decline Phases

Price Adjustment Factor for other Years in Introduction and Decline Phase

Year	Factor	Price ($)	Demand (Units)
2	1.12	1570.91	52000
9	0.9	1262.34	53333

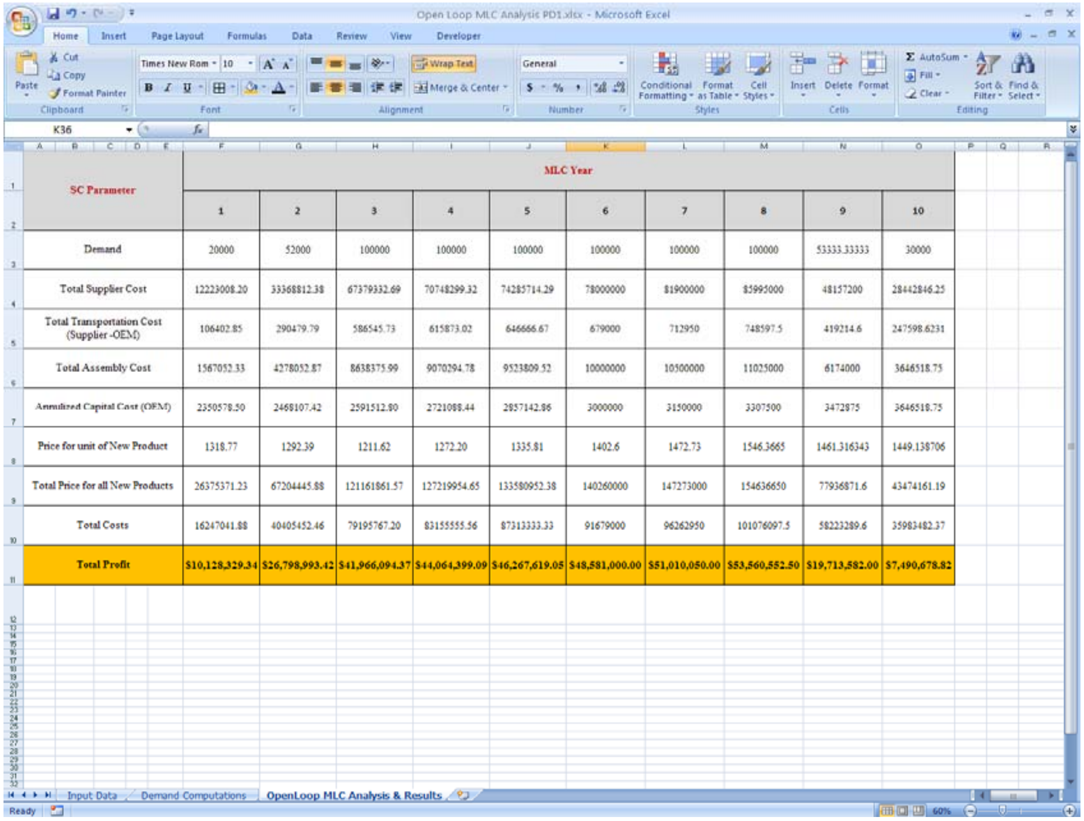
Price, Demand Computations for all Years in MLC Analysis

SC Parameter	MLC Year				
	1	2	3 to 8	9	10
Price New Product/Unit ($)	1683.12	1570.91	1402.60	1262.34	1192.21
Demand (Units)	20000	52000	100000.00	53333	30000

Figure 4.8: MLC$_{Osc}$ 'Demand Computations' Sheet for PD$_1$

4.6.3 Results

For each PDSCC combination, the MLC$_{Osc}$ tool uses the input data and demand computations, to calculate the different annual SC costs, annual SC prices, annual SC revenue and thereby annual profit for the 10 year period. All these computations are performed in the 'Open-loop MLC Analysis and Results' sheet. As an example, the results obtained for PD$_1$ are illustrated in Figure 4.9.



SC Parameter	MLC Year									
	1	2	3	4	5	6	7	8	9	10
Demand	20000	52000	100000	100000	100000	100000	100000	100000	53333.33333	30000
Total Supplier Cost	12223008.20	33368812.38	67379332.69	70748299.32	74285714.29	78000000	81900000	85995000	48157200	28442846.25
Total Transportation Cost (Supplier -OEM)	106402.85	290479.79	586545.73	615873.02	646666.67	679000	712950	748597.5	419214.6	247598.6231
Total Assembly Cost	1567052.33	4278052.87	8638375.99	9070294.78	9523809.52	10000000	10500000	11025000	6174000	3646518.75
Annulized Capital Cost (OEM)	2350578.50	2468107.42	2591512.80	2721088.44	2857142.86	3000000	3150000	3307500	3472875	3646518.75
Price for unit of New Product	1318.77	1292.39	1211.62	1272.20	1335.81	1402.6	1472.73	1546.3665	1461.316343	1449.138706
Total Price for all New Products	26375371.23	67204445.88	121161861.57	127219954.65	133580952.38	140260000	147273000	154636650	77936871.6	43474161.19
Total Costs	16247041.88	40405452.46	79195767.20	83155555.56	87313333.33	91679000	96262950	101076097.5	58223289.6	35983482.37
Total Profit	$10,128,329.34	$26,798,993.42	$41,966,094.37	$44,064,399.09	$46,267,619.05	$48,581,000.00	$51,010,050.00	$53,560,552.50	$19,713,582.00	$7,490,678.82

Figure 4.9: MLC_{Osc} 'Open-loop MLC Analysis and Results' Sheet for PD_1

The Open-loop MLC analysis is performed in a similar way for other PDSCC combinations and the results are obtained. Table 4.8 summarized the annual cumulative profits obtained for each combination in a 10 year time period.

Table 4.10: Cumulative Profits from Open-loop SC Model (Example Problem)

PDSCC	Annual Cumulative Profit (in Millions of $)									
	1	2	3	4	5	6	7	8	9	10
PD_1 – SCC_1	$10.12	$36.92	$78.89	$122.95	$169.22	$217.80	$268.81	$322.37	$342.09	$349.58
PD_2 – SCC_2	$20.95	$57.94	$109.20	$163.02	$219.53	$278.87	$341.18	$406.60	$430.45	$439.01
PD_3 – SCC_3	$12.77	$42.14	$86.87	$133.83	$183.14	$234.92	$289.29	$346.37	$361.66	$361.99
PD_4 – SCC_4	$13.93	$43.54	$86.38	$131.37	$178.61	$228.21	$280.29	$334.97	$349.93	$351.32

4.7 Closed-loop versus Open-loop Models

In this section, the annual cumulative profits obtained from closed-loop and open-loop SC models are compared for each PDSCC combination for a period of 10 years (Figure 4.10).

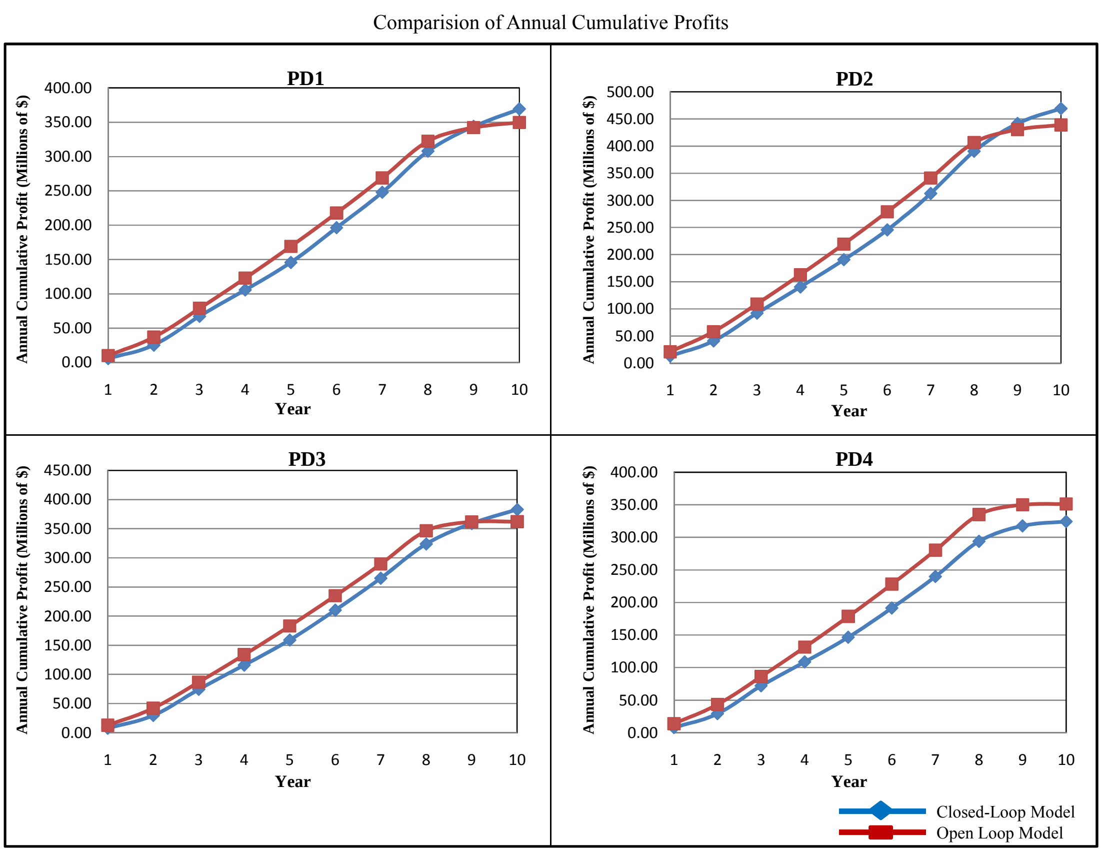


Figure 4.10: Comparision of Annual Cumulative Profits

4.7.1 Results Summary

From Figure 4.10, it can be observed that during the first few years, the open-loop model generates more profits as compared to the closed-loop. This is due to the fact that the closed-loop model incurs additional reverse loop related costs, and during the initial years, until the first year's products are used and returned, year 6 in this case, all the demand is satisfied by only new products. However, from the year the recovered products are available to satisfy the demand, less new products are produced, and therefore, cumulative profit increases for the closed-loop model. The annual demand and the number of refurbished and remanufactured products used to satisfy the demand impact profit to a large extent. However, the open-loop model's profit merely depends on the demand satisfied from new products and the price of the product.

Therefore, in this case, the results indicate that at the end of the 10 year period, for the PD_1-SCC_1, PD_2-SCC_2, PD_3-SCC_3 the closed-loop model generates more cumulative profits as compared to open-loop. However, for PD_4-SCC_4 the closed-loop model is not able to generate better profits, as of year 10, as compared to the open-loop because the demand for the design is 80,000 units which is comparatively low as compared to that of PD_1 (100,000 units) , PD_2(110,000 units), PD_3 (90,000 units), respectively. Also, the total reverse loop capital cost of PD_4-SCC_4 combination is $9.25 million which is very high as compared to that of PD_1-SCC_1, PD_2-SCC_2, PD_3-SCC_3, whose costs are $6.15, $6.07, $5.77 million, respectively. Hence, for the PD_4-SCC_4 combination to realize benefits from closed-loop flow either the demand has to increase or the potential reverse loop facilities must be readdressed, with an aim to reduce the huge annualized capital costs.

Therefore, this type of decision-support tool that can compare the benefits of pursuing the closed-loop flow among PDSCC alternatives and can provide areas for improvements both with respect to product design and with respect to SC configuration, can answer several sustainability-related questions from both product and SC design perspective, such as for which product types pursuing the closed-loop flow provides greater benefits? and, why for some products greater benefits are achieved within fewer years while for others it takes several years to achieve the benefits?, what are the product design and SC configuration related factors that impact these closed-loop economic benefits? Therefore, at the end of this stage, all the ranked PDSCC combinations, are sent to the environmental MLC analysis stage.

4.8 Environmental Multi Life-cycle Analysis Description

A description of the environmental MLC analysis performed on the ranked PDSCC combinations is presented here.

4.8.1 Assumptions

All the assumptions considered in the methodology are considered for the example problem.

4.8.2 Analysis Description

For each ranked PDSCC combination, the environmental MLC analysis is performed using the MLC_{Env} tool as described in the methodology section to identify the combinations having minimal environmental impact. The performance criteria used are Material Usage (Number of new components used to satisfy the demand), Energy Consumed (BTU), CO_2 Emissions (Lb). Just similar to others, each PDSCC combination is analyzed separately.

Input data

The transportation, processing, use related conversion factors computed and explained in methodology section are used for the analysis. For each PDSCC combination, the MLC_{Env} tool's 'Environmental Input Spreadsheet' takes in the annual product's energy usage data in KWh/Year. This data is presented in Table 4.11.

Table 4.11: Energy Usage Data (Example Problem)

Product Design ID	Annual Energy Usage (KWh)
PD_1	400
PD_2	340
PD_3	600
PD_4	550

The other data required for analysis such as the reverse loop quantities (shown in Table 4.12); the weights of the product and the average weight of components (shown in Table 4.1) are all provided in the spreadsheet. A snapshot of the spreadsheet for PD_1 is shown in Figure 4.11.

Table 4.12: Reverse Loop Processing Quantities (Example Problem)

Processing Operation (Unit)	PD1	PD2	PD3	PD4
Collection (Product)	40000	44000	36000	32000
Refurbishing (Product)	10000	32000	22800	8000
Disassembly (Product)	30000	12000	13200	24000
Remanufacturing (Component)	60000	12000	18400	17600
Recycling (Component)	10000	12000	21200	43200

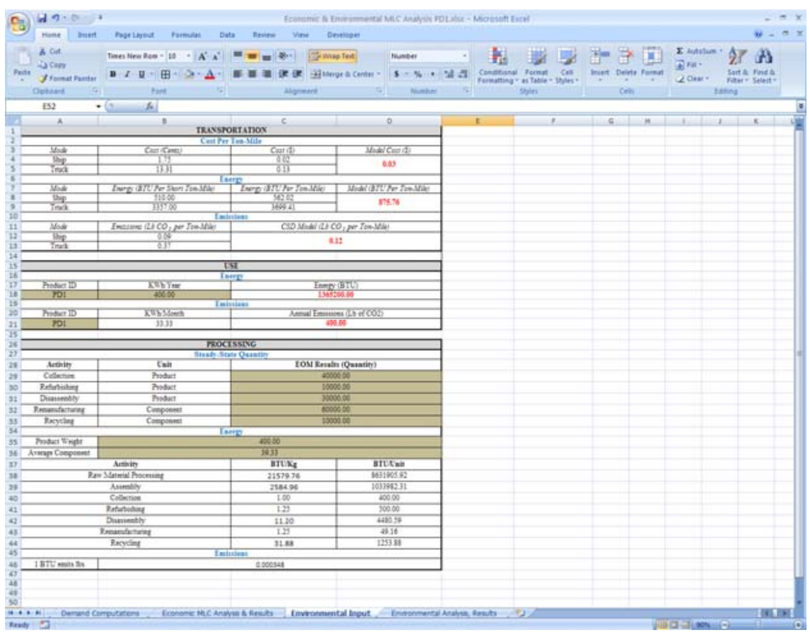
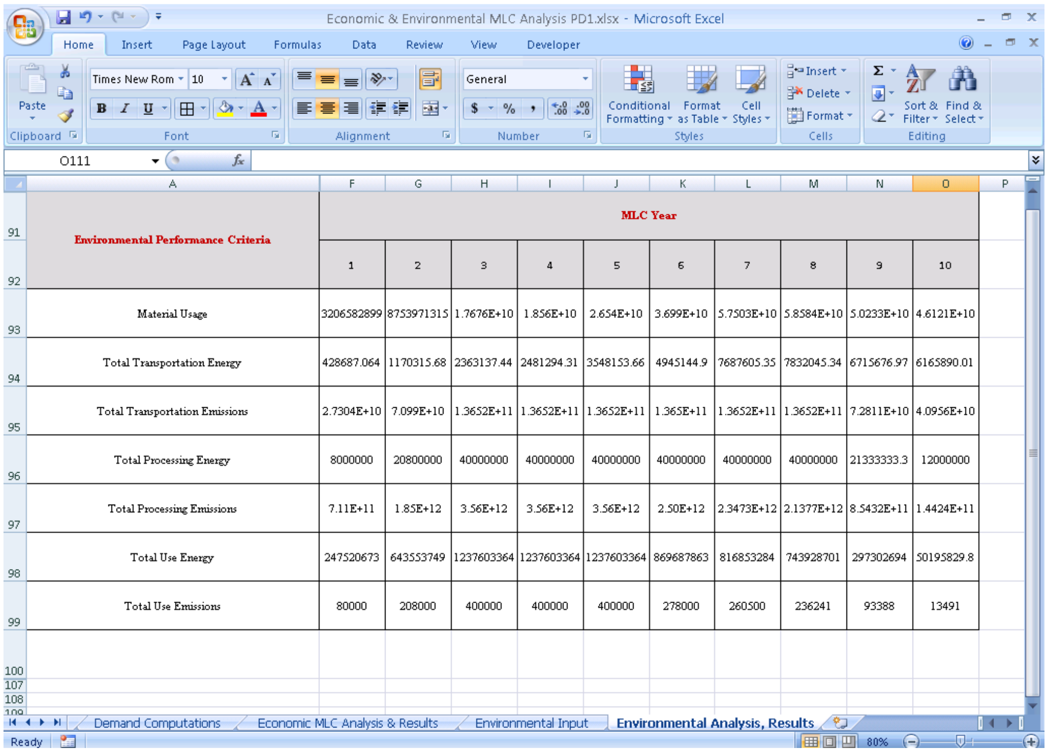


Figure 4.11: MLC_{Env} 'Environmental Input Spreadsheet' for PD_1

<u>4.8.3 Results</u>

For each PDSCC combination, the SC costs and refurbished and remanufactured quantity related data from the economic MLC results is gathered by the 'Environmental Analysis, Results' sheet to perform the MLC analysis by computing the environmental impact for each PDSCC separately. The seven performance criteria (total material usage, total processing energy and CO_2 emissions, total transportation energy and CO_2

emissions and use energy and CO_2 emissions) are all computed to evaluate the environmental performance for each combination. Figure 4.12 shows a snapshot of the 'Environmental MLC analysis and Results' sheet for PD_1.



Environmental Performance Criteria	MLC Year									
	1	2	3	4	5	6	7	8	9	10
Material Usage	3206582899	8753971315	1.7676E+10	1.856E+10	2.654E+10	3.699E+10	5.7503E+10	5.8584E+10	5.0233E+10	4.6121E+10
Total Transportation Energy	428687.064	1170315.68	2363137.44	2481294.31	3548153.66	4945144.9	7687605.35	7832045.34	6715676.97	6165890.01
Total Transportation Emissions	2.7304E+10	7.099E+10	1.3652E+11	1.3652E+11	1.3652E+11	1.365E+11	1.3652E+11	1.3652E+11	7.2811E+10	4.0956E+10
Total Processing Energy	8000000	20800000	40000000	40000000	40000000	40000000	40000000	40000000	21333333.3	12000000
Total Processing Emissions	7.11E+11	1.85E+12	3.56E+12	3.56E+12	3.56E+12	2.50E+12	2.3473E+12	2.1377E+12	8.5432E+11	1.4424E+11
Total Use Energy	247520673	643553749	1237603364	1237603364	1237603364	869687863	816853284	743928701	297302694	50195829.8
Total Use Emissions	80000	208000	400000	400000	400000	278000	260500	236241	93388	13491

Figure 4.12: MLC_{Env} 'Environmental Analysis, Results' sheet for PD_1

The MLC_{Env} tool is used to compute the environmental performance criteria for rest of the PDSCC combinations. At the end of analysis, each of the seven performance criteria across SC are compared for each ranked PDSCC combination to select the best combinations. Table 4.13 presents the summary of results obtained for each ranked PDSCC combination.

Table 4.13: Summary of Environmental MLC Analysis Results (Example Problem)

PDS CC	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
	Cumulative Transportation Energy (10^9 BTU)									
PD_1-SCC_1	3.21	12	29.6	48.2	74.7	112	169	228	278	324
PD_2-SCC_2	10	29.6	64.4	101	147	202	267	332	374	411
PD_3-SCC_3	6.1	21.2	50.5	81.2	133	212	336	466	574	682
PD_4-SCC_4	10.4	34.4	80.3	128	192	271	378	488	568	635
PDS CC	Cumulative Transportation Emissions (10^5 Lb of CO_2)									
PD_1-SCC_1	4.2	15.9	39.6	64.4	99.9	149.3	226.2	304.5	371.7	433.3
PD_2-SCC_2	13.4	39.5	86.0	134.8	197.0	270.4	356.8	443.2	500.5	549.4
PD_3-SCC_3	8.27	28.3	67.5	108.6	178.2	283.3	449.6	623.4	767.4	912.4
PD_4-SCC_4	13.9	46.0	107.3	171.7	256.5	361.9	504.9	652.9	759.4	849.1
PDS CC	Cumulative Use Energy (10^{10} BTU)									
PD_1-SCC_1	2.73	9.83	23.5	37.1	50.8	64.4	78.1	91.7	99	103
PD_2-SCC_2	4.06	1.16	24.4	37.1	49.9	62.7	75.4	88.2	94.7	98.1
PD_3-SCC_3	4.3	1.43	3.27	51.1	69.5	88	106	125	132	134
PD_4-SCC_4	3.75	12	2.7	4.2	57.1	72.1	87.1	102	108	111
PDS CC	Cumulative Use Emissions (10^8 Lb of CO_2)									
PD_1-SCC_1	0.08	0.28	0.68	1.09	1.49	1.89	2.29	2.69	2.9	3.02
PD_2-SCC_2	0.1	0.34	0.71	1.09	1.46	1.84	2.21	2.58	2.77	2.87
PD_3-SCC_3	0.1	0.41	0.95	1.5	2.04	2.58	3.12	3.66	3.87	3.93
PD_4-SCC_4	0.1	0.35	0.79	1.23	1.67	2.11	2.55	2.99	3.18	3.24

PDS CC	Cumulative Processing Energy (10^{13} BTU)									
PD_1-SCC_1	0.07	0.25	0.61	0.96	1.32	1.57	1.81	2.02	2.11	2.12
PD_2-SCC_2	0.14	0.4	0.84	1.28	1.72	2.02	2.3	2.56	2.63	2.65
PD_3-SCC_3	0.06	0.22	0.52	0.82	1.12	1.31	1.51	1.7	1.72	1.72
PD_4-SCC_4	0.07	0.23	0.52	0.82	1.1	1.3	1.5	1.69	1.75	1.76
PDS CC	Cumulative Processing Emissions (10^9 Lb of CO_2)									
PD_1-SCC_1	0.2	0.89	2.13	3.37	4.6	5.47	6.29	7.03	7.33	7.38
PD_2-SCC_2	0.48	1.39	2.92	4.46	5.99	7.04	8.02	8.91	9.16	9.23
PD_3-SCC_3	0.24	0.79	1.83	2.86	3.89	4.57	5.25	5.91	5.99	5.99
PD_4-SCC_4	0.25	0.81	1.83	2.84	3.86	4.52	5.21	5.88	6.09	6.11
PDS CC	Cumulative Material Usage (10^5 Units of Components)									
PD_1-SCC_1	8	2.8	6.8	10.8	14.8	17.6	20.2	22.6	23.5	23.6
PD_2-SCC_2	1.4	4	8.4	12.8	17.2	20.1	22.9	25.4	26.2	26.4
PD_3-SCC_3	0.8	2.7	6.3	9.9	13.5	15.9	18.2	20.5	20.8	20.8
PD_4-SCC_4	0.8	2.5	5.7	8.9	12.1	14.2	16.3	18.4	19.1	19.1

To compare the performance of each PDSCC combination, graphs are plotted for each of the energy, emissions, and material usage related criteria. Figure 4.13 presents the energy consumption results for each combination.

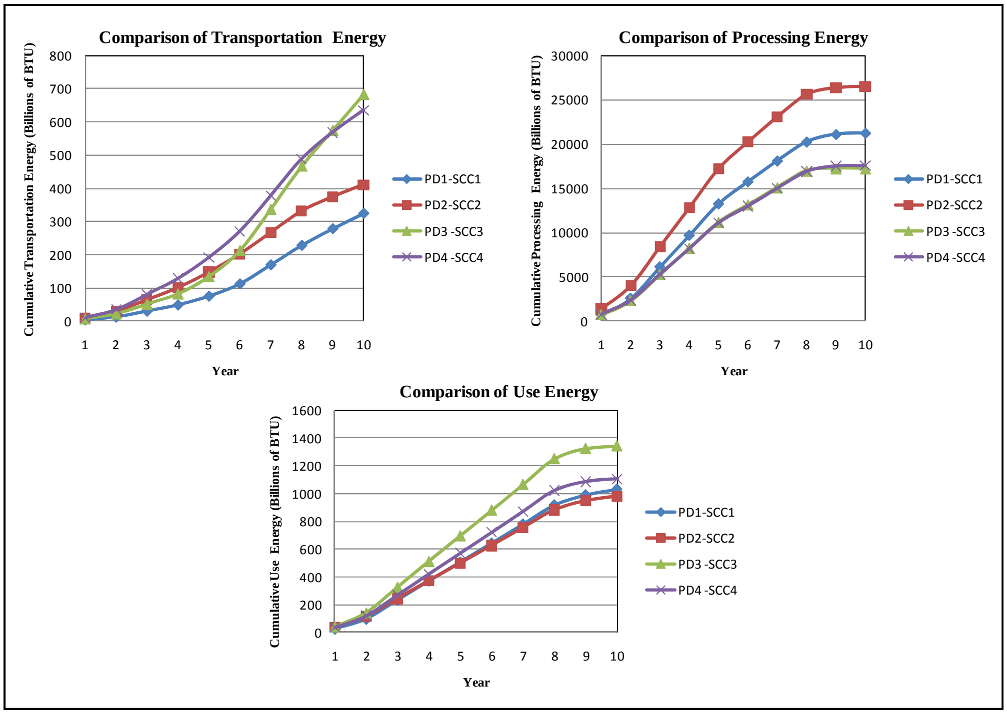


Figure 4.13: Energy Consumption of PDSCC Combinations (Example Problem)

Figure 4.14 presents the emissions released from each PDSCC combination.

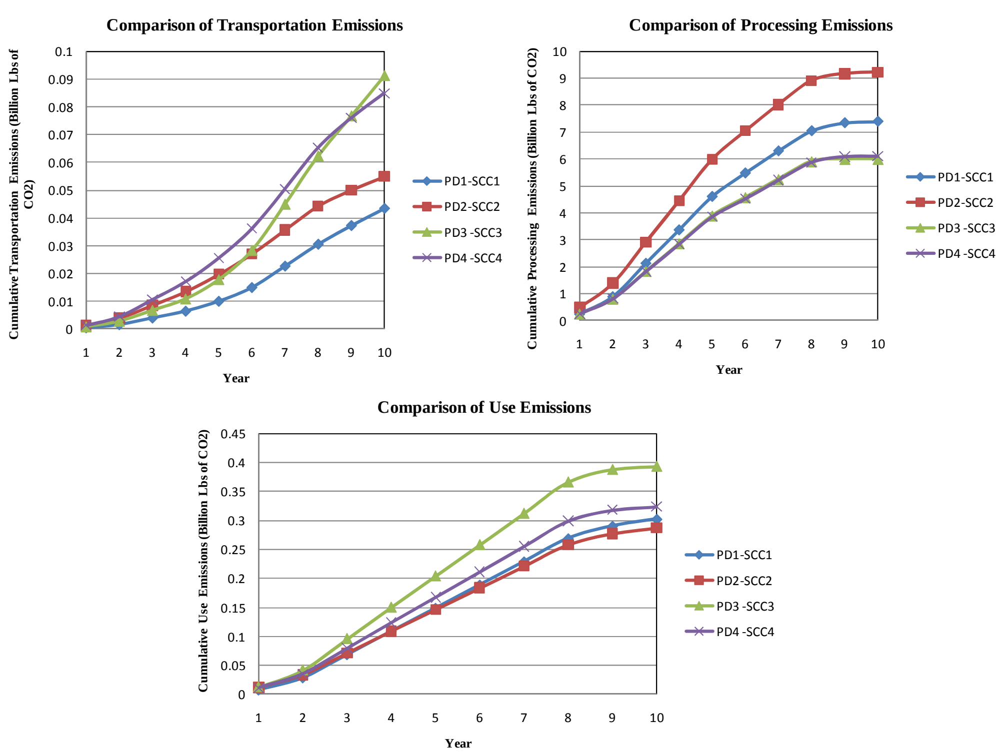


Figure 4.14: Emissions Released from PDSCC Combinations (Example Problem)

Figure 4.15 presents the material usage for each PDSCC combination.

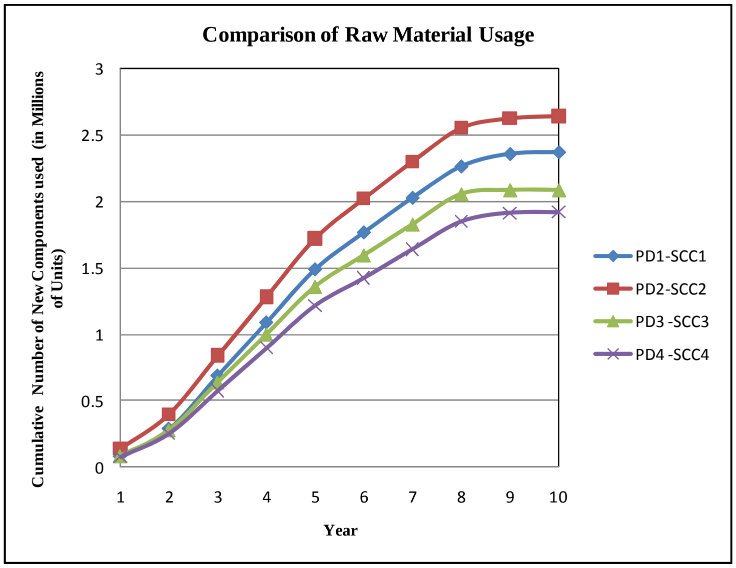


Figure 4.15: Material Usage for PDSCC Combinations (Example Problem)

The total energy, emissions and material usage for each PDSCC is computed at the end of the 10th year to select the best PDSCC combinations with maximum environmental performance (Table 4.14). However, as in case, as no PDSCC combinations are eliminated in economic MLC analysis stage the best combinations with respect to economic performance are also presented for comparison.

Table 4.14: Cumulative MLC Performance (Example Problem)

PDSCC	Economic MLC Performance		Environmental MLC Performance				
	Profit (10^6 \$)	Rank	Energy (10^9 BTU)	Emissions (10^9 of Lb CO_2)	Material Usage (10^6 Components)	Ranking Based on 'Energy and Emissions'	Ranking Based on 'Material Usage'
PD_1-SCC_1	369.24	3	22567	7.72	2.36	3	3
PD_2-SCC_2	469.49	1	27909	9.57	2.64	4	4
PD_3-SCC_3	382.81	2	19249	6.47	2.08	1	2
PD_4-SCC_4	324.27	4	19292	6.51	1.91	2	1

4.8.4 Summary

Energy: The energy consumption for transportation depends on the transportation quantity, the distance and the cost of transportation.

$$Transportation\ Energy\ = f(transportation\ quantity, distance,\ transportation\ cost)$$

The higher the transportation distances, cost and quantity the greater is the transportation energy consumed. Therefore in this case, the PD_1-SCC_1 combination consumes least transportation energy, followed by PD2 –SSC_2, PD_4 –SCC_4, PD_3-SCC_3 combinations.

The processing energy depends on processing quantity, their weights and the energy consumed during each operation such as (raw material processing, assembly, collection, disassembly, remanufacturing and recycling).

$$Processing\ Energy\ = f\ (processing\ quantity\ and\ weights, energy\ per\ operation)$$

Therefore, as more products or components are processed for each operation, the more energy is consumed. Also, the higher the energy consumed per operation, the higher is the total processing energy. As the weight of quantities increases, more energy is consumed for processing activity. In this case, the PD_3-SCC_3 combination consumes less energy which is followed by PD_4-SCC_4, PD_1-SSC_1, PD_2-SCC_2.

The energy consumed during use stage depends on the annual energy usage and the annual demand. For this problem, the combination PD_2-SCC_2 consumes less energy, followed by PD_1-SSC_1, PD_4-SCC_4, PD_3-SCC_3.

$$Use\ Energy\ = f\ (Annual\ Demand, Annual\ Energy\ Usage)$$

The tool besides from computing the environmental performance of the alternate PDSCC combinations can also help a company improve its performance through identifying the critical factors that impact the total SC energy.

Emissions: The emissions released for each PDSCC combination follows similar patterns as that of energy. This is because of the fact that the transportation emissions depend on the transportation quantities and cost and distances. Similarly, the processing emissions depend on processing energy. And the use emissions depend on annual energy usage and annual demand. Therefore, the PDSCC combination that has less transportation energy releases less transportation emissions, and the one with less processing energies releases fewer emissions. Also, in the use stage, the PDSCC combination that consumes less energy releases fewer emissions.

$$SC\ Emissions\ =\ f\ (Correpsonding\ SC\ Energy)$$

Material Usage: The PDSCC combination that enables more products to be reused, and components to be refurbished and remanufactured consumes less material. As more refurbished and remanufactured products and components are used to satisfy the demand less new components are used. Eventually, after a period of time all the demand could also be satisfied by refurbished and remanufactured products and components, if a company prefers to do so. Also, lower the annual demand lower is the material consumption. Therefore, in this case, the combination PD_4-SCC_4 consumes less material, followed by PD_3-SSC_3, PD_1-SCC_1, PD_2-SCC_2.

$$Material\ Usage\ =\ f\ (Steady - State\ Refurbishing, Remanufacturing\ and\ Recycling\ Results, Demand\ Ratio,\ Percentage\ of\ Past\ Refurbished\ and\ Remanufactured\ \ quantity\ used\ )$$

The objective of the environmental MLC analysis is to identify and select the best PDSCC combinations that have maximum environmental performance. As opposed to economic performance criteria the environmental performance is measured with respect to energy, emissions and material usage criteria. Hence, each combination can perform differently with respect to each of these three criteria and the best combination identified for all the three criteria can vary. As in this case, it can be observed that the while some combinations perform best with respect to energy and emissions criteria, others perform well with respect to material usage. Therefore, the four PDSCC combinations are ranked based on the environmental performance and sent to next stage. If several combinations are present at this stage, and a selection has to be made, one way a company can narrow down their PDSCC alternatives is to identify the common PDSCC combinations that perform best will respect to all three criteria. In this example, the PD_3-SCC_3 and PD_4-SCC_4 have best environmental performance from both energy and emissions and material usage perspective. However, it has to be remembered that no selection is performed at the economic MLC stage, however, if selection is performed, then the PD_4-SCC_4 may or may not be selected, as it has least economic performance. If there are no common combinations that perform best with respect to all three criteria, then the company can select the combinations that perform best based on their most important criteria. Given the situation, this can be a reasonable approach for companies to follow if there are focused on a single environmental criteria in particular. Therefore, at the end of the environmental MLC analysis, the PDSCC are ranked based on their environmental performance and are sent to next stage.

4.9 Societal Multi Life-cycle Analysis Description

In this section, the societal MLC analysis performed on the PDSCC combinations ranked based on their economic and environmental performance is presented.

4.9.1 Assumptions

All the assumptions presented in the methodology section for the societal MLC analysis are considered here.

4.9.2 Analysis Description

All the alternate PDSCC combinations are evaluated based on their societal performance. The MLC_{Soc} tool developed and described in the methodology section is used to perform the analysis for each combination separately. The performance criteria used are supplier societal-compliance ratio, supplier training and development, employee training and development, product customizability rate.

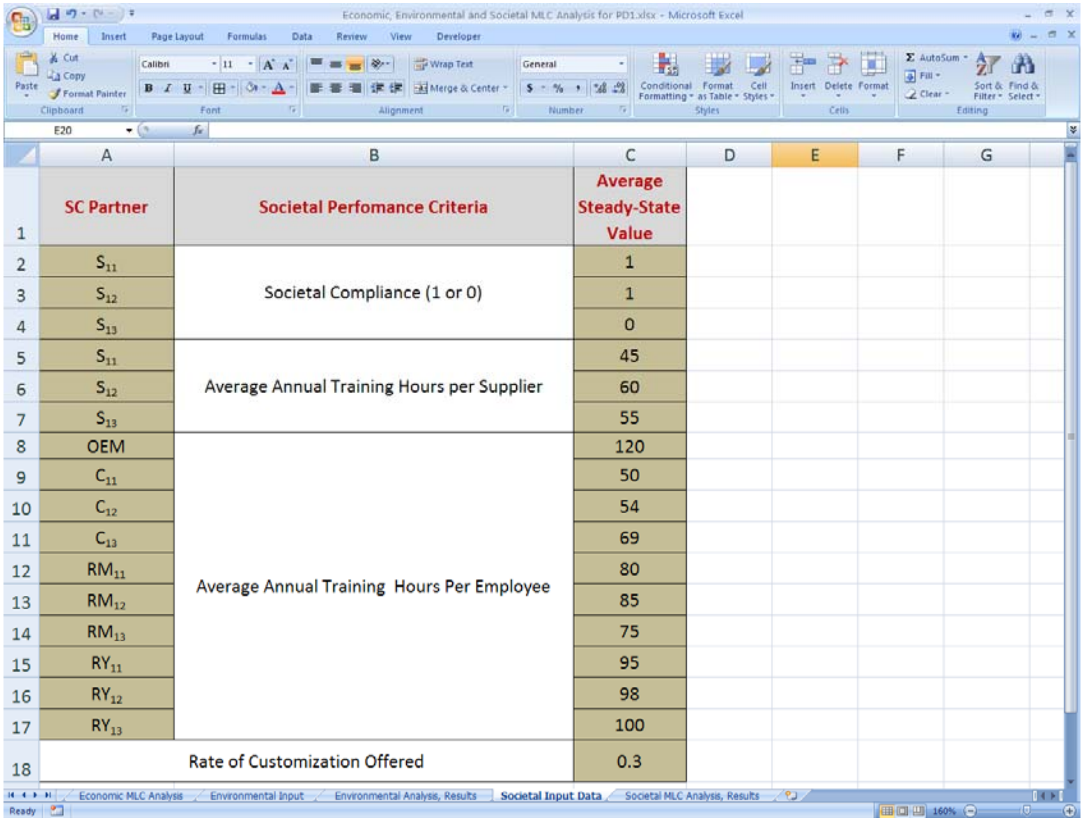
Input Data

The 'Societal Input data' spreadsheet takes all the steady-state input values such as supplier societal compliance, average supplier training hours, average employee training hours, product customizability rate and computes the corresponding societal metrics for period of 10 years. The input data for this problem is established based on the subjective estimated values. Table 4.15 presents the input data for each of the PDSCC combinations.

