A Bi-Objective Tactical Planning Model for the Reverse Supply Chain of Durable Products

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A Thesis
In the Department
of
Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements
For the Degree of
Master of Applied Science (Industrial Engineering) at
Concordia University
Montreal, Quebec, Canada

June 2013

CONCORDIA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

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Master of Applied Science (Industrial Engineering)

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Abstract

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Recent environmental legislations and customer awareness on environmental impacts of landfill activities as well as the profitability of reverse supply chains (RSC) have drawn the attention of researchers and companies to RSC management. RSCs include the series of activities from acquiring a used product until its recovery and sending it back to the market. In this thesis, we propose an integrated RSC tactical planning model under the context of complex durable products. The durable products consist of various types of components. This attribute makes them subject to the all disposition options including remanufacturing, part harvesting, material and bulk recycling. The proposed model decides on the coordinated decisions on acquisition, disassembly, grading, and disposition activities in the reverse supply chain. Unlike the majority of works in the literature, our contributions include two objective functions addressing both financial and environmental criteria. Furthermore, we also consider two quality levels for returns, as well as a multi-indenture structure for the end-of-life (EOL) products, and consequently all possible recovery options in the RSC. We formulate the problem as a bi-objective, multi-period mixed integer linear programming (MILP) model. We applied the proposed model to an academic case study in the context of an EOL electronic device. The bi-objective model is solved by the aid of the epsilon constraint method and a set of non-dominated solutions are provided. Finally, we conduct a set of sensitivity analysis tests for each objective function in order to determine the most significant parameters that affect the financial and environmental criteria in this problem.

Keywords: Reverse supply chain; remanufacturing; production planning; durable products, bi - objective optimization; epsilon-constraint method.

Acknowledgments

I would like to express my sincere appreciation and gratitude to Dr.Masoumeh Kazemi Zanjani for her memorable trust and confidence in nominating me as her student. She is not only an excellent supervisor but also a wonderful human being. I am much indebted to Dr.Masoumeh Kazemi Zanjani for her supervision, recommendations and patient feedbacks during each stage of this thesis.

I profoundly thank my parents, my sister and my brother-in-law. I have been blessed with a supportive father and a lovely mother that although they are miles away, their love and dedication have enabled me to reach to this educational level.

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Chapter 1 Introduction

1.1 Foreword

During a United Nations conference on human environment in 1972, in which developed and developing nations had been gathered to discuss the preservation and enhancement of the human environment, the concept of sustainability was brought out. The concept has been further developed to the point that a global consciousness regarding the environmental issues such as earth, natural resources and human life threats has been aroused [18]. This awareness has been enforced recently by government's participation in the sustainable development. Therefore, new legislations are enacted that require producer's responsibility of their waste and emission to achieve environmental sustainability. Many European countries created a system, called ERP (Extended Producer Responsibility), by which the producers require to take-back, recycle and dispose their end-of-life (EOL) products.

Sustainability includes three pillars: 1) environmental, 2) social and 3) economical ones. Firms' contribution could be along the three mentioned pillars by increasing the profit generated and decreasing the environmental and social footprints. As the result, closed loop supply chains (CLSC), has drawn the attention of researchers and companies. In the reverse side of CLSC's, environmental responsibilities could be met by the recovery of EOL products and diverting them from landfill to reuse. Products are the source of environmental issues, because in order to create a product, natural resources are consumed, manufacturers' machineries exhaust and pollute water and earth. Eventually the EOL products could damage the environment by leaving their hazardous and non-hazardous compounds on the earth.

Socially wise, green activities help the producer to build a good creditability among the consumers who reasonably expect them to eliminate their environmental harm. Another advantage of the EOL recovery practices is the Profitability and the value generated by the firms. Producing a brand new unit of product is always more expensive than remanufacturing it. Moreover, by remanufacturing, many parts and components could be reused, therefore resources would be preserved. Further, upon reuse, firms are extending the product's life cycle by keeping them out of landfill [14].For instance, over the last decade Kodak has recycled more than 310 million single-cameras in more than 20 countries [16].