Table 4.15: Societal Input Data (Example Problem)

Optimal SC Partner*		Criteria	Parameter	Product design ID (PD_i)			
				PD_1	**PD_2**	**PD_3**	**PD_4**
Supplier	S_{i1}	Supplier Societal-compliance Ratio	Societal Compliance (1 or 0)	1	1	1	0
	S_{i2}			1	1	1	0
	S_{i3}			0	1	0	1
	S_{i1}	Supplier Training and Development	Average Annual Training Hours per Supplier	45	65	45	70
	S_{i2}			60	84	41	75
	S_{i3}			55	62	39	84
OEM	OEM	Employee Training and Development	Average Annual Training Hours Per Employee	120	140	80	100
Collection Center	C_{i1}			50	40	50	55
	C_{i2}			54	45	60	45
	C_{i3}			69	39	45	28
Remanufacturing Center	RM_{i1}			80	82	90	120
	RM_{i2}			85	87	98	130
	RM_{i3}			75	89	96	125
Recycling Center	Ry_{i1}			95	104	110	100
	Ry_{i2}			98	120	115	105
	Ry_{i3}			100	95	85	106
Product Customizability Rate			Rate of Customization Offered	0.3	0.4	0.8	0.6
* i = 1,2,3,4 (refers to product design ID)							

Figure 4.16 shows a snapshot of the ‘Societal Input data’ sheet of the MLC_{Soc} tool. The data is entered into the highlighted cells.

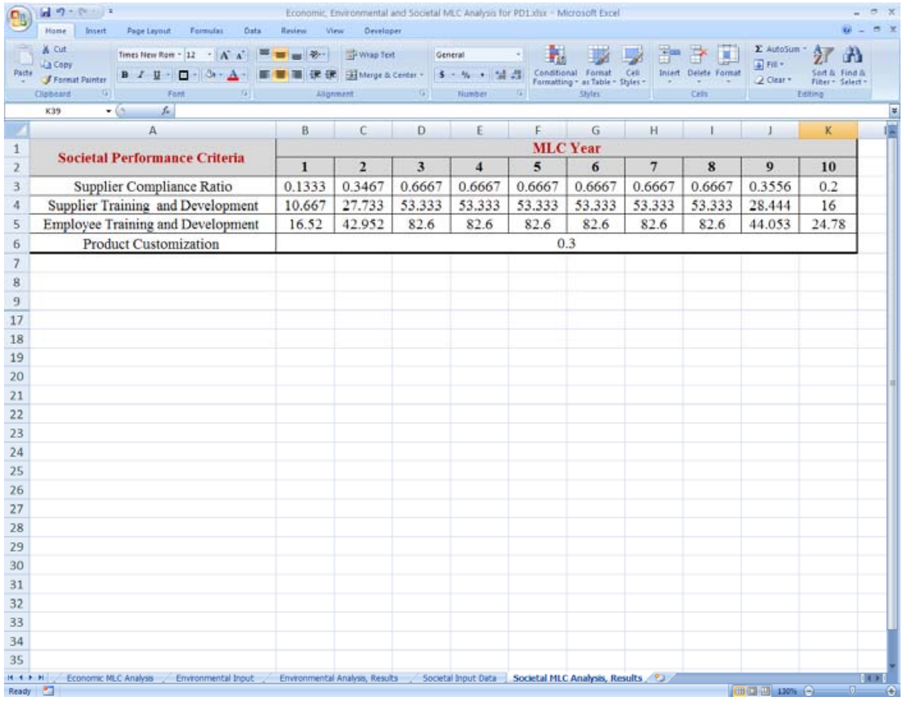


SC Partner	Societal Perfomance Criteria	Average Steady-State Value
S_{11}	Societal Compliance (1 or 0)	1
S_{12}		1
S_{13}		0
S_{11}	Average Annual Training Hours per Supplier	45
S_{12}		60
S_{13}		55
OEM	Average Annual Training Hours Per Employee	120
C_{11}		50
C_{12}		54
C_{13}		69
RM_{11}		80
RM_{12}		85
RM_{13}		75
RY_{11}		95
RY_{12}		98
RY_{13}		100
Rate of Customization Offered		0.3

Figure 4.16: MLC_{Soc} ‘Societal Input Data’ Sheet for PD_1

4.9.3 Results

For each PDSCC combination, the ‘Societal MLC Analysis & Results’ sheet performs the societal MLC analysis as described in methodology section. The four performance criteria (supplier societal-compliance ratio, supplier training and development, employee training and development, product customizability rate) are computed to evaluate the societal performance for each PDSCC combination. Figure 4.17 illustrates the societal MLC analysis criteria and the results for PD_1.



Societal Performance Criteria	MLC Year									
	1	2	3	4	5	6	7	8	9	10
Supplier Compliance Ratio	0.1333	0.3467	0.6667	0.6667	0.6667	0.6667	0.6667	0.6667	0.3556	0.2
Supplier Training and Development	10.667	27.733	53.333	53.333	53.333	53.333	53.333	53.333	28.444	16
Employee Training and Development	16.52	42.952	82.6	82.6	82.6	82.6	82.6	82.6	44.053	24.78
Product Customization	0.3									

Figure 4.17: MLC_{Soc} 'Societal MLC Analysis, Results' sheet for PD_1

The MLC_{Soc} tool is used to compute the societal performance criteria for rest of the PDSCC combinations. At the end of analysis, each of the four performance criteria across SC is compared for each PDSCC combination to select the best combinations. Table 4.16 presents the summary of results obtained for all the PDSCC combinations.

Table 4.16: Societal MLC Analysis Results (Example Problem)

PDSCC	Cumulative Supplier Compliance Rate									
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
PD_1-SCC_1	0.13	0.48	1.15	1.81	2.48	3.15	3.81	4.48	4.84	5.04
PD_2-SCC_2	0.32	0.91	1.91	2.91	3.91	4.91	5.91	6.91	7.42	7.68
PD_3-SCC_3	0.16	0.52	1.18	1.85	2.52	3.18	3.85	4.52	4.78	4.85
PD_4-SCC_4	0.08	0.27	0.60	0.93	1.27	1.60	1.93	2.27	2.41	2.45
PDSCC	**Cumulative Supplier Training and Development**									
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
PD_1-SCC_1	10.67	38.40	91.73	145.07	198.40	251.73	305.07	358.40	386.84	402.84
PD_2-SCC_2	22.38	63.94	134.27	204.61	274.94	345.27	415.61	485.94	521.75	540.29
PD_3-SCC_3	9.72	32.22	73.89	115.56	157.22	198.89	240.56	282.22	298.89	303.06
PD_4-SCC_4	19.08	61.07	137.40	213.73	290.07	366.40	442.73	519.07	551.51	562.00
PDSCC	**Cumulative Employee Training and Development**									
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
PD_1-SCC_1	16.52	59.47	142.07	224.67	307.27	389.87	472.47	555.07	599.13	623.91
PD_2-SCC_2	26.76	76.45	160.55	244.65	328.75	412.85	496.95	581.05	623.87	646.04
PD_3-SCC_3	19.34	64.11	147.01	229.91	312.81	395.71	478.61	561.51	594.67	602.96
PD_4-SCC_4	22.85	73.12	164.52	255.92	347.32	438.72	530.12	621.52	660.37	672.93
PDSCC	**Customization**									
PD_1-SCC_1	0.30									
PD_2-SCC_2	0.40									
PD_3-SCC_3	0.80									
PD_4-SCC_4	0.60									

To compare the performance of each PDSCC combination, graphs are plotted for the supplier compliance, supplier training and development, and employee training and development criteria. Since the product customizability remains same for all years a bar graph is plotted. Figure 4.18 presents comparison of societal performance across PDSCC combinations.

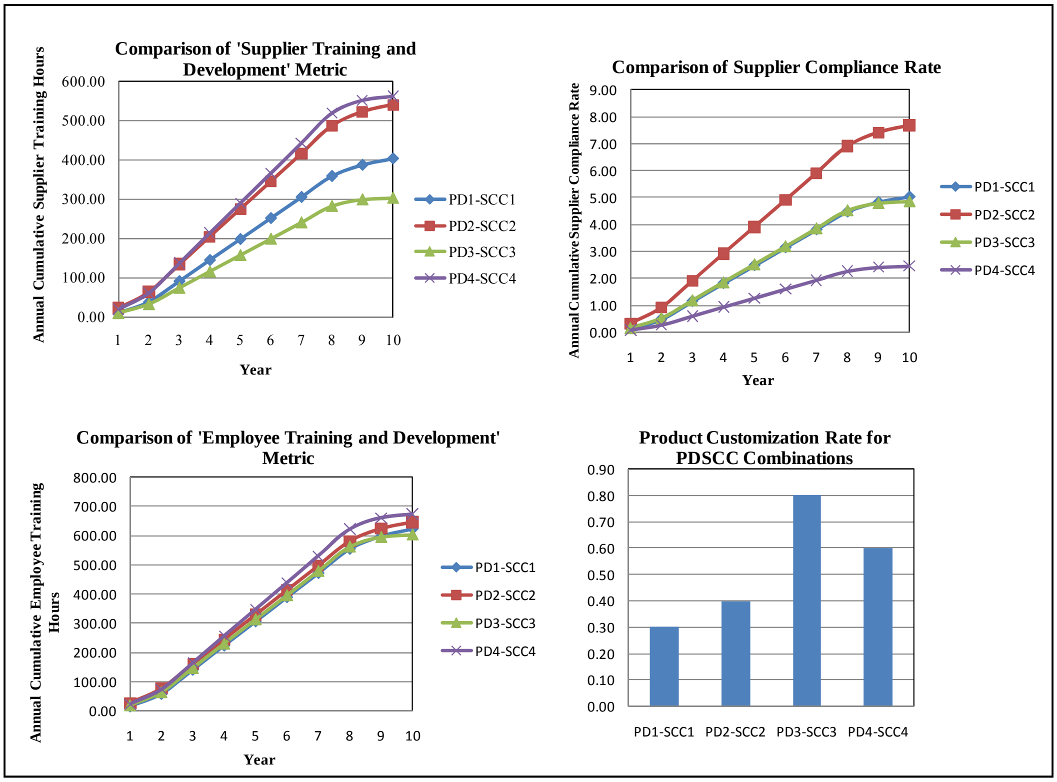


Figure 4.18: Societal Performance Criteria (Example Problem)

The total cumulative value of each performance is computed at the end of the 10th year to select the best PDSCC combinations with maximum societal performance. However, as no PDSCC combinations are eliminated in economic and environmental MLC analysis stages, the best combinations with respect to these criteria are also presented for comparison in Table 4.17.

Table 4.17: PDSCC Combinations Ranked based on their TBL Performance

PD-SCC Combination	Cumulative Economic MLC Performance		Cumulative Environmental MLC Performance					Cumulative Societal MLC Performance						
	Maximum Profit (Millions of $)	Rank	Energy (Billions of BTU)	Emissions (Billions of Lb of CO_2)	Material Usage (Millions of Components)	Rank Based on 'Energy and Emissions'	Rank Based on 'Material Usage'	Supplier Compliance Rate	Supplier Training and Development (Hours)	Employee Training and Development (Hours)	Customization Rate	Rank Based on Supplier Compliance	Rank Based on Training Hours	Rank Based on Customization
PD_1-SCC_1	369.24	3	22567	7.72	2.36	3	3	5.04	402.84	623.91	0.30	2	3	4
PD_2-SCC_2	469.49	1	27909	9.57	2.64	4	4	7.68	540.29	646.04	0.40	1	2	3
PD_3-SCC_3	382.81	2	19249	6.47	2.08	1	2	4.85	303.06	602.96	0.80	3	4	1
PD_4-SCC_4	324.27	4	19292	6.51	1.91	2	1	2.45	562.00	672.93	0.60	4	1	2

4.9.4 Summary

From the above results, it can be observed that the supplier societal compliance rate, supplier training and development, employee training and development all depend on their steady-state values and the annual demand. As there is no quantitative data available, the values are estimated to depend on the annual demand. As the product customization rate remains constant throughout the 10 years, it is independent of annual demand, and depends only on the steady-state value.

Each of the PDSCC combinations may perform differently with respect to the four societal criteria. In this case, while the PDSCC combinations performance remains same with respect to supplier and employee training and development criteria (similar raking for both criteria), for rest of the two criteria their societal performance differs. Therefore the PD_2-SCC_2 performs best with respect to societal-compliance ratio, while the PD_4-SCC_4 and PD_3-SCC_3 performs best with respect to supplier and employee training and development and product customization rate.

4.10 Selection of Best PDSCC Combination

The objective of the societal MLC analysis is to identify and select the best PDSCC combination that has maximum societal performance. As the number of design alternatives is comparatively less, in this problem, all the combinations are ranked based on their economic and environmental performance and sent to next stage, as opposed to selecting only few best ones. Ideally, if selection is performed at the economic and environmental MLC stages, the Table 4.17 would be much simpler with fewer rankings and the decision making would have been very easy.

Therefore, following the hierarchical approach, the top three best combinations, PD_2-SCC_2, PD_3-SCC_3, PD_1-SCC_1, are chosen at the end of economic MLC analysis, in order of their sequence. In the next stage, two combinations from the above three that perform best with respect to the environmental performance are selected. As the PD_2-SCC_2 has least environmental performance, it is eliminated at this stage, while the remaining combinations are sent to societal MLC analysis stage. As both PD_3-SCC_3, PD_1-SCC_1 perform differently with respect to the societal performance criteria, the one with minimum societal impact, PD_3-SCC_3 (the total ranking is 8, which is better than the total ranking for PD_1-SCC_1(9)) is selected as the final combination that maximizes sustainability benefits. The reason for choosing total ranking as the basis is for ease of computation, the less the rank the better is the PDSCC combination's performance.

5. CHAPTER FIVE: CASE STUDY

The CSD model is applied for the case of refrigerators. In this section, a detailed description of the refrigerator case is presented.

5.1 Company Description

A case example from a company located in the USA and is one of the leading domestic (we focus on domestic or household refrigerators, as opposed to industrial, here) refrigerator manufacturers was selected to evaluate the application of the CSD model. While some refrigerator parts are made in-house most are acquired from suppliers located within the US and other parts of the world. Refrigerators are assembled at the OEM plant located in USA. Once the refrigerators are manufactured, they are distributed through retailers primarily to customers within North America and USA and also to different parts of the world.

Currently, the company conducts forward loop SC activities and no reverse loop operations are performed. Therefore, to evaluate the benefits of pursuing closed-loop flow and MLC analysis a closed-loop SC model is considered. While the forward loop information is obtained from company sources, reverse loop data is estimated from reverse loop SC literature on refrigerators. The CSD model is applied for a single product type (side-by-side refrigerators) to study and identify the benefits/impact of considering a closed-loop flow within SC operations over MLCs.

5.2 Refrigerators: Components and Functionality

All refrigerators work in a similar fashion. The major components of a domestic refrigerator are the compressor, condenser, capillary tube, evaporator, and a thermostat. The refrigeration process is based on the following two principles: (a) whenever a gas expands its temperature reduces, and (b) when two surfaces of different temperatures come in contact with each other, the surface at a higher temperature cools and the surface at a lower temperature warms up, based on the second law of thermodynamics.

Refrigeration Process

The refrigeration cycle starts with the compressor, the workhorse of a refrigerator. The refrigerant gas is passed through compressor, where it gets mechanically compressed and the gas pressure increases. This in turn increases the temperature of the gas. The high-pressure gas flows through a set of condenser coils which consists of bent tubes. As the gas flows through the tubes it releases heat to the surroundings lowering its temperature and becoming a liquid. The capillary tube connects the condenser coils to the evaporator coils. As the refrigerant passes through the exit of the capillary tube, the liquid refrigerant becomes a cold, low-pressure gas which flows through the evaporator coils where the gas absorbs heat and therefore cools the items in the refrigerator. The hot refrigerant enters the compressor where the cycle is repeated. A thermostat controls the temperature of the refrigeration process. Figure 5.1 illustrates the refrigerator cycle.

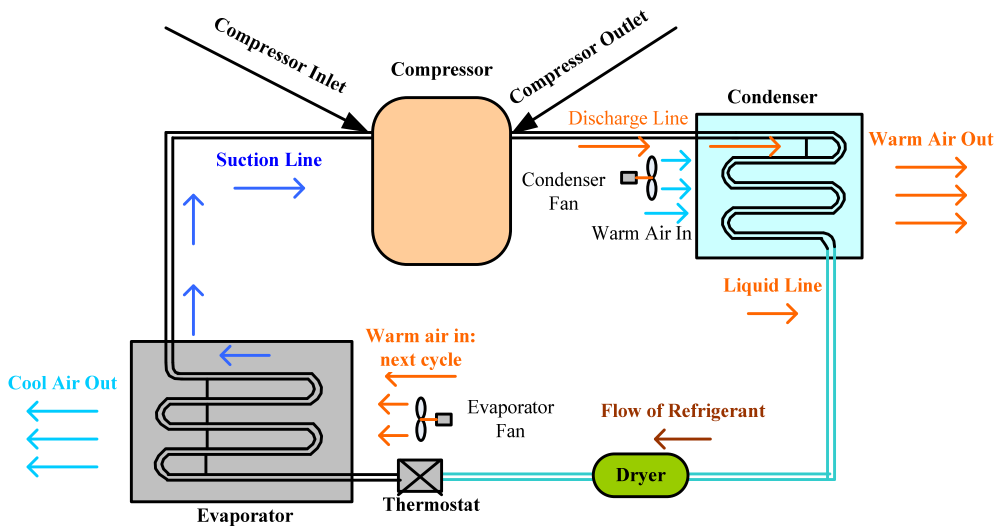


Figure 5.1: Refrigerator Cycle (Air-Conditioning-and-Refrigeration-Guide)

5.2.1 Energy Driving Components of a Refrigerator

Domestic refrigerators consume about 24% of the electricity consumed by all household electrical appliances (James, 2003). It has been identified that the performance of domestic refrigerators can be improved through encouraging manufacturers to: (a) develop new energy efficient designs for refrigerator parts/components, (b) develop innovative technologies that are environmentally safe and, (c) provide more opportunities to the customers to adapt to sustainable use and disposal practices (recycle old refrigerators, take up more efficient models). During past decade, several developments were made in the areas of designing energy efficient refrigerators, environmentally safe fluids, etc. (Radermacher and Kim, 1996). A majority of these improvements have been driven by the federal standards that have mandated domestic refrigerator manufacturers to embrace environmentally safe practices within their operations.

Several studies in the past have repeatedly proven that producing refurbished and remanufactured refrigerators consumes much less energy compared to a new refrigerator (Boustani, 2010). Recently, Sundin (2007) investigated product design properties in general for successful remanufacturing. His work considered six different case studies, with a few focusing on domestic refrigerators. Based on the theoretical and case study results the paper concluded that producing a new refrigerator consumes 50% more energy than refurbishing one.

The excessive energy consumed by a domestic refrigerator is due to the inefficient operation of the compressor(s), the heat gain from polyurethane insulation, improper door sealing and due to inefficient operation of the evaporator(s) (data from company sources). The compressor is the single major energy consuming component of a refrigerator. Following the compressor, the insulation material, the door gasket and the evaporator are the major components that consume energy. A brief description of how the four major components impact the energy efficiency of a refrigerator is presented below:

Compressor

An inefficient compressor could consume more energy to deliver the same performance as that of a normal one. Also, the compressor design plays a major role in the noise levels generated from the refrigerator (USEPA, 1993). Two types of compressor, reciprocating and rotary, are used in domestic refrigerators. Both of these are welded hermetic, that is the compressor pump and motor are sealed inside a welded shell. Some factors that influence compressor performance include speed of rotation, size, pressure at suction and discharge and type of refrigerant being used. During the past years, several new and improved compressor designs such as a liner compressor, variable capacity compressors have been developed (Monyane et al., 2004). These compressor designs have a potential in reducing the energy consumption up to 30%, depending on other components used and noise reduction to a great extent. Figure 5.2(a) shows a typical hermetic compressor used in a domestic refrigerator.

Insulation

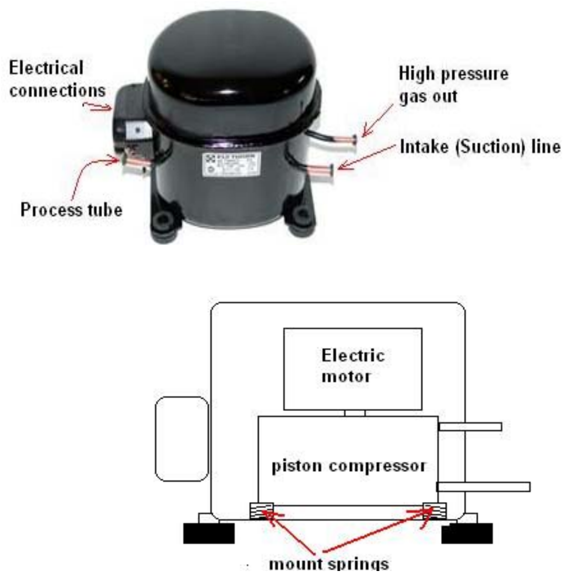
One of the common ways to reduce energy consumption in domestic refrigerators is to improve the insulation. This can be performed through providing thicker insulation material or through providing insulation with lower coefficient of thermal transmission. The drawback of using thick insulation is that the storage space is reduced inside the cabinet. Conventionally, polyurethane (PUR) foams were widely used as insulation material due to their excellent binding properties. Until recently, CFC-11 has been used as a blowing agent to produce PUR foam. However, since the Montreal Protocol (1987) the domestic refrigerator manufacturing industry is expected to completely transit from CFC-11 to alternative blowing agents. This accelerated research in the field and thereby alternative materials have been studied. Among the alternatives, the non-ozone depleting ones include several HFCs, as well as pentane and cyclopentane. Recently, Vacuum Insulation Panels (VIP) technology has been developed and it has been observed that with these panels, depending on the cabinet design; almost 20-30% of energy savings could be achieved. In addition, these panels are environmentally friendly (Wacker et al., 1996). Figure 5.2(b) shows types of different insulation used in domestic refrigerators.

Evaporator

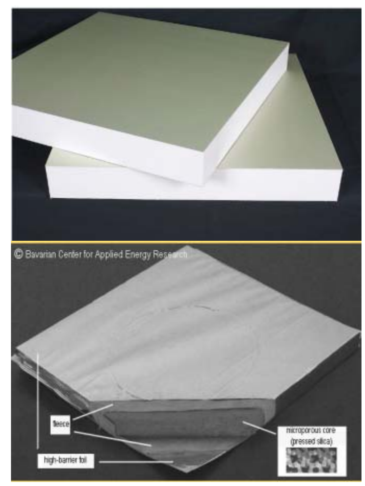
Three different types including bare tube, finned and plate surface evaporator are most commonly used in refrigerators. The latter is most commonly used in domestic refrigerators (Figure 5.2(c)). The evaporator must be designed in such a way that it can be operated at a minimum temperature difference. This enables the refrigerant heat extraction temperature to be as high as possible thereby requiring less energy to cool the items. Some of the aspects that effect the energy efficiency of an evaporator include refrigerant distribution, circuiting and velocity, use of enhanced surfaces, air speeds (for air coolers) etc. (International Institute of Refrigeration, 1993). Recently, the dual evaporators were developed, which proved to perform efficiently. It has been observed that when the dual evaporators are coupled with efficient compressors they produced even better energy savings (Gerlach and Newell, 2001).

Door Gasket

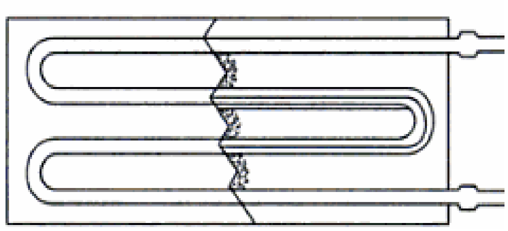
The sealing function of the door gasket is another critical aspect that determines a refrigerator's energy efficiency. If the door gaskets are damaged, warm air enters the refrigerator and more energy is consumed to maintain the desired temperature inside the cabinet. Further, the door gasket's sealing properties also determine the life-span of the compressor to a large extent. Five major types of door gaskets, are used for domestic refrigerators including magnetic, compression, snap-on, push-in, and screw-on. Typical door gaskets available in market are shown in Figure 5.2(d).



(a) Hermetic Refrigerator (USEPA, 1993)



(b) PUR Foams and Vacuum Insulation Panels (Top and Bottom) (Home Improvement Place; Bavarian Center for Applied Energy Research)



(c) Plate Surface Evaporator (Ananthanarayanan, 2003)

(d) Refrigerator Door Gaskets (Al Rawan Industrial Co. Ltd)

Figure 5.2: Major Components of a Domestic Refrigerator

Although there are many other components in a refrigerator, to reduce the complexity, the CSD model considers only the above four critical components. The design of these critical components influences the refrigerator's energy efficiency and the economic, environmental and societal impact. In reality, all of the components could be considered as needed.

5.3 Case Study Model Formulation

This section describes the model formulation for the case example. The forward-loop logistic data is obtained from the company. Most of the data for fixed and processing costs is obtained from literature (Srivastava, 2008). The reuse, remanufacture and recycling ratings, estimated demand, and the reverse loop logistic data were generated based on realistic estimates due to unavailability of accurate data.

5.3.1 Product Design Description

Four alternate side-by-side refrigerator designs identified at the NPD stage are chosen. While most components for these refrigerators vary with respect to type of design, type of material etc, for simplicity, only four major components that influence the TBL aspects are considered. These include the insulation material, compressor, evaporator and door gasket.

Alternate Refrigerator Design Description

The alternate refrigerator designs selected for this case study are derived by drawing inferences from actual refrigerator models produced by the company. A few of the alternate designs already exist in market while others are hypothetical designs studied at the NPD stage to be launched in future. Due to lack of available data the actual designs produced by the company are not considered. Four critical components of refrigerator models are considered in this model. A description of each of the alternate refrigerator designs and their specific characteristics are presented below:

Design 1 (Model Number: RD_1): This is a conventional side-by-side refrigerator model (and the number) that was produced in the early 1990s. The model's TBL performance is assessed based on the 1990 design specification for the four major components identified above. Thus, based on past literature, this design is considered to include a non-magnetic (compression) door gasket, a conventional single speed compressor, a standard evaporator and a *Polyurethane (*PUR) foam insulation material with *Carboflouro*-Compounds (CFC) as blowing agent. This model does not currently exist in the market, however, for the purpose of this study, the model is considered to compare its performance with current models.

Design 2 (Model Number: RD_2): This is a side-by-side refrigerator model introduced in 2010. The components considered are: a snap in magnetic door gasket, an efficient single speed compressor, an efficient evaporator and a thick PUR foam insulation material with cyclopentane as blowing agent.

Design 3 (Model Number: RD_3): This is a side-by-side energy efficient refrigerator model. The components considered are: a screw on magnetic gasket (which makes a good seal and reduces installation time), a two compressor and dual evaporator system (which consumes less energy and has a quite operation), and a PUR foam insulation material with HFC-245 FA as a blowing agent. HFC-245 FA provides very good insulation even with thin insulation layers unlike other alternatives.

Design 4 (Model Number: RD_4): This is a hypothetical sustainable side-by-side refrigerator model and is assumed to have economically, environmentally and socially beneficial features to provide overall sustainability benefits. The four components include: a top quality magnetic door gasket, a variable capacity compressor, a dual evaporator and Vacuum insulation panel. All the components are assumed to be designed and manufactured from the latest technological developments. Hence, this model is assumed to have enhanced performance features while simultaneously reducing environmental and societal impact.

Table 5.1 captures the variations between four components for the alternate refrigerator models. The component design aspects are derived from reviewing relevant literature as discussed above.

Table 5.1: Component Design Aspects for Alternate Refrigerator Models

Component Name	Characteristic	Model Number			
		RD_1	RD_2	RD_3	RD_4
Insulation Material	Type	PUR foam (CFC-11)	PUR foam (Cyclopentane)	PUR foam (HFC-245 FA)	VIP
	Weight (lb)	2	2	2	3
	Property	Thick layers, causes environmental impact, good insulation	Thick layers, environmental friendly, strong insulation	Thin layer, strong insulation	Thin layer, very strong insulation, high cost
Compressor	Type	Conventional single speed compressor	Efficient single speed compressor	Two compressors	Variable speed compressor
	Weight (lb)	25	20	30	10
	Property	Energy consuming, high noise levels	Efficient design, medium noise levels	Energy efficient, low noise levels	Energy efficient, very low noise levels
Evaporator	Type	Conventional evaporator design	Efficient evaporator design	Dual evaporator	Dual evaporator
	Weight (lb)	11	9	15	15
	Property	Very less energy savings	Good energy savings	Very good energy savings	High energy savings*
Door Gasket	Type	Non-magnetic compression gasket	Snap-on gasket	Screw-in gasket	Top quality magnetic gasket
	Weight (lb)	2.5	3	3	2
	Property	Sealing capability reduces over years	Time consumed during installation	Less time consumed during installation	Very good sealing capability
*High energy saving as a result of an efficient (compressor + evaporator) system					

Table 5.2 presents the key performance features of the different models that depend on properties of critical components.

Table 5.2: Key Performance Attributes of Alternate Refrigerator Designs

Performance Attributes	*Model Number*			
	RD_1	*RD_2*	*RD_3*	*RD_4*
Air Flow Type	No multi air flow system	No multi air flow system	Multi air flow system	Multi air flow system
Noise Level Rating (1-5; 1- very low, 5 - very high)	5	3	2	1
Color	White	Black	Stainless steel	Stainless steel
Estimated Weight (lb)	400	344	340	335
Estimated Electricity Usage (KWh/Year)	1100	612	542	350

5.3.2 SC configuration Description

The scope of the company's operations is very broad and their SC spans across multiple countries. Moreover the consideration of both forward and reverse-loop SC partners makes the SC network very complex. Thus the optimal SC configuration for alternate refrigerator designs can be very different. This section presents the potential SC configuration considered for each alternate refrigerator design, including detailed description of the SC operations across the four refrigerator life-cycle stages.

Components/Parts Acquisition

The CSD model assumes that each of the four major components is provided by a different supplier. Table 5.3 presents the distance from each supplier to the OEM Plant and their corresponding transportation costs. The estimated cost for acquiring components from each supplier is also presented. The transportation costs are computed as described in methodology chapter and depends on the distance travelled, weight of the component and the mode of transportation.

Table 5.3: Supplier Related Information for Alternate Refrigerator Models

Model Number	RD_1			RD_2			RD_3			RD_4		
Component	Name and Location	Distance	Cost	Name and Location	Distance	Cost	Name and Location	Distance	Cost	Name and Location	Distance	Cost
Door Gasket	AI, USA	178.8	21	AR, USA	78.8	23	AI, USA	178.8	22	AR, USA	78.8	24
Evaporator	AC, Jiangsu, China	7047.7	20	AS, Shanghai, China	7127.7	18	AS, Shanghai, China	7127.7	21	AC, Jiangsu, China	7047.7	21
Compressor	AE, Santa Catarina, Brasil	5269.8	26	AZ, Tianjin, China	6708.4	28	AL, Greater Noida, India	7591.7	29	AZ, Tianjin, China	6708.4	30
Insulation Material	ABC, USA	725.1	15	AD, USA	713.4	17	ABC, USA	725.1	16	ABC, USA	725.1	19
(estimated distance in miles, average cost in dollars)												

Manufacturing

The OEM holds inventory of the following three categories (a) new components from suppliers (b) refurbished refrigerators from past life-cycles and, (c) remanufactured components. The total demand is satisfied by a mixture of refrigerators made from (a) all new components, (b) one or more remanufactured components and (c) refurbished refrigerators from past life-cycles. Always a specific percentage of refurbished refrigerators and remanufactured components are used to satisfy current life-cycle demand. The OEM assesses current inventory and based on the annual demand acquires the additional quantity required from suppliers. The OEM assembles the components to produce the refrigerators that are then distributed to customers. As only four components are considered in this case, the model assumes a certain cost for acquiring rest of the components needed for assembling the refrigerator. The demand data for alternate refrigerator designs is presented in Appendix A. Several costs are incurred by the OEM in performing the assembly and holding operations including fixed, assembly and holding costs (presented in Appendix A). The fixed costs incurred by OEM are annualized.

Use

The projected annual steady-state demand for alternate refrigerators designs is presented in Table 5.4. On an average 600,000 energy efficient units are sold annually. While there exists different refrigerator types: side-by-side refrigerators, top-freezer refrigerators, bottom-freezer refrigerators, previous studies have indicated that side-by-side refrigerators contribute to about 35% of total refrigerator sales (USEPA and USDOE, 2007). As we consider only side-by side refrigerators, the demand for only this type is considered. Based on this value, the annual demand for rest of the models is estimated. As RD_1 is conventional model from 1990's, it was assumed that demand is low for this model. However, while increasing number of customers are aware of benefits of sustainable models, the current market prices indicate that they are priced a little higher than the non-sustainable ones (such as current model and energy efficient model in this case) and therefore, not every customer can afford them. Hence, the steady-state demand for the RD_4 (sustainable) model is assumed to be approximately mid-way between conventional and energy efficient models. As the company is US-based, most of the demand is satisfied within USA. This is because different regions have different electrical supply (voltage and frequency) which differ from that of USA, have different safety and regulatory requirements, different consumer expectations all of which makes it difficult to sell the US-based models in those regions. Also, for large products like refrigerators the cost of product combined with the shipping costs to transport them to those regions could make the refrigerators very expensive. While, the company sells a very small volume of customized and expensive refrigerators in these regions, these are not considered in the model. Therefore, the demand in this model is considered to be distributed within the USA. The use locations are assumed to be centralized and the delivery charges from OEM to use locations are paid by the customer. The current census population data from the U.S. Census Bureau (2009) is used to estimate the demand distribution to locations.

Table 5.4: Demand Market for Alternate Refrigerator Models

ID	Location	Population	Ratio	Estimated Demand Market (Quantity)			
				RD_1	RD_2	RD_3	RD_4
U_{NY}	New York, New York	8,391,881	0.433	43300	110000	95000	65000
U_{LA}	Los Angeles, California	3,831,868	0.197	19700	49000	43000	30000
U_{CH}	Chicago, Illinois	2,851,268	0.147	14700	36000	32000	22000
U_{HO}	Houston, Texas	2,257,926	0.116	11600	29000	25000	17000
U_{JV}	Jacksonville, Florida	813,518	0.041	4500	11000	9000	6500
U_{SA}	Seattle, Washington	616,627	0.031	3200	6000	7000	4500
U_{DV}	Denver, Colorado	610,345	0.031	3000	9000	9000	5000
Total		19,373,433	≈ 1	100,000	250,000	220,000	150,000

Collection

The average lifespan of refrigerators is assumed to be 8 years (data from company sources). At the end of use, refrigerators are collected by the collection centers. Since all the refrigerators are not likely to be collected at end of use, a specific recovery rate is used to indicate the percentage collected. The collection centers are geographically dispersed within USA and have different processing and fixed costs, capacities and capabilities. The collection centers are distributed in regions similar to that of demand, to reduce transportation costs. Table 5.5 presents the locations, fixed and processing costs, and maximum capacity data for each possible collection centers for each alternate refrigerator design. All collection centers are assumed to have the capability to perform collecting and sorting operations. The collection costs are established using literature as a guideline. However, due to differences in operations performed in each collection center (collection centers also perform disassembly operations) the fixed costs for setting-up disassembly equipment is also considered. The fixed and processing costs at facilities also vary based on that location's cost of living. The distance from each use location to collection centers and the corresponding transportation costs for all designs are presented in Appendix C.

Sorting Operations

The sorting operations are performed as described in the methodology section.

Evaluation of Alternate Refrigerator Designs

The evaluation of alternate refrigerator designs is performed as described in the methodology section. In this case, too, the probabilities for the criteria for the alternate refrigerator designs are subjective and are based on a rating from 0 to 10. Similarly, only two possibilities 1 or 0 is considered for recycling. The ratings for each of the criteria that affect reuse, remanufacturing and recycling probabilities for alternate refrigerator designs are presented in Appendix B.

The reuse and remanufacturing ratings between 0-10 are converted into probabilities as described in the methodology section. The probabilities obtained are compared with corresponding threshold limits set to select refrigerators or components for refurbishing and remanufacturing, respectively. The probabilities for one model, RD_1 is presented in Table 5.6, while those for others are presented in Appendix B.

Table 5.5: Collection Center Data for Alternate Refrigerator Models

ID	Location	Fixed Cost ($/Year) (Hong et al., 2008)	Processing Cost ($/Unit) (Srivastava, 2008; Beamon 2004)				Capacity (Thousands of Quantity)			
			RD_1	RD_2	RD_3	RD_4	RD_1	RD_2	RD_3	RD_4
C_{MX}	Tijuana, Mexico	50000	2	1.9	1.8	1.7	19	31	22	18
C_{SC}	Greenville, South Carolina	52500	2.1	1.92	1.82	1.71	9	17	14	21
C_{AK}	Little Rock, Arkansas	54000	2.15	1.95	1.84	1.75	18	23	25	24
C_{MN}	Duluth, Minnesota	58000	2.21	1.96	1.87	1.79	14	29	24	7.5
C_{ID}	Boise, Idaho	59850	2.3	2.09	1.89	1.83	26	27	29	18
C_{NB}	Grand Isaland, Nebraska	61000	2.34	2.1	1.91	1.84	15	10	25	23
C_{KY}	Louisville, Kentucky	62500	2.9	2.2	1.93	1.86	17	14	16	19
C_{NE}	Carson City, Nevada	65000	2.95	2.4	1.98	1.89	19	23	26	16

All the collection centers perform refurbishing and disassembly operations on the recovered refrigerators. The refurbished refrigerators are sent back to OEM for their next life. The distances from each collection center to the OEM and the associated transportation costs are presented in Appendix C. The components that can be remanufactured and recycled are sent to remanufacturing and recycling centers. The rest of the components are considered to be disposed at Guadalajara, Mexico. The distance from each collection center to the disposal location along with associated transportation costs are presented in Appendix C.

The refurbishing cost is established from Srivastava (2008) who indicated that refurbishing a unit of refrigerator can cost anywhere in between $10 and $76. Using this range, the per-unit refurbishing cost of alternate refrigerator designs is established (Appendix A). Due to lack of accurate data, the disassembly cost at each collection center is estimated and presented in Appendix A. There is evidence from literature that sustainable designs are designed for ease of performing reverse loop operations such as refurbishing, disassembly etc. Hence, these models incur lower costs for above operations as compared to the energy efficient, current and conventional models.

Remanufacturing

All the components chosen for remanufacturing operations at the collection centers are sent to remanufacturing centers for their subsequent operations. Table 5.7 presents the location and the fixed costs for each possible remanufacturing center. Similar to collection centers, the potential remanufacturing centers are distributed within the USA, close to potential collection facilities for reduced transportation costs. Srivastava (2008) mentioned that it costs approximately $15,900,000 to open a new refrigerator remanufacturing facility. This value is annualized for total number of years a facility remains open in a given period ($(t-(v-q))$ years), in this case 13 years. The remanufacturing facilities will be opened q years before the first year's products are retuned at end of their life, year 8 in this case. The capital cost for each remanufacturing facility is established from this data, cost of electricity, cost of goods and services for these locations.

Table 5.6: Reuse, Remanufacturing and Recycling Probabilities for Model RD_1

Criteria for Model RD_1			Use Center						
			U_{Mex}	U_{Ger}	U_{Fra}	U_{ind}	U_{Jap}	U_{Bra}	U_{Arg}
Reuse		U_p	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Reuse		Q_e	0.13	0.20	0.18	0.14	0.17	0.16	0.14
Reuse		S_a	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Reuse		Total	0.37	0.43	0.42	0.38	0.40	0.39	0.37
Reuse		Threshold	0.39						
Remanufacture	IM	A_s	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Remanufacture	IM	H_l	0.10	0.15	0.13	0.13	0.15	0.14	0.12
Remanufacture	IM	T_l	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Remanufacture	IM	I_m	0.06	0.10	0.09	0.08	0.10	0.07	0.07
Remanufacture	IM	Total	0.46	0.55	0.52	0.50	0.54	0.51	0.49
Remanufacture	IM	Threshold	0.45						
Remanufacture	CP	A_s	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Remanufacture	CP	H_l	0.13	0.16	0.15	0.13	0.15	0.15	0.13
Remanufacture	CP	T_l	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Remanufacture	CP	I_m	0.04	0.07	0.08	0.05	0.06	0.07	0.03
Remanufacture	CP	Total	0.39	0.46	0.45	0.41	0.43	0.45	0.38
Remanufacture	CP	Threshold	0.41						
Remanufacture	ER	A_s	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Remanufacture	ER	H_l	0.09	0.13	0.12	0.09	0.13	0.13	0.11
Remanufacture	ER	T_l	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Remanufacture	ER	I_m	0.05	0.06	0.07	0.08	0.10	0.09	0.10
Remanufacture	ER	Total	0.42	0.48	0.47	0.46	0.52	0.50	0.50
Remanufacture	ER	Threshold	0.49						
Remanufacture	DG	A_s	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Remanufacture	DG	H_l	0.14	0.16	0.17	0.15	0.17	0.17	0.15
Remanufacture	DG	T_l	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Remanufacture	DG	I_m	0.05	0.07	0.06	0.08	0.07	0.07	0.05
Remanufacture	DG	Total	0.54	0.58	0.59	0.58	0.59	0.59	0.54
Remanufacture	DG	Threshold	0.48						
Recycle*	IM	E_C	1	0	1	0	0	0	1
Recycle*	CP	E_C	1	1	0	1	0	0	1
Recycle*	ER	E_C	1	0	1	0	1	0	1
Recycle*	DG	E_C	0	1	0	0	0	1	0

*1 -Yes, 0 – No
IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket

Srivastava (2008) estimated $17-$84/unit processing cost. However, as individual components such as the insulation material, compressor, evaporator and door gasket are considered in this case as opposed to the entire refrigerator a proportional cost is considered. Also, the costs for alternate refrigerators are established in such a way that it is cheaper to remanufacture the components of the sustainable model as compared to that of an energy efficient, current and conventional models, in order of their sequence. This is because sustainable models are designed for not only manufacturing and assembly, but also for disassembly and remanufacturing. The capabilities and capacities of potential remanufacturing centers vary with respect each refrigerator design (Presented in Table 5.8).

Table 5.7: Location and Fixed Cost for Possible Remanufacturing Centers

ID	Location	Annualized Fixed Cost ($/Year)
RM_{MX}	Albuquerque, New Mexico	1,210,000
RM_{MO}	Kansas City, Missouri	1,219,000
RM_{MI}	Detroit, Michigan	1,237,000
RM_{OR}	Portland, Oregon	1,249,000

The CSD model selects remanufacturing centers that must be opened and the quantity of components that must be sent to each center to maximize profit. Appendix C provides the distances and transportation costs from each collection center to possible remanufacturing centers. The selected components are transported to remanufacturing centers and the remanufacturing operations performed. The remanufactured components are sent back to OEM to be used in new refrigerators. The distances and associated transportation costs from possible remanufacturing centers to OEM are shown in Appendix C.

Recycling:

All the components chosen for recycling at the collection centers are sent to recycling centers for their subsequent operations. Table 5.9 presents the locations and fixed costs for potential recycling centers. The capital costs for these facilities are assumed to be in similar range to that of remanufacturing facilities due to unavailability of appropriate data. The estimated processing costs, capabilities and capacities of all possible recycling centers vary with respect each design and are presented in Appendix A. The processing costs of four alternate designs are established such that the costs are higher for recycling a conventional model, followed by the current, energy efficient and the sustainable models (assuming latter are designed for ease of extracting major material from components).

Table 5.8: Data for all the Possible Remanufacturing Centers

ID		Capability (1 - Yes, 0 - No)				Processing Cost ($/Component)				Capacity (Quantity in Thousands)			
		RD_1	RD_2	RD_3	RD_4	RD_1	RD_2	RD_3	RD_4	RD_1	RD_2	RD_3	RD_4
RM_{MX}	Insulation Material	1	1	1	1	2.00	NA	1.81	1.71	17	28	25.7	28
	Compressor	1	1	1	0	2.12	2.01	NA	1.82	12	42	31.2	NA
	Evaporator	1	1	0	1	NA	2.04	1.94	1.84	10	30	NA	11.4
	Door Gasket	0	1	1	1	NA	2.09	NA	NA	NA	32	19.9	12
RM_{MO}	Insulation Material	1	1	1	1	NA	2.09	1.95	1.81	10	40	20	24
	Compressor	1	1	1	1	2.24	NA	1.94	1.80	16	29	19	14
	Evaporator	1	0	0	0	NA	1.99	1.85	NA	15	NA	NA	NA
	Door Gasket	1	1	1	1	2.17	2.02	1.88	1.75	15.5	45	18	19
RM_{MI}	Insulation Material	0	1	1	1	NA	2.04	1.89	NA	NA	44.5	12.5	10
	Compressor	1	0	0	0	2.20	2.05	1.90	NA	14.5	NA	NA	NA
	Evaporator	0	0	1	1	NA	2.00	1.86	1.73	NA	NA	21	22
	Door Gasket	1	1	1	1	2.18	NA	1.89	NA	20	30	16	10
RM_{OR}	Insulation Material	1	0	0	1	NA	NA	NA	NA	24	NA	NA	12
	Compressor	0	1	1	1	NA	NA	1.99	1.85	NA	45	25	20
	Evaporator	1	1	1	1	2.31	2.15	2.00	NA	24	34	14	11
	Door Gasket	0	0	1	1	NA	NA	2.02	1.88	NA	NA	19	14
0 - Not capable, NA - Not applicable as a result of no capability													

Table 5.9: Location and Fixed Cost for Possible Recycling Centers

ID	Location	Annualized Fixed Cost ($/Year)
RY_{MX}	Mexico City, Mexico	1,250,000
RY_{NC}	Raleigh, North Carolina	1,270,000
RY_{UT}	Salt Lake City, Utah	1,275,000
RY_{MN}	Saint Paul, Minnesota	1,285,000

The Appendix C provides the distances and transportation costs from each collection center to potential recycling centers. The distances and transportation costs from recycling centers to suppliers are also shown.

Therefore, the possible closed-loop SC configuration for each of the four alternate product designs is illustrated in Figure 5.3. The suppliers are represented with suffix ranging from s_1 through s_4, use locations are represented with suffix ranging from u_1 through u_7, and collection, remanufacturing and recycling facilities are represented by suffix ranging from $c_{1,} d_1, e_1$through $c_{8,} d_4, e_4$, respectively.

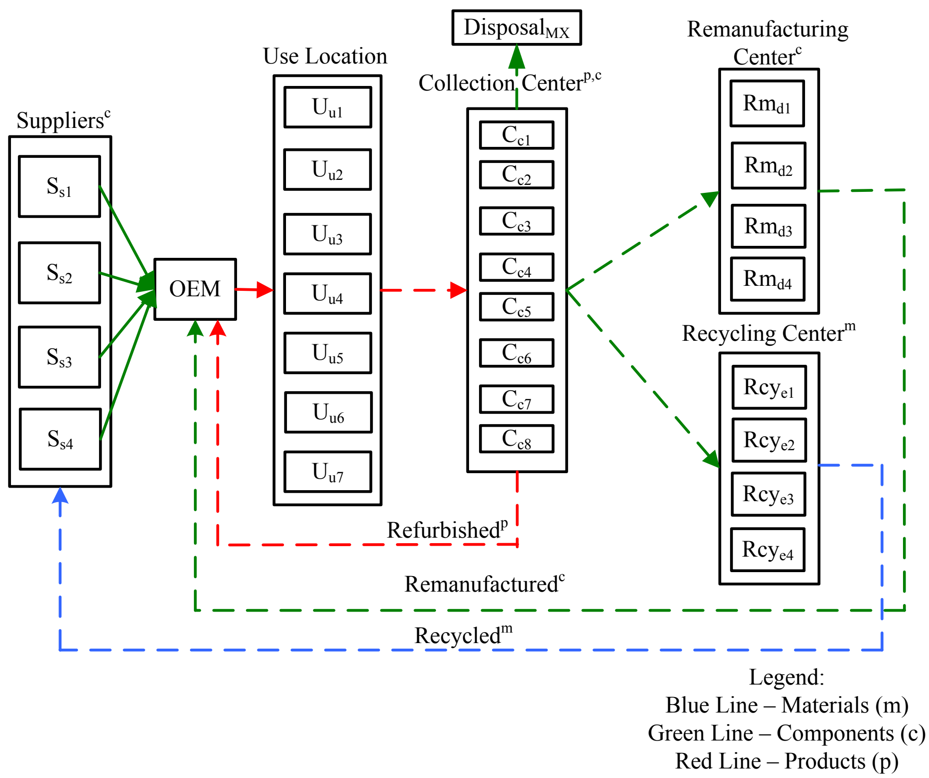


Figure 5.3: Possible Closed-loop SC Configuration (Refrigerator Case Study)

5.4 CSD Model Framework

The estimated demand over total period in this problem is illustrated in Figure 5.4. The EOM is run at the steady-state condition in year 10 (t_n). The time horizon for this model is considered as 20(T) years. Considering that a refrigerator has a use life from anywhere between 8-12 years (data from company sources), the use life for all alternate refrigerators is assumed to be 8 years, and therefore the MLC analysis is performed for 20 years to identify the benefits of pursuing the closed-loop flow for each model. The steady-state period ranges from 5 (t_{s1}) to 15 (t_{sf}) years. The economic, environmental and societal MLC analysis is conducted for all years between 1 to 20 using the tools MLC_{Eco}, MC_{Env}, and MLC_{Soc} tools as described in methodology section.

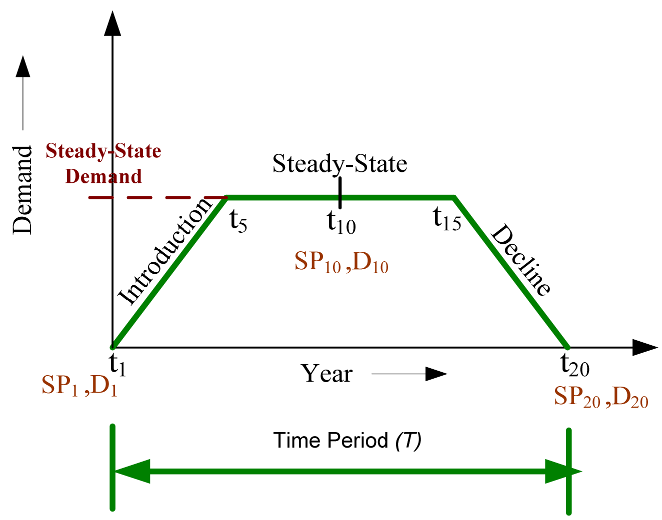


Figure 5.4: Demand Graph for Refrigerator Case Study

5.5 Economic Optimization Model (EOM) Description

A detailed description of the EOM for the refrigerator case study is presented in this section. The EOM developed and described in the methodology section is used to identify an optimal SC configuration for each refrigerator design that maximizes the SC profit. The EOM in this case is run at steady-state condition for year 10. Figure 5.5 illustrates a snapshot of EOM for the refrigerator model RD_1.

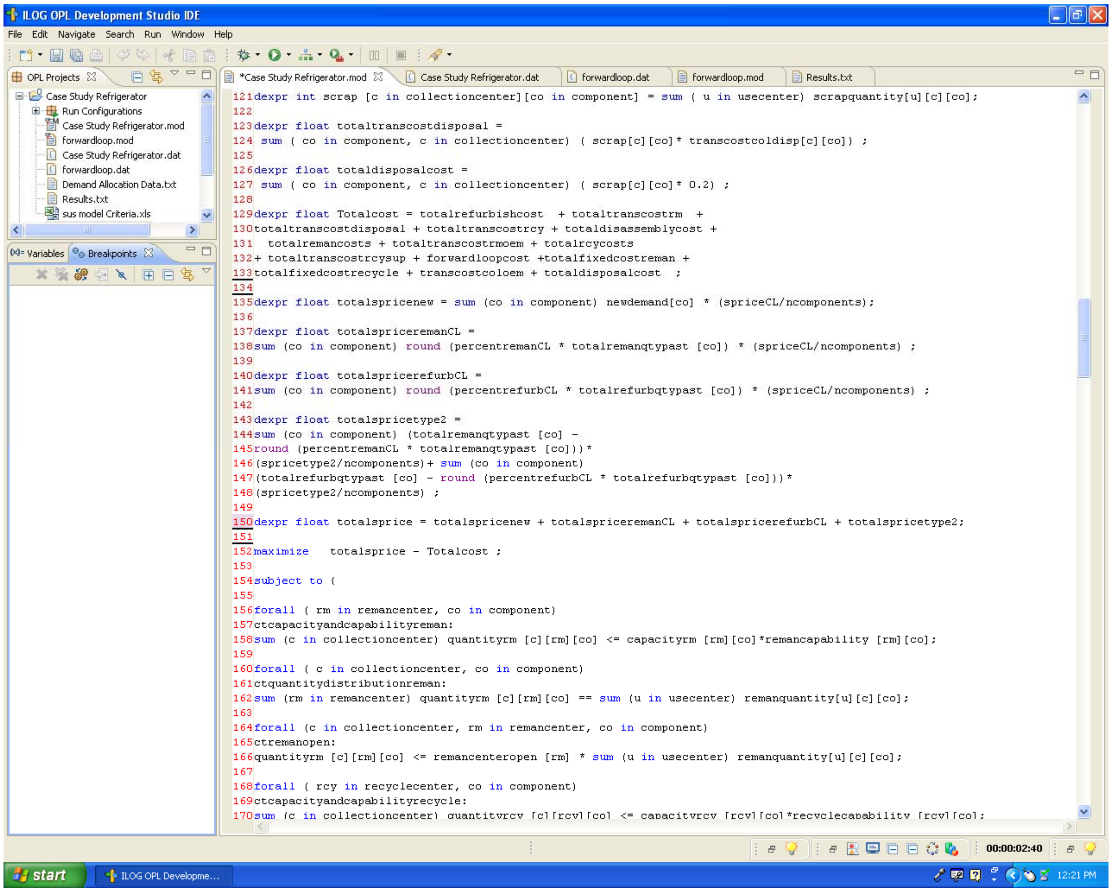


Figure 5.5: Economic Optimization Model for Refrigerator Design RD_1

The impact of the components on refrigerator performance is evaluated separately based on their probabilities for recovery, reuse, recycling, remanufacturing operations with associated SC partner costs (such as fixed, and recurring costs), their capabilities and capacities. The objective of this model is to select an optimal closed-loop SC configuration for each refrigerator design that maximizes the profit.

5.5.1 Model Assumptions

All the assumptions presented for the EOM in the methodology section are considered for the refrigerator case study, too. In addition, the following specific assumptions are considered for the case study. The actual distance between each SC partner is computed and the corresponding transportation costs are computed for each refrigerator design based on their individual weights and the per-unit transportation costs. The transportation distance from and to suppliers is travelled 90% by ship and 10% by truck. However, for transportation of units within USA, all the distances are assumed to be travelled by truck only. This assumption is based on the fact the transporting units by ship could become more expensive within USA, however, if the partners are located outside USA, like the suppliers, transporting the items by ship will create better economic and environmental benefits. Brody, Weiser and Burns, a consultant company in Baltimore, USA, identified that if a used refrigerator is priced at approximately 20% to 40% of the new unit cost, demand existed for thousands of used refrigerators. However, their assumption was that the refrigerators are of suitable quality. Therefore, in this model, the price discount for the refurbished and remanufactured refrigerators for alternate refrigerator designs is varied in this range. The additional data including other component cost, recovery rates, capacity threshold multiplication factors for collection, remanufacturing and recycling facilities and the profit margin for alternate refrigerator designs is presented in Table 5.10.

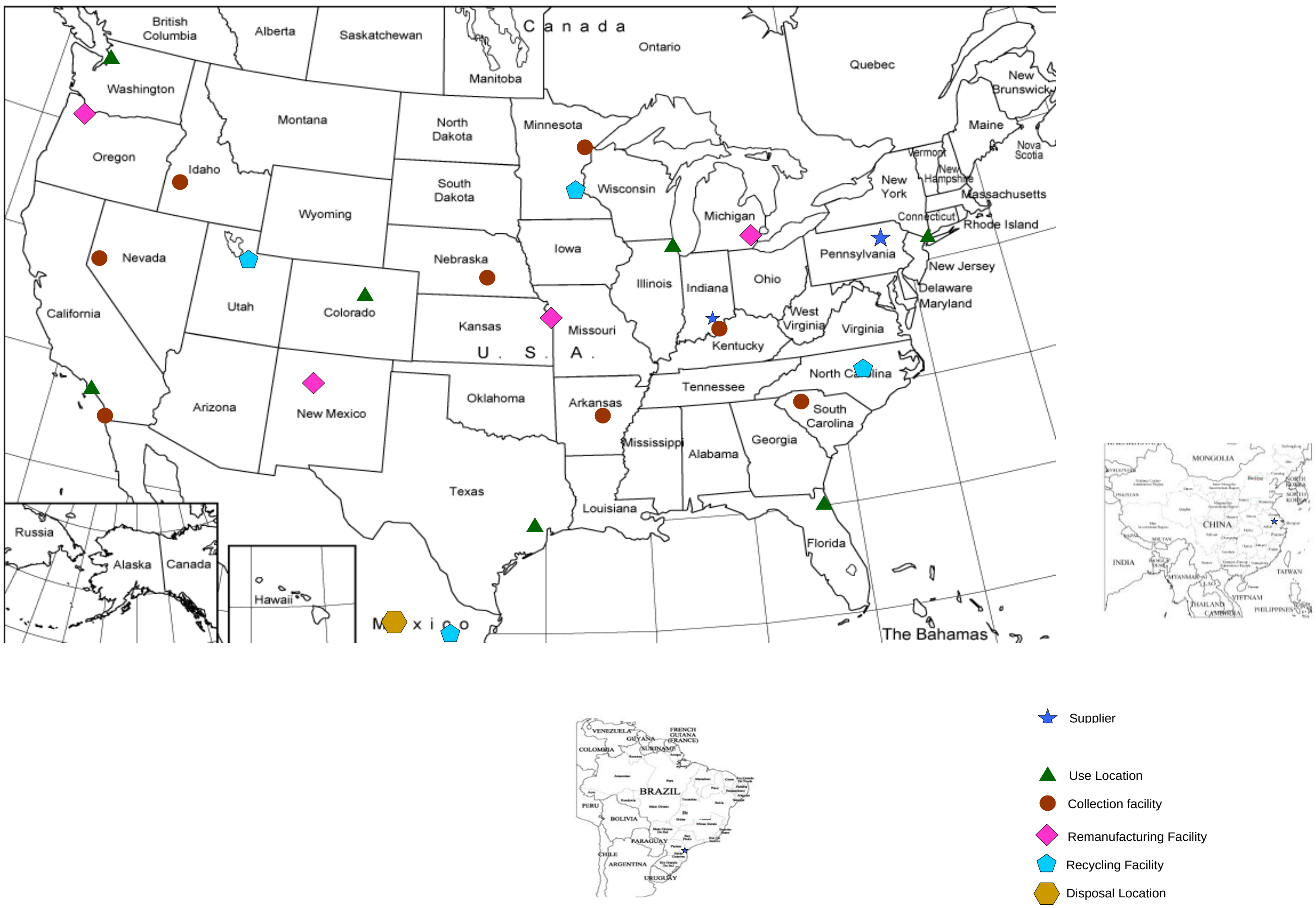
Table 5.10: Additional EOM Data for Refrigerator Case Study

Refrigerator Model	Other Component Cost ($/Refrigerator)	Recovery Rate	Capacity Threshold Multiplication Factor			Profit Margin	Price Discount for Refurbished and Remanufactured Products (Rate)
			Collection	Remanufacturing	Recycle		
RD_1	560	0.3	0.5	0.3	0.3	0.1	0.3
RD_2	590		0.45	0.25	0.27	0.09	0.25
RD_3	600		0.4	0.21	0.2	0.11	0.23
RD_4	605		0.43	0.2	0.21	0.095	0.21

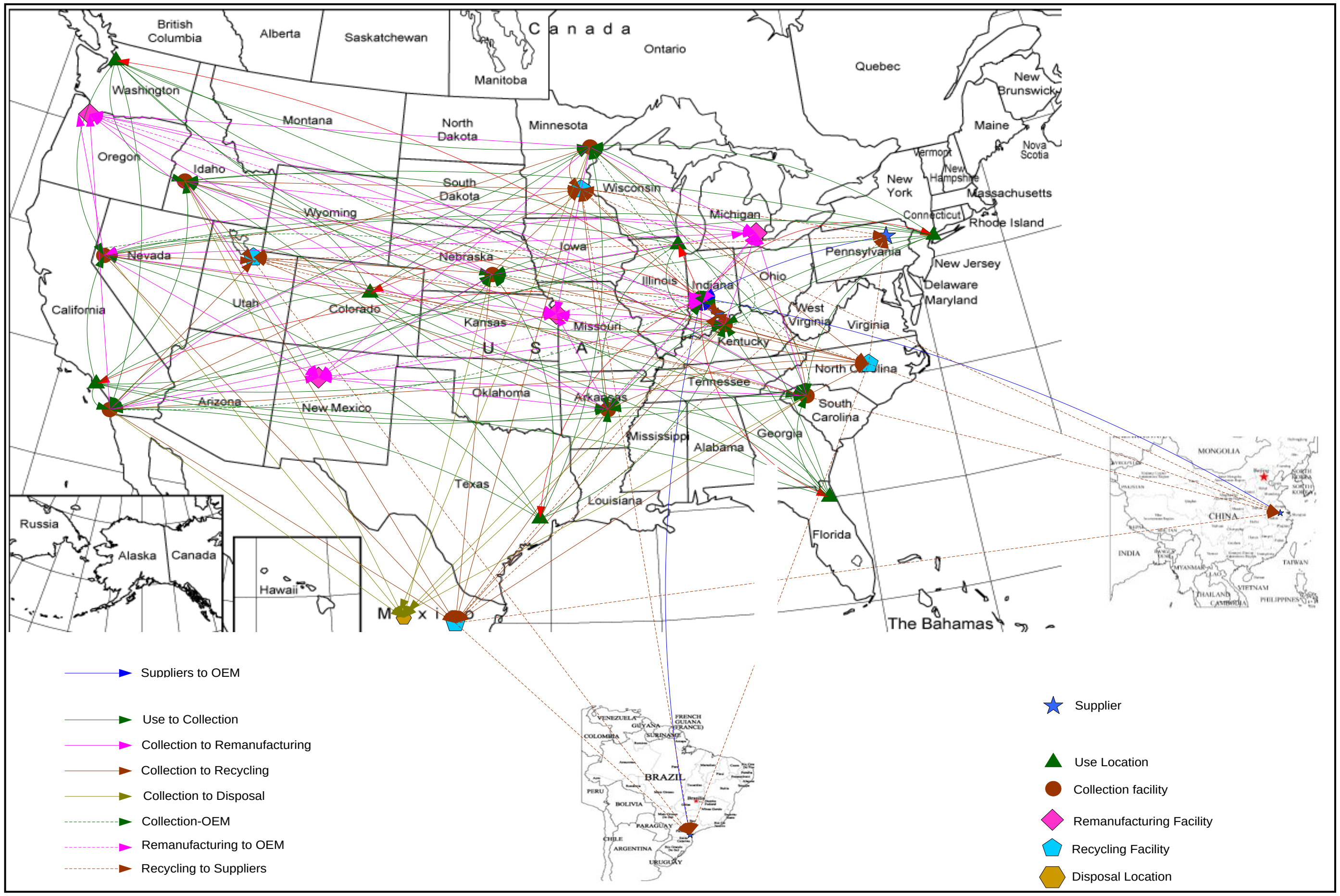
5.5.2 Results

The outputs from the EOM are optimal SC configurations that maximize the profit for each alternate refrigerator design. The potential SC partners, together with their linkages, and the optimal SC configuration chosen by the EOM for model RD_1 are graphically illustrated in Figure 5.6. Figure 5.6(a) illustrates the locations of SC partners on a map. Figure 5.6(b) illustrates all the possible SC partners and the transportation routes between each of them. Figure 5.6(c) illustrates the optimal SC configuration chosen by the EOM solved in the IBM ILOG CPLEX software.

(a) Locations of Potential SC Partners for Refrigerator Model RD_1



(b) Possible SC Partners and Transportation Routes for Refrigerator Model RD_1



(c) Optimal SC Partners and Transportation Routes for Refrigerator Model RD_1

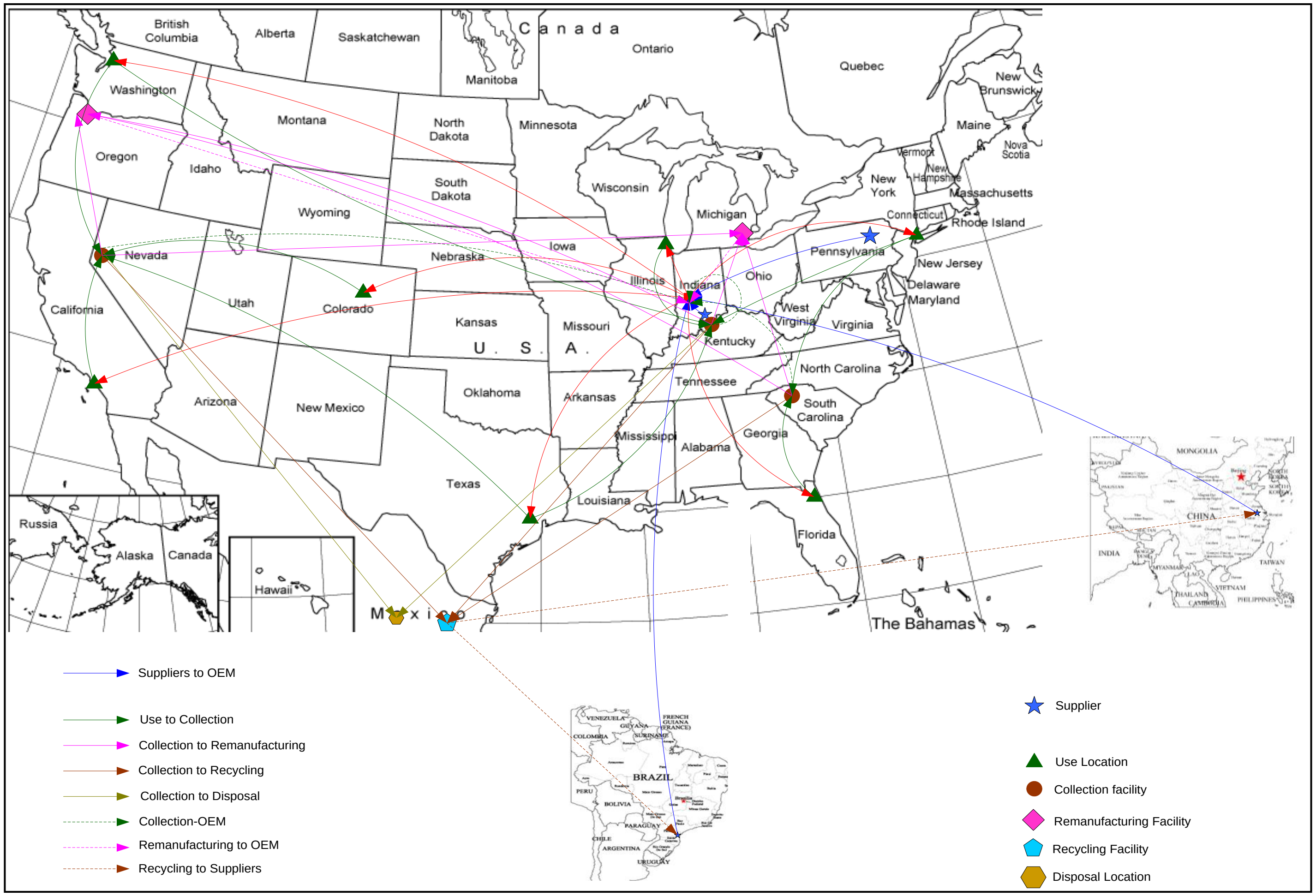


Figure 5.6: Locations of Possible and Optimal SC Partners for Model RD_1

Table 5.11 presents the alternate refrigerator designs and the optimal SC configuration identified for each design through EOM, ranked in order of their maximum profit. The optimal SC configurations identified for RD_1, RD_2, RD_3 and RD_4 are represented by RSC_1, RSC_2, RSC_3, and RSC_4, respectively.

Table 5.11: Optimal SC Configuration for Alternate Refrigerator Designs

SC Partner	Refrigerator Model (Optimal SC Configuration)			
	RD_1 (RSC_1)	RD_2 (RSC_2)	RD_3 (RSC_3)	RD_4 (RSC_4)
Supplier	S_{Pa}	S_{De}	S_{Pa}	S_{Pa}
	S_{Jo}	S_{Ti}	S_{No}	S_{Ti}
	S_{Ji}	S_{Sh}	S_{Sh}	S_{Ji}
	S_{Sc}	S_{Br}	S_{Sc}	S_{Br}
OEM	USA			
Use	U_{NY}			
	U_{LA}			
	U_{CH}			
	U_{HO}			
	U_{JV}			
	U_{SA}			
	U_{DV}			
Collection	C_{SC}	C_{SC}	C_{SC}	C_{SC}
	C_{KY}	C_{AK}	C_{AK}	C_{AK}
	C_{NE}	C_{MN}	C_{MN}	C_{NE}
		C_{KY}	C_{KY}	
		C_{NE}	C_{NE}	
Remanufacturing	RM_{OR}	RM_{OR}	RM_{MO}	RM_{MI}
	RM_{MI}	RM_{MO}	RM_{MX}	RM_{MX}
Recycle	RY_{MX}	RY_{UT}	RY_{UT}	RY_{UT}
				RY_{NC}
Maximum Profit (in Millions of $)	-1.64	7.48	9.61	4.27

5.5.3 Summary

As it can be observed from Table 5.11, the refrigerator model RD_3 gives the maximum profit, followed by model RD_4, RD_2 and RD_1. It has been observed that the profit depends on several factors, while the major ones include the steady-state demand, and the number of refurbished and remanufactured components used to satisfy this demand. As the steady-state demand increases the annual profit also increases, as more revenue is generated by the SC. This factor alone, however, does not contribute to the total steady-state profit. This is because, although higher demand exists, if all demand is satisfied by new components, then the profit realized will not be significant (because the cost for manufacturing a new refrigerator is very high, as compared to refurbished and remanufactured components). One the other hand if increasing demand is satisfied by refurbished refrigerators or remanufactured components, the total SC costs will be comparatively less, as no supplier and other component costs are incurred. Hence, the total profit is a function of demand and quantity of refurbished and remanufactured components (which depends on how sustainable a design is) used to satisfy the demand. Due to this reason, although the demand for model RD_2 (250,000 units) is greater than RD_3 (220,000 units), the quantity of refurbished refrigerators and remanufactured components are more for RD_3 than RD_2 which lead to RD_3 generating better profits. On the other hand, although the RD_4 model is 'the sustainable' one among all the designs, and considers maximum quantity of refurbished and remanufactured units to satisfy the steady-state demand (100,000 units), this criteria alone is not sufficient for it to generate maximum profit, as the annual demand for this model is very less compared to RD_2 and hence the RD_4, is still holding second place due to insufficient demand.

Moreover, in steady-state analysis, reverse loop costs are incurred, which depend on the recovery rate. Considering steady-state alone, one might think that performing reverse loop operations adds to the total costs for that particular year, as higher the recovery rate more quantity of products or its components must be sent for reverse loop operations. In reality, the actual benefits of performing these closed-loop operations are not observed in short-term, as initially only the capital and operational costs are incurred. However, once the recovered products are ready for their next lives they start bringing in the desired closed-loop benefits. Therefore, one must not derive conclusions based on EOM results which can be misleading. Hence, during steady-state period only optimal SC configuration is identified and no selection of designs is performed. However, the economic MLC analysis performed in the next section captures the true economic performance of alternate refrigerator designs over their total life-cycle.

5.6 Economic Multi Life-Cycle (MLC) Analysis

In this section, all the economic MLC analysis performed on the PDSCC combinations is presented. The objective of performing the Economic MLC analysis is to identify and select the best PDSCC combinations that have maximum cumulative profit at the end of the total period (T =20, in this case). In addition, the benefits/impact of pursing a closed-loop flow on each of the PDSCC combination is studied in detail. This is performed by comparing the closed-loop SC performance with the open-loop SC performance for 20 years to gain insights into such models.

5.6.1 Assumptions

All the assumptions presented in the methodology section are considered for the case study too. In addition, the following aspects are considered: the use stage of the product is 8 years (v); the reverse loop SC operations take 1 year (q); and the economic MLC analysis is performed for a period of 20 years (T) for each PDSCC combination identified by EOM separately.

5.6.2 Analysis Description

The economic MLC analysis is performed using the MLC_{Eco} tool as described in the methodology section. Each PDSCC combination is analyzed separately and the cumulative profit at the end of year 20 is compared to select the best combinations for next stage.

Input Data

The input data for this analysis are the results of EOM, the steady-state year (year 10) price and demand, the number of refurbished and remanufactured components available for sales for year 10, the number of critical components considered, the per-unit costs such as the supplier component cost, the transportation cost from suppliers to OEM, the assembly and holding cost for year 10. All the input data is captured in the 'Economic MLC Input Data' sheet.

Further, additional data (presented in Table 5.12) such as the demand for the year 1 and 20, the probability for refurbished and remanufactured components returned from each past years 1 through 11 are generated based on estimates. Beamon and Fernandas (2004) in their multi-period model for a SC configuration with product recovery used an interest rate of 0.11. Due to unavailability of data, this value is used for the case study in this research.

As an example, the 'Economic MLC Input Data' sheet for refrigerator model RD_1 is illustrated in the Figure 5.7.

Table 5.12: Economic MLC Analysis Additional Input Data (Case Study)

SC Parameter		Refrigerator Model			
		RD_1	RD_2	RD_3	RD_4
Demand for year 1		30000	50000	45000	43000
Demand for year 20		40000	55000	60000	50000
Interest/Discount rate		0.11			
Probability of refurbished components returned from past years satisfying later year's demand (a)	Year 1	0.4	0.5	0.45	0.5
	Year 2	0.66	0.72	0.6	0.92
	Year 3	0.45	0.49	0.5	0.65
	Year 4	0.55	0.60	0.7	0.77
	Year 5	0.34	0.37	0.46	0.97
	Year 6	0.76	0.83	0.96	0.65
	Year 7	0.67	0.73	0.85	0.84
	Year 8	0.5	0.55	0.63	0.70
	Year 9	0.75	0.82	0.95	0.65
	Year 10	0.6	0.66	0.76	0.84
	Year 11	0.5	0.65	0.74	0.33
Probability of remanufactured components returned from past years satisfying later year's demand (b)	Year 1	0.35	0.35	0.86	0.8
	Year 2	0.69	0.76	0.80	0.88
	Year 3	0.47	0.52	0.55	0.60
	Year 4	0.58	0.64	0.67	0.74
	Year 5	0.36	0.39	0.41	0.46
	Year 6	0.80	0.48	0.92	0.52
	Year 7	0.70	0.78	0.81	0.90
	Year 8	0.53	0.58	0.61	0.67
	Year 9	0.79	0.87	0.91	0.71
	Year 10	0.63	0.69	0.73	0.80
	Year 11	0.73	0.21	0.47	0.73

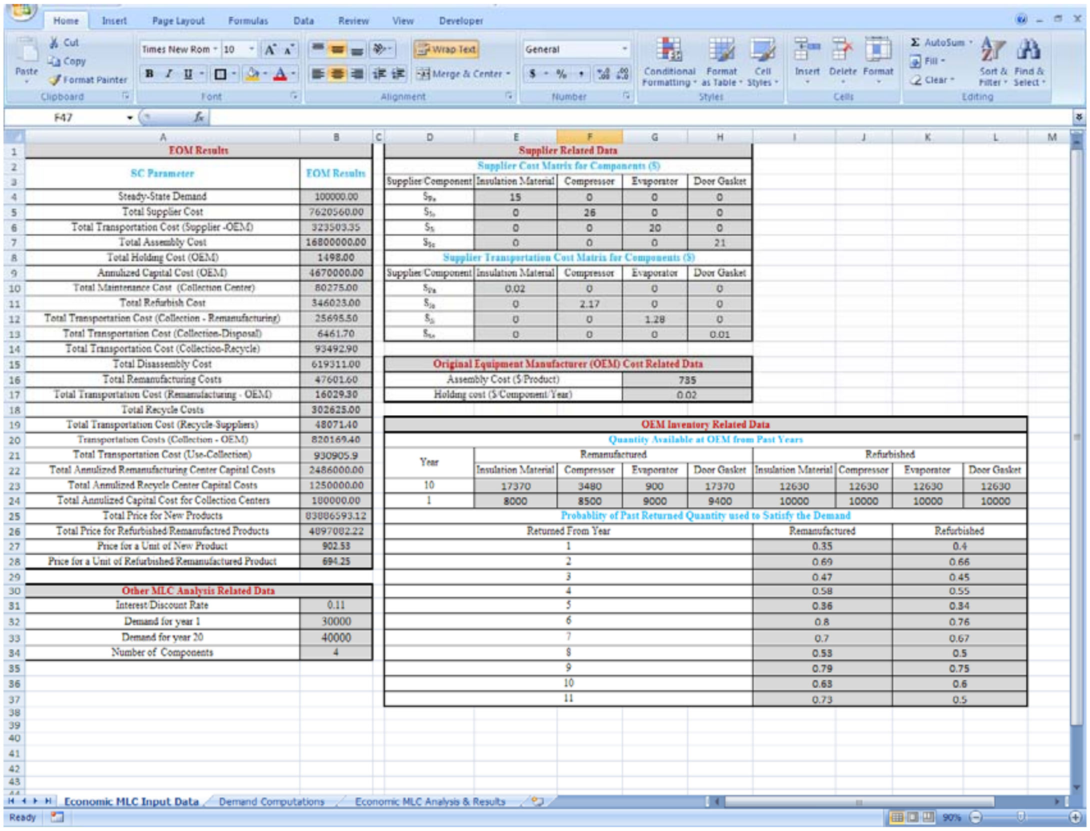
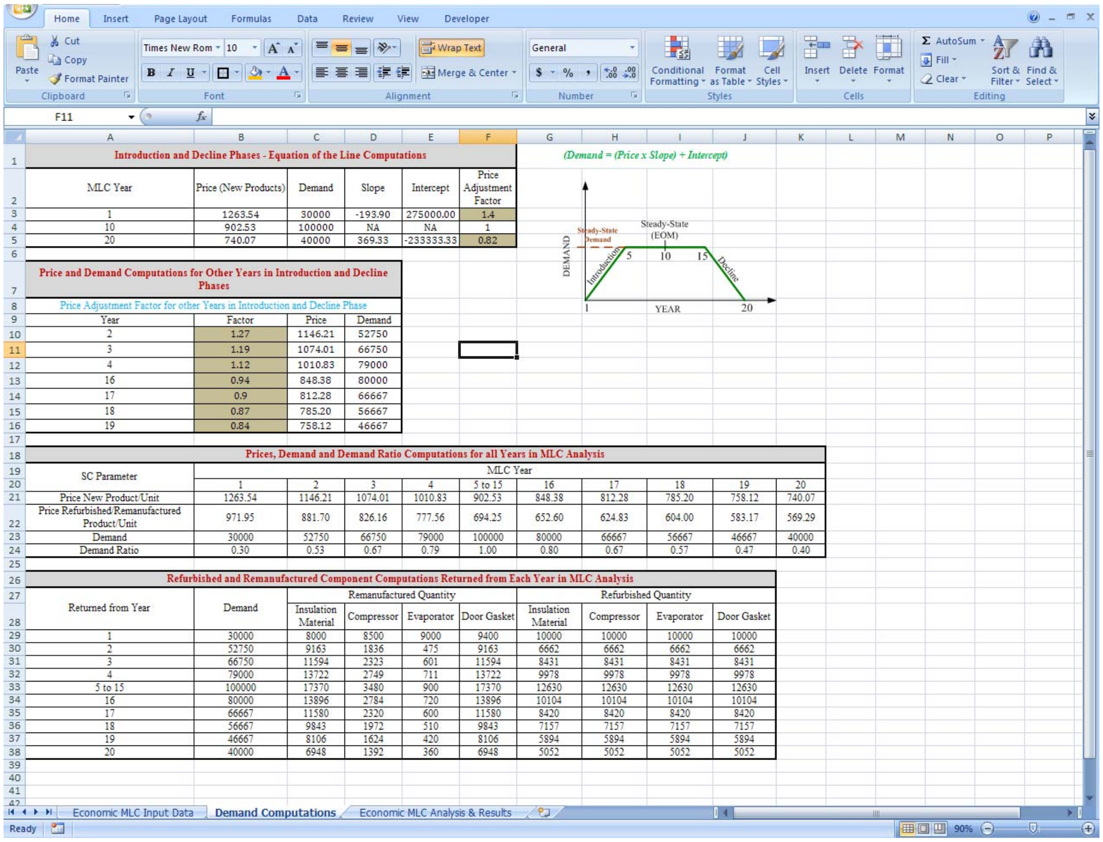


Figure 5.7: 'Economic MLC Input Data' Spreadsheet for Model RD_1

From the input data, the price, the demand for each of the 20 years, and the refurbished and remanufactured component quantity returned for each year is computed as described in methodology section by the MLC_{Eco} tool in sheet 'Demand Computations' as shown in Figure 5.8.