According to the above mentioned advantages, reverse supply chains are becoming an essential part of businesses, among which the OEMs (original equipment manufacturers) of automotive parts, cranes and forklifts, furniture, medical equipment, pallets, personal computers, photocopiers, telephones, televisions, tires, and toner cartridges are ahead of others [14]. Recovering the EOL products could vary significantly from one industry to another. This deference roots back to the nature of the products. Some products, such as sand and paper are simple and they do not contain hazardous materials. On the other hand, complex products such as electronic wastes consist of a considerable amount of materials and parts, some of which are hazardous. Also, the recovery of such components in the underlying industry is expected to be profitable. Therefore, maintaining an efficient and effective reverse supply chain system is the key factor that gives the firm the ability to succeed and stay competitive in the market, both financially and environmentally.

Reverse supply chain includes the series of activities from acquiring a used product until recovering and sending it back to the consumer market. In the process of a typical RSC to recover a complex product, such as an electronic waste core, there are several key decisions involved, namely product acquisition, grading (inspection), and disposition, including disassembly, remanufacturing, recycling, part harvesting, and disposal. Regarding the acquisition, firms could passively accept all returned items or exert control over the acquired products through acquisition decisions [16]. Grading decisions are directly influenced by the acquisition policies. When the firms accept all the returns without exerting control over the quality levels of returns, the evaluation responsibility burden the grading center. Generally, grading unit is the link between acquisition and disposition decisions. The Disposition problem can be defined as "a given set of cores and a set of available recovery options" [24].

In order to have an efficient RSC, an integrated tactical planning to combine all the sections in the above mentioned RSC is required. Another important aspect is raised from the environmental viewpoint, in which by acquiring more of EOLs, firms would be able to prevent the waste placement into the landfill. Thus, first as a social result, a good public reputation would be built up based on the fact that companies are environmentally friendly. And second, it helps the manufacturer financially because if the OEMs fail to take back a certain amount of their products, they will end up paying high penalties.

1.2 Goal of the study

The goal in the underlying study is to propose an integrated tactical planning tool in a RSC corresponding to durable products. Durable products, such as computers, mobile phones, copy machines, washing machines and automobiles, require to be treated differently than other wastes such as papers, containers, etc. EOL durable products are distinguished by their high recoverable value and long product life cycle. They often consist of multiple and various types of components. The specific characteristic of durable products rises to the challenge of choosing a proper RSC setting. In this context, our reverse supply chain consists of different facilities, such as collection, disassembly and inspection, disposition and redistribution. We are also interested to integrate all the reverse supply chain tactical-level decisions. In other words, we aim for integrating all the tactical level decisions from collecting the EOL to selling the recovered items to the market. Demand is estimated over a multiple period setting, and returns are assumed belonging to two different quality levels, good and poor qualities, where the proportion is known in advance. The tactical level decisions in this study correspond to a complete bill-of-material of a durable product in electronic industry and include all the possible recovery options. The decision variables in each period in the planning horizon are as follows:

- Number of products of different quality levels purchased and disassembled.
- Number of modules and parts to remanufacture and harvest.
- Mass of each material to recycle.
- Inventory of products, modules, parts, materials, residues and disposal.
- Sales amount of recovered modules, parts and materials.

To formulate the underlying problem mathematically, a MILP (mixed integer programming model) is proposed that includes two objective functions: 1) financial and 2) environmental ones. According to the current literature, most of the researchers and firms try to maximize their profit (or minimize the cost), but the environmental criteria is seemed to be overlooked from the common practice. Investigating the solution of two objective functions is a challenge, given the fact that our financial and environmental objectives are in conflict. Therefore, there is a need to find a set of “most-preferred” solutions by the aim of multi-objective optimization methods. In this study we apply the epsilon-constraint method to find a pareto-front for the trade-off between the two objective functions.

Finally, we also conduct a set of sensitivity analysis tests for each objective function in order to determine the most significant parameters that affect the financial and environmental criteria in this problem.

1.3 Research contribution

According to the literature, the majority of works that have been done in the context of RSC tactical planning only addressed the financial aspects of the problem (profit maximization/cost minimization) and they failed to consider the minimization of negative environmental impacts, although RSC activities, target the reduction of environmental footprint by its nature. Furthermore, considering the most possible recovery options and different quality levels of EOL returns are other shortcomings of the current contributions in the literature.

The key considerations in this study that contribute to the existing literature are as follows:

- An integrated tactical planning model including acquisition, grading and disposition (remanufacturing, harvesting, recycling and disposal) decisions in the context of a durable product RSC proposed.
- A multi-indenture structure is considered for the EOL products. Consequently, all possible recovery options are taken into account.
- Two objective functions addressing both financial and environmental criteria are

proposed.