Introduction and Decline Phases - Equation of the Line Computations

MLC Year	Price (New Products)	Demand	Slope	Intercept	Price Adjustment Factor
1	1263.54	30000	-193.90	275000.00	1.4
10	902.53	100000	NA	NA	1
20	740.07	40000	369.33	-233333.33	0.82

Price and Demand Computations for Other Years in Introduction and Decline Phases

Price Adjustment Factor for other Years in Introduction and Decline Phase

Year	Factor	Price	Demand
2	1.27	1146.21	52750
3	1.19	1074.01	66750
4	1.12	1010.83	79000
16	0.94	848.38	80000
17	0.9	812.28	66667
18	0.87	785.20	56667
19	0.84	758.12	46667

Prices, Demand and Demand Ratio Computations for all Years in MLC Analysis

SC Parameter	MLC Year									
	1	2	3	4	5 to 15	16	17	18	19	20
Price New Product/Unit	1263.54	1146.21	1074.01	1010.83	902.53	848.38	812.28	785.20	758.12	740.07
Price Refurbished/Remanufactured Product/Unit	971.95	881.70	826.16	777.56	694.25	652.60	624.83	604.00	583.17	569.29
Demand	30000	52750	66750	79000	100000	80000	66667	56667	46667	40000
Demand Ratio	0.30	0.53	0.67	0.79	1.00	0.80	0.67	0.57	0.47	0.40

Refurbished and Remanufactured Component Computations Returned from Each Year in MLC Analysis

Returned from Year	Demand	Remanufactured Quantity				Refurbished Quantity			
		Insulation Material	Compressor	Evaporator	Door Gasket	Insulation Material	Compressor	Evaporator	Door Gasket
1	30000	8000	8500	9000	9400	10000	10000	10000	10000
2	52750	9163	1836	475	9163	6662	6662	6662	6662
3	66750	11594	2323	601	11594	8431	8431	8431	8431
4	79000	13722	2749	711	13722	9978	9978	9978	9978
5 to 15	100000	17370	3480	900	17370	12630	12630	12630	12630
16	80000	13896	2784	720	13896	10104	10104	10104	10104
17	66667	11580	2320	600	11580	8420	8420	8420	8420
18	56667	9843	1972	510	9843	7157	7157	7157	7157
19	46667	8106	1624	420	8106	5894	5894	5894	5894
20	40000	6948	1392	360	6948	5052	5052	5052	5052

Figure 5.8: ‘Demand Computations’ Sheet for Refrigerator Model RD_1

5.6.3 Results

The results of the economic MLC analysis are presented in this section. Using the input data and the demand computations, the MLC_{Eco} tool computes the annual transportation quantities, annual costs, annual prices, annual revenue and annual profit for the 20 year period in the ‘Economic MLC Analysis and Results’ sheet. As an example, the MLC results obtained for each year in 20 year period for the refrigerator model RD_1 are shown (Figure 5.9).

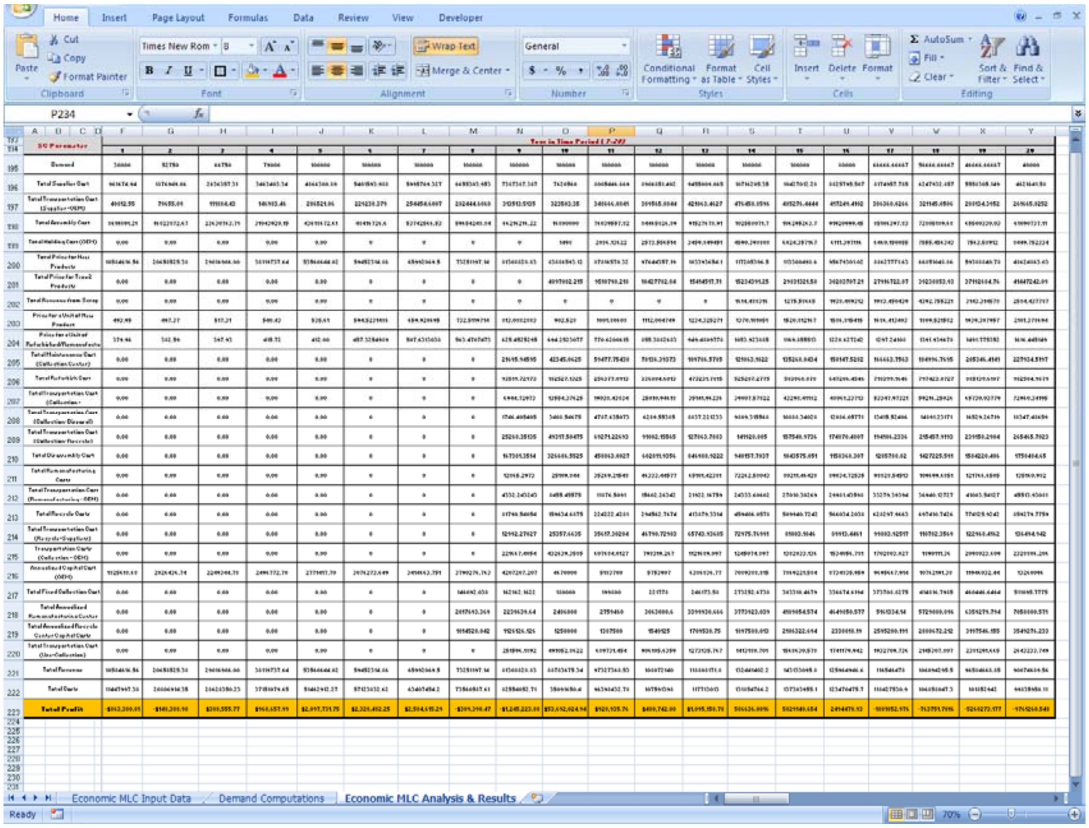


Figure 5.9: ‘Economic MLC Analysis and Results’ for Model RD_1

The economic MLC analysis is performed separately for rest of the PDSCC combinations identified at end of EOM, and the cumulative profits for each year in 20 year time period are summarized in Table 5.13. Finally, the PDSCC combinations are ranked based on the cumulative profit at the end of year 20.

Table 5.13: Economic MLC Analysis Results (Case Study)

Year	Cumulative Profit for PDSCC ($)			
	RD_1-RSC_1	RD_2-RSC_2	RD_3-RSC_3	RD_4-RSC_4
1	-0.86	-0.36	-0.24	-0.54
2	-1.01	1.34	1.69	0.01
3	-0.62	4.66	5.36	1.41
4	0.35	9.75	10.88	3.72
5	2.44	18.05	19.81	7.74
6	4.77	27.27	29.71	12.20
7	7.36	37.50	40.71	17.15
8	7.05	45.59	49.67	18.46
9	5.80	53.35	58.59	18.91
10	59.49	207.84	198.63	109.15
11	60.42	218.92	214.26	117.77
12	60.90	229.30	232.06	124.53
13	62.00	239.99	255.42	134.08
14	62.59	251.22	279.74	150.29
15	68.41	271.45	321.00	159.98
16	70.91	280.37	350.63	173.06
17	69.03	281.36	370.62	180.46
18	68.26	280.88	400.01	185.60
19	63.00	271.82	414.91	194.50
20	**53.23**	**261.36**	**430.60**	**183.73**
Rank	**4**	**2**	**1**	**3**

If there were numerous PDSCC combinations, at this stage some of the designs can be eliminated. However, as there are only few combinations (four), all the combinations are ranked and then sent to the environmental MLC analysis stage, but no combination is eliminated yet, at this stage.

5.7 Economic MLC Analysis for Open-loop SC Model

In this section, the economic open-loop MLC performance of the PDSCC combinations is evaluated in order to compare these results with those obtained from closed-loop SC model. This is performed with an objective to study the impact of pursuing the closed-loop flow for different PDSCC combinations and answer some of the research questions raised in chapter 1 of this dissertation. As the closed-loop results are already obtained, the open-loop SC is run using the MLC_{Osc} tool for each PDSCC combinations to obtain the cumulative profits for a period of 20 years in one year increment in an open-loop flow.

5.7.1 Analysis Assumptions

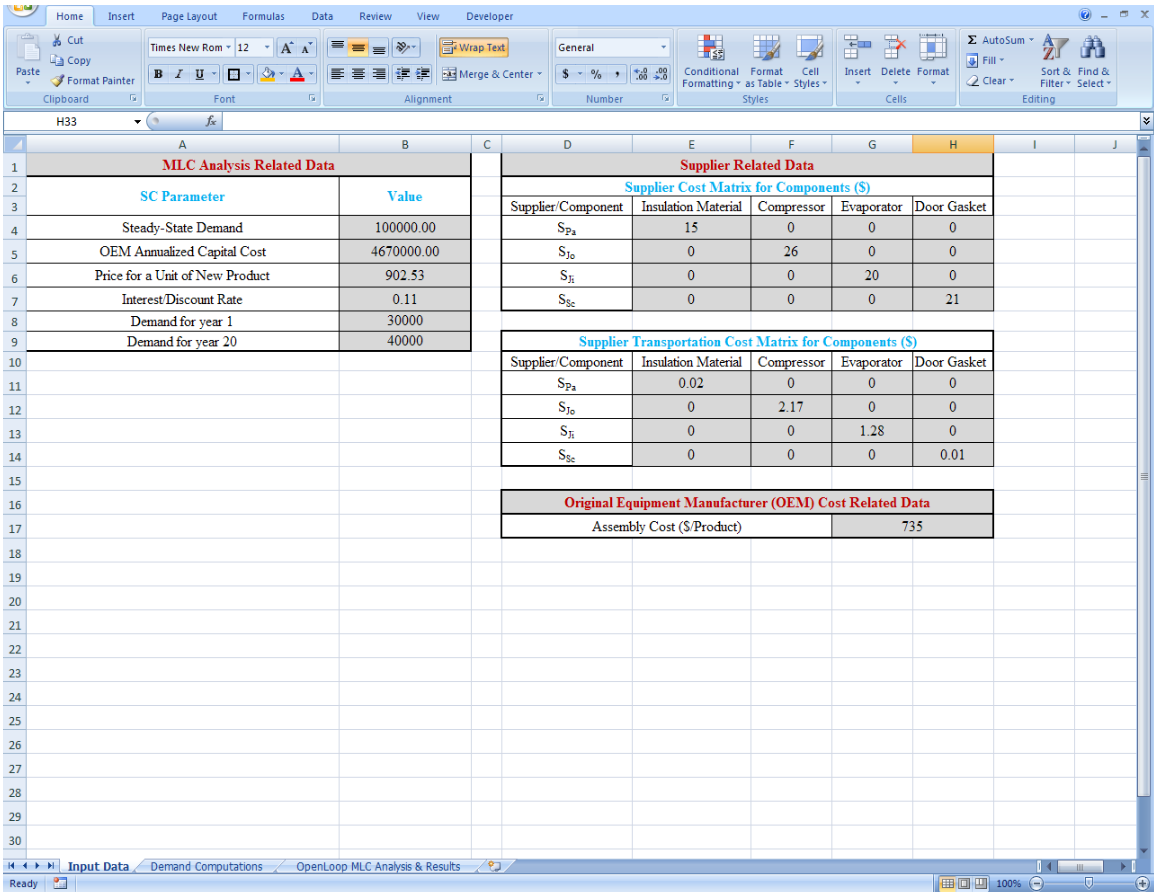
The assumptions considered for the MLC_{Osc} tool are all considered for this model. The MLC analysis is performed for a period of 20 years (T) for each of the PDSCC combinations identified by EOM.

5.7.2 Analysis Description

The open-loop MLC analysis for each PDSCC combination is performed separately, as described in the methodology section, by the MLC_{Osc} tool.

Input Data

The input data such as the price and demand for steady-state year 10, and the demand for the first and the year 20, the steady-state per-unit costs (supplier component cost, transportation cost from supplier to OEM, the assembly cost), the OEM annualized capital costs and the interest/discount rate are acquired by the 'Input Data' sheet for each PDSCC combination. As an example, the input data sheet for RD_1 is shown (Figure 5.10).



MLC Analysis Related Data	
SC Parameter	Value
Steady-State Demand	100000.00
OEM Annualized Capital Cost	4670000.00
Price for a Unit of New Product	902.53
Interest/Discount Rate	0.11
Demand for year 1	30000
Demand for year 20	40000

Supplier Related Data

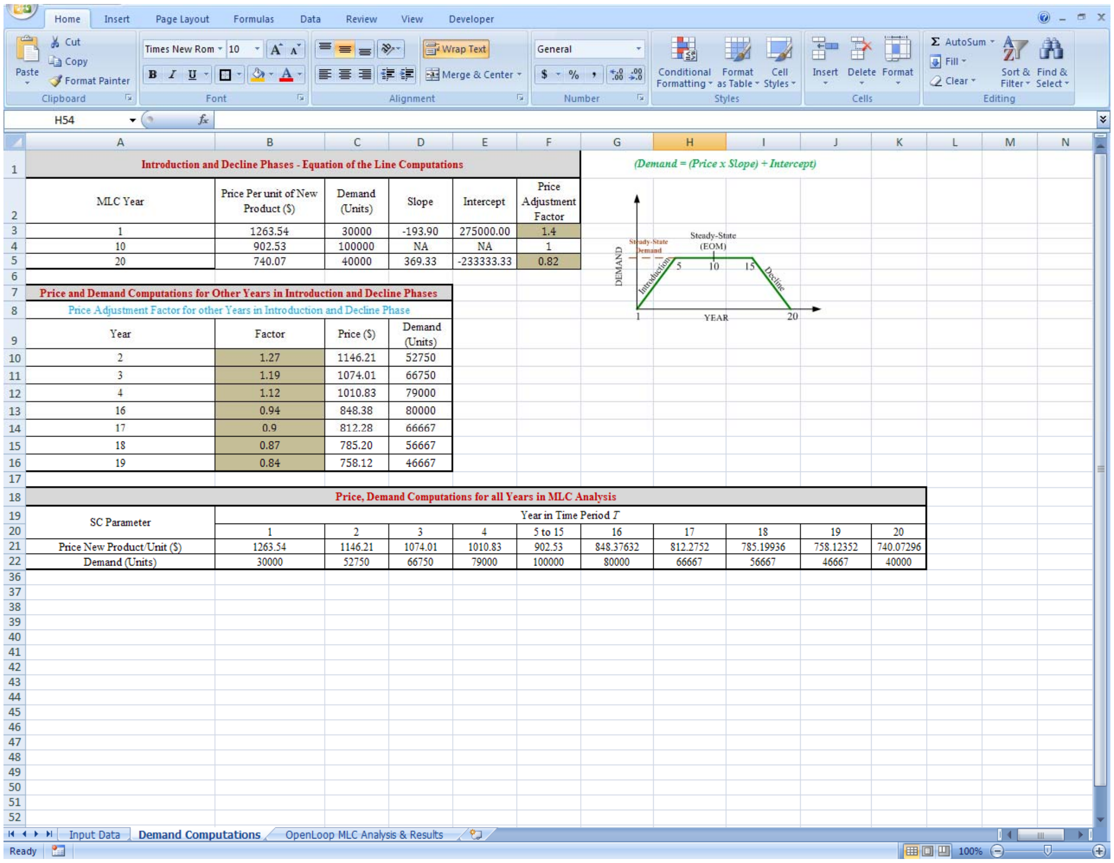
Supplier Cost Matrix for Components ($)				
Supplier/Component	Insulation Material	Compressor	Evaporator	Door Gasket
S_{Pa}	15	0	0	0
S_{Jo}	0	26	0	0
S_{Ji}	0	0	20	0
S_{Sc}	0	0	0	21

Supplier Transportation Cost Matrix for Components ($)				
Supplier/Component	Insulation Material	Compressor	Evaporator	Door Gasket
S_{Pa}	0.02	0	0	0
S_{Jo}	0	2.17	0	0
S_{Ji}	0	0	1.28	0
S_{Sc}	0	0	0	0.01

Original Equipment Manufacturer (OEM) Cost Related Data	
Assembly Cost ($/Product)	735

Figure 5.10: MLC$_{Osc}$ 'Input Data' Sheet for Refrigerator Model RD$_1$

From this input data, the price and the demand for each of the 20 years is computed in 'Demand Computations' sheet (Figure 5.11).



Introduction and Decline Phases - Equation of the Line Computations					
MLC Year	Price Per unit of New Product ($)	Demand (Units)	Slope	Intercept	Price Adjustment Factor
1	1263.54	30000	-193.90	275000.00	1.4
10	902.53	100000	NA	NA	1
20	740.07	40000	369.33	-233333.33	0.82

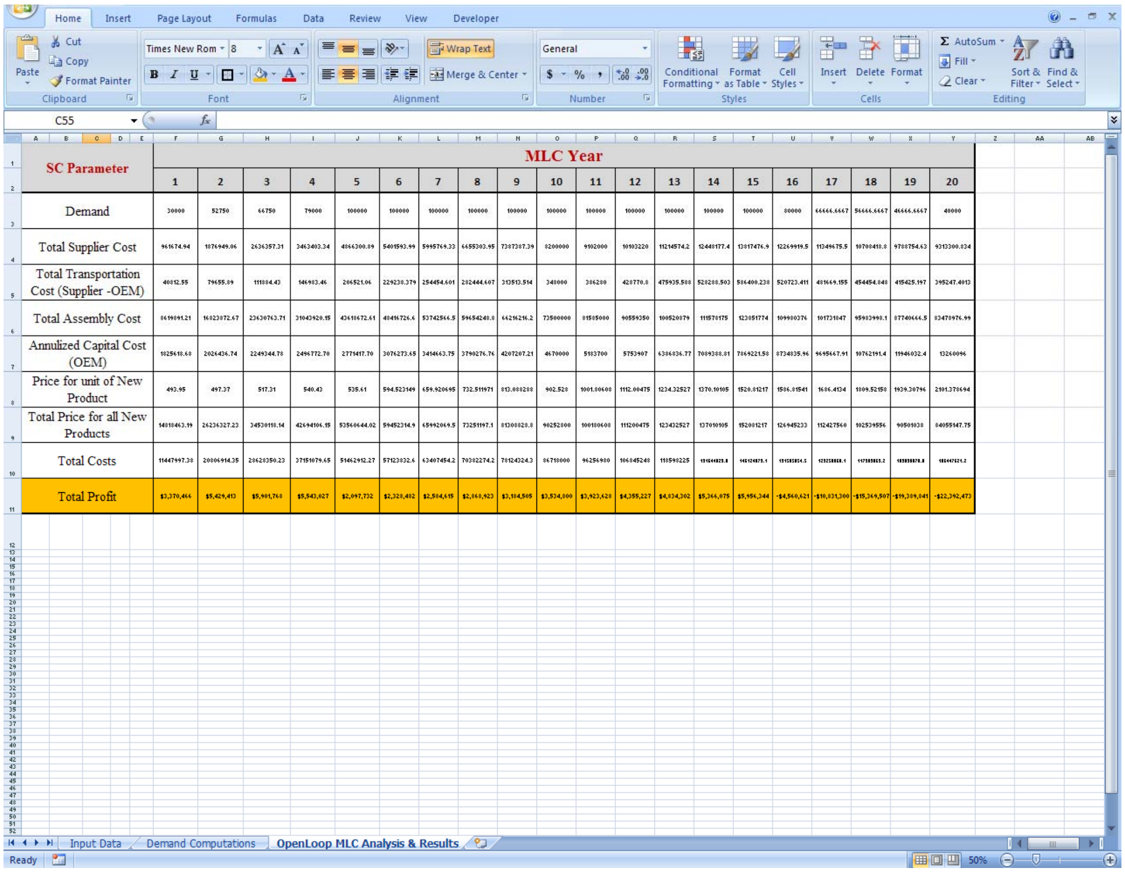
Price and Demand Computations for Other Years in Introduction and Decline Phases			
Price Adjustment Factor for other Years in Introduction and Decline Phase			
Year	Factor	Price ($)	Demand (Units)
2	1.27	1146.21	52750
3	1.19	1074.01	66750
4	1.12	1010.83	79000
16	0.94	848.38	80000
17	0.9	812.28	66667
18	0.87	785.20	56667
19	0.84	758.12	46667

Price, Demand Computations for all Years in MLC Analysis										
SC Parameter	Year in Time Period T									
	1	2	3	4	5 to 15	16	17	18	19	20
Price New Product/Unit ($)	1263.54	1146.21	1074.01	1010.83	902.53	848.37632	812.2752	785.19936	758.12352	740.07296
Demand (Units)	30000	52750	66750	79000	100000	80000	66667	56667	46667	40000

Figure 5.11: MLC_{Osc} 'Demand Computations' Sheet for Model RD_1

5.7.3 Results

The results of the open-loop MLC analysis are presented in this section. Using the input data and demand computations, the MLC_{Osc} tool, calculates the annual SC costs, prices, revenue and thereby the annual profit for each year in the 20 year period. All these computations are performed in the 'Open-loop MLC Analysis and Results' sheet illustrated in Figure 5.12 for refrigerator model RD_1.



SC Parameter	1	2	3	4	5	6	7	8	9	10
Demand	30000	52750	66750	79000	100000	100000	100000	100000	100000	100000
Total Supplier Cost	961674.94	1876949.06	2636357.31	3463403.34	4866300.89	5401593.99	5995769.33	6655303.95	7387387.39	8200000
Total Transportation Cost (Supplier -OEM)	40812.55	79655.89	111884.43	146983.46	206521.06	229238.379	254454.601	282444.607	313513.514	348000
Total Assembly Cost	8619891.21	16823872.67	23630763.71	31043920.15	43618672.61	48416726.6	53742566.5	59654248.8	66216216.2	73500000
Annulized Capital Cost (OEM)	1825618.68	2026436.74	2249344.78	2496772.70	2771417.70	3076273.65	3414663.75	3790276.76	4207207.21	4670000
Price for unit of New Product	493.95	497.37	517.31	540.43	535.61	594.523149	659.920695	732.511971	813.088288	902.528
Total Price for all New Products	14818463.19	26236327.23	34530118.14	42694106.15	53560644.02	59452314.9	65992069.5	73251197.1	81308828.8	90252800
Total Costs	11447997.38	20806914.35	28628350.23	37151079.65	51462912.27	57123832.6	63407454.2	70382274.2	78124324.3	86718000
Total Profit	$3,370,466	$5,429,413	$5,901,768	$5,543,027	$2,097,732	$2,328,482	$2,584,615	$2,868,923	$3,184,505	$3,534,800

SC Parameter	11	12	13	14	15	16	17	18	19	20
Demand	100000	100000	100000	100000	100000	80000	66666.6667	56666.6667	46666.6667	40000
Total Supplier Cost	9102000	10103220	11214574.2	12448177.4	13817476.9	12269919.5	11349675.5	10708418.8	9788754.63	9313300.834
Total Transportation Cost (Supplier -OEM)	386280	428770.8	475935.588	528288.503	586400.238	520723.411	481669.155	454454.848	415425.197	395247.4013
Total Assembly Cost	81585000	90559350	100520879	111578175	123851774	109980376	101731847	95983998.1	87740666.5	83478976.99
Annulized Capital Cost (OEM)	5183700	5753907	6386836.77	7089388.81	7869221.58	8734835.96	9695667.91	10762191.4	11946032.4	13260096
Price for unit of New Product	1001.80608	1112.00475	1234.32527	1370.10105	1520.81217	1586.81541	1686.4134	1809.52158	1939.30796	2101.378694
Total Price for all New Products	100180608	111200475	123432527	137010105	152081217	126945233	112427560	102539556	90501038	84055147.75
Total Costs	96256980	106845248	118598225	[illegible]	[illegible]	[illegible]	[illegible]	117909065.2	[illegible]	106447621.2
Total Profit	$3,923,628	$4,355,227	$4,834,302	$5,366,075	$5,956,344	-$4,560,621	-$10,831,300	-$15,369,507	-$19,389,841	-$22,392,473

Figure 5.12: 'Open-loop MLC Analysis and Results' Sheet for Model RD_1

For the rest of the PDSCC combinations, the Open-loop MLC analysis is performed in a similar way and the results (annual cumulative profits) are summarized in Table 5.14.

Table 5.14: Cumulative Profits from Open-loop SC Model (Case Study)

Year	Cumulative Profit for PDSCC (Millions of $)			
	RD_1-RSC_1	RD_2-RSC_2	RD_3-RSC_3	RD_4-RSC_4
1	3.37	6.70	6.11	5.36
2	8.80	20.58	18.83	13.92
3	14.70	36.73	33.80	23.28
4	20.24	52.84	49.03	32.24
5	22.34	61.14	57.96	36.26
6	24.67	70.36	67.86	40.72
7	27.26	80.59	78.86	45.67
8	30.12	91.95	91.06	51.16
9	33.31	104.56	104.61	57.27
10	36.84	118.55	119.65	64.04
11	40.77	134.09	136.34	71.55
12	45.12	151.33	154.87	79.90
13	49.96	170.47	175.44	89.16
14	55.32	191.71	198.27	99.44
15	61.28	215.29	223.61	110.85
16	56.72	213.63	225.92	107.27
17	45.89	199.31	216.04	95.33
18	30.52	177.77	198.61	77.79
19	11.13	152.11	175.77	55.83
20	**-11.26**	**125.11**	**150.12**	**30.99**

5.8 Closed-loop versus Open-loop Models

For each PDSCC combination, the annual cumulative profits obtained from closed-loop and open-loop SC models are compared for a period of 20 years in increments of one year and plotted in Figure 5.13.

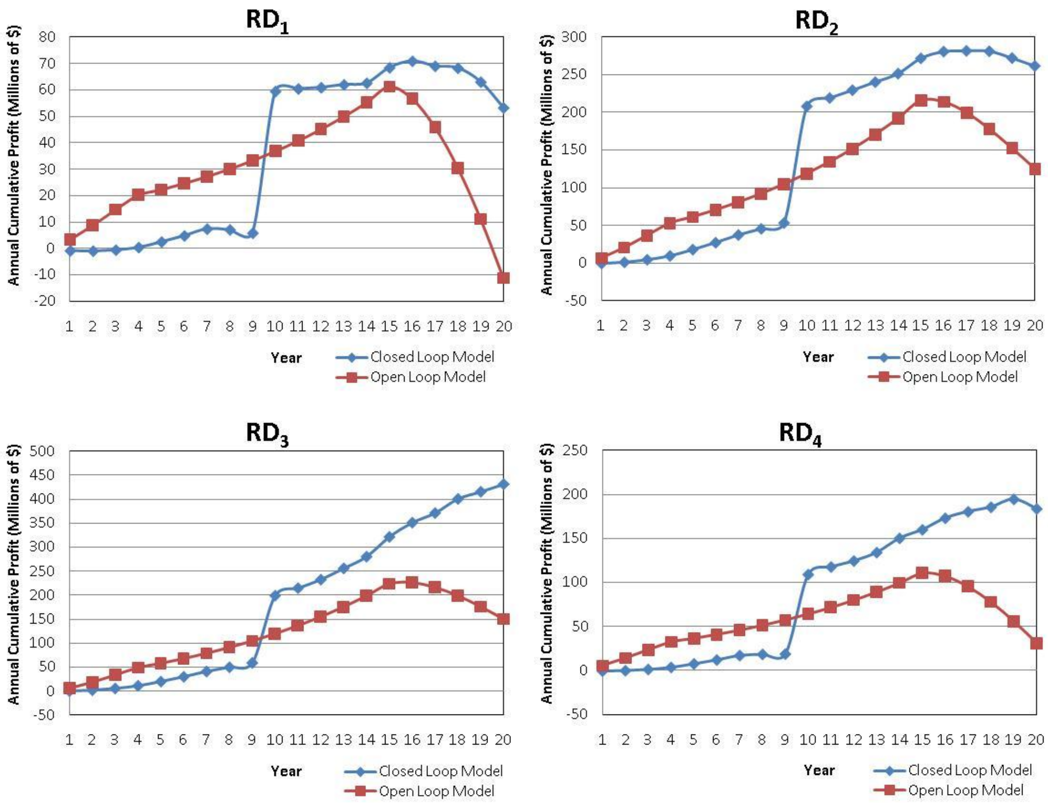


Figure 5.13: Comparison of Annual Cumulative Profits

5.8.1 Results Summary

For all the PDSCC combinations, for the first few years, the open-loop model generates more profits as compared to the closed-loop model. This is because until the year recovered products are available for their next life, all the demand is satisfied by only new products in closed-loop model. However, in the open-loop, while all the demand is satisfied by only new product throughout the 20 year period, the additional reverse loop related costs are not incurred. Hence, the open-loop SC model generates better profits during the first few years. However, once the refrigerators returned from year 1 are processed and are available for their next life, the closed-loop model starts performing better than the open-loop. As it can be observed, for all the PDSCC combinations, the closed-loop model generated higher profits compared to the open-loop at the end of 20 year period.

From this graphs, several research questions mentioned in the introduction chapter can be answered. For example, if a company is currently operating in an open-loop flow, as in this case, the above comparison can provide information on the minimum number of years that must be considered for a given refrigerator model (that is the minimum years that a product is designed to exist in market (introduction, maturity, and decline phases) for it to start generating the benefits of closed-loop flow. For example, if a closed-loop flow is pursued for the RD_1-RSC_1 combination, then the refrigerator model RD_1 must exist in the market for at least 10 years ($T = 10$) for it to generate better profits than the open-loop SC model. If for some reason, the RD_1-RSC_1 combination is not designed to be sold in the market for at least 10 years then pursuing closed-loop flow on this combination could result in more losses than profits. Also from this analysis, an interesting observation has been made. For all the PDSCC combinations, the refrigerators returned from year 1 are available to satisfy the demand for year 10. Therefore, a sudden rise in the cumulative profit is observed during the year 10, as the demand from this period onwards is satisfied by new, refurbished and remanufactured refrigerators as opposed to the demand from year 1 to 9 which is satisfied by only new refrigerators.

Secondly, once the minimum value of T is identified for all PDSCC combinations, the above comparison can also enable in identifying the best combination for which pursuing closed-loop flow generates more economic benefits. For example, in this case, while all PDSCC combinations must exist in market for at least 9 years to realize the closed-loop benefits, the amount of benefits obtained from each combination is very different. From the plot, the RD_3-RSC_3 combination has the best economic performance, as it generates maximum cumulative profit at the end of year 20, followed RD_2-$RSC_{2,}$ RD_4-$RSC_{4,}$ and RD_1-RSC_1.

Thirdly, using the EOM and the MLC_{Eco} tool, the main factors that drive the economic performance of the closed-loop SC models can also be identified. As discussed earlier the annual total demand and the number of refurbished and remanufactured products used to satisfy this demand, impact the economic performance of the closed-loop SC models to a large extent. Ideally higher the demand, the costs incurred are more and therefore the revenue generated is also higher. However, as more refurbished and remanufactured quantity satisfies the demand, better profits are realized as no material acquisition costs are incurred. However, the open-loop model's profits merely depend on the total demand and the price of the product. Therefore, all the ranked PDSCC combinations are sent to the environmental MLC analysis stage.

5.9 Environmental MLC Analysis Description

In this section the environmental MLC analysis performed on the ranked PDSCC combinations is presented.

5.9.1 Assumptions

All the assumptions considered in the methodology are considered for the case study.

5.9.2 Analysis Description

The environmental MLC analysis is performed using the MLC_{Env} tool as described in the methodology section to identify the best combinations that have minimal environmental impact. The performance criteria used are material usage (number of new components used to satisfy the demand), energy consumed (BTU), CO_2 emissions (Lb).

Each PDSCC combination is analyzed separately, to evaluate their performance with respect to above three criteria.

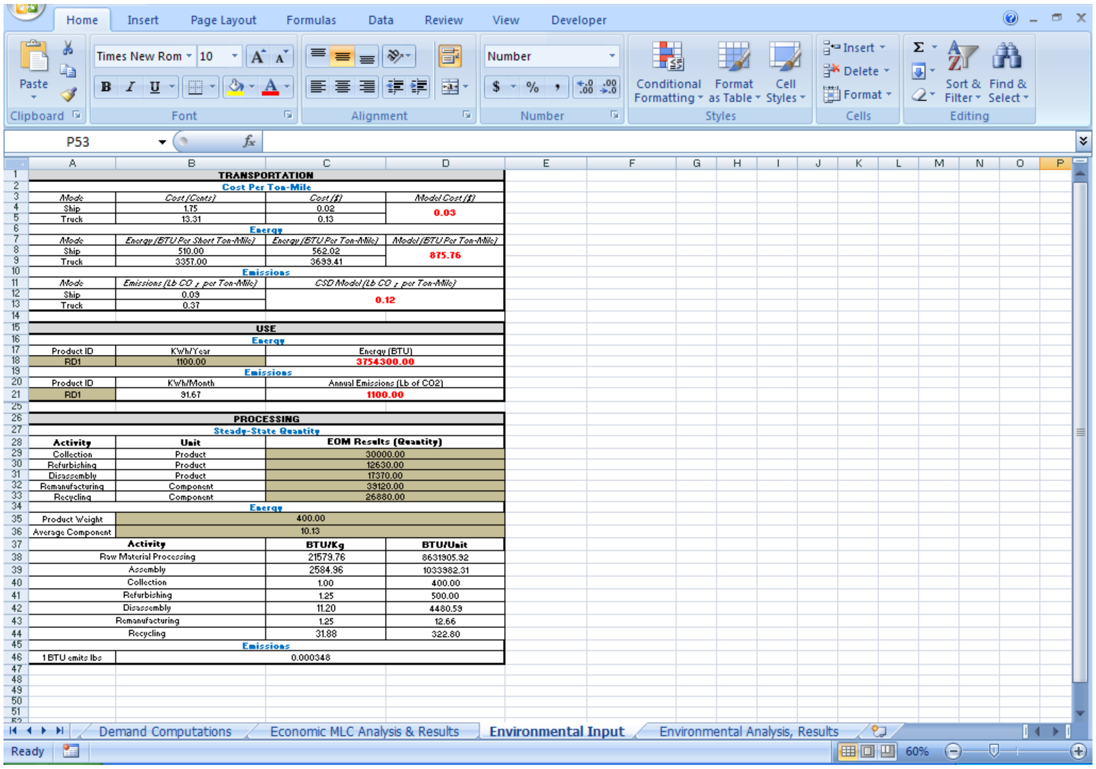
Input data

The transportation, processing, and use related energy and emission conversion factors computed in methodology section are used. As the per-unit energy consumption data for processing operations is based on refrigerators, the same data is used to evaluate the energy performance of alternate PDSCC combinations.

Just similar to the example problem, for each PDSCC combination, the annual refrigerator's energy use data in KWh, the weight of the refrigerator and the average weight of its components, the reverse loop processing quantities, shown in Table 5.15, are entered in to the MLC_{Env} tool's 'Environmental Input Spreadsheet' separately. A snapshot of the spreadsheet for RD_1 is shown in Figure 5.14.

Table 5.15: Input Data for Environmental Multi Life-cycle Analysis

Input Parameter		RD_1	RD_2	RD_3	RD_4
Reverse Loop Processing Quantities (Units)	Collection (Product)	30000	75000	66000	45000
	Refurbishing (Product)	12630	14700	25200	17400
	Disassembly (Product)	17370	60300	40800	27600
	Remanufacturing (Component)	39120	132000	85500	19500
	Recycling (Component)	26880	61800	21900	56700
Weights (Lb)	Refrigerator	400	344	340	335
	Average Component	10.125	8.5	12.5	7.5
Annual Energy Usage (KWh)	Refrigerator	1100	612	542	50

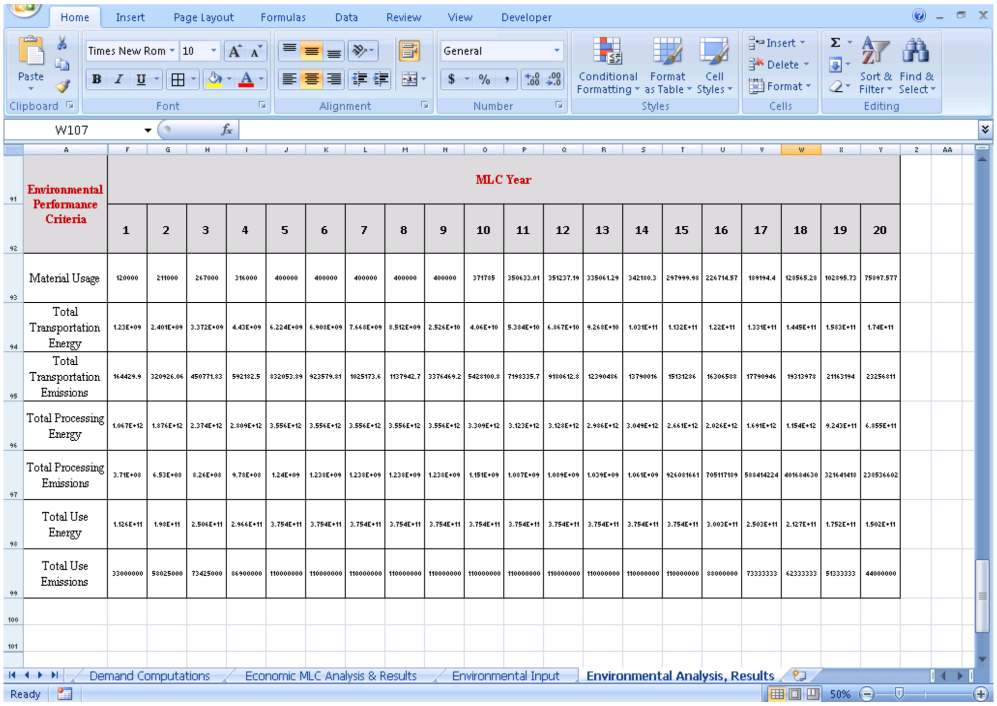


TRANSPORTATION			
Cost Per Ton-Mile			
Mode	*Cost (Cents)*	*Cost ($)*	*Model Cost ($)*
Ship	1.75	0.02	**0.03**
Truck	13.31	0.13	
Energy			
Mode	*Energy (BTU Per Short Ton-Mile)*	*Energy (BTU Per Ton-Mile)*	*Model (BTU Per Ton-Mile)*
Ship	510.00	562.02	**875.76**
Truck	3357.00	3699.41	
Emissions			
Mode	*Emissions (Lb CO 2 per Ton-Mile)*	*CSD Model (Lb CO 2 per Ton-Mile)*	
Ship	0.09	**0.12**	
Truck	0.37		
USE			
Energy			
Product ID	KWh/Year	Energy (BTU)	
RD1	1100.00	**3754300.00**	
Emissions			
Product ID	KWh/Month	Annual Emissions (Lb of CO2)	
RD1	91.67	**1100.00**	
PROCESSING			
Steady-State Quantity			
Activity	**Unit**	**EOM Results (Quantity)**	
Collection	Product	30000.00	
Refurbishing	Product	12630.00	
Disassembly	Product	17370.00	
Remanufacturing	Component	39120.00	
Recycling	Component	26880.00	
Energy			
Product Weight	400.00		
Average Component	10.13		
Activity		**BTU/Kg**	**BTU/Unit**
Raw Material Processing		21579.76	8631905.92
Assembly		2584.96	1033982.31
Collection		1.00	400.00
Refurbishing		1.25	500.00
Disassembly		11.20	4480.59
Remanufacturing		1.25	12.66
Recycling		31.88	322.80
Emissions			
1 BTU emits lbs	0.000348		

Figure 5.14: MLC_{Env} ‘Environmental Input Spreadsheet’ for RD_1

5.9.3 Results

The SC costs, the past refurbished and remanufactured quantity data from the economic MLC results is gathered by the ‘Environmental Analysis, Results’ spreadsheet to compute the environmental impact for each PDSCC separately. The total material usage, the total processing energy, total processing CO_2 emissions, total transportation energy, total transportation CO_2 emissions, total use energy and total use CO_2 emissions are all computed for each PDSCC combination separately to evaluate their environmental performance. Figure 5.15 presents the results obtained for the model RD_1.



Environmental Performance Criteria	MLC Year 1	2	3	4	5	6	7	8	9	10
Material Usage	120000	211000	267000	316000	400000	400000	400000	400000	400000	371785
Total Transportation Energy	1.23E+09	2.401E+09	3.372E+09	4.43E+09	6.224E+09	6.908E+09	7.668E+09	8.512E+09	2.526E+10	4.06E+10
Total Transportation Emissions	164429.9	320926.06	450771.83	592182.5	832053.89	923579.81	1025173.6	1137942.7	3376469.2	5428100.8
Total Processing Energy	1.067E+12	1.876E+12	2.374E+12	2.809E+12	3.556E+12	3.556E+12	3.556E+12	3.556E+12	3.556E+12	3.309E+12
Total Processing Emissions	3.71E+08	6.53E+08	8.26E+08	9.78E+08	1.24E+09	1.238E+09	1.238E+09	1.238E+09	1.238E+09	1.151E+09
Total Use Energy	1.126E+11	1.98E+11	2.506E+11	2.966E+11	3.754E+11	3.754E+11	3.754E+11	3.754E+11	3.754E+11	3.754E+11
Total Use Emissions	33000000	58025000	73425000	86900000	110000000	110000000	110000000	110000000	110000000	110000000

Environmental Performance Criteria	MLC Year 11	12	13	14	15	16	17	18	19	20
Material Usage	350633.01	351237.19	335061.29	342180.3	297999.98	226714.57	189194.4	128565.28	102895.73	75897.577
Total Transportation Energy	5.384E+10	6.867E+10	9.268E+10	1.031E+11	1.132E+11	1.22E+11	1.331E+11	1.445E+11	1.583E+11	1.74E+11
Total Transportation Emissions	7198335.7	9180612.8	12390486	13790016	15131286	16306588	17790946	19313978	21163194	23256811
Total Processing Energy	3.123E+12	3.128E+12	2.986E+12	3.049E+12	2.661E+12	2.026E+12	1.691E+12	1.154E+12	9.243E+11	6.855E+11
Total Processing Emissions	1.087E+09	1.089E+09	1.039E+09	1.061E+09	926081661	705117189	588414224	401684630	321641418	238536602
Total Use Energy	3.754E+11	3.754E+11	3.754E+11	3.754E+11	3.754E+11	3.003E+11	2.503E+11	2.127E+11	1.752E+11	1.502E+11
Total Use Emissions	110000000	110000000	110000000	110000000	110000000	88000000	73333333	62333333	51333333	44000000

Figure 5.15: ‘Environmental Analysis, Results’ sheet for Model RD_1

Similar computations are performed to calculate the environmental performance of rest of the PDSCC combinations using the MLC_{Env} tool. At the end of analysis, each of the seven performance criteria across SC are compared for each ranked PDSCC combinations to select the best combinations for the subsequent stage. Table 5.16 presents the summary of results obtained for ranked PDSCC combination.

Table 5.16: Summary of Environmental MLC Analysis Results (Case Study)

60		Year																			
61	PDSCC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
62		Cumulative Transportation Energy (BTU)																			
63	RD1-RSC1	1223937858	3638466742	7882249858	11431779967	17655544143	24569929851	32292296299	40744857938	56888875679	1.06682E+11	1.60446E+11	2.29117E+11	3.21798E+11	4.24947E+11	5.3813E+11	6.60183E+11	7.93179E+11	9.37648E+11	1.09535E+12	1.26391E+12
64	RD2-RSC2	1949866841	6986556842	14991171829	24493499968	39188866947	55565789568	79744888247	99929766298	1.35917E+11	2.07693E+11	3.05395E+11	4.31992E+11	6.0562E+11	7.98771E+11	1.01083E+12	1.29227E+12	1.47116E+12	1.72611E+12	2.00412E+12	2.31855E+12
65	RD3-RSC3	2347687778	10954788498	24481265994	36486496284	58282698782	82565286599	1.09519E+11	1.99497E+11	1.30841E+11	2.78462E+11	3.75877E+11	5.09526E+11	6.0741E+11	8.05445E+11	1.09785E+12	1.32819E+12	1.55771E+12	1.80582E+12	2.07969E+12	2.36447E+12
66	RD4-RSC4	1458953821	4380884614	8534824983	14084918984	21798369848	38986835326	39826179888	58992572418	79888288656	1.23789E+11	1.84239E+11	2.62844E+11	3.66357E+11	4.82679E+11	6.1223E+11	7.49637E+11	8.98666E+11	1.06877E+12	1.23614E+12	1.49851E+12
67	PDSCC	Cumulative Transportation Emissions (Lbs of CO_2)																			
68	RD1-RSC1	164429.3883	405955.9584	996427.7864	1528848.289	2968964.47	3289949.984	4989117.579	5447868.268	8829529.454	14251698.28	24449965.97	30698578.77	49824864.99	56844888.66	74942966.47	88248954.58	106899988.5	125959878.6	146547872.6	169779889.2
69	RD2-RSC2	259874.8424	929995.915	1915929.874	3266498.858	5299848.481	7428561.519	9858929.948	12556698.91	18898472.9	27758352.99	48828897.62	57744848.39	88965194.87	106787456.7	195145614.2	164741588.2	196678498.5	298769422.4	267998597.8	308896686.5
70	RD3-RSC3	994864.764	1984916.667	2864128.542	4867165.857	7794786.654	11898416.62	14641542.89	18644946.84	25519488.79	96458897.47	58258878.94	68118551.86	91899627.8	118974827	146771869.6	176495529	208249589.9	241912165	277229995.8	316185887.6
71	RD4-RSC4	195847.8817	586641.6582	1148911.117	1872912.874	2985286.554	4851719.428	5924948.717	6796967.228	18548159.82	16598591.97	24698888.62	35892579.15	49858485.98	64529267.99	81848872.91	100218794.1	120142999.8	141814828.1	165258698	191249791.4
72	PDSCC	Cumulative User Energy (BTU)																			
73	RD1-RSC1	1.12629E+11	3.18668E+11	5.61268E+11	8.57858E+11	1.29929E+12	1.68872E+12	1.98415E+12	2.35958E+12	2.79581E+12	3.11844E+12	3.48587E+12	3.8619E+12	4.29679E+12	4.61216E+12	4.98759E+12	5.28799E+12	5.59822E+12	5.75896E+12	5.92616E+12	6.07699E+12
74	RD2-RSC2	1.84498E+11	3.44645E+11	6.68482E+11	1.86527E+12	1.58745E+12	2.18964E+12	2.69189E+12	3.15482E+12	3.67624E+12	4.4984E+12	4.72859E+12	5.24278E+12	5.76497E+12	6.28746E+12	6.88994E+12	7.19576E+12	7.49467E+12	7.74969E+12	7.87989E+12	7.99471E+12
75	RD3-RSC3	89249878888	2.71696E+11	5.24894E+11	8.94749E+11	1.24171E+12	1.64868E+12	2.05564E+12	2.46261E+12	2.86957E+12	3.27654E+12	3.68351E+12	4.09847E+12	4.49744E+12	4.9044E+12	5.31197E+12	5.61968E+12	5.86221E+12	6.05542E+12	6.1999E+12	6.31829E+12
76	RD4-RSC4	51965658888	1.44272E+11	2.62741E+11	4.09579E+11	5.82761E+11	7.61944E+11	9.41126E+11	1.12891E+12	1.29949E+12	1.47867E+12	1.65786E+12	1.89784E+12	2.01622E+12	2.1954E+12	2.37459E+12	2.51995E+12	2.62677E+12	2.71968E+12	2.79268E+12	2.85241E+12
77	PDSCC	Cumulative User Emissions (Lbs of CO_2)																			
78	RD1-RSC1	99000000	91825000	164450000	251950000	361950000	471950000	581950000	691950000	801950000	911950000	1021950000	1131950000	1241950000	1351950000	1461950000	1549950000	1622609999	1685816667	1796950000	1788950000
79	RD2-RSC2	30600000	100300000	195840000	312120000	465120000	618120000	771120000	924120000	1077120000	1230120000	1383120000	1536120000	1689120000	1842120000	1995120000	2100340000	2195040000	2261050000	2300770000	2342430000
80	RD3-RSC3	24990000	79606250	159792500	244577500	369817500	489057500	602297500	721537500	840777500	960017500	1079257500	1198497500	1317737500	1436977500	1556217500	1646550899	1717649856	1774224944	1816577500	1848897500
81	RD4-RSC4	15050000	42271250	76302500	118247500	170747500	229247500	275747500	328247500	388747500	433247500	485747500	538247500	590747500	643247500	695747500	796500899.9	769696300.9	796858611.1	810247500	835747500
82	PDSCC	Cumulative Processing Energy (BTU)																			
83	RD1-RSC1	1.06608E+12	2.94281E+12	5.91662E+12	8.12687E+12	1.16829E+13	1.52986E+13	1.87949E+13	2.29511E+13	2.59874E+13	2.9216E+13	3.29991E+13	3.54675E+13	3.84599E+13	4.15828E+13	4.41699E+13	4.61981E+13	4.7881E+13	4.90952E+13	4.99595E+13	5.06449E+13
84	RD2-RSC2	1.52924E+12	5.04698E+12	9.78692E+12	1.55979E+13	2.92499E+13	3.889E+13	3.8596E+13	4.6182E+13	5.3828E+13	6.11619E+13	6.84446E+13	7.5119E+13	8.47768E+13	8.85844E+13	9.48214E+13	9.88954E+13	1.01829E+14	1.03468E+14	1.04498E+14	1.05281E+14
85	RD3-RSC3	1.36827E+12	4.49978E+12	8.57727E+12	1.36485E+13	2.82987E+13	2.69489E+13	3.35912E+13	4.82414E+13	4.68916E+13	5.38151E+13	5.98579E+13	6.58451E+13	7.06758E+13	7.69729E+13	8.12592E+13	8.4846E+13	8.76482E+13	8.91428E+13	9.82999E+13	9.88791E+13
86	RD4-RSC4	1.2087E+12	3.59714E+12	6.55894E+12	1.08624E+13	1.459E+13	1.89976E+13	2.34651E+13	2.79327E+13	3.24883E+13	3.62982E+13	4.01685E+13	4.42276E+13	4.81599E+13	5.19294E+13	5.50955E+13	5.86984E+13	6.08954E+13	6.254E+13	6.36289E+13	6.46085E+13
87	PDSCC	Cumulative Processing Emissions (Lbs of CO_2)																			
88	RD1-RSC1	371274164.9	1824837895	1858182984	2827871529	4865452866	5383892684	6548619142	7778199679	9815774247	10167168921	11254881412	12942682818	13981979799	14442968687	15369842268	16874159457	16662579688	17864258918	17985899729	17624496998
89	RD2-RSC2	592169542.6	1756199691	3485846679	5428868195	8888885848	10749789561	13418521274	16871998987	18792156788	21284115626	23714919126	26144486178	28458998249	30799544584	32997868817	34934718864	35496668524	36886946928	36965928657	36697692589
90	RD3-RSC3	479974679.9	1545842999	2984898585	4746896896	7861172228	9975448489	11689724587	14884888771	16918276955	18458699426	20551929585	22697869899	24595174462	26577778629	28276111888	29526424282	30498797721	31824787289	31489496462	31625928471
91	RD4-RSC4	445884426.2	1251889176	2279727664	3581792172	5856445287	6611158482	8165871517	9728584691	11275297746	12688125956	13975849214	15391212728	16757948491	18869951982	19451627849	20489371248	21178789129	21769919262	22199854958	22588881912
92	PDSCC	Cumulative Material Usage (Units of Quantity)																			
93	RD1-RSC1	120000	331000	530000	914000	1314000	1714000	2114000	2514000	2914000	3205785	3696418.81	3907655.205	4922716.494	4664896.792	4962896.771	5183611.34	5378885.749	5587971.824	5610266.752	5686164.929
94	RD2-RSC2	200000	660000	1200000	2040000	3040000	4040000	5040000	6040000	7040000	7990700	8910499.24	9820865.545	10680972.99	11566984.27	12909424.16	12909794.85	13297649.86	13587290.4	13690465.76	13790974.89
95	RD3-RSC3	100000	587500	1135000	1885000	2685000	3565000	4445000	5325000	6205000	7014660	7812595.299	8684408.878	9947208.198	10099598.25	10742210.82	11215845.54	11582661.49	11778562.91	11921469.9	12084274.86
96	RD4-RSC4	472000	489100	879000	1954400	1951400	2551400	3151400	3751400	4351400	4864520	5391045.948	5997760.475	6464540.869	6578494.59	7589472.865	7878896.858	8165627.165	8999992.58	8598459.977	8688298.946

To compare the environmental performance of each PDSCC combination, graphs are plotted for the total cumulative energy (Figure 5.16), total cumulative CO_2 emissions (Figure 5.17), and total cumulative ratio of cumulative material used and cumulative annual demand (Figure 5.18). As the materials used is directly proportional to the individual year's demand, the ratio of cumulative materials used for new components over cumulative demand is plotted for comparison.

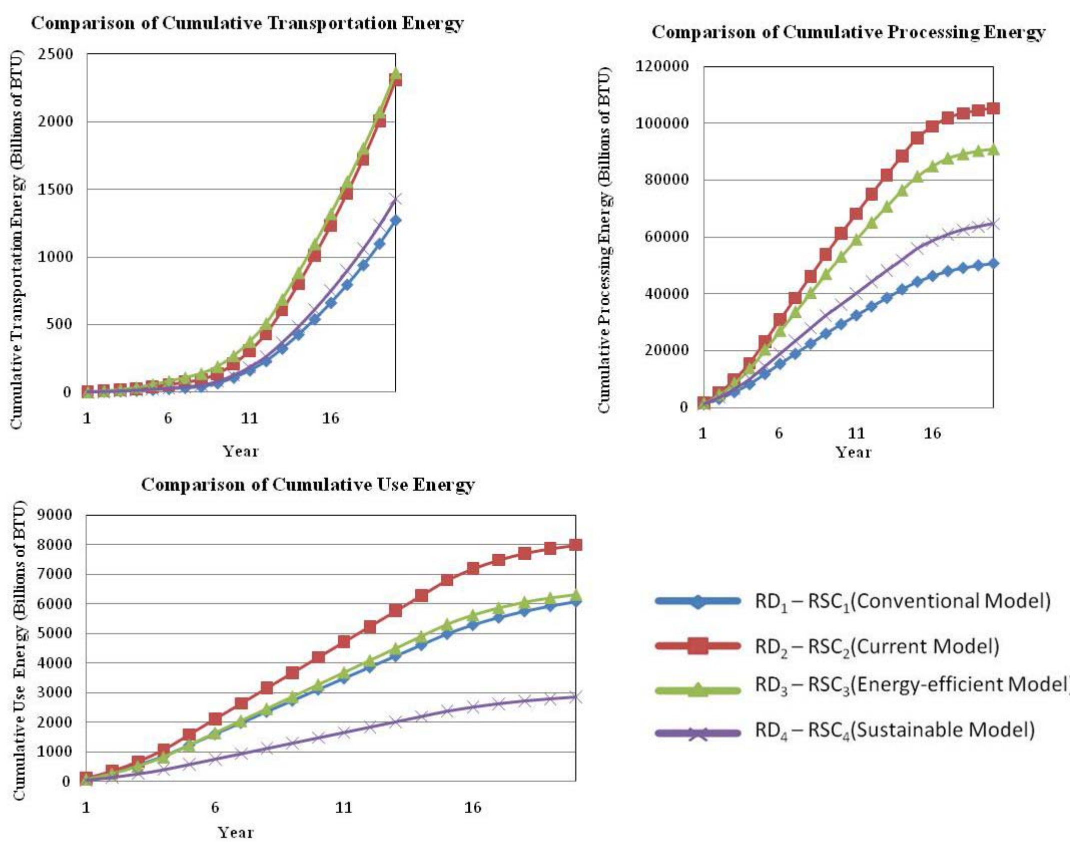


Figure 5.16: Comparison of Total Cumulative Energy Consumption

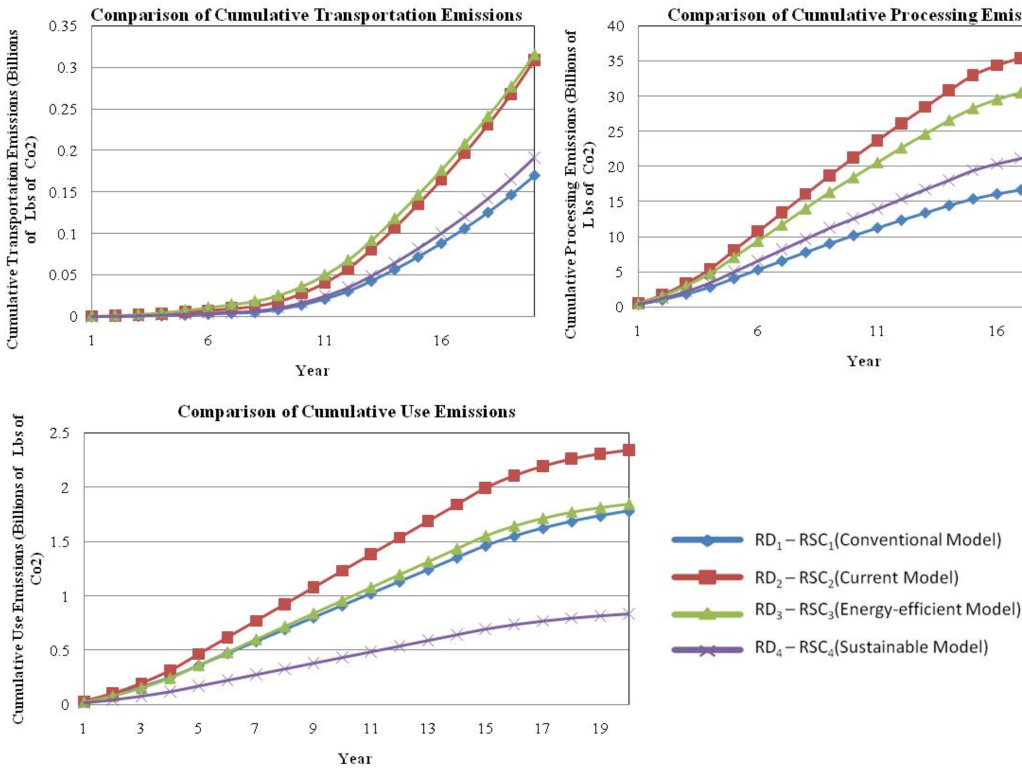


Figure 5.17: Comparison of Total Cumulative Emissions Released

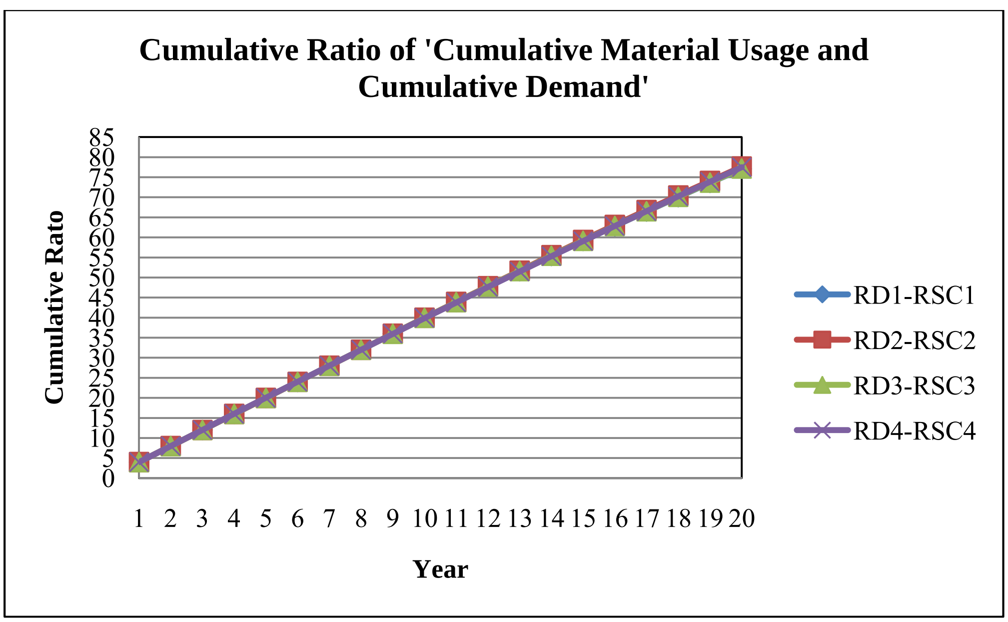


Figure 5.18: Cumulative Ratio of Material Usage over Demand

The total cumulative energy, total cumulative CO_2 emissions and total cumulative material usage ratio for each PDSCC is computed at the end of the 20^{th} year to select the best PDSCC combinations with maximum environmental performance for the next stage (Table 5.17).

As the environmental performance criteria are highly impacted by the demand, comparing just the cumulative energy and emissions values at the end of year 20 may not be the best way to evaluate the alternate PDSCC environmental performance. The high demand for the alternate refrigerator models is impacting the cumulative energy and emissions values to an extent that the actual environmental performance is not clearly observed. Hence for comparison purposes, the ratio of the cumulative energy and emissions values at the end of the year 20 values over the cumulative demand at the end of the year 20 is computed to evaluate the environmental performance of the PDSCC combinations. As the material usage plot already considers the total cumulative demand factor, the cumulative ratio values at the end of year 20 are used to compare the alternate PDSCC combinations. However the transportation, processing and use activities related graphs for the energy and emissions criteria compare the actual values, as each of these depend on several other individual parameters apart from demand. The combinations are finally ranked based on their economic and environmental performance.

Table 5.17: MLC Performance of PDSCC Combinations (Case Study)

PDSCC	Economic		Environmental				
	Maximum Profit (Millions of $)	Ranking	Energy Ratio (BTU/Unit)	Emission Ratio (Lb/ Unit)	Cumulative Material Usage (Ratio)	Rank 'Energy and Emissions'	Rank 'Material Usage'
RD_1-RSC_1	53.23	4	35830090	12091.44	77.12	4	1
RD_2-RSC_2	261.36	2	30198824	10262.57	77.67	3	4
RD_3-RSC_3	430.60	1	29183730	9905.45	77.20	2	2
RD_4-RSC_4	183.73	3	28880792	9854.05	77.50	1	3

5.9.4 Summary

Energy

The transportation energy for alternate PDSCC combinations increases with increase in the transportation quantity, the distance transported and the cost of transportation. Therefore in this case, the RD_1-RSC_1combination consumes least transportation energy, as the demand for this combination is very less, followed by RD_4-RSC_4, RD_2-RSC_2, RD_3-RSC_3combinations.

The processing energy increases with increase in the processing quantity and the average weights of the refrigerator and its critical components. As the average weights among alternate PDSCC combinations does not differ much in this case, it can be observed that the processing quantity (annual demand) impacts the processing energy to a large extent. While the energy consumed during each operation such as (raw material processing, assembly, collection, disassembly, remanufacturing and recycling) impacts the processing energy components, these values remain constant among alternate PDSCC combinations. Hence, the RD_1-RSC_1 combination consumes least processing energy, followed by RD_4-RSC_4, RD_3-RSC_3, RD_2-RSC_2 combinations following the demand pattern.

The energy consumed during use stage increases as the annual energy usage and the annual demand increases for PDSCC combination. Therefore, the combination RD_4-RSC_4 consumes least use energy, followed by RD_1-RSC_1, RD_3-RSC_3 and RD_2-RSC_2. Although the energy usage for the RD_1-RSC_1 is very high the combination still ranks second place because of its very low demand.

Therefore, from above energy plots it has been observed that the annual demand plays a major role in energy consumptions and also making decisions based on this demand does not provide accurate environmental assessment. Hence, to evaluate the alternate PDSCC combinations the total cumulative energy consumed by each combination is divided by cumulative demand at the end of year 20, so that the actual environmental performance is observed. The RD_4-RSC_4, combination has least total energy ratio followed by RD_3-RSC_3, RD_2-RSC_2, and RD_1-RSC_1.

Emissions

The emissions released from each combination depend on energy consumption. Therefore, the combination that consumes less transportation energy, less processing energy, and less use energy releases less transportation emissions, less processing emissions and less use emissions. As energy is highly dependent on the demand, the emissions also depend on the demand. Therefore, in this case too, the ratio of the total cumulative emissions released over cumulative annual demand at the end of year 20 is computed to evaluate the emissions related environmental criteria and the rankings of PDSCC combinations is shown in Table 5.17.

Material Usage

The material usage criteria depends on steady-state refurbished and remanufactured quantities, the demand ratio for each year in the period of 20 years, and the percentage of past refurbished and remanufactured quantities that can be used for each year in the 20 year period. In this case, the ratio of the cumulative quantity of new components over cumulative demand is plotted to observe the performance of each combination. From these plots it has been observed that RD_1-RSC_1 combination requires least quantity of new components followed by RD_3-RSC_3, RD_4-RSC_4 and RD_2-RSC_2. While it is not an expected outcome for the RD_1-RSC_1 combination to perform better than others, as the conventional model has the least refurbishing, remanufacturing and recycling probabilities, these results indicate that this criteria considerably depends on the other factors such as demand ratios, the steady-state results, and the percentages values given by the user and these values are highest for the RD_1-RSC_1 combination in this case, as compared to others. Therefore, from these plots it has been observed that merely having high refurbishing, remanufacturing and recycling ratings is not enough for a PDSCC to perform well with respect to material consumption criteria over MLCs. Several other factors as mentioned above, such as demand ratios, steady-state results and percentages play an important role in the material usage criteria.

Therefore, the environmental MLC analysis is performed and the best PDSCC combinations that have maximum environmental performance are ranked. As all the combinations do not have similar performance with respect to the energy, emissions and material usage criteria the ranking for each of these criteria are presented separately. As there are only four combinations, the combinations are ranked based on the environmental performance and are sent to next stage.

If selection has to be made at this stage, one way is to identify the common PDSCC combinations that have best performance with respect to all three environmental criteria. However, in this case, as the rankings for energy, emissions and material usage are very different, one way to select the best combinations is to sum the energy, emissions and material usage rankings of each PDSCC combination and select the top combinations with least ranks. Therefore, following this approach, the combinations RD_4-RSC_4, and RD_3-RSC_3 have a total ranking of 4 which is less than the ranks of combinations RD_1-RSC_1 (5) and RD_2-RSC_2(7), respectively. Therefore, at the end of the environmental MLC analysis, all the PDSCCs are ranked based on their environmental performance and are sent to next stage.

5.10 Societal MLC Analysis Description

In this section, the societal MLC analysis performed on the PDSCC combinations ranked based on their economic and environmental performance is presented.

5.10.1 Assumptions

All the assumptions presented in the methodology section for the societal MLC analysis are considered here.

5.10.2 Analysis Description

The MLC_{Soc} tool developed and described in the methodology section is used to perform the analysis for each combination separately. The performance criteria used are supplier societal-compliance ratio, supplier training and development, employee training and development, product customizability rate.

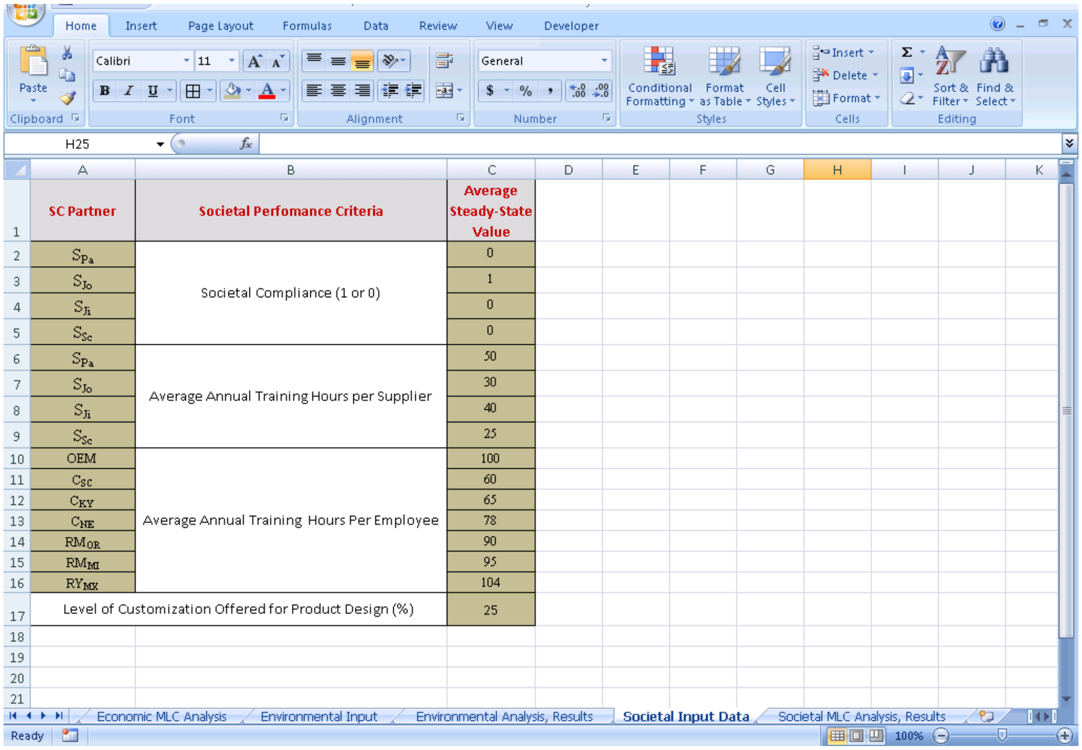
Input Data

The steady-state input values such as supplier societal compliance, average supplier training hours, average employee training hours, product customizability rate are entered into the 'Societal Input data' spreadsheet to compute the corresponding societal metrics for a period of 20 years. Due to unavailability of actual company data, the input data for the case study problem is established based on the subjective estimated values. However, if the actual data is provided the MLC_{Soc} tool computes the societal performance of PDSCC combinations. Table 5.18 presents the input data for each of the combinations.

Table 5.18: Societal Metrics Data for PDSCC Combinations (Case Study)

Stakeholder Sector	Metric	Parameter	RD$_1$		RD$_2$		RD$_3$		RD$_4$	
			Partner	Value	Partner	Value	Partner	Value	Partner	Value
Supplier	Societal-Compliance Ratio	Societal Compliance (1 or 0)	S_{Pa}	0	S_{De}	1	S_{Pa}	1	S_{Pa}	1
			S_{Jo}	1	S_{Ti}	0	S_{No}	1	S_{Ti}	1
			S_{Ji}	0	S_{Sh}	1	S_{Sh}	1	S_{Ji}	1
			S_{Sc}	0	S_{Br}	0	S_{Sc}	0	S_{Br}	1
	Training (Hours/Supplier)	Average Annual Training Hours	S_{Pa}	50	S_{De}	54	S_{Pa}	55	S_{Pa}	60
			S_{Jo}	30	S_{Ti}	34	S_{No}	35	S_{Ti}	37
			S_{Ji}	40	S_{Sh}	45	S_{Sh}	50	S_{Ji}	55
			S_{Sc}	25	S_{Br}	29	S_{Sc}	31	S_{Br}	35
Employee	Training and Development (Hours/Employee)	Average Annual Training Hours Per Employee	OEM	100	OEM	110	OEM	121	OEM	133
			C_{SC}	60	C_{SC}	66	C_{SC}	69	C_{SC}	65
			C_{KY}	65	C_{AK}	72	C_{AK}	75	C_{AK}	79
			C_{NE}	78	C_{MN}	86	C_{MN}	79	C_{NE}	87
			RM_{OR}	90	C_{KY}	81	C_{KY}	79	RM_{MI}	105
			RM_{MI}	95	C_{NE}	79	C_{NE}	82	RM_{MX}	111
			RY_{MX}	104	RM_{OR}	99	RM_{MO}	103	RY_{UT}	117
					RM_{MO}	102	RM_{MX}	107	RY_{NC}	119
					RY_{UT}	110	RY_{UT}	115		
Customer	Customization Level (%)	Customization Rate	25		38		54		75	

A snapshot of the 'Societal Input data' sheet of the MLC$_{Soc}$ tool is shown in Figure 5.19. The data is entered into the highlighted cells.

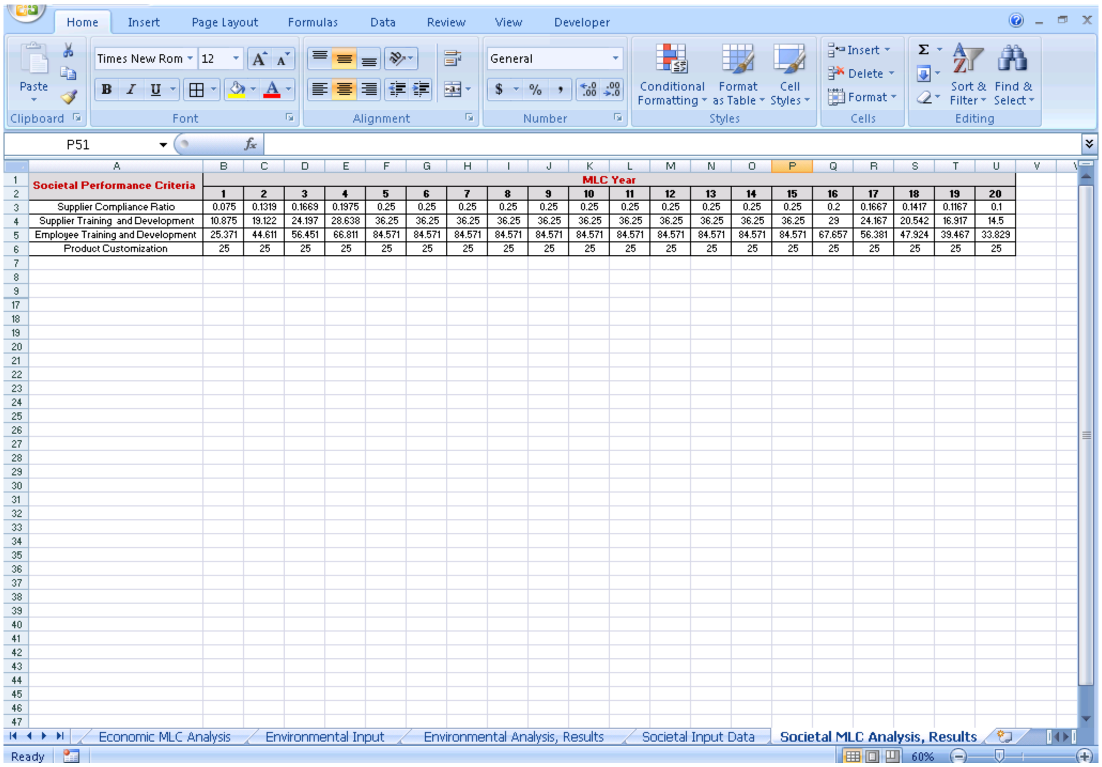


SC Partner	Societal Perfomance Criteria	Average Steady-State Value
S_{Pa}	Societal Compliance (1 or 0)	0
S_{Jo}		1
S_{Ji}		0
S_{Sc}		0
S_{Pa}	Average Annual Training Hours per Supplier	50
S_{Jo}		30
S_{Ji}		40
S_{Sc}		25
OEM	Average Annual Training Hours Per Employee	100
C_{SC}		60
C_{KY}		65
C_{NE}		78
RM_{OR}		90
RM_{MI}		95
RY_{MX}		104
Level of Customization Offered for Product Design (%)		25

Figure 5.19: MLC$_{Soc}$ 'Societal Input Data' Sheet for Model RD$_1$

5.10.3 Results

The 'Societal MLC Analysis & Results' sheet performs all the societal MLC analysis as described in methodology section for each of the PDSCC combinations separately. The four performance criteria (supplier societal-compliance Ratio, supplier training and development, employee training and development, product customizability rate) are all computed to evaluate the societal performance for each combination. Figure 5.20 illustrates the societal MLC analysis criteria and the results for model RD$_1$.