- Two quality levels for returns are considered. They differ in the acquisition price, recovery and processing costs, and the amounts of recoverable components.

This study contributes to a valid and strong tool for researchers and practitioners in the RSC related fields. The tactical planning model proposed in this thesis is applicable in the durable products context. Since sustainability is a fairly new concept and most companies seem to be unaware of their environmental footprint, by the aim of this tool companies will be able to increase their profit while eliminating their environmental footprint.

1.4 Thesis outline

Following the introductory chapter, a literature review is provided in chapter 2. In chapter 3, problem description, model formulation and solution methodology are presented. Chapter 4 includes our case study and the experimental results. Finally, conclusions and recommendations for future contributions are discussed in chapter 5.

Chapter 2 Literature review

2.1 Introduction

Profitability and the value generated by reverse supply chains (RSC), as well as recent increase in legislations and customer awareness on environmental impacts of landfill activities have drawn the attention of researchers to RSC's management. Environmental responsibilities could be met through improving the recovery of end-of-life (EOL) products and diverting them from landfilling to reuse which is the main motivation of RSC management. According to the growing concerns, the producers need to take advantage of practicing in closed loop and reverse supply chains. In this chapter, relevant literature of reverse supply chains is discussed. Prior to describe the current literature, we briefly review the features of supply chains and RCS's, as follows:

2.1.2 Supply chains

A supply-chain encompasses all activities associated with the flow of goods from acquiring the raw material, adding value through manufacturing, and delivering the final goods to the end user. There are five entities in every supply chain: 1) raw material suppliers, 2) manufacturers, 3) wholesalers/distributors 4) retailers, and 5) customers. The objective of every supply chain could be seen from different perspectives, but the consensus is to maximize the overall value generated. This value is the difference between what the final product worth to the customer and the costs that supply chain incurs in filling the customer's request. This generated value is a measure of profitability. The higher the supply chain profitability is, the more successful the supply chain would be [15].

Successful supply chain management requires making many decisions relating to the flow of information, product, and funds. According to Chopra and Meindl [15], these decisions fall into three basic categories in which we consider activities over specific time horizon. These categories are as follows:

1) *Supply chain strategic planning:* during this phase company decides how to structure and design the supply chain over a long period of time (years). The decisions are mainly focused on the location and capacity of the production, and the warehousing facilities, the quantity of products to be manufactured and stored at various locations, the mode of transportation and the type of information system to be utilized. These decisions are long term and are very expensive to change.

2) *supply chain tactical planning:* The time frame considered in SC tactical planning is a quarter to a year. Company decides on medium-term decisions, such as procurement planning, supplier selection, production, inventory and distribution planning. Given a shorter time frame and better forecasts than the design phase, companies in the tactical planning level, try to incorporate any flexibility built into the supply chain in the design phase, and exploit it to optimize performance.

3) *Supply chain operation planning: these* decisions are short-term (daily or weekly) plans. Companies make decisions regarding individual customer orders, allocating inventory or production to individual orders, set a date that an order is to be filled, generate pick lists at a warehouse, set delivery schedule of trucks and place replenishment orders. Given a shorter time frame than the tactical planning phase, the goal is to exploit the reduction of uncertainty and optimize performance.

2.1.3 Closed-loop and reverse supply chains

Reverse supply chains are supply chains where in addition to the typical forward flow of materials from suppliers to the end customers, there are flows of products back to manufacturers [14]. A reverse supply chain network begins with the collection of used products from end-user. According to Aras et al. [17], there are different structures of the reverse supply chains in practice, and the nature of the used product and the type of recovery activity play an important bearing on the structure of the RSC. However, collecting or acquisition, grading and disposition decisions are the major elements of a RSC.