Societal Performance Criteria	MLC Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Supplier Compliance Ratio	0.075	0.1319	0.1669	0.1975	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.2	0.1667	0.1417	0.1167	0.1
Supplier Training and Development	10.875	19.122	24.197	28.638	36.25	36.25	36.25	36.25	36.25	36.25	36.25	36.25	36.25	36.25	36.25	29	24.167	20.542	16.917	14.5
Employee Training and Development	25.371	44.611	56.451	66.811	84.571	84.571	84.571	84.571	84.571	84.571	84.571	84.571	84.571	84.571	84.571	67.657	56.381	47.924	39.467	33.829
Product Customization	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

Figure 5.20: MLC_{Soc} 'Societal MLC Analysis, Results' sheet for Model RD_1

The MLC_{Soc} tool is used to compute the societal performance criteria for rest of the PDSCC combinations. At the end of analysis, each of the four performance criteria is compared for each combination to select the best combination with minimum societal performance. Table 5.19 presents the summary of results obtained for the combinations.

Table 5.19: Summary of Societal MLC Analysis Results (Case Study)

1	PDSCC	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
2		Supplier Compliance Ratio																			
3	RD1-RSC1	0.075	0.207	0.374	0.571	0.821	1.071	1.321	1.571	1.821	2.071	2.321	2.571	2.821	3.071	3.321	3.521	3.688	3.83	3.946	4.0463
4	RD2-RSC2	0.1	0.33	0.64	1.02	1.52	2.02	2.52	3.02	3.52	4.02	4.52	5.02	5.52	6.02	6.52	6.89	7.173	7.392	7.545	7.655
5	RD3-RSC3	0.153	0.501	0.967	1.538	2.288	3.038	3.788	4.538	5.288	6.038	6.788	7.538	8.288	9.038	9.788	10.36	10.8	11.16	11.42	11.629
6	RD4-RSC4	0.287	0.805	1.466	2.252	3.252	4.252	5.252	6.252	7.252	8.252	9.252	10.25	11.25	12.25	13.25	14.03	14.66	15.18	15.59	15.919
7	PDSCC	Supplier Training and Development																			
8	RD1-RSC1	10.88	30	54.19	82.83	119.1	155.3	191.6	227.8	264.1	300.3	336.6	372.8	409.1	445.3	481.6	510.6	534.7	555.3	572.2	586.71
9	RD2-RSC2	8.1	26.73	51.84	82.62	123.1	163.6	204.1	244.6	285.1	325.6	366.1	406.6	447.1	487.6	528.1	558.1	581	598.7	611.1	620.06
10	RD3-RSC3	8.744	28.54	55.14	87.69	130.4	173.2	215.9	258.7	301.4	344.2	386.9	429.7	472.4	515.2	557.9	590.3	615.8	636.1	651.2	662.87
11	RD4-RSC4	13.4	37.64	68.55	105.3	152	198.8	245.5	292.3	339	385.8	432.5	479.3	526	572.8	619.5	655.9	685.3	709.6	728.6	744.21
12	PDSCC	Employee Training and Development																			
13	RD1-RSC1	25.37	69.98	126.4	193.2	277.8	362.4	447	531.5	616.1	700.7	785.2	869.8	954.4	1039	1124	1191	1248	1295	1335	1368.8
14	RD2-RSC2	17.89	59.03	114.5	182.5	271.9	361.4	450.8	540.2	629.7	719.1	808.6	898	987.5	1077	1166	1233	1283	1322	1350	1369.4
15	RD3-RSC3	18.86	61.57	118.9	189.2	281.4	373.6	465.8	558	650.3	742.5	834.7	926.9	1019	1111	1204	1273	1328	1372	1405	1430
16	RD4-RSC4	29.24	82.13	149.6	229.7	331.7	433.7	535.7	637.7	739.7	841.7	943.7	1046	1148	1250	1352	1431	1495	1548	1590	1623.7
17	PDSCC	Customization																			
18	RD1-RSC1	0.25																			
19	RD2-RSC2	0.38																			
20	RD3-RSC3	0.54																			
21	RD4-RSC4	0.75																			

To compare the performance of each PDSCC combination, graphs are plotted for the supplier compliance, supplier training and development, and employee training and development criteria. Since the product customizability remains same overall years as it depends on the refrigerator model, a bar graph for this criterion is plotted. Figure 5.21 presents comparison of societal performance of all combinations.

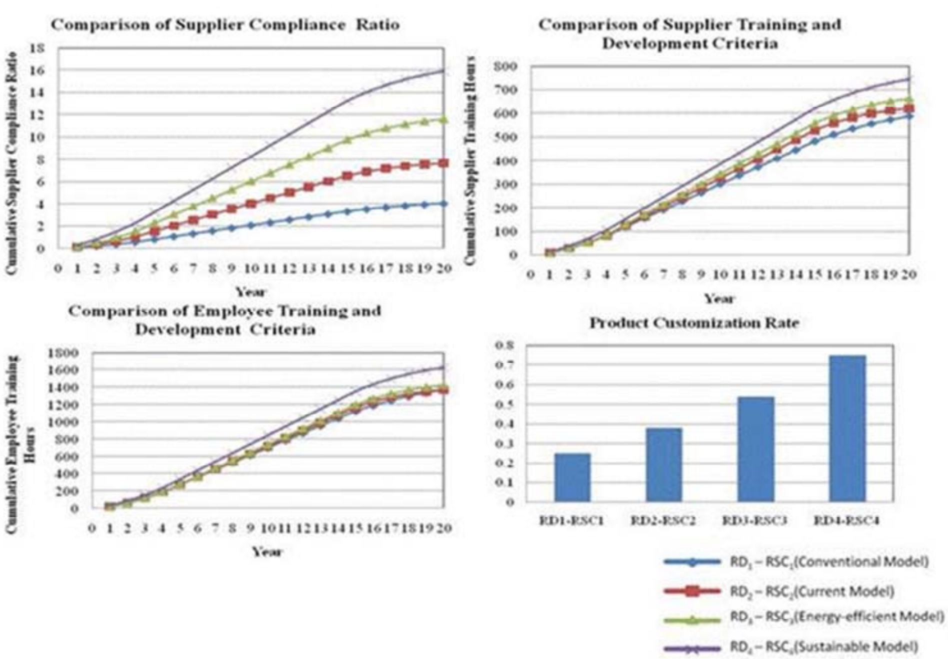


Figure 5.21: Societal Performance of PDSCC Combinations (Case Study)

The total cumulative value of each performance is computed at the end of year 20 to select the best PDSCC combinations with maximum societal performance (Table 5.20). As no PDSCC combinations are eliminated in economic and environmental MLC analysis steps, the best combinations with respect to these criteria are presented for comparison.

Table 5.20: TBL Performance of PDSCC Combinations (Ranks in Parenthesis)

PDSCC	Economic	Environmental Per-unit			Societal			
	Profit (10^6 of $)	Energy Ratio (10^6 BTU)	Emission Ratio (Lb CO_2)	Cumulative Material Usage (Ratio)	Supplier Compliance Rate	Supplier Training (Hours)	Employee Training (Hours)	Customization Rate
RD_1-RSC_1	53.23 [4]	35.83 [4]	12091 [4]	77.12 [1]	4.04 [4]	586.70 [4]	1368.78 [4]	0.25 [4]
RD_2-RSC_2	261.36 [2]	30.19 [3]	10262 [3]	77.67 [4]	7.65 [3]	620.05 [3]	1369.39 [3]	0.38 [3]
RD_3-RSC_3	430.60 [1]	29.18 [2]	9905 [2]	77.20 [2]	11.63 [2]	662.86 [2]	1429.96 [2]	0.54 [2]
RD_4-RSC_4	183.73 [3]	28.88 [1]	9854 [1]	77.50 [3]	15.91 [1]	744.21 [1]	1623.73 [1]	0.75 [1]

5.10.4 Summary

The supplier societal compliance rate, supplier training and development, employee training and development all depend on their steady-state values and the annual demand over MLC years. These values are estimated to depend on the demand over the 20 year period, due to lack of available data. The product customization rate remains constant throughout the period of 20 years and is equal to the input value. Each of the PDSCC combinations may perform differently with respect to the four societal criteria. However, in this case, the PDSCC combinations performance remains same with respect to all the four different criteria (Table 5.20). Therefore, the RD_4-RSC_4 performs best followed by RD_3-RSC_3, RD_2-RSC_2 and RD_1-RSC_1. If PDSCC combinations rank differently with respect to each individual criteria then the total ranking for each combination can be computed and the one with least rank could be considered as the best combination.

5.11 Selection of Best PDSCC Combination

Based on the hierarchical approach, at the end of the societal MLC analysis the best PDSCC combination with maximum societal performance is selected. However, in this case study, as the number of design alternatives is comparatively less, all the combinations are ranked based on their economic and environmental performance and sent to next stages, as opposed to selecting only few best ones at each stage. Ideally, if selection is performed at the economic and environmental MLC stages, the Table 5.20 would have been much simpler. However, to select the best combination the hierarchical approach must be followed.

Therefore, to select the best PDSCC combination, based on the hierarchical approach, the top three combinations that have maximum economic performance (RD_3-RSC_3, RD_2-RSC_2, and RD_4-RSC_4) are chosen at the end of economic MLC analysis. In the next stage, two combinations from the above three that perform best with respect to the environmental performance criteria are selected. As the total ranking for the combinations RD_3-RSC_3 and RD_4-RSC_4, is four which is less than the ranking of RD_2-RSC_2 combination, the combinations RD_3-RSC_3 and RD_4-RSC_4, are selected at the end of environmental MLC analysis to be sent to the next stage. The combination RD_4-RSC_4, ranks first between the two combinations with respect to societal performance and therefore the best combination is RD_4-RSC_4.

As some of the data used for this case study is estimated due to lack of availability, performing sensitivity analysis provides insights on the closed-loop SC behavior during various situations. This analysis also provides information on the key factors that influence the closed-loop SC behavior and also provides areas for overall performance improvement. Hence, in the next chapter the sensitivity analysis performed on the best PDSCC combination, RD_4-RSC_4, is presented.

6. CHAPTER SIX: SENSITIVITY ANALYSIS

6.1 Overview

Sensitivity analysis is an important tool in model development and validation process. It is the process of systematically varying the input parameter values to evaluate the impact of these variations on the system's behavior. This type of analysis enables a company to predict the outcome of a decision in a variety of situations, and also helps in identifying the critical factors that affect the system. Usually in sensitivity analysis one parameter value is changed, while others are kept constant, and the effect of the change in this value on the system's outcome is observed. By experimenting with different input parametric values, the most important parameters that have influence on the system outcome can be identified. In reality, SC models are often subject to numerous uncertainties with several conflicting objectives. Although it is very challenging to capture all the dynamics of the SC, performing sensitivity analysis can provide insights into the system's behavior during a variety of situations.

The parameters of the EOM (such as the steady-state demand, recovery rate, steady-state probability of refurbished refrigerators used to satisfy the demand, steady-state probability of remanufactured refrigerators used to satisfy the demand) used to compute the optimal SC configuration for each refrigerator design are static values. As these values are based on estimates, it is useful to study how these parametric values impact the optimal SC configuration and the cumulative profit at the end of the 20 year period for each of the PDSCC combination. While performing sensitivity analysis on the four combinations is possible, however, in this research the analysis is performed on the best combination selected at the end of hierarchical approach. As only the best PDSCC combination is chosen, it is reasonable to perform an in-depth analysis on this combination to observe the system's behavior under various situations. Therefore, in this section all the sensitivity analysis performed on the RD_4-RSC_4 combination is presented.

6.2 Analysis Description

As discussed earlier, several input parameters are involved in the EOM. Four key parameters were identified for the RD_4-RSC_4 combination, to study in detail their influence on the system's behavior. Table 6.1 presents the parameters, their ranges and the increment steps considered for the sensitivity analysis.

Table 6.1: Parameters for the Sensitivity Analysis

Parameters	Lower Bound	Upper Bound	Increment Steps	Other Variables
Steady-state demand	30,000	273,000	27000	Steady-state forward loop costs and cumulative profit
Recovery rate	0.15	0.7	0.05	Steady-state reverse loop costs and cumulative profit
Steady-state probability of refurbished quantity used to satisfy the demand	0	1	0.1	Steady-state forward loop costs and cumulative profit
Steady-state probability of remanufactured quantity used to satisfy the demand	0	1	0.1	

The steady-state demand is market driven and there is always an uncertainty associated with this value. Therefore, this is an important variable whose impact must be studied. The recovery rate impacts the entire reverse loop SC network and has a bearing on overall profitability as well as environmental and societal performance due to the reverse SC. Hence, the impact of the recovery rate is studied on steady-state optimal profit and the cumulative profit values. The steady-state probability of refurbished and remanufactured refrigerators used to satisfy the demand influences the number of new refrigerators and components to be manufactured and the total steady-state forward loop costs and also the environmental performance. Each parameter in Table 6.1 is varied one at a time to capture its impact on the SC system. By performing this type of analysis on the model, the behavior of the actual SC system in real-life can be predicted which can help companies to make informed decisions to improve their overall benefits.

6.3 Results

This section presents the results of the sensitivity analysis performed for the best combination identified for the case study problem. The impact of each parameter on the system's outcome (steady-state profit, optimal cumulative profit at the end of year 20) is presented for RD_4-RSC_4 combination in this section.

6.3.1 Effect of change in Steady-state demand

Figure 6.1 shows the impact of change in steady-state demand on the cumulative profit at the end of 20 year period. The related parameters such as demand distributed for different use locations, demand for year 1 and year 20 in the economic MLC analysis are changed proportionately with change in steady-state demand to maintain the consistency. The capacity threshold factors for collection, remanufacturing and recycling facilities are maintained same for demand greater than 150,000 units and are adjusted proportionally for demand less than 150,000 units. This is because when the demand is less than 150,000 units, less quantity is transported to the corresponding facilities, and using same factors returns infeasibility. Therefore, the minimum quantity limit is adjusted accordingly. However, this issue does not arise when the demand is greater than 150,000 units.

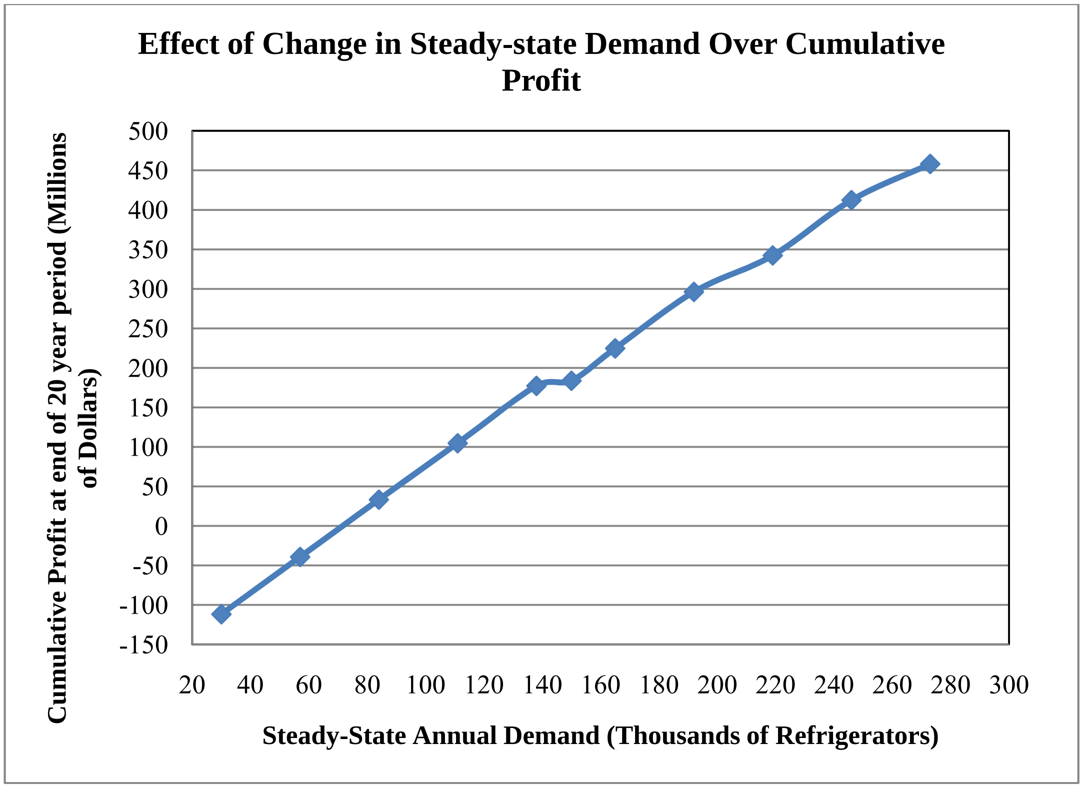


Figure 6.1: Effect of Change in Demand on Cumulative Profit

Table 6.2 summarizes the results obtained from varying the steady-state demand for the RD_4-RSC_4 combination. The results obtained from varying the steady-state demand: the total steady-state forward loop costs, the opening of reverse loop facilities, and the cumulative profit at the end of 20 years are presented. Also, the steady-state demand used for the optimization model is highlighted.

Table 6.2: Results from Varying Steady-state Demand

Demand (Thousands of Units)	Steady-state Forward Loop Cost (Millions of Dollars)	Number of Facilities Opened	Cumulative Profit (Millions of Dollars)
30	19.21	Collection = 2 Remanufacturing = 1 Recycling = 2	-111.71
57	41.08		-39.22
84	62.94		33.28
111	84.80	Collection = 3 Remanufacturing = 1 Recycling = 2	104.68
138	106.65		177.20
150	116.37	Collection = 3 Remanufacturing = 2 Recycling = 2	183.72
165	128.53		224.69
192	150.35	Collection = 4 Remanufacturing = 2 Recycling = 2	296.18
219	172.18	Collection = 4 Remanufacturing = 2 Recycling = 3	342.28
246	194.14		412.27
273	216.05	Collection = 5 Remanufacturing = 3 Recycling = 3	458.12

Results Summary

As the steady-state demand increases from 30,000 units to 273,000 units additional collection, remanufacturing and the recycling facilities are opened for processing the used refrigerators. Table 6.2 presents the change in number of opened facilities with the increase in demand. Also as expected, the cumulative profit is directly proportional to the steady-state demand, as more revenue is generated with increase in sales. Therefore, maximum cumulative profit over 20 years is obtained when the steady-state demand is **273,000 units**. However, the steady-state forward loop costs increase with increase in steady-state demand, as more resources are required to satisfy this demand.

6.3.2 Effect of change in recovery rate

The recovery rate, as discussed earlier influences not only the reverse loop SC costs, but also determines the number of past refurbished or remanufactured refrigerators available to satisfy next life-cycle's demand. In order to observe the impact of this recovery rate on the steady-state optimal profit, and the cumulative profit at the end of 20 year period, experimentations are conducted for different recovery rate values varying from 0.15 to 0.7 in steps of 0.05 and the results are plotted as shown in Figure 6.2.

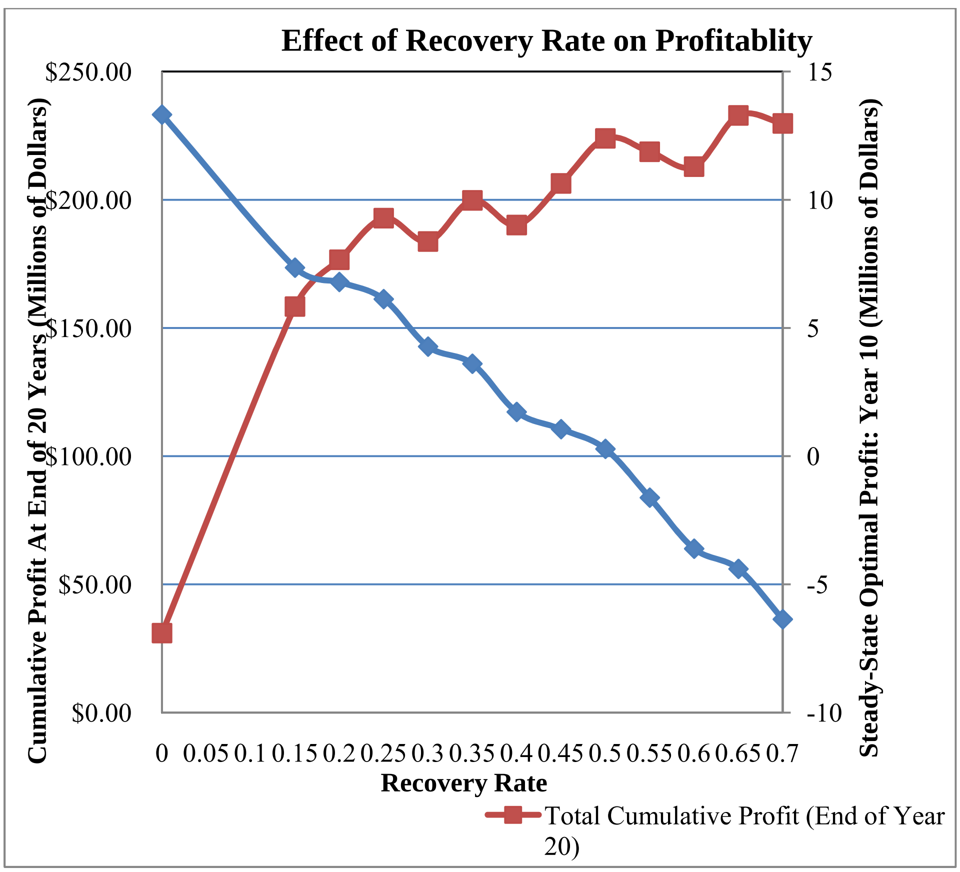


Figure 6.2: Effect of Varying Recovery Rate on Profitability

Table 6.3 summarizes the results obtained from varying recovery rate on the RD_4-RSC_4 combination.

Table 6.3: Results from Varying Recovery Rates

Recovery Rate	Reverse Loop Costs (Millions of Dollars)	Number of Facilities Opened	Optimal Profit (Millions of Dollars)	Total Cumulative Profit (Millions of Dollars)
0	0	Collection =0 Remanufacturing = 0 Recycling = 0	13.32	30.99
0.15	5.21	Collection =2 Remanufacturing = 1 Recycling = 2	7.35	158.35
0.2	5.58	Collection =3 Remanufacturing = 1 Recycling = 2	6.79	176.58
0.25	6.08		6.12	192.81
0.3	7.74	Collection =3 Remanufacturing = 2 Recycling = 2	4.27	183.72
0.35	8.23	Collection =4 Remanufacturing = 2 Recycling = 2	3.60	199.75
0.4	9.94	Collection =4 Remanufacturing = 2 Recycling = 3	1.72	190.12
0.45	10.42		1.05	206.35
0.5	10.90		0.28	223.93
0.55	12.57	Collection =5 Remanufacturing = 3 Recycling = 3	-1.61	218.74
0.6	14.31	Collection =6 Remanufacturing = 3 Recycling = 4	-3.60	212.90
0.65	14.81		-4.39	232.88
0.7	16.50	Collection =6 Remanufacturing = 4 Recycling = 4	-6.36	229.78

Results Summary

When the recovery rate is zero, no used products are recovered. This implies that the steady-state reverse loop SC costs are not incurred and therefore the steady-state optimal profit is maximum at this value. This system is similar to that of an open-loop SC model. From results it has been observed that as the recovery rate increases, more facilities are opened to recover and refurbish the used refrigerators and to remanufacture and recycle their components. Therefore, the reverse loop SC costs begin to increase and hence the steady-state optimal profit decreases. Also, in steady-state period (year 10) the refurbished refrigerators and remanufactured components are available from only year 1. Hence, less quantity of previous year's products and components are available to satisfy the year 10 demand, thereby increasing the demand for new products (hence forward loop costs). Therefore, the optimal profit decreases with increase in number of recovered products during the year 10. However, if the cumulative profits at the end of year 14 or 15 are computed (refurbished and remanufactured quantities available from years 1, 2, 3, 4, 5, and/or 6) the cumulative profit increases with increase in recovery rate, as more quantities from previous years are satisfying the demand and therefore less forward loop costs.

While in short-term (from the steady-state results) recovering products and performing reverse loop operations increase the steady-state reverse loop SC costs (decreases steady-state profit in Figure 6.2), pursuing the closed-loop flow generates much higher cumulative profits in a long-term (shown in cumulative profit graph). While the cumulative profit (end of year 20) increases with increase in recovery rate from 0.15 to 0.7, however it does not increase at a steadily at every 0.05 increment (the peaks and lows) because whenever a new facility is added the cumulative profit decreases as more capital and processing costs are incurred. Therefore considering only steady-state profit values (as opposed to the total period) might mislead a company in making right financial decisions (for a recovery rate of 0.7, steady-state optimal profit = -\$6.36 million, cumulative profit at the end of total period = \$229.78 million). Therefore, pursuing a closed-loop flow generates better profits in a long-term and if company is intended to consider only short-term benefits, then it might be better off pursuing an open-loop SC flow.

From this analysis, the best recovery rate that generates more cumulative profits at end of year 20 is observed to be **0.65**. Although only financial benefits are observed explicitly through this analysis, a higher recovery rate also implies better environmental and societal benefits in a closed-loop SC model as the recovered products are used to satisfy the demand for next life-cycles, thereby reducing the overall energy usage, emissions released and reducing the disposal to landfill (improving the living conditions of society).

6.3.3 Effect of change in Probability of Refurbished Products

The steady-state probability of refurbished products used to satisfy the demand determines the number of new products to be produced and therefore the steady-state forward loop SC costs. Therefore, the steady-state optimal profit and the overall cumulative profit at the end of 20 year period is also impacted with change in this probability. To study the impact of the refurbished product probability on the steady-state optimal profit and the cumulative profit, experiments are conducted by varying the probability in the range of 0 to 1 in steps of 0.1. Figure 6.3 presents the results obtained from these experimentations for the RD_4-RSC_4 combination.

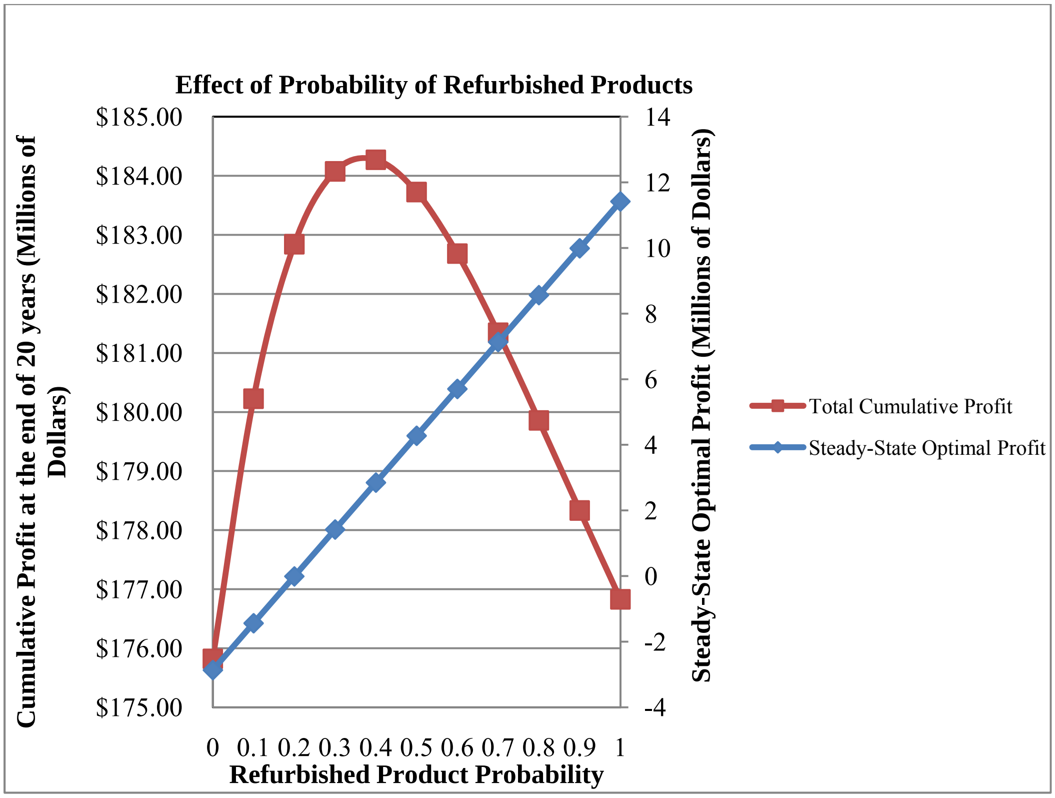


Figure 6.3: Effect of Probability of Refurbished Products on Profitability

Table 6.4 summarizes the results obtained from varying the steady-state probability of refurbished products. The value used for the optimization model is highlighted.

Table 6.4: Results from Varying Steady-state Probability of Refurbished Products

Probability of Refurbished Products	Forward Loop SC Costs (Millions of Dollars)	Number of Facilities Opened	Optimal Profit (Millions of Dollars)	Cumulative Profit (Millions of Dollars)
0	125.19	3,2,2	-2.86	175.82
0.1	123.43		-1.44	180.22
0.2	121.66		-0.01	182.84
0.3	119.90		1.41	184.07
0.4	118.14		2.84	184.27
0.5	116.37		4.27	183.72
0.6	114.61		5.70	182.68
0.7	112.84		7.13	181.34
0.8	111.08		8.56	179.85
0.9	109.32		9.99	178.33
1	107.55		11.41	176.82

Results Summary

As the steady-state probability of refurbished products increases more demand is satisfied by refurbished products available from year 1, and less new products are required from suppliers, thereby reducing the steady-state forward loop SC costs (trend is observed in Table 6.4). However, the steady-state probability of refurbished products does not have an impact on the reverse loop SC configuration and costs because the demand at each use location does not change (and therefore all the reverse loop transportation quantities remain same). Hence, the selection of reverse loop SC partners is not influenced by change in the steady-state probability of refurbished products. Also, with increase in the quantity of refurbished products satisfying the demand, the total revenue decreases because these products are sold at a discounted price. As the rate of decrease in total revenue is comparatively low as compared to rate of reduction in steady-state forward loop costs, the steady-state optimal profit is observed to increases with increase in this probability.

The overall cumulative profit obtained at the end of 20 year period follows a different pattern. The cumulative profit increases with increase in the steady-state probability value upto a certain limit, 0.4 in this case, reaches a peak at this point, and decreases from there onwards. This is because the cumulative revenue (at end of year 20) decreases considerable as more demand is satisfied by refurbished products. When a probability of 0.4 is crossed the rate of decrease in this cumulative revenue is much higher than the rate of reduction in cumulative forward loop costs. Therefore, the cumulative profits decrease from that point.

To summarize, in this case, an increase in steady-state probability of refurbished products always produces higher steady-state optimal profits but does not always produce higher total cumulative profits. From the Figure 6.3, it can be observed that using a steady-state probability value of **0.4** generates maximum cumulative profits at the end of 20 years.

6.3.4 Effect of Steady-State Probability of Remanufactured Components

The effect of change in steady-state probability of refurbished products used to satisfy the demand is already observed in the previous section. In this section, the effect of varying the steady-state probability of remanufactured components used to satisfy the steady-state demand is studied. Ideally, the more remanufactured components are used to satisfy the demand the less number of new components are acquired from the suppliers and this influences the forward loop SC costs. However, as opposed to refurbished products the remanufactured products incur the additional 'other component acquisition costs' which again influences the steady-state forward loop costs. In order to study the impact of this probability value on the steady-state forward loop SC costs, steady-state optimal profit and the cumulative profit at the end of 20 year period, experimentations are conducted with varying this value in the range of 0 to 1 with 0.1 increments. Figure 6.4 presents the results obtained from varying the steady-state probability of remanufactured components for the RD_4-RSC_4 combination.

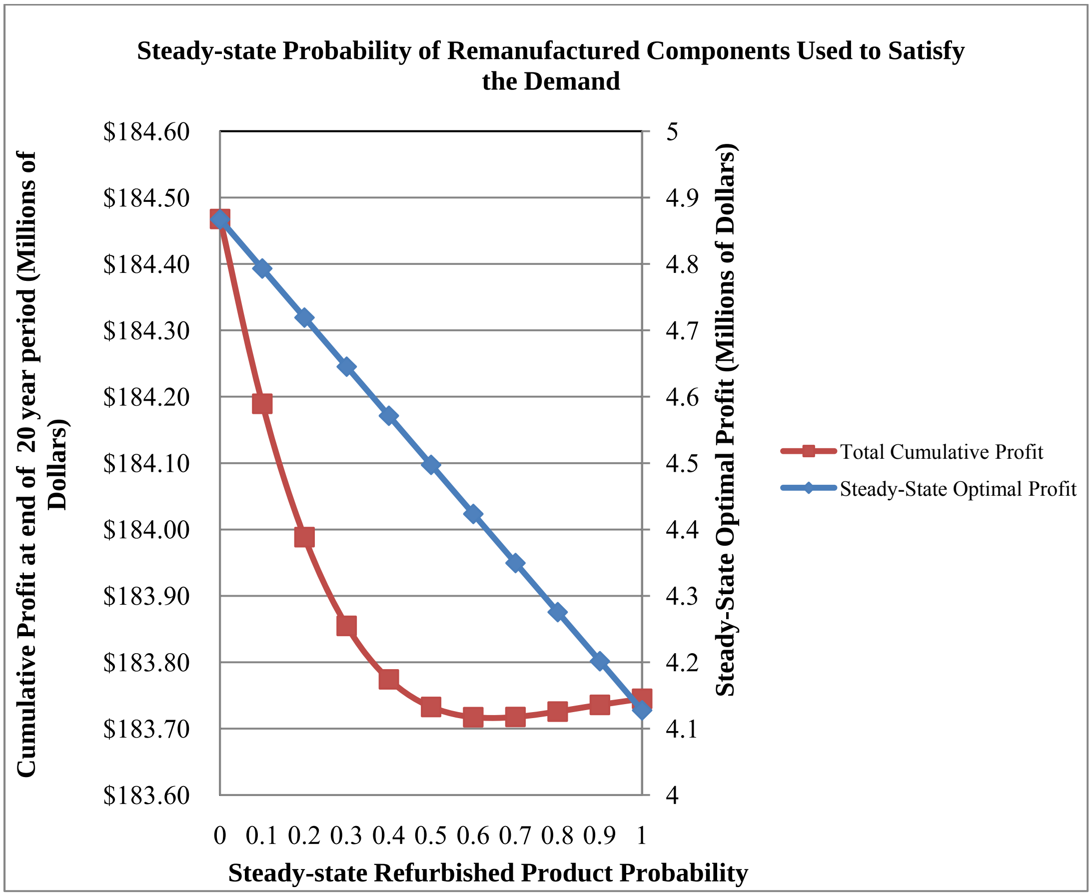


Figure 6.4: Effect of Probability of Remanufactured Components on Profitability

Table 6.5 summarizes the results of varying the steady-state probability of remanufactured components satisfying the demand on profitability. The value considered in the optimization model is also highlighted.

Table 6.5: Results from Varying Probability of Remanufactured Components

Probability of Remanufactured Components	Forward Loop SC Costs (Millions of Dollars)	Number of Facilities Opened	Optimal Profit (Millions of Dollars)	Cumulative Profit (Millions of Dollars)
0.00	117.42	3,2,2	4.87	184.47
0.10	117.29		4.79	184.19
0.20	117.16		4.72	183.99
0.30	117.03		4.65	183.85
0.40	116.90		4.57	183.77
0.50	116.77		4.50	183.73
0.60	116.64		4.42	183.72
0.70	116.51		4.35	183.72
0.80	116.38		4.28	183.73
0.90	116.25		4.20	183.74
1.00	116.12		4.13	183.74

Results Summary

For each unit of remanufactured refrigerator the other component acquisition cost is incurred. As more number of remanufactured components are used to satisfy the steady-state demand, the higher is the other component acquisition cost. However, the supplier cost for acquiring the remanufactured components is not incurred. Both of these parameters impact the steady-state forward loop costs. It has been observed from Table 6.5 that increasing the steady-state probability of remanufactured components reduces the steady-state forward loop costs. However, the rate of decrease in steady-state forward loop costs is very low as compared to that of the case of refurbished products. The reverse loop SC configuration and costs remain same as the quantities are not changed. The remanufactured components too, are sold at a discounted price and as more number of these components are used to satisfy the demand the total steady-state revenue decreases. Therefore, the steady-state optimal profit (factor of steady-state forward loop costs and revenue) is observed to decreases with increase in steady-state probability of remanufactured components. This is because of the increased steady-state forward loop costs incurred from the ‘other component acquisition cost’ (which is not incurred for refurbished products, as they are already assembled).

The cumulative profit at the end of 20 year period also decreases with increase in steady-state probability from 0 to 0.8 and then starts increasing from there onwards. This decreasing trend is due to the high other component acquisition cost incurred for remanufactured products coupled with decreased cumulative revenue generated from them. The cumulative profit starts increasing from probability of 0.8, due to lesser supplier related costs (as more remanufactured components are used in place of new components). However, the decreased revenue and increased other component acquisition costs are overshadowing the economic benefits of increasing the steady-state probability of remanufactured components.

Both the steady-state profit and the cumulative profits are highly influenced by the other component acquisition cost parameter. From the above results it can be observed that if other component acquisition cost is lowered, then increasing the steady-state probability of remanufactured components can generate better economic benefits. However, for this case it can be concluded that if no remanufactured components are used to satisfy the steady-state demand then the maximum cumulative profit over 20 year period is realized. However, meeting the demand with new components when it could be satisfied by remanufactured components is not environmentally friendly as more raw material and resources are utilized during new component production.

7. CHAPTER SEVEN: CONCLUSIONS AND FUTURE RESEARCH

This Chapter presents the findings of this research and summarizes the conclusions. Future research opportunities and ideas for extending the developed CSD model are also presented.

7.1 Summary and Conclusions

In this dissertation, a decision support model for coordinating product and SC design from a sustainability perspective is presented. The model developed using a hierarchical approach considers a total life-cycle approach and incorporates a closed-loop flow within the SC to promote sustainability. The model evaluates the impact of alternate product designs on their corresponding SC configurations to select the best PDSCC combination that maximizes the economic, environmental and societal benefits. An optimization model (EOM) is first developed which selects for each product design an optimal closed-loop SC configuration combination that maximizes profit. The EOM is formulated as a MILP problem and solved using the IBM ILOG CPLEX Optimization software. Following this, the economic, environmental and societal MLC analysis is performed for each PDSCC combination separately to select the best combination that maximizes the overall SC profit, and also minimizes environmental and societal impacts. The MLC_{Eco}, MLC_{Env}, and MLC_{Soc} models, developed for performing the economic, environmental and societal MLC analysis, are easy-to-use, Microsoft Excel based software tools that compute the TBL performance of each PDSCC combination over a given time period *T*. An open-loop SC tool (MLC_{Osc}), created for computing the economic performance of product designs and open-loop SC configurations over MLCs, is also developed using a Microsoft Excel Based Application. The MLC economic performance of PDSCC combinations obtained from the MLC_{Eco} and MLC_{Osc} tools are compared to quantify the benefits/impact of pursuing a closed-loop flow.