Product acquisition activities represent the supply side of CLSCs and include feeding the products back into the supply chain [24]. There are two types of acquisition systems, market-driven and waste-stream. In the market-driven case, firms exert control over the quality of acquired items via different methods. This control could be through pricing decisions. In a waste-stream system, firms accept all the returns without exerting careful control over the quality levels of returns, therefore the role of acquisition management is not significant. In this situation, the focus is more on the grading activities after acquisition. In the grading activities, the used products are evaluated and tested for proper recovery decisions. Different grading methods exist in order to define the quality status of products. Once the quality of products is known they are classified for further treatments. The objective is to optimize the performance by determining the right grading decisions. The grading unit is the link between acquisition and disposition activities. After grading, a RSC is faced with multiple options for further treatment depending on the type of the products. These decisions are recalled as disposition decisions. The disposition problem is straightforward for a single core, but when disassembling a product yields multiple components, a good disposition decision has to take into account all of these components and seek global optimum among them. The simplest form of disposition decision for a core is the choice of remanufacturing and disposal [24]. However for a more complex product, this could be a combination of remanufacturing, refurbishing, recycling, part harvesting, land filling, incineration, internal reuse, and resale. Remanufacturing or refurbishing is the highest profitable, and at the same time the most costly recovery activity among the disposition options. Remanufacturing includes disassembly, cleaning, repairing, replacing parts and reassembly and consists of bringing the used product to a common operating and aesthetic standard [25]. Refurbishing is defined as 'light' remanufacturing and it include a minor disassembly. The parts recovery includes cleaning and repairing a used part in order to reuse it. Incineration could be used to reduce the landfill amount and energy recovery, however there exist some disadvantages such as emission and pollution in the incineration practices. Resale and reuse refer to activities where there is no need for treatment and the equipment could be used as-is.

A comprehensive literature on the aforementioned elements of RSC's are described as follows.

2.2 Current literature

In this section, we briefly review the existing literature on acquisition, grading, and disposition planning in reverse and closed-loop supply chains, as follow.

2.2.1 Acquisition planning

Guide and Van Wassenhove [16] stated that firms could passively accept all returned items or exert control over the acquired products through acquisition decisions. Different works in this regard have been done. Some addressed the optimal acquisition price regardless of different quality levels of returns [19-22], while others discussed a situation where manufacturer must grade the collected items to effectively manage the quality variability [2-4].

Robotis et al. [3], studied the effect of remanufacturing on procurement decisions for resellers in the secondary markets. At first, it is assumed that the reseller procures used products from two classes of suppliers and after sorting them, she sells those products whose quality is higher than the acceptable quality level for that class, and then disposes off the rest. In the proposed model framework, the reseller observes the quality of returned products and decides to remanufacture some of them. They have considered two quality levels of products and the objective is to maximize the profit. They concluded that using remanufacturing to serve secondary markets reduces the number of units procured from the suppliers and it is always better to use remanufacturing to a certain extent. They also showed that by using remanufacturing, resellers can eliminate some of their suppliers who may be providing items of low quality.

Atasu and cetinkaya [1] presented a RSC study on lot sizing and optimal collection and use of remanufactruable returns over a finite life-cycle. They considered a setting where a collector obtains used product at a constant return rate. The collector then, ships these returns to the manufacturer regularly. Since all remanufactured products are substitutable for satisfying the demand for new products, the manufacturer would like to cover demand using as many remanufactured products as possible. The model concentrates on the case where a single production lot of new items are produced by the manufacturer early in the active market demand period. They also provided a method for making better use of returns by taking advantage of their time value in the manufacturer-collector collaboration.

Zikopolous and Tagaras [4] investigated the impact of uncertainty in the quality of returns on the profitability of a RSC. They developed a stochastic programming model for a single-period reverse supply chain planning. The underlying reverse network includes two collection facilities and one refurbishing site. Returns are conveyed to the refurbishing facility from two collection sites. The authors took into account two different uncertain quality levels of returns such that qualities are revealed only after being received by the refurbishing center. The uncertainty in quality of returns is considered as a continuous random variable. Returned units are sorted upon arrival to the refurbishing facility and disposed if they do not meet the quality standards for refurbishing. Refurbished items are sold to the market. The demand for the refurbished items is assumed to be continuous random variables. The problem in this study contains three decision variables, including the quantities to transport from each collection site to the refurbishing center and the quantity to be refurbished. The objective function is to maximize the expected profit. They concluded that the quality of returns has a significant effect on the profitability of the reverse supply chain. Furthermore, they proposed splitting the total procurement quantity between the two collection sites is beneficial to the system.

Galbreth and blackburn [2] studied the optimal acquisition quantities in remanufacturing. The remanufacturer should decide on the quantity of used items to acquire for remanufacturing and the quantity to scrap. These used items are classified into different quality levels which are widely varying and uncertain. The condition variability was described by a continuum as well as two discrete categories of remanufacturable used items. Acquiring higher volume of used products results in having more of better quality products and therefore remanufacturing costs would decrease, but this reduction in cost would incur higher acquisition cost. Hence, in this work, the tradeoff between acquisition, scrapping and remanufacturing costs is examined. The objective was to minimize the total cost. Data were taken from a cell phone remanufacturer. They concluded that when costs are linear, the optimal acquisition quantity has a closed form and increases with the square root of the degree of condition variability.

2.2.2 Grading and disposition planning

Black burn et al. [23] discussed the appropriate location of grading operations, in term of testing returns at the centralized and decentralized facilities. Guide et al. [19] proposed an analytical model to quantify the trade-offs in the grading location decisions. Denizel et al. [5] investigated a remanufacturing environment where returns are graded and grouped into a number of different quality levels. A promising work in the closed loop supply chain is done by Sheu et al. [10]. In this work, an integrated logistics operational model for green supply chain management was proposed. A linear programming model was formulated to optimize the operations of both integrated forward and reverse logistics in a green-supply chain. Their comprehensive framework is classified into manufacturing supply chain and used-product reverse supply chain. The manufacturing supply chain includes raw material supply unit, manufacturing facility, whole sale unit, retailing and end-customers. Similarly, the reverse supply chain consists of collection centers, recycling plants, disassembly plants, secondary material markets and final disposal locations of wastes. The objective is to find equilibrium solution to maximize the net profit for the both forward and reverse supply chain. For the numerical study a real case of notebook computer manufacturer was considered. Their findings showed that, in an integrated forward-reverse supply chain, increased profit from the reverse supply chain is relatively small compared to the forward manufacturing chain. However, reverse supply chains can be benefited from the governmental subsidy policies and ultimately lead to prevention of environmental legislation expenses.

Sodhi and Reimer [11] presented a model for RSC of recycling EOL electronics. In the proposed model, the reverse channels for the recycling of electronics are represented as a network of flow between generators, recyclers and material processors. The recyclers collect electronics waste from different sources and manufacturers. Then, through further processes, such as disassembly and separation, products are broken down to different parts and components. From there, they are forwarded to smelters to process into pure stream of metal and plastics. A typical electronics recycling network includes three processing units, mixed material sources, recyclers and smelters. Linear mathematical models were formulated to optimize the profit for each processing unit, separately. At the recycler's level, an integrated disassembly and material recovery problem was formulated.

Jayaraman [9] addressed production planning for closed-loop supply chains with product recovery and reuse options. In this framework, first, products are returned from the end users. Once the products are returned, there are several options to treat them such as sell, clean and repair, refurbish and sell, remanufacture, retrieve valuable parts, recycle and disposal. It is profitable to employ all of the mentioned treatment options except disposal, which has to be minimized or eliminated. The profitability of such systems also depends on the ability to minimize the environmental impact of used products. They assumed the incoming products have different quality levels. Decision variables in their model include the number of unit cores acquired in each period, the number of unit core disassembled in each period, the number of unit cores and modules remanufactured in each period, the number of unit cores and modules disposed in each period, and the number of cores, modules and remanufactured cores, remaining in the inventory at the end of each period. A linear programming model was formulated to minimize the total cost of the reverse supply chain in a multi period setting. They collected the data from a cellular phone manufacturer for their case study. It was concluded that the acquisition price affects the acquisition quantity of used products.

Walther and Spengler [12], examined the impacts of waste electrical and electronics equipment (WEEE) directives on reverse logistics in Germany. The adoption of these directives causes essential changes in the field of electronic scrap recycling. Hence, they developed a mixed integer optimization model for integrated disassembly and recycling planning to predict relevant impact of the legislations on the treatment of discarded electronic products. The decision variables include the masses of products to acquire, masses of products or disassembly fraction accepted from another disassembly company, number of executions of disassembly activities and masses of disassembly fraction delivered to recycling or disposal site. The objective is to maximize annual marginal income of the network. The data were collected from a real case study in entertainment electronics in Germany. Some of their findings include that by increasing centralization tendencies, transportation costs and thus emissions will rise which contradicts the sustainability practices, therefore small companies need to cooperate and bundle capacities and acquisition processes. Joint utilization of vehicles and joint investments in vehicles with higher capacity are other possibilities for network cooperation.