In order to show the solution procedure, the CSD model is first applied for an example problem that considers four alternate product designs with three critical components. The EOM and the MLC_{Eco}, MLC_{Env}, and MLC_{Soc} tools are used in multiple stages to identify the best PDSCC combination that maximizes all the TBL benefits. The MLC_{Osc} tool is also used to compute the economic performance of each PDSCC combination in an open-loop SC network. Later, the model is applied for a refrigerator case study to identify the best PDSCC combination that maximizes all the TBL benefits. Similar procedure to that of the example problem is followed to find the best PDSCC combination with maximum TBL performance. However, for this case, actual data from company is used wherever available, and rest of the data is gathered from literature. Hence, this problem is more realistic and comparatively larger as compared to the example problem. The sensitivity analysis is also performed on the optimization model (corresponding to the best PDSCC combination) for the case study problem to gain insights into the SC system's behavior under various situations. Four major parameters of the optimization model were varied to determine the best values for these parameters that produced maximum economic benefits.

The results indicated that both product design and SC design play an important role in improving the TBL performance of entire SC. From the results, several product design and SC design related parameters that significantly influence this performance have been identified. For given designs, the minimum total period *T* that must be considered to gain economic benefits from pursuing a closed-loop flow (as compared to that of an open-loop flow) can be determined. The designs for which pursuing closed-loop flow will provide greater benefits can also be identified from these results. It has been observed that pursuing a closed-loop flow generates more benefits in a long-term and therefore companies that are interested in obtaining short-term benefits may be better off with an open-loop SC model. However, the product type also plays an important role in determining these benefits. For example, the length of the use stage can significantly impact how quickly a company can realize the benefits from pursuing closed-loop flow. Ideally, more quickly the products are made available for next life (used, recovered, and refurbished/remanufactured/recycled), more demand is satisfied by these products within shorter period, and hence, the benefits are realized faster (assuming that demand exists for the product, company has established its reverse loop facilities, etc.,). Also, the demand has a significant influence on all economic, environmental and societal performance of PDSCC combinations. The results from sensitivity analysis provided information on the system's behavior when steady-state parameters such as demand, recovery rate, and the probabilities for refurbished products and remanufactured components are varied. From the results, the best values for the above parameters that will maximize the economic performance of the best PDSCC combination have been identified. The results also indicated that these models tend to be very complex, due to the nature of the SCs operations and the complex relationships between product design and SC design variables. These models grow exponentially in size when the number of product designs or number of components or number of SC partners increase.

The developed model provides significant addition to the existing SSC research through coordinating product and SC design decisions from a sustainability perspective, a critical aspect for improving the SSC performance. This research aims to fill in the gap in SSC literature which lacks an integrated approach to SSCs through considering all the four product life-cycle stages, the TBL aspects, and incorporating a 6R approach to promote a closed-loop flow among multiple product life-cycles. Well-established product design and the SC design criteria are considered in this research. The TBL performance metrics considered in this research are commonly used by most of the companies. The developed CSD model, which can be applicable to any type of product, is solved using an MILP approach and Excel Based tool. The model is applied and tested for the case of domestic refrigerators and the results proved the efficiency of the model in identifying best solution and provided several insights into the closed-loop SC systems. Decision support models such as above can help companies identify the best product designs that will bring highest sustainability benefits to the entire SC. The CSD model helps the decision makers to view a holistic picture and the long-term and the short-term impact of their decisions and also areas for performance improvements. Further, the economic, environmental and societal MLC analysis models are easy-to-use Excel based tools that can be used with minimum supervision.

7.2 Future Research Directions

In this research, the CSD model is developed using a hierarchical approach and the optimization is performed for economic aspect and economic, environmental and societal MLC analysis is performed. The CSD model can be extended to include optimization of all the economic, environmental and societal aspects for multiple product life-cycles.

There is also a need for an in-depth study to identify the most suitable metrics that can be used to evaluate environmental and societal sustainability for the PDSCC combinations. These environmental and societal metrics must be quantifiable. Also, when all the TBL aspects are considered in an optimization model, the relative importance for each aspect must be determined.

While the deterministic approach employed in this dissertation identifies most important product design and SC design criteria, explicitly modeling the stochastic variables can be another extension to this research. Several uncertainties influence the performance of SC's to a great extent. Therefore, to develop more effective CSD models, there is a need to consider these uncertainties during the modeling stage for stochastic optimization. These models must comprehensively consider the uncertainties associated with new products, both in forward and reverse loop SC operations within the SC.

In this research, the CSD model has been applied to the case of domestic refrigerators. The model can be further applied to different case studies to study the performance of different types of products and to identify common factors that influence the SC's performance. While the sensitivity analysis performed in this research presented the system's behavior when major steady-state parameters are varied, further analysis can be performed on the Excel based MLC tools to evaluate the vulnerability to such factors.

APPENDIX A

<u>Demand and SC Cost Related Data</u>

(a) Example Problem

Demand Related Data (Estimated)

Design	Steady-state demand *	Refurbished Product Quantity*	Remanufactured Component Quantity*			Percent (%)	
			C_1	C_2	C_3	Refurbished	Remanufactured
PD_1	100	10	8	7	5	85	67
PD_2	110	7	9	10.5	7.8	30	20
PD_3	90	14	5.6	4.5	5	45	56
PD_4	80	9	8	8.5	6.4	23	50
*Quantity in Thousands							

OEM Cost Related Data (Average values)

Product Design	Fixed Cost ($/Yr)	Assembly Cost ($/Unit)	Holding Cost ($/Component)
PD_1	3000000	100	1
PD_2	3200000	105	2
PD_3	3090000	98	1.75
PD_4	2950000	101	0.75

Collection Center Cost Related Data

Collection Center	Cost ($/Product)							
	Refurbishing				Disassembly			
	PD_1	PD_2	PD_3	PD_4	PD_1	PD_2	PD_3	PD_4
C_1	10	12	9	9	29	20	25	22
C_2	12	9	10	12	28	25	21	23
C_3	11	8	8	7	27	24	24	21

Data for Possible Remanufacturing Centers

Design	Component	RM_1			RM_2			RM_3		
		Processing Cost*	Capability**	Capacity***	Processing Cost*	Capability**	Capacity***	Processing Cost*	Capability**	Capacity***
PD_1	C_1	1.17	1	22	1.35	1	21	1.24	0	NA
	C_2	2.15	0	NA	1.71	1	21	2.55	1	34
	C_3	1.82	1	30	1.77	1	44	1.03	1	21
PD_2	C_1	1.10	1	22	1.71	0	38	1.55	0	NA
	C_2	1.58	1	35	1.51	1	30	1.06	1	31
	C_3	2.69	1	35	1.17	0	NA	1.64	1	35
PD_3	C_1	1.83	1	39	2.25	1	34	1.33	0	NA
	C_2	1.26	0	NA	1.08	1	26	2.77	1	44
	C_3	2.15	1	30	2.30	1	35	2.06	0	NA
PD_4	C_1	1.01	0	NA	2.41	1	27	1.77	1	40
	C_2	1.95	1	30	2.92	0	NA	1.67	1	44
	C_3	1.40	1	21	2.51	1	43	2.80	1	23

* Units: $/Components,** 0 - Not capable
NA - Not applicable as a result of no capability
*** Units: thousands

Data for Possible Recycling Centers

Product	Component	RY1			RY2			RY3		
		Processing Cost*	Capability**	Capacity***	Processing Cost*	Capability**	Capacity***	Processing Cost*	Capability**	Capacity***
PD_1	C_1	2.15	1	33	2.17	0	NA	2.49	1	15
	C_2	2.4	0	NA	2.5	1	29	2.51	0	NA
	C_3	3.21	1	27	2.18	1	19	0.88	1	29
PD_2	C_1	2.47	1	28	0.57	0	NA	1.64	0	NA
	C_2	2.81	0	NA	2.65	1	29	1.23	1	17
	C_3	0.66	1	44	0.55	0	NA	2.66	0	NA
PD_3	C_1	3.07	1	37	3.18	0	NA	2.07	1	17
	C_2	3.5	1	39	1.57	1	24	2.02	1	26
	C_3	1.11	0	NA	3.23	1	22	3.26	1	20
PD_4	C_1	1.36	1	26	3.13	0	NA	0.77	0	NA
	C_2	1.01	0	NA	2.63	1	27	2.7	0	NA
	C_3	1.71	1	28	3.47	0	NA	0.58	1	21
* Units: $/Components,** 0 - Not capable NA - Not applicable as a result of no capability *** Units: thousands										

(b) Case Study Problem

Demand Related Data (Estimated)

Model	Steady-state demand*	Refurbished Refrigerator Quantity*	Remanufactured Component Quantity*				Percent (%)	
			Insulation Material	Compressor	Evaporator	Door Gasket	Refurbished	Remanufactured
RD_1	100	10	8	8.5	9	9.4	40	35
RD_2	250	14	9	10.2	9.2	9.6	50	35
RD_3	220	17	11	11.5	12	11.7	45	86
RD_4	150	22	12.5	13.4	13.7	14	50	80
*Units: Thousands								

OEM Cost Related Data (Average values)

Refrigerator Design	Fixed Cost ($/Yr)	Assembly Cost ($/Refrigerator)	Holding Cost ($/Component) (Beamon, 2004)
RD_1	4,670,000	175	0.02
RD_2	4,665,000	150	0.019
RD_3	4,650,000	120	0.018
RD_4	4,655,000	100	0.017

Collection Center Costs Related Data

Collection Center	Cost ($/Refrigerator)							
	Refurbishing				Disassembly			
	RD_1	RD_2	RD_3	RD_4	RD_1	RD_2	RD_3	RD_4
C_{MX}	24	23.5	22.75	21	34	32.5	31.4	30.1
C_{SC}	24.5	24	23.5	21.5	34.5	33	31.9	30.4
C_{AK}	25	24.75	23.9	21.75	35.2	33.7	32.4	30.9
C_{MN}	26	25.1	24.1	22	35.4	34.3	32.5	31.1
C_{ID}	26.5	25.6	24.9	22.4	35.9	34.6	32.9	31.4
C_{NB}	26.7	25.9	25.1	22.8	36.1	35.1	33.4	31.9
C_{KY}	27.5	26.1	25.9	23.1	36.4	35.6	33.9	32.1
C_{NE}	27.9	26.8	26.1	23.4	37	36.4	34.7	32.4

Data for Possible Recycling Centers

Recycling Center		Capability (1 - Yes, 0 - No)				Processing Cost ($/Component)				Capacity (Quantity in 10^3)			
		RD_1	RD_2	RD_3	RD_4	RD_1	RD_2	RD_3	RD_4	RD_1	RD_2	RD_3	RD_4
RY_{MX}	IM	1	1	1	1	11.10	NA	9.09	7.91	21.0	33	22.4	15
	CP	1	0	1	1	11.50	10.3	9.42	8.19	15.0	NA	24	20
	ER	1	1	1	1	11.00	NA	9.01	7.84	21.0	25	23	14
	DG	1	0	0	0	NA	10.4	NA	NA	5	NA	NA	NA
RY_{UT}	IM	1	1	1	0	NA	10.9	9.96	8.67	14	34	17.8	NA
	CP	1	1	1	1	11.20	NA	9.38	8.16	24	40	20	21
	ER	1	1	1	1	NA	10.7	9.80	8.52	10.5	23	34.1	14
	DG	1	1	1	1	11.40	NA	NA	NA	19	29	12	10
RY_{MN}	IM	1	1	1	1	NA	10.7	9.80	8.52	7	17	26	20
	CP	1	1	0	0	12.10	NA	NA	NA	24.0	27	NA	NA
	ER	0	1	1	1	NA	10.76	9.58	8.33	NA	19	21	13
	DG	1	1	1	1	11.40	10.49	NA	8.12	19.0	31	19.7	17
RY_{NC}	IM	0	1	1	1	NA	11.13	9.91	8.62	NA	30	20	21
	CP	1	1	1	1	12.40	11.66	10.37	NA	10.0	20	10	11
	ER	1	1	0	1	11.90	NA	NA	8.48	25.0	25	NA	21
	DG	0	1	1	0	NA	10.53	9.37	NA	NA	15	26	NA

NA - Not applicable as a result of no capability
IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket

APPENDIX B

(a) Example Problem

Ratings

Criteria for Design PD_1			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		6	6	6	6
	Q_e		8	6.5	7	7.1
	S_a		7	7	7	7
Remanufacture	C_1	A_s	8	8	8	8
		H_l	4	4.6	5	5.1
		T_l	6	6	6	6
		I_m	5	5.6	6	5.8
	C_2	A_s	7	7	7	7
		H_l	5	5.3	5.7	5.9
		T_l	6.4	6.4	6.4	6.4
		I_m	6.1	6.5	6.7	7.2
	C_3	A_s	7.5	7.5	7.5	7.5
		H_l	8	8.3	8.5	7
		T_l	6.1	6.1	6.1	6.1
		I_m	5	5.8	6	6.5
Recycle*	C_1	E_C	1	0	1	1
	C_2		0	1	1	1
	C_3		0	1	0	0
*1 -Yes, 0 - No						

Criteria for Design PD_2			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		8	8	8	8
	Q_e		7	7.1	7.3	7.6
	S_a		8	8	8	8
Remanufacture	C_1	A_s	6	6	6	6
		H_l	6.1	6.4	6.8	6.9
		T_l	7	7	7	7
		I_m	5	5.1	5.6	6
	C_2	A_s	7	7	7	7
		H_l	7.6	7.1	7.9	7
		T_l	6	6	6	6
		I_m	6	6.7	7.1	7.5
	C_3	A_s	8	8	8	8
		H_l	5.4	5.7	6.4	6.8
		T_l	7	7	7	7
		I_m	6.8	7.2	7.5	7
Recycle*	C_1	E_C	1	1	0	0
	C_2		1	1	1	1
	C_3		0	1	1	1
*1 -Yes, 0 - No						

Criteria for Design PD_3			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		9	9	9	9
	Q_e		7	7.9	7.2	8
	S_a		8	8	8	8
Remanufacture	C_1	A_s	8	8	8	8
		H_l	9	8.3	8.5	8.9
		T_l	9	9	9	9
		I_m	7.8	8	8.3	8.9
	C_2	A_s	8	8	8	8
		H_l	8.1	8.7	8.3	8.1
		T_l	9	9	9	9
		I_m	9.1	9.3	9.3	9.7
	C_3	A_s	8.9	8.9	8.9	8.9
		H_l	8	7.6	7.4	7.9
		T_l	9.1	9.1	9.1	9.1
		I_m	9	9.2	9.3	9.4
Recycle*	C_1	E_C	1	1	1	0
	C_2		1	1	1	1
	C_3		0	1	1	1
*1 -Yes, 0 - No						

Criteria for Design PD_4			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		9	9	9	9
	Q_e		8	8.9	7.8	8
	S_a		8	8	8	8
Remanufacture	C_1	A_s	9	9	9	9
		H_l	7	7.9	8.3	8.1
		T_l	8	8	8	8
		I_m	8.1	8.7	8.6	8.9
	C_2	A_s	9	9	9	9
		H_l	8.9	8.1	8.7	8.7
		T_l	8	8	8	8
		I_m	7.8	9	8.9	8.5
	C_3	A_s	9	9	9	9
		H_l	8.1	9.8	9	8.7
		T_l	7	7	7	71
		I_m	9	9.1	8.9	9.3
Recycle*	C_1	E_C	1	1	1	1
	C_2		1	1	1	1
	C_3		0	1	1	1
*1 -Yes, 0 - No						

Probabilities

Criteria for Design PD_1			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		0.20	0.20	0.20	0.20
	Q_e		0.27	0.22	0.23	0.24
	S_a		0.23	0.23	0.23	0.23
	Total		0.70	0.65	0.67	0.67
	Threshold		0.66			
Remanufacture	C_1	A_s	0.20	0.20	0.20	0.20
		H_l	0.10	0.12	0.13	0.13
		T_l	0.15	0.15	0.15	0.15
		I_m	0.13	0.14	0.15	0.15
	Total		0.58	0.61	0.63	0.62
	Threshold		0.60			
	C_2	A_s	0.18	0.18	0.18	0.18
		H_l	0.13	0.13	0.14	0.15
		T_l	0.16	0.16	0.16	0.16
		I_m	0.15	0.16	0.17	0.18
	Total		0.61	0.63	0.65	0.66
	Threshold		0.62			
	C_3	A_s	0.19	0.19	0.19	0.19
		H_l	0.20	0.21	0.21	0.18
		T_l	0.15	0.15	0.15	0.15
		I_m	0.13	0.15	0.15	0.16
	Total		0.67	0.69	0.70	0.68
	Threshold		0.68			
Recycle*	C_1	E_C	1	0	1	1
	C_2		0	1	1	1
	C_3		0	1	0	0
*1 -Yes, 0 - No						

Criteria for Design PD_2			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		0.27	0.27	0.27	0.27
	Q_e		0.23	0.24	0.24	0.25
	S_a		0.27	0.27	0.27	0.27
	Total		0.77	0.77	0.78	0.79
	Threshold		0.66			
Remanufacture	C_1	A_s	0.15	0.15	0.15	0.15
		H_l	0.15	0.16	0.17	0.17
		T_l	0.18	0.18	0.18	0.18
		I_m	0.13	0.13	0.14	0.15
	Total		0.60	0.61	0.64	0.65
	Threshold		0.60			
	C_2	A_s	0.18	0.18	0.18	0.18
		H_l	0.19	0.18	0.20	0.18
		T_l	0.15	0.15	0.15	0.15
		I_m	0.15	0.17	0.18	0.19
	Total		0.67	0.67	0.70	0.69
	Threshold		0.62			
	C_3	A_s	0.20	0.20	0.20	0.20
		H_l	0.14	0.14	0.16	0.17
		T_l	0.18	0.18	0.18	0.18
		I_m	0.17	0.18	0.19	0.18
	Total		0.68	0.70	0.72	0.72
	Threshold		0.68			
Recycle*	C_1	E_C	1	1	0	0
	C_2		1	1	1	1
	C_3		0	1	1	1
*1 -Yes, 0 - No						

Criteria for Design PD_3			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		0.30	0.30	0.30	0.30
	Q_e		0.23	0.26	0.24	0.27
	S_a		0.27	0.27	0.27	0.27
	Total		0.80	0.83	0.81	0.83
	Threshold		0.66			
Remanufacture	C_1	A_s	0.20	0.20	0.20	0.20
		H_l	0.23	0.21	0.21	0.22
		T_l	0.23	0.23	0.23	0.23
		I_m	0.20	0.20	0.21	0.22
	Total		0.85	0.83	0.85	0.87
	Threshold		0.60			
	C_2	A_s	0.20	0.20	0.20	0.20
		H_l	0.20	0.22	0.21	0.20
		T_l	0.23	0.23	0.23	0.23
		I_m	0.23	0.23	0.23	0.24
	Total		0.86	0.88	0.87	0.87
	Threshold		0.62			
	C_3	A_s	0.22	0.22	0.22	0.22
		H_l	0.20	0.19	0.19	0.20
		T_l	0.23	0.23	0.23	0.23
		I_m	0.23	0.23	0.23	0.24
	Total		0.88	0.87	0.87	0.88
	Threshold		0.68			
Recycle*	C_1	E_C	1	1	1	0
	C_2		1	1	1	1
	C_3		0	1	1	1
*1 -Yes, 0 - No						

Criteria for Design PD_4			Use Center			
			U_1	U_2	U_3	U_4
Reuse	U_p		0.30	0.30	0.30	0.30
	Q_e		0.27	0.30	0.26	0.27
	S_a		0.27	0.27	0.27	0.27
	Total		0.83	0.86	0.83	0.83
	Threshold		0.66			
Remanufacture	C_1	A_s	0.23	0.23	0.23	0.23
		H_l	0.18	0.20	0.21	0.20
		T_l	0.20	0.20	0.20	0.20
		I_m	0.20	0.22	0.22	0.22
	Total		0.80	0.84	0.85	0.85
	Threshold		0.60			
	C_2	A_s	0.23	0.23	0.23	0.23
		H_l	0.22	0.20	0.22	0.22
		T_l	0.20	0.20	0.20	0.20
		I_m	0.20	0.23	0.22	0.21
	Total		0.84	0.85	0.87	0.86
	Threshold		0.62			
	C_3	A_s	0.23	0.23	0.23	0.23
		H_l	0.20	0.25	0.23	0.22
		T_l	0.18	0.18	0.18	1.78
		I_m	0.23	0.23	0.22	0.23
	Total		0.83	0.87	0.85	2.45
	Threshold		0.68			
Recycle*	C_1	E_C	1	1	1	1
	C_2		1	1	1	1
	C_3		0	1	1	1
*1 -Yes, 0 - No						

(b) Case Study Problem

Ratings

Criteria for Model RD_1			Use Center						
			U_{NY}	U_{LA}	U_{CH}	U_{HO}	U_{JV}	U_{SA}	U_{DV}
Reuse	U_p		4	4	4	4	4	4	4
	Q_e		4	6	5.5	4.3	5	4.8	4.2
	S_a		3	3	3	3	3	3	3
Remanufacture	IM**	A_s	5	5	5	5	5	5	5
		H_l	4	5.9	5.3	5	5.9	5.4	4.9
		T_l	7	7	7	7	7	7	7
		I_m	2.5	4	3.6	3	3.8	2.9	2.6
	CP**	A_s	4	4	4	4	4	4	4
		H_l	5	6.4	6.1	5.3	5.8	6	5.2
		T_l	5	5	5	5	5	5	5
		I_m	1.7	2.9	3	2.1	2.5	2.8	1
	ER**	A_s	6	6	6	6	6	6	6
		H_l	3.4	5.3	4.6	3.7	5.1	5	4.5
		T_l	5.5	5.5	5.5	5.5	5.5	5.5	5.5
		I_m	2	2.5	2.7	3	4	3.5	3.9
	DG**	A_s	7	7	7	7	7	7	7
		H_l	5.5	6.5	6.9	6.1	6.9	6.8	5.8
		T_l	7	7	7	7	7	7	7
		I_m	2	2.7	2.5	3	2.8	2.7	1.9
Recycle*	IM	E_C	1	0	1	0	0	0	1
	CP		1	1	0	1	0	0	1
	ER		1	0	1	0	1	0	1
	DG		0	1	0	0	0	1	0
*1 -Yes, 0 – No, ** Symbols for criteria are described in Table 3.2 IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket									

Criteria for Model RD_2			Use Center						
			U_{NY}	U_{LA}	U_{CH}	U_{HO}	U_{JV}	U_{SA}	U_{DV}
Reuse	U_p		7	7	7	7	7	7	7
	Q_e		6.5	7.8	7.5	6.3	7	6.8	6
	S_a		8	8	8	8	8	8	8
Remanufacture	IM	A_s	6	6	6	6	6	6	6
		H_l	7	9	7.5	6	7.8	8.6	8
		T_l	6	6	6	6	6	6	6
		I_m	6.5	5.2	6.1	5.8	6	6.5	6.7
	CP	A_s	5	5	5	5	5	5	5
		H_l	7.5	6.3	6.4	7.5	7.4	6.9	7.4
		T_l	6	6	6	6	6	6	6
		I_m	5.6	6.5	5.4	6.8	6.3	6.1	5.7
	ER	A_s	4	4	4	4	4	4	4
		H_l	6	5.4	5.1	5.8	5.6	5.2	5.6
		T_l	6	6	6	6	6	6	6
		I_m	6.4	5.3	6.9	7	5.7	6.5	5.1
	DG	A_s	5	5	5	5	5	5	5
		H_l	5.5	6.9	6.8	5.7	5.4	6.2	6.7
		T_l	7	7	7	7	7	7	7
		I_m	4.5	6	5.6	5.1	5.3	4.9	5.7
Recycle*	IM	E_C	1	0	0	1	0	0	1
	CP		1	1	1	0	0	1	1
	ER		1	0	0	1	1	1	0
	DG		0	1	0	1	0	1	1
*1 -Yes, 0 – No IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket									

Criteria for Model RD_3			Use Center						
			U_{NY}	U_{LA}	U_{CH}	U_{HO}	U_{JV}	U_{SA}	U_{DV}
Reuse	U_p		9	9	9	9	9	9	9
	Q_e		7.5	8.7	8.3	7.3	7.9	8	7.3
	S_a		7	7	7	7	7	7	7
Remanufacture	IM	A_s	7	7	7	7	7	7	7
		H_l	7.2	8.6	8.7	7.5	8.1	7.8	7.2
		T_l	5	5	5	5	5	5	5
		I_m	8	8.2	8.1	8.6	8.4	8.9	8.7
	CP	A_s	8	8	8	8	8	8	8
		H_l	6.2	7.5	8	7.1	7.3	6.8	6.7
		T_l	7	7	7	7	7	7	7
		I_m	8	8.2	8.4	8.7	8.6	8.9	8
	ER	A_s	7	7	7	7	7	7	7
		H_l	6.5	7.4	7.6	8	7.2	6.7	6.4
		T_l	6	6	6	6	6	6	6
		I_m	7.6	8.9	8.4	7.9	8	8.4	8.5
	DG	A_s	7	7	7	7	7	7	7
		H_l	6.2	7.5	7.6	6.9	8	7.1	6.7
		T_l	8	8	8	8	8	8	8
		I_m	8	7.8	6	6.4	6.9	6.7	6.3
Recycle*	IM	E_C	1	1	1	1	0	1	0
	CP		1	1	0	1	0	0	1
	ER		0	0	1	0	0	1	1
	DG		1	1	0	0	1	1	0
*1 -Yes, 0 – No IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket									

Criteria for Model RD_4			Use Center						
			U_{NY}	U_{LA}	U_{CH}	U_{HO}	U_{JV}	U_{SA}	U_{DV}
Reuse	U_p		10	10	10	10	10	10	10
	Q_e		6.4	8	7	6.3	7.3	7.9	6.3
	S_a		8	8	8	8	8	8	8
Remanufacture	IM	A_s	8	8	8	8	8	8	8
		H_l	7.8	8.1	8.5	9	8.4	7.8	7.6
		T_l	7	7	7	7	7	7	7
		I_m	8.9	8.1	8.6	8.4	8.7	8.6	8.7
	CP	A_s	9	9	9	9	9	9	9
		H_l	6.5	6.2	8	7.9	6.9	7.1	7.6
		T_l	7	7	7	7	7	7	7
		I_m	9	8.6	8.7	8.2	8.6	8.7	8.5
	ER	A_s	8	8	8	8	8	8	8
		H_l	7.2	7.4	6.9	6.3	6.7	7.9	7.5
		T_l	7	7	7	7	7	7	7
		I_m	9	8.7	8.6	8.1	8.4	7.5	7.2
	DG	A_s	9	9	9	9	9	9	9
		H_l	7.4	7.6	7.9	8.5	8.7	8.9	8.1
		T_l	9	9	9	9	9	9	9
		I_m	8.9	8.4	8.6	7.5	7.1	7.9	8
Recycle*	IM	E_C	1	1	0	1	1	1	1
	CP		0	1	1	1	1	0	1
	ER		1	1	1	1	1	1	1
	DG		0	1	0	1	0	1	0

*1 -Yes, 0 – No
IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket

Probabilities

Criteria for Model RD_2			Use Center						
			U_{NY}	U_{LA}	U_{CH}	U_{HO}	U_{JV}	U_{SA}	U_{DV}
Reuse	U_p		0.23	0.23	0.23	0.23	0.23	0.23	0.23
	Q_e		0.22	0.26	0.25	0.21	0.23	0.23	0.20
	S_a		0.27	0.27	0.27	0.27	0.27	0.27	0.27
	Total		0.72	0.76	0.75	0.71	0.73	0.73	0.70
	Threshold		0.70						
Remanufacture	IM	A_s	0.15	0.15	0.15	0.15	0.15	0.15	0.15
		H_l	0.18	0.23	0.19	0.15	0.20	0.22	0.20
		T_l	0.15	0.15	0.15	0.15	0.15	0.15	0.15
		I_m	0.16	0.13	0.15	0.15	0.15	0.16	0.17
		Total	0.64	0.66	0.64	0.60	0.65	0.68	0.67
		Threshold	0.63						
	CP	A_s	0.13	0.13	0.13	0.13	0.13	0.13	0.13
		H_l	0.19	0.16	0.16	0.19	0.19	0.17	0.19
		T_l	0.15	0.15	0.15	0.15	0.15	0.15	0.15
		I_m	0.14	0.16	0.14	0.17	0.16	0.15	0.14
		Total	0.60	0.60	0.57	0.63	0.62	0.60	0.60
		Threshold	0.61						
	ER	A_s	0.10	0.10	0.10	0.10	0.10	0.10	0.10
		H_l	0.15	0.14	0.13	0.15	0.14	0.13	0.14
		T_l	0.15	0.15	0.15	0.15	0.15	0.15	0.15
		I_m	0.16	0.13	0.17	0.18	0.14	0.16	0.13
		Total	0.56	0.52	0.55	0.57	0.53	0.54	0.52
		Threshold	0.52						
	DG	A_s	0.13	0.13	0.13	0.13	0.13	0.13	0.13
		H_l	0.14	0.17	0.17	0.14	0.14	0.16	0.17
		T_l	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		I_m	0.11	0.15	0.14	0.13	0.13	0.12	0.14
		Total	0.55	0.62	0.61	0.57	0.57	0.58	0.61
		Threshold	0.58						
Recycle*	IM	E_C	1	0	0	1	0	0	1
	CP		1	1	1	0	0	1	1
	ER		1	0	0	1	1	1	0
	DG		0	1	0	1	0	1	1
*1 -Yes, 0 – No IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket									

Criteria for Model RD_3			Use Center						
			U_{NY}	U_{LA}	U_{CH}	U_{HO}	U_{JV}	U_{SA}	U_{DV}
Reuse	U_p		0.30	0.30	0.30	0.30	0.30	0.30	0.30
	Q_e		0.25	0.29	0.28	0.24	0.26	0.27	0.24
	S_a		0.23	0.23	0.23	0.23	0.23	0.23	0.23
	Total		0.78	0.82	0.81	0.78	0.80	0.80	0.78
	Threshold		0.80						
Remanufacture	IM	A_s	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		H_l	0.18	0.22	0.22	0.19	0.20	0.20	0.18
		T_l	0.13	0.13	0.13	0.13	0.13	0.13	0.13
		I_m	0.20	0.21	0.20	0.22	0.21	0.22	0.22
		Total	0.68	0.72	0.72	0.70	0.71	0.72	0.70
		Threshold	0.70						
	CP	A_s	0.20	0.20	0.20	0.20	0.20	0.20	0.20
		H_l	0.16	0.19	0.20	0.18	0.18	0.17	0.17
		T_l	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		I_m	0.20	0.21	0.21	0.22	0.22	0.22	0.20
		Total	0.73	0.77	0.79	0.77	0.77	0.77	0.74
		Threshold	0.76						
	ER	A_s	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		H_l	0.16	0.19	0.19	0.20	0.18	0.17	0.16
		T_l	0.15	0.15	0.15	0.15	0.15	0.15	0.15
		I_m	0.19	0.22	0.21	0.20	0.20	0.21	0.21
		Total	0.68	0.73	0.73	0.72	0.71	0.70	0.70
		Threshold	0.72						
	DG	A_s	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		H_l	0.16	0.19	0.19	0.17	0.20	0.18	0.17
		T_l	0.20	0.20	0.20	0.20	0.20	0.20	0.20
		I_m	0.20	0.20	0.15	0.16	0.17	0.17	0.16
		Total	0.73	0.76	0.72	0.71	0.75	0.72	0.70
		Threshold	0.73						
Recycle*	IM	E_C	1	1	1	1	0	1	0
	CP		1	1	0	1	0	0	1
	ER		0	0	1	0	0	1	1
	DG		1	1	0	0	1	1	0
*1 -Yes, 0 – No IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket									

Criteria for Model RD_4			Use Center						
			U_{NY}	U_{LA}	U_{CH}	U_{HO}	U_{JV}	U_{SA}	U_{DV}
Reuse	U_p		0.33	0.33	0.33	0.33	0.33	0.33	0.33
	Q_e		0.21	0.27	0.23	0.21	0.24	0.26	0.21
	S_a		0.27	0.27	0.27	0.27	0.27	0.27	0.27
	Total		0.81	0.87	0.83	0.81	0.84	0.86	0.81
	Threshold		0.82						
Remanufacture	IM	A_s	0.20	0.20	0.20	0.20	0.20	0.20	0.20
		H_l	0.20	0.20	0.21	0.23	0.21	0.20	0.19
		T_l	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		I_m	0.22	0.20	0.22	0.21	0.22	0.22	0.22
		Total	0.79	0.78	0.80	0.81	0.80	0.79	0.78
		Threshold	0.78						
	CP	A_s	0.23	0.23	0.23	0.23	0.23	0.23	0.23
		H_l	0.16	0.16	0.20	0.20	0.17	0.18	0.19
		T_l	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		I_m	0.23	0.22	0.22	0.21	0.22	0.22	0.21
		Total	0.79	0.77	0.82	0.80	0.79	0.80	0.80
		Threshold	0.78						
	ER	A_s	0.20	0.20	0.20	0.20	0.20	0.20	0.20
		H_l	0.18	0.19	0.17	0.16	0.17	0.20	0.19
		T_l	0.18	0.18	0.18	0.18	0.18	0.18	0.18
		I_m	0.23	0.22	0.22	0.20	0.21	0.19	0.18
		Total	0.78	0.78	0.76	0.74	0.75	0.76	0.74
		Threshold	0.76						
	DG	A_s	0.23	0.23	0.23	0.23	0.23	0.23	0.23
		H_l	0.19	0.19	0.20	0.21	0.22	0.22	0.20
		T_l	0.23	0.23	0.23	0.23	0.23	0.23	0.23
		I_m	0.22	0.21	0.22	0.19	0.18	0.20	0.20
		Total	0.86	0.85	0.86	0.85	0.85	0.87	0.85
		Threshold	0.81						
Recycle*	IM	E_C	1	1	0	1	1	1	1
	CP		0	1	1	1	1	0	1
	ER		1	1	1	1	1	1	1
	DG		0	1	0	1	0	1	0
*1 -Yes, 0 – No IM-Insulation Material, CP-Compressor, ER-Evaporator, DG-Door Gasket									

APPENDIX C

(a) Example Problem

<u>Transportation Distance</u>

From /To (PD_1)	Distance (10^3 Miles)												
	OEM	C_1	C_2	C_3	RM_1	RM_2	RM_3	RY_1	RY_2	RY_3	S_1	S_2	S_3	D_p
S_1	3													
S_2	2													
S_3	5													
U_1		12	10	3										
U_2		5	11	2										
U_3		3.4	5.4	10										
U_4		12	6	1										
C_1	2				13	2	15	1.2	14.5	6				6
C_2	3				2.3	1	7	12	0.4	0.7				2
C_3	1.2				1.9	3.4	0.3	13	0.2	17.6				4
RM_1	2.5													
RM_2	4													
RM_3	1													
RY_1											0.2	14.5	2.3	
RY_2											4.5	2	1	
RY_3											2.7	1.4	10	

From /To (PD_2)	Distance (10^3 Miles)												
	OEM	C_1	C_2	C_3	RM_1	RM_2	RM_3	RY_1	RY_2	RY_3	S_1	S_2	S_3	D_p
S_1	1.2													
S_2	3.9													
S_3	12													
U_1		1.3	12	3.4										
U_2		13	23	1										
U_3		2.3	4.5	1.3										
U_4		1	2	6										
C_1	1.4				1.4	7.2	11.1	6.3	2.2	13.2				9
C_2	0.5				2.5	9.1	4.3	13.6	1.9	13.8				8.7
C_3	1.2				7.5	14.6	11.9	10.2	4.4	2.3				7.8
RM_1	2.6													
RM_2	3													
RM_3	4.5													
RY_1											1.2	1.4	2.4	
RY_2											10	2	5	
RY_3											2	5	10	

From/To (PD_3)	Distance (10^3 Miles)													
	OEM	**C_1**	**C_2**	**C_3**	**RM_1**	**RM_2**	**RM_3**	**RY_1**	**RY_2**	**RY_3**	**S_1**	**S_2**	**S_3**	**D_p**
S_1	5.6													
S_2	8													
S_3	12.4													
U_1		9.1	3.5	11.3										
U_2		1.1	7.6	11.2										
U_3		13.1	7.4	15.6										
U_4		7.9	3.6	1.0										
C_1	15.3				9.2	11.8	14.2	7.9	2.9	11.2				9.3
C_2	10.6				5.3	14.4	10.5	14.5	5.7	13.5				16.8
C_3	8.7				7.7	9.4	16.1	16	6.0	2.1				16.3
RM_1	9.3													
RM_2	8.2													
RM_3	5.7													
RY_1											10.9	14.5	13.5	
RY_2											4.3	3.2	16.3	
RY_3											4.6	15.3	14.4	

From/To (PD_4)	Distance (10^3 Miles)													
	OEM	**C_1**	**C_2**	**C_3**	**RM_1**	**RM_2**	**RM_3**	**RY_1**	**RY_2**	**RY_3**	**S_1**	**S_2**	**S_3**	**D_p**
S_1	11.6													
S_2	6.1													
S_3	13.6													
U_1		9.1	12.7	6.6										
U_2		10.7	8.1	5.1										
U_3		2.2	9.1	10.1										
U_4		6.9	11.2	4.7										
C_1	10				5.4	0.5	5.4	10.3	9.1	0.9				13.9
C_2	1.5				12.1	13.8	2.3	13.1	5.3	2.5				7.5
C_3	3.6				4.1	6.3	2.5	3.6	0.9	0.4				9.7
RM_1	7.8													
RM_2	0.4													
RM_3	7													
RY_1											1.7	5.1	4.9	
RY_2											2.8	8.5	8.7	
RY_3											0.4	7.1	1.4	

Transportation Costs

Product Design 1

From/To		Collection Center ($/Unit)		
		C_1	C_2	C_3
Use Location	U_1	79.39	66.16	19.85
	U_2	33.08	72.78	13.23
	U_3	22.49	35.73	66.16
	U_4	79.39	39.70	6.62

From/To		OEM ($/Unit)
		OEM
Collection Center	C_1	13.23
	C_2	19.85
	C_3	7.94

Component	Supplier	To OEM ($/Unit)
$Component_1$	S_3	4.13
$Component_2$	S_1	1.24
$Component_3$	S_2	1.42

From/To ($Component_1$)		Remanufacturing Center ($/Unit)			Recycle Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	10.75	1.65	12.41	0.99	11.99	4.96
	C_2	1.90	0.83	5.79	9.92	0.33	0.58
	C_3	1.57	2.81	0.25	10.75	0.17	14.60