Ferguson et al [6] investigated the value of grading in remanufacturing. They considered a tactical production planning problem in a remanufacturing firm. In this study, products are returned to the firm's return facility. Returned products are coming from a broad range of different quality levels. Afterward, they are graded to three different quality levels. Grading procedure determines the proper disposition option for the product to undergo. The decision variables are the number of products to remanufacture, the quantity of returns to salvage and inventory of both returned and remanufactured products. Demand is forecasted for the remanufactured products but it is considered to be different than the demand for new products. They collected the data from a mailing equipment manufacturer. A greedy heuristic solution algorithm was developed to solve the problem. Based on their analysis, grading the returns would increase profit by 4 %.They proposed a number of managerial insights as follows. First, the ratio of return rates to demand rates has a direct relation with the value of grading. Second, the major benefits of applying a grading system in remanufacturing occur when there are no more than five quality levels for grading.

In a comprehensive work regarding grading and disposition planning, Doh and Lee [8] proposed a grading and production planning model in a reverse supply chain. In their problem, the used products are collected through the collection facilities and stored at the "collected items" inventory. Then in the grading step, they are inspected, and tested to determine if products are remanufacturable or not. Remanufacturable products are disassembled to parts and components and are stored in the inventory for further processing and reassembly. Non-remanufacturable products are sent to disposal units. The decision variables are the number of products to be disassembled or disposed, the number of parts or components to remanufacture or dispose and the number of products to be reassembled in each period. The objective is to maximize the profit. They formulated the problem as a mixed integer programming model. They also provided two heuristic solution algorithms.

Kim et al [7] proposed a supply planning model for remanufacturing in a reverse logistics network. In this framework, end-of-life products are returned to the collection facility, then, they are disassembled and disposed to different parts. Disassembled parts are classified into reusable and non-reusable parts. In this study, only one disposition option, refurbishing, is considered and the products beyond the capacity are sent to external remanufacturing subcontractors. Non-usable parts are sent to disposal. The author also considered the possibility of obtaining some new parts from an external supplier. The decision variables include the number of disassembled products, the number of refurbished and disposed products in each period and the inventory level of products and parts. Moreover the manager has to decide on the number of purchased new parts as well as the number of outsourced products. The objective function is to maximizing the profit and the problem was formulated as a mixed integer programming model. The data were taken from a real case study. Sensitivity analyses were also performed to examine the different ways of cost savings.

Denizel et al [5] proposed a multi-period remanufacturing planning model with uncertain quality of inputs. In this model, one type of product with the uncertain quality levels is considered. Demand is forecasted and known for different periods. They assumed that cores arrive at the firm and are graded, then after observing the outcome of the grading process, the manager decides upon the amount to salvage and refurbish for each quality grade. Decision variables are the number of products to grade, the graded core to remanufacture as well as the number of cores to salvage. A multi-stage stochastic programming model was proposed to formulate this problem. The objective function is to maximize the total expected profit. Data were obtained from a real business case study, namely remanufacturing mailing equipment. The authors also did a broad numerical study and regression analysis to measure the relative impact of each parameter on profit. Some of their findings can be summarized as follows: firm's profit is vastly related to the quality of the cores, the salvage value of unused products and the cost of grading. Furthermore, most of the times it is more profitable to remanufacture all of the higher quality cores, except when the cost of grading is high and firms have to grade and remanufacture only enough to meet the demand.

According to the literature review in this section, the characteristics of different reverse and closed-loop supply chains studied in the literature are summarized in table1. The last row of the table contains the features of the RSC investigated in this thesis.

Reference	Different quality levels of returns	Objective function		Multi period setting	Disposition decision				Acquisition Decision	Case study
		Bi objective	Single objective		remanufacturing	Part harvesting /refurbishing	Material recycling	Disposal		
[1]			✓		✓				✓	
[2]	✓		✓		✓			✓	✓	cellphone
[3]	✓		✓		✓			✓	✓	
[4]	✓		✓		✓			✓	✓	
[5]	✓		✓	✓	✓			✓		Mailing equipment
[6]	✓		✓		✓	✓		✓		Mailing equipment
[7]	✓		✓	✓	✓			✓		
[8]	✓		✓		✓			✓	✓	Cellular
[9]			✓	✓	✓			✓		Notebook manufacturer
[10]			✓				✓	✓		Electronic products
This thesis	✓	✓		✓	✓	✓	✓	✓	✓	Electronic waste(academic)

Table 2-1 Characteristics of the closed-loop supply chains in the current literature

2.3 Conclusion

In this chapter, we reviewed the most recent literature in the field of CLCS's and RSC's tactical planning. Firms in many industries are trying to increase their activities on reverse supply chain according to the new legislations. Existing models have tried to capture different aspects of closed-loop and reverse supply chains. However