From/To ($Component_2$)		Remanufacturing Center ($/Unit)			Recycle Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	5.38	0.83	6.20	0.50	6.00	2.48
	C_2	0.95	0.41	2.89	4.96	0.17	0.29
	C_3	0.79	1.41	0.12	5.38	0.08	7.30

From/To ($Component_3$)		Remanufacturing Center ($/Unit)			Recycle Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	9.25	1.42	10.67	0.85	10.31	4.27
	C_2	1.64	0.71	4.98	8.53	0.28	0.50
	C_3	1.35	2.42	0.21	9.25	0.14	12.56

From/To	D_p ($/Unit)		
Collection Center	$Component_1$	$Component_2$	$Component_3$
C_1	4.96	2.48	4.27
C_2	1.65	0.83	1.42
C_3	3.31	1.65	2.84

From/To	OEM ($/Unit)		
Remanufacturing Center	$Component_1$	$Component_2$	$Component_3$
RM_1	2.07	1.03	1.78
RM_2	3.31	1.65	2.84
RM_3	0.83	0.41	0.71

From/To		Supplier ($/Unit)		
		S_1	S_2	S_3
Recycle Center	RY_1	0.08	10.31	1.91
	RY_2	1.86	1.42	0.83
	RY_3	1.12	1.00	8.27

Product Design 2

Component	Supplier	To OEM ($/Unit)
$Component_1$	S_1	0.89316
$Component_2$	S_2	1.93518
$Component_3$	S_3	9.32856

From/To		Collection Center ($/Unit)		
		C_1	C_2	C_3
Use Location	U_1	9.68	89.32	25.31
	U_2	96.76	171.19	7.44
	U_3	17.12	33.49	9.68
	U_4	7.44	14.89	44.66

From/To		OEM ($/Unit)
Collection Center	C_1	10.42
	C_2	3.72
	C_3	8.93

From/To (Component$_1$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	1.05	5.38	8.27	4.74	1.70	9.84
	C_2	1.91	6.81	3.21	10.15	1.42	10.29
	C_3	5.62	10.87	8.88	7.60	3.33	1.72

From/To (Component$_2$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	0.70	3.59	5.51	3.16	1.14	6.56
	C_2	1.27	4.54	2.14	6.77	0.95	6.86
	C_3	3.74	7.25	5.92	5.07	2.22	1.14

From/To (Component$_3$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	1.10	5.62	8.64	4.95	1.78	10.28
	C_2	1.99	7.11	3.35	10.61	1.49	10.74
	C_3	5.87	11.35	9.28	7.94	3.48	1.79

From/To	D_p ($/Unit)		
Collection Center	Component$_1$	Component$_2$	Component$_3$
C_1	6.70	4.47	7.00
C_2	6.48	4.32	6.76
C_3	5.87	3.92	6.13

From/To	OEM ($/Unit)		
Remanufacturing Center	Component$_1$	Component$_2$	Component$_3$
RM_1	1.94	1.29	2.02
RM_2	2.23	1.49	2.33
RM_3	3.35	2.23	3.50

From/To		Supplier ($/Unit)		
		S_1	S_2	S_3
Recycle Center	RY_1	0.89	0.69	1.87
	RY_2	7.44	0.99	3.89
	RY_3	1.49	2.48	7.77

Product Design 3

Component	Supplier	To OEM ($/Unit)
$Component_1$	S_1	2.81
$Component_2$	S_3	4.33
$Component_3$	S_2	5.35

From/To		Collection Center ($/Unit)		
		C_1	C_2	C_3
Use Location	U_1	55.99	21.49	69.67
	U_2	6.21	46.83	68.71
	U_3	79.92	45.78	95.89
	U_4	48.46	22.47	6.21

From/To		OEM ($/Unit)
Collection Center	C_1	93.91
	C_2	65.17
	C_3	53.55

From/To (Component$_1$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	4.61	5.88	7.07	3.96	1.46	5.60
	C_2	2.64	7.18	5.26	7.24	2.83	6.73
	C_3	3.86	4.67	8.01	7.98	3.02	1.07

From/To (Component$_2$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	3.22	4.11	4.95	2.77	1.03	3.92
	C_2	1.85	5.02	3.68	5.07	1.98	4.71
	C_3	2.70	3.27	5.61	5.59	2.12	0.75

From/To (Component$_3$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	6.14	7.84	9.43	5.28	1.95	7.47
	C_2	3.52	9.57	7.01	9.65	3.78	8.97
	C_3	5.14	6.23	10.68	10.65	4.03	1.43

From/To	D_p ($/Unit)		
Collection Center	Component$_1$	Component$_2$	Component$_3$
C_1	4.62	3.24	6.16
C_2	8.37	5.86	11.16
C_3	8.13	5.69	10.84

From/To	OEM ($/Unit)		
Remanufacturing Center	$Component_1$	$Component_2$	$Component_3$
RM_1	4.62	3.24	6.16
RM_2	4.09	2.87	5.46
RM_3	2.86	2.00	3.81

From/To		Supplier ($/Unit)		
		S_1	S_2	S_3
Recycle Center	RY_1	5.41	9.65	4.71
	RY_2	2.14	2.12	5.68
	RY_3	2.33	10.16	5.03

Product Design 4

Component	Supplier	To OEM ($/Unit)
$Component_1$	S_2	6.03
$Component_2$	S_1	5.59
$Component_3$	S_3	10.41

From/To		Collection Center ($/Unit)		
		C_1	C_2	C_3
Use Location	U_1	61.45	86.40	45.31
	U_2	72.95	55.50	34.98
	U_3	15.01	61.98	68.66
	U_4	47.08	76.41	32.31

From/To		OEM ($/Unit)
Collection Center	C_1	67.81
	C_2	10.17
	C_3	24.41

From/To (Component$_1$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	5.44	0.54	5.37	10.32	9.11	0.90
	C_2	11.97	13.72	2.38	13.05	5.30	2.54
	C_3	4.08	6.26	2.53	3.63	0.91	0.44

From/To (Component$_2$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	2.63	0.26	2.60	4.99	4.40	0.44
	C_2	5.79	6.63	1.15	6.31	2.56	1.23
	C_3	1.97	3.03	1.22	1.75	0.44	0.21

From/To (Component$_3$)		Remanufacturing Center ($/Unit)			Recycling Center ($/Unit)		
		RM_1	RM_2	RM_3	RY_1	RY_2	RY_3
Collection Center	C_1	4.17	0.42	4.12	7.91	6.99	0.69
	C_2	9.18	10.52	1.82	10.00	4.07	1.94
	C_3	3.13	4.80	1.94	2.78	0.69	0.34

From/To	D_p ($/Unit)		
Collection Center	Component$_1$	Component$_2$	Component$_3$
C_1	13.86	6.70	10.63
C_2	7.47	3.61	5.72
C_3	9.71	4.69	7.45

From/To	OEM ($/Unit)		
Remanufacturing Center	Component$_1$	Component$_2$	Component$_3$
RM_1	7.74	3.74	5.93
RM_2	0.45	0.22	0.34
RM_3	6.95	3.36	5.33

From/To		Supplier ($/Unit)		
		S_1	S_2	S_3
Recycle Center	RY_1	0.84	5.15	3.74
	RY_2	1.35	8.46	6.69
	RY_3	2.14	6.96	1.12

(b) Case Study problem

Distances between SC partners

From/To		Distance (Miles)							
		C_{NE}	C_{MX}	C_{KY}	C_{NB}	C_{SC}	C_{AK}	C_{MN}	C_{ID}
Use Location	U_{NY}	2397.16	2206.94	648.36	1267.51	610.45	1077.44	992.21	2145.54
	U_{LA}	362.87	551.64	1824.5	1185.56	2030.82	1475.26	1619.16	669.15
	U_{CH}	1686.26	1556.52	267.61	557.15	560.45	550.92	405.42	1446.08
	U_{HO}	1526.83	925.84	802.69	788.58	833.5	388.01	1188.07	1491.08
	U_{JV}	2228.51	1741.56	594.8	1184.64	315.06	689.39	1265.66	2094.75
	U_{SA}	596.86	1411.86	1937.31	1266.3	2222.64	1779.77	1410.18	404.24
	U_{DV}	788.19	797.13	1034.68	358.97	1281.97	777.26	808.11	636.73

From/To		Remanufacturing Facility- Distance (Miles)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}
Collection Facility	C_{NE}	463.44	1918.17	1344.64	1030.22
	C_{MX}	2208.9	1734.78	1291.1	785.39
	C_{KY}	1944.05	315.66	478.74	1174.86
	C_{NB}	1259.38	794.26	235.53	605.27
	C_{SC}	2221.88	517.57	732.46	1369.14
	C_{AK}	1754.2	722.64	326.02	812.74
	C_{MN}	1455.43	540.92	544.95	1104.62
	C_{ID}	344.43	1666.29	1159.52	777.97

From/To		Recycle Facility-Distance (Miles)			
		RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	430.97	1417.18	1526.9	2246.66
	C_{MX}	1605.49	1701.75	295.15	1574.92
	C_{KY}	1397.49	596.77	1423.86	428.19
	C_{NB}	707.05	383.77	1255.72	1121.73
	C_{SC}	1651.42	896.52	1435.48	220.88
	C_{AK}	1144.64	705.4	999.99	772.22
	C_{MN}	1066.68	135.54	1731.78	1029.76
	C_{ID}	295.71	1142.2	1636.95	2048.85

From/To		Distance (Miles)								
		S_{Pa}	S_{De}	S_{Jo}	S_{Ti}	S_{No}	S_{Ji}	S_{Sh}	S_{Br}	S_{Sc}
Recycle	RY_{UT}	1910.07	1902.62	6141.2	6106.2	7599.17	7104.18	5435.06	1417.11	1389.31
	RY_{MN}	961.03	962.2	5652.6	6325.5	7309.16	7343.86	5708.06	561.83	572.87
	RY_{MX}	1959.5	1928.7	4918.8	7447.6	8860.42	8431.25	6769.99	1508.48	1443.92
	RY_{NC}	359.92	322.08	4705.5	7158.39	7710.02	8160.24	7987.39	430.09	440.47

From/To		Distance (Miles)	
		OEM	$Disposal_{MX}$
Collection Facility	C_{NE}	1769.28	1055.53
	C_{MX}	1538.76	209.22
	C_{KY}	75.27	1484.2
	C_{NB}	635.7	1080.5
	C_{SC}	374.84	1591.25
	C_{AK}	440.48	1054.58
	C_{MN}	596.38	1589.84
	C_{ID}	1558.92	1207.35
Remanufacturing Facility	RM_{OR}	1879.24	
	RM_{MI}	284.43	
	RM_{MO}	431.12	
	RM_{MX}	1140.51	

Transportation costs

Refrigerator Model RD_1

Component	Supplier	To OEM ($/Unit)
Insulation Material	S_{Pa}	0.02
Compressor	S_{Jo}	2.18
Evaporator	S_{Ji}	1.28
Door Gasket	S_{Sc}	0.01

From/To		Collection Facility ($/Unit)							
		C_{NE}	C_{MX}	C_{KY}	C_{NB}	C_{SC}	C_{AK}	C_{MN}	C_{ID}
Use Location	U_{NY}	127.53	117.41	34.49	67.43	32.48	57.32	52.79	114.14
	U_{LA}	19.30	29.35	97.06	63.07	108.04	78.48	86.14	35.60
	U_{CH}	89.71	82.81	14.24	29.64	29.82	29.31	21.57	76.93
	U_{HO}	81.23	49.25	42.70	41.95	44.34	20.64	63.21	79.33
	U_{JV}	118.56	92.65	31.64	63.02	16.76	36.68	67.33	111.44
	U_{SA}	31.75	75.11	103.06	67.37	118.24	94.68	75.02	21.51
	U_{DV}	41.93	42.41	55.04	19.10	68.20	41.35	42.99	33.87

From/To		OEM ($/Unit)
Collection Facility	C_{NE}	94.13
	C_{MX}	81.86
	C_{KY}	4.00
	C_{NB}	33.82
	C_{SC}	19.94
	C_{AK}	23.43
	C_{MN}	31.73
	C_{ID}	82.93

Insulation Material		Remanufacturing Facility (\$/Unit)				Recycling Facility (\$/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.12	0.51	0.36	0.27	0.11	0.38	0.41	0.60
	C_{MX}	0.59	0.46	0.34	0.21	0.43	0.45	0.08	0.42
	C_{KY}	0.52	0.08	0.13	0.31	0.37	0.16	0.38	0.11
	C_{NB}	0.33	0.21	0.06	0.16	0.19	0.10	0.33	0.30
	C_{SC}	0.59	0.14	0.19	0.36	0.44	0.24	0.38	0.06
	C_{AK}	0.47	0.19	0.09	0.22	0.30	0.19	0.27	0.21
	C_{MN}	0.39	0.14	0.14	0.29	0.28	0.04	0.46	0.27
	C_{ID}	0.09	0.44	0.31	0.21	0.08	0.30	0.44	0.54

Compressor		Remanufacturing Facility (\$/Unit)				Recycling Facility (\$/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	1.54	6.38	4.47	3.43	1.43	4.71	5.08	7.47
	C_{MX}	7.34	5.77	4.29	2.61	5.34	5.66	0.98	5.24
	C_{KY}	6.46	1.05	1.59	3.91	4.65	1.98	4.73	1.42
	C_{NB}	4.19	2.64	0.78	2.01	2.35	1.28	4.18	3.73
	C_{SC}	7.39	1.72	2.44	4.55	5.49	2.98	4.77	0.73
	C_{AK}	5.83	2.40	1.08	2.70	3.81	2.35	3.32	2.57
	C_{MN}	4.84	1.80	1.81	3.67	3.55	0.45	5.76	3.42
	C_{ID}	1.15	5.54	3.86	2.59	0.98	3.80	5.44	6.81

Evaporator		Remanufacturing Facility (\$/Unit)				Recycling Facility (\$/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.68	2.81	1.97	1.51	0.63	2.07	2.23	3.29
	C_{MX}	3.23	2.54	1.89	1.15	2.35	2.49	0.43	2.30
	C_{KY}	2.84	0.46	0.70	1.72	2.04	0.87	2.08	0.63
	C_{NB}	1.84	1.16	0.34	0.89	1.03	0.56	1.84	1.64
	C_{SC}	3.25	0.76	1.07	2.00	2.42	1.31	2.10	0.32
	C_{AK}	2.57	1.06	0.48	1.19	1.67	1.03	1.46	1.13
	C_{MN}	2.13	0.79	0.80	1.62	1.56	0.20	2.53	1.51
	C_{ID}	0.50	2.44	1.70	1.14	0.43	1.67	2.39	3.00

Door Gasket		Remanufacturing Facility (\$/Unit)				Recycling Facility (\$/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.15	0.64	0.45	0.34	0.14	0.47	0.51	0.75
	C_{MX}	0.73	0.58	0.43	0.26	0.53	0.57	0.10	0.52
	C_{KY}	0.65	0.10	0.16	0.39	0.46	0.20	0.47	0.14
	C_{NB}	0.42	0.26	0.08	0.20	0.24	0.13	0.42	0.37
	C_{SC}	0.74	0.17	0.24	0.46	0.55	0.30	0.48	0.07
	C_{AK}	0.58	0.24	0.11	0.27	0.38	0.23	0.33	0.26
	C_{MN}	0.48	0.18	0.18	0.37	0.35	0.05	0.58	0.34
	C_{ID}	0.11	0.55	0.39	0.26	0.10	0.38	0.54	0.68

Collection Facility	$Disposal_{MX}$ ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
C_{NE}	0.28	3.51	1.54	0.35
C_{MX}	0.06	0.70	0.31	0.07
C_{KY}	0.39	4.93	2.17	0.49
C_{NB}	0.29	3.59	1.58	0.36
C_{SC}	0.42	5.29	2.33	0.53
C_{AK}	0.28	3.51	1.54	0.35
C_{MN}	0.42	5.29	2.33	0.53
C_{ID}	0.32	4.01	1.77	0.40

Remanufacturing Facility	OEM ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RM_{OR}	0.50	6.25	2.75	0.62
RM_{MI}	0.08	0.95	0.42	0.09
RM_{MO}	0.11	1.43	0.63	0.14
RM_{MX}	0.30	3.79	1.67	0.38

Recycle Facility	Supplier ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RY_{UT}	0.06	2.54	1.29	0.06
RY_{MN}	0.03	2.34	1.34	0.02
RY_{MX}	0.06	2.03	1.53	0.06
RY_{NC}	0.01	1.95	1.48	0.02

Refrigerator Design RD_2

Component	Supplier	TO OEM ($/Unit)
Insulation Material	S_{De}	0.02
Compressor	S_{Ti}	2.21
Evaporator	S_{Sh}	1.06
Door Gasket	S_{Br}	0.01

From/To		Collection Facility ($/Unit)							
		C_{NE}	C_{MX}	C_{KY}	C_{NB}	C_{SC}	C_{AK}	C_{MN}	C_{ID}
Use Location	U_{NY}	109.67	100.97	29.66	57.99	27.93	49.30	45.40	98.16
	U_{LA}	16.60	25.24	83.47	54.24	92.91	67.50	74.08	30.61
	U_{CH}	77.15	71.21	12.24	25.49	25.64	25.21	18.55	66.16
	U_{HO}	69.86	42.36	36.72	36.08	38.13	17.75	54.36	68.22
	U_{JV}	101.96	79.68	27.21	54.20	14.41	31.54	57.91	95.84
	U_{SA}	27.31	64.60	88.64	57.94	101.69	81.43	64.52	18.49
	U_{DV}	36.06	36.47	47.34	16.42	58.65	35.56	36.97	29.13

From/To		OEM ($/Unit)
Collection Facility	C_{NE}	80.95
	C_{MX}	70.40
	C_{KY}	3.44
	C_{NB}	29.08
	C_{SC}	17.15
	C_{AK}	20.15
	C_{MN}	27.29
	C_{ID}	71.32

Insulation Material		**Remanufacturing Facility ($/Unit)**				**Recycling Facility ($/Unit)**			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.12	0.51	0.36	0.27	0.11	0.38	0.41	0.60
	C_{MX}	0.59	0.46	0.34	0.21	0.43	0.45	0.08	0.42
	C_{KY}	0.52	0.08	0.13	0.31	0.37	0.16	0.38	0.11
	C_{NB}	0.33	0.21	0.06	0.16	0.19	0.10	0.33	0.30
	C_{SC}	0.59	0.14	0.19	0.36	0.44	0.24	0.38	0.06
	C_{AK}	0.47	0.19	0.09	0.22	0.30	0.19	0.27	0.21
	C_{MN}	0.39	0.14	0.14	0.29	0.28	0.04	0.46	0.27
	C_{ID}	0.09	0.44	0.31	0.21	0.08	0.30	0.44	0.54

Compressor		**Remanufacturing Facility ($/Unit)**				**Recycling Facility ($/Unit)**			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	1.23	5.10	3.58	2.74	1.15	3.77	4.06	5.98
	C_{MX}	5.88	4.61	3.43	2.09	4.27	4.53	0.79	4.19
	C_{KY}	5.17	0.84	1.27	3.13	3.72	1.59	3.79	1.14
	C_{NB}	3.35	2.11	0.63	1.61	1.88	1.02	3.34	2.98
	C_{SC}	5.91	1.38	1.95	3.64	4.39	2.38	3.82	0.59
	C_{AK}	4.67	1.92	0.87	2.16	3.04	1.88	2.66	2.05
	C_{MN}	3.87	1.44	1.45	2.94	2.84	0.36	4.61	2.74
	C_{ID}	0.92	4.43	3.08	2.07	0.79	3.04	4.35	5.45

Evaporator		**Remanufacturing Facility ($/Unit)**				**Recycling Facility ($/Unit)**			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.55	2.30	1.61	1.23	0.52	1.70	1.83	2.69
	C_{MX}	2.64	2.08	1.55	0.94	1.92	2.04	0.35	1.89
	C_{KY}	2.33	0.38	0.57	1.41	1.67	0.71	1.70	0.51
	C_{NB}	1.51	0.95	0.28	0.72	0.85	0.46	1.50	1.34
	C_{SC}	2.66	0.62	0.88	1.64	1.98	1.07	1.72	0.26
	C_{AK}	2.10	0.87	0.39	0.97	1.37	0.84	1.20	0.92
	C_{MN}	1.74	0.65	0.65	1.32	1.28	0.16	2.07	1.23
	C_{ID}	0.41	1.99	1.39	0.93	0.35	1.37	1.96	2.45

Door Gasket		**Remanufacturing Facility ($/Unit)**				**Recycling Facility ($/Unit)**			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.18	0.77	0.54	0.41	0.17	0.57	0.61	0.90
	C_{MX}	0.88	0.69	0.52	0.31	0.64	0.68	0.12	0.63
	C_{KY}	0.78	0.13	0.19	0.47	0.56	0.24	0.57	0.17
	C_{NB}	0.50	0.32	0.09	0.24	0.28	0.15	0.50	0.45
	C_{SC}	0.89	0.21	0.29	0.55	0.66	0.36	0.57	0.09
	C_{AK}	0.70	0.29	0.13	0.32	0.46	0.28	0.40	0.31
	C_{MN}	0.58	0.22	0.22	0.44	0.43	0.05	0.69	0.41
	C_{ID}	0.14	0.66	0.46	0.31	0.12	0.46	0.65	0.82

Collection Facility	Disposal$_{MX}$($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
C_{NE}	0.28	2.81	1.26	0.42
C_{MX}	0.06	0.56	0.25	0.08
C_{KY}	0.39	3.95	1.78	0.59
C_{NB}	0.29	2.87	1.29	0.43
C_{SC}	0.42	4.23	1.90	0.63
C_{AK}	0.28	2.81	1.26	0.42
C_{MN}	0.42	4.23	1.90	0.63
C_{ID}	0.32	3.21	1.45	0.48

Remanufacturing Facility	OEM ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RM_{OR}	0.50	5.00	2.25	0.75
RM_{MI}	0.08	0.76	0.34	0.11
RM_{MO}	0.11	1.15	0.52	0.17
RM_{MX}	0.30	3.03	1.37	0.46

Recycle Facility	Supplier ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RY_{UT}	0.06	2.02	0.81	0.07
RY_{MN}	0.03	2.09	0.85	0.03
RY_{MX}	0.06	2.46	1.01	0.07
RY_{NC}	0.01	2.37	1.19	0.02

Refrigerator Model RD_3

Component	Supplier	To OEM ($/Unit)
Insulation Material	S_{Pa}	0.02
Compressor	S_{No}	3.76
Evaporator	S_{Sh}	1.76
Door Gasket	S_{Sc}	0.01

From/To		Collection Facility ($/Unit)							
		C_{NE}	C_{MX}	C_{KY}	C_{NB}	C_{SC}	C_{AK}	C_{MN}	C_{ID}
Use Location	U_{NY}	108.40	99.80	29.32	57.32	27.60	48.72	44.87	97.02
	U_{LA}	16.41	24.95	82.50	53.61	91.83	66.71	73.22	30.26
	U_{CH}	76.25	70.39	12.10	25.19	25.34	24.91	18.33	65.39
	U_{HO}	69.04	41.87	36.30	35.66	37.69	17.55	53.72	67.43
	U_{JV}	100.77	78.75	26.90	53.57	14.25	31.17	57.23	94.72
	U_{SA}	26.99	63.84	87.61	57.26	100.51	80.48	63.77	18.28
	U_{DV}	35.64	36.05	46.79	16.23	57.97	35.15	36.54	28.79

From/To		OEM ($/Unit)
Collection Facility	C_{NE}	80.01
	C_{MX}	69.58
	C_{KY}	3.40
	C_{NB}	28.75
	C_{SC}	16.95
	C_{AK}	19.92
	C_{MN}	26.97
	C_{ID}	70.49

Insulation Material		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.12	0.51	0.36	0.27	0.11	0.38	0.41	0.60
	C_{MX}	0.59	0.46	0.34	0.21	0.43	0.45	0.08	0.42
	C_{KY}	0.52	0.08	0.13	0.31	0.37	0.16	0.38	0.11
	C_{NB}	0.33	0.21	0.06	0.16	0.19	0.10	0.33	0.30
	C_{SC}	0.59	0.14	0.19	0.36	0.44	0.24	0.38	0.06
	C_{AK}	0.47	0.19	0.09	0.22	0.30	0.19	0.27	0.21
	C_{MN}	0.39	0.14	0.14	0.29	0.28	0.04	0.46	0.27
	C_{ID}	0.09	0.44	0.31	0.21	0.08	0.30	0.44	0.54

Compressor		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	1.85	7.65	5.37	4.11	1.72	5.65	6.09	8.96
	C_{MX}	8.81	6.92	5.15	3.13	6.41	6.79	1.18	6.28
	C_{KY}	7.76	1.26	1.91	4.69	5.58	2.38	5.68	1.71
	C_{NB}	5.02	3.17	0.94	2.42	2.82	1.53	5.01	4.48
	C_{SC}	8.87	2.07	2.92	5.46	6.59	3.58	5.73	0.88
	C_{AK}	7.00	2.88	1.30	3.24	4.57	2.81	3.99	3.08
	C_{MN}	5.81	2.16	2.17	4.41	4.26	0.54	6.91	4.11
	C_{ID}	1.37	6.65	4.63	3.10	1.18	4.56	6.53	8.17

Evaporator		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.92	3.83	2.68	2.06	0.86	2.83	3.05	4.48
	C_{MX}	4.41	3.46	2.58	1.57	3.20	3.39	0.59	3.14
	C_{KY}	3.88	0.63	0.96	2.34	2.79	1.19	2.84	0.85
	C_{NB}	2.51	1.58	0.47	1.21	1.41	0.77	2.51	2.24
	C_{SC}	4.43	1.03	1.46	2.73	3.29	1.79	2.86	0.44
	C_{AK}	3.50	1.44	0.65	1.62	2.28	1.41	1.99	1.54
	C_{MN}	2.90	1.08	1.09	2.20	2.13	0.27	3.45	2.05
	C_{ID}	0.69	3.32	2.31	1.55	0.59	2.28	3.27	4.09

Door Gasket		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.18	0.77	0.54	0.41	0.17	0.57	0.61	0.90
	C_{MX}	0.88	0.69	0.52	0.31	0.64	0.68	0.12	0.63
	C_{KY}	0.78	0.13	0.19	0.47	0.56	0.24	0.57	0.17
	C_{NB}	0.50	0.32	0.09	0.24	0.28	0.15	0.50	0.45
	C_{SC}	0.89	0.21	0.29	0.55	0.66	0.36	0.57	0.09
	C_{AK}	0.70	0.29	0.13	0.32	0.46	0.28	0.40	0.31
	C_{MN}	0.58	0.22	0.22	0.44	0.43	0.05	0.69	0.41
	C_{ID}	0.14	0.66	0.46	0.31	0.12	0.46	0.65	0.82

Collection Facility	$Disposal_{MX}$ ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
C_{NE}	0.28	4.21	2.11	0.42
C_{MX}	0.06	0.83	0.42	0.08
C_{KY}	0.39	5.92	2.96	0.59
C_{NB}	0.29	4.31	2.16	0.43
C_{SC}	0.42	6.35	3.17	0.63
C_{AK}	0.28	4.21	2.10	0.42
C_{MN}	0.42	6.34	3.17	0.63
C_{ID}	0.32	4.82	2.41	0.48

Remanufacturing Facility	OEM ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RM_{OR}	0.50	7.50	3.75	0.75
RM_{MI}	0.08	1.13	0.57	0.11
RM_{MO}	0.11	1.72	0.86	0.17
RM_{MX}	0.30	4.55	2.28	0.46

Recycle Facility	Supplier ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RY_{UT}	0.06	3.77	1.35	0.07
RY_{MN}	0.03	3.63	1.42	0.03
RY_{MX}	0.06	4.40	1.68	0.07
RY_{NC}	0.01	3.83	1.98	0.02

Refrigerator Model RD_4

Component	Supplier	To OEM ($/Unit)
Insulation Material	S_{Pa}	0.03
Compressor	S_{Ti}	1.10
Evaporator	S_{Ji}	1.74
Door Gasket	S_{Br}	0.01

From/To		Collection Facility ($/Unit)							
		C_{NE}	C_{MX}	C_{KY}	C_{NB}	C_{SC}	C_{AK}	C_{MN}	C_{ID}
Use Location	U_{NY}	106.81	98.33	28.89	56.47	27.20	48.01	44.21	95.59
	U_{LA}	16.17	24.58	81.29	52.82	90.48	65.73	72.14	29.81
	U_{CH}	75.13	69.35	11.92	24.82	24.97	24.55	18.06	64.43
	U_{HO}	68.03	41.25	35.76	35.14	37.14	17.29	52.93	66.44
	U_{JV}	99.29	77.60	26.50	52.78	14.04	30.72	56.39	93.33
	U_{SA}	26.59	62.91	86.32	56.42	99.03	79.30	62.83	18.01
	U_{DV}	35.12	35.52	46.10	15.99	57.12	34.63	36.01	28.37

From/To		OEM ($/Unit)
Collection Facility	C_{NE}	78.83
	C_{MX}	68.56
	C_{KY}	3.35
	C_{NB}	28.32
	C_{SC}	16.70
	C_{AK}	19.63
	C_{MN}	26.57
	C_{ID}	69.46

Insulation Material		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.18	0.77	0.54	0.41	0.17	0.57	0.61	0.90
	C_{MX}	0.88	0.69	0.52	0.31	0.64	0.68	0.12	0.63
	C_{KY}	0.78	0.13	0.19	0.47	0.56	0.24	0.57	0.17
	C_{NB}	0.50	0.32	0.09	0.24	0.28	0.15	0.50	0.45
	C_{SC}	0.89	0.21	0.29	0.55	0.66	0.36	0.57	0.09
	C_{AK}	0.70	0.29	0.13	0.32	0.46	0.28	0.40	0.31
	C_{MN}	0.58	0.22	0.22	0.44	0.43	0.05	0.69	0.41
	C_{ID}	0.14	0.66	0.46	0.31	0.12	0.46	0.65	0.82

Compressor		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.62	2.55	1.79	1.37	0.57	1.88	2.03	2.99
	C_{MX}	2.94	2.31	1.72	1.04	2.14	2.26	0.39	2.09
	C_{KY}	2.59	0.42	0.64	1.56	1.86	0.79	1.89	0.57
	C_{NB}	1.67	1.06	0.31	0.81	0.94	0.51	1.67	1.49
	C_{SC}	2.96	0.69	0.97	1.82	2.20	1.19	1.91	0.29
	C_{AK}	2.33	0.96	0.43	1.08	1.52	0.94	1.33	1.03
	C_{MN}	1.94	0.72	0.72	1.47	1.42	0.18	2.30	1.37
	C_{ID}	0.46	2.22	1.54	1.03	0.39	1.52	2.18	2.72

Evaporator		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.92	3.83	2.68	2.06	0.86	2.83	3.05	4.48
	C_{MX}	4.41	3.46	2.58	1.57	3.20	3.39	0.59	3.14
	C_{KY}	3.88	0.63	0.96	2.34	2.79	1.19	2.84	0.85
	C_{NB}	2.51	1.58	0.47	1.21	1.41	0.77	2.51	2.24
	C_{SC}	4.43	1.03	1.46	2.73	3.29	1.79	2.86	0.44
	C_{AK}	3.50	1.44	0.65	1.62	2.28	1.41	1.99	1.54
	C_{MN}	2.90	1.08	1.09	2.20	2.13	0.27	3.45	2.05
	C_{ID}	0.69	3.32	2.31	1.55	0.59	2.28	3.27	4.09

Door Gasket		Remanufacturing Facility ($/Unit)				Recycling Facility ($/Unit)			
		RM_{OR}	RM_{MI}	RM_{MO}	RM_{MX}	RY_{UT}	RY_{MN}	RY_{MX}	RY_{NC}
Collection Facility	C_{NE}	0.12	0.51	0.36	0.27	0.11	0.38	0.41	0.60
	C_{MX}	0.59	0.46	0.34	0.21	0.43	0.45	0.08	0.42
	C_{KY}	0.52	0.08	0.13	0.31	0.37	0.16	0.38	0.11
	C_{NB}	0.33	0.21	0.06	0.16	0.19	0.10	0.33	0.30
	C_{SC}	0.59	0.14	0.19	0.36	0.44	0.24	0.38	0.06
	C_{AK}	0.47	0.19	0.09	0.22	0.30	0.19	0.27	0.21
	C_{MN}	0.39	0.14	0.14	0.29	0.28	0.04	0.46	0.27
	C_{ID}	0.09	0.44	0.31	0.21	0.08	0.30	0.44	0.54

Collection Facility	$Disposal_{MX}$ ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
C_{NE}	0.42	1.40	2.11	0.28
C_{MX}	0.08	0.28	0.42	0.06
C_{KY}	0.59	1.97	2.96	0.39
C_{NB}	0.43	1.44	2.16	0.29
C_{SC}	0.63	2.12	3.17	0.42
C_{AK}	0.42	1.40	2.10	0.28
C_{MN}	0.63	2.11	3.17	0.42
C_{ID}	0.48	1.61	2.41	0.32

Remanufacturing Facility	OEM ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RM_{OR}	0.75	2.50	3.75	0.50
RM_{MI}	0.11	0.38	0.57	0.08
RM_{MO}	0.17	0.57	0.86	0.11
RM_{MX}	0.46	1.52	2.28	0.30

Recycle Facility	Supplier ($/Unit)			
	Insulation Material	Compressor	Evaporator	Door Gasket
RY_{UT}	0.09	1.01	1.76	0.05
RY_{MN}	0.05	1.05	1.82	0.02
RY_{MX}	0.10	1.23	2.09	0.05
RY_{NC}	0.02	1.18	2.02	0.01

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1. Background

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1. Kentucky Graduate Scholarship, University of Kentucky, 2005-2011
2. Best Poster Award, Second International Forum on Sustainable Manufacturing, 2010
3. Ann Taylor Best Paper Award, International Conference on Value Chain Sustainability, 2009
4. National Science Foundation sponsored travel grant, First International Congress on Sustainability Science and Engineering, 2009
5. Chair, Manufacturing Systems Session, North American Manufacturing Research Conference, 2009
6. University of Kentucky Travel Fellowship, North American Manufacturing Research Conference, 2009
7. Harper Fellowship, University of Kentucky, 2007-2008
8. University of Kentucky Travel Fellowship, The World Conference on Mass Customization and Personalization, 2007

4. Professional Experience

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5. Publications, Book Chapters and Conference Papers

Publications

1. Fazleena Badurdeen, Ibrahim Jawahir, **Haritha Metta**, Sonal Gupta, Deepak Iyengar, and Thomas J. Goldsby (2009), "Extending Total Lifecycle Thinking to Sustainable Supply Chain Design," International Journal of Product Lifecycle Management, Vol.4, No.1/2/3, pp. 49-67.

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Book Chapter

1. Mohannad Shuaib, **Haritha Metta**, Fazleena Badurdeen, Tao Lu, Ibrahim Jawahir, and Thomas Goldsby (2010), "Methodologies for Design and Performance Evaluation of Sustainable Supply Chains", Accepted as a Book Chapter in Advances in Sustainable Manufacturing, Springer, Presented at the 8th Global Conference on Sustainable Manufacturing, November 22-24, 2010, Abu Dhabi University.

2. Fazleena Badurdeen, **Haritha Metta**, and Brandon Stump (2009), "Simulation Models to Demonstrate Mass Customization Strategies", Handbook of Research In Mass Customization and Personalization, World Scientific, Vol. 2, pp.1005-1019.

Referred Full Conference Papers

1. **Haritha Metta** and Fazleena Badurdeen (2011), "Optimized Closed-loop Supply Chain Configuration Selection for Sustainable Product Designs", Submitted to the 7th Annual IEEE Conference on Automation Science and Engineering, August 24-27, 2011, Trieste, Italy.

2. **Haritha Metta** and Fazleena Badurdeen (2011), "Economic Optimization and Assessment for Sustainable Product and Closed-loop Supply Chain Design", 44th CIRP International Conference on Manufacturing Systems, June 1-3, 2011, Madison, Wisconsin.

3. **Haritha Metta** and Fazleena Badurdeen (2011), "Environmental and Societal Assessment for Sustainable Product and Supply Chain Design", Industrial Engineering Research Conference, May 21-25, 2011, Reno, Nevada.

4. **Haritha Metta** and Fazleena Badurdeen (2009), "A Framework for Coordinated Sustainable Product and Supply Chain Design", Proceedings of International Conference on Value Chain Sustainability, Oct 19-21, 2009, Louisville, KY. **(Best Paper Awarded)**

5. Fazleena Badurdeen, Ibrahim Jawahir, **Haritha Metta**, Chris Stoval, Ken Wijekoon, Tom Goldsby and Deepak Iyengar (2009), "Sustainable Supply Chains: A Framework for Implementation and Performance Measurement", Proceedings of International Conference on Value Chain Sustainability, Oct 19-21, 2009, Louisville, KY.

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Conference Presentations

1. Fazleena Badurdeen, Ibrahim Jawahir, Thomas Goldsby, Deepak Iyengar**, Haritha Metta**, Sonal Gupta, "Moving Forward: Sustainable Supply Chain Management", Defense Manufacturing Conference, Dec 1-4, 2008, Orlando, FL.

2. **Haritha Metta**, Kirthi Bedida, Fazleena Badurdeen, Phil Marksberry, "Total Productive Maintenance for a Sustainable Enterprise: Status and Future Directions", International Mechanical Engineering Congress and Exposition, Nov 2007, Seattle, WA.

Poster Presentations

1. **Haritha Metta**, "Optimization for Coordinated Sustainable Product and Supply Chain Design", Second International Forum on Sustainability Manufacturing, Sept 17, 2010, Lexington, KY.

2. **Haritha Metta**, Chris Stoval, Ken Wijekoon, Mohannad Shauib, Ankur Gupta, Fazleena Badurdeen, Thomas Goldsby, Deepak Iyengar, and Ibrahim Jawahir, ”Total Life-cycle Approach to Sustainable Supply Chains”, First International Congress on Sustainability Science and Engineering (ICOSSE), Aug 9-13, 2009, Cincinnati, OH.

3. Ibrahim Jawahir, Fazleena Badurdeen, Thomas Goldsby, Deepak Iyengar, **Haritha Metta**, Chris Stovall, Ken Wijekoon, Ankur Gupta, Mohannad Shuaib, “Next Generation Supply Chain Modeling”, United States Army Logistics Symposium, June 11-13, 2009, Richmond, VA.

4. Ibrahim Jawahir, Fazleena Badurdeen, Thomas Goldsby, Deepak Iyengar, Ankur Gupta, Ken Wijekoon, Mohannad Shuaib, **Haritha Metta**, Chris Stovall, “Risk Assessment for Next Generation Supply Chain Readiness**”**, United States Army Logistics Symposium, June 11-13, 2009, Richmond, VA.

5. **Haritha Metta**, and Kirthi Bedida, “Application of Meta-Heuristic Methods To Solve Complex Manufacturing Problems”, University of Kentucky Graduate School Interdisciplinary Conference, Apr 2007, Lexington, KY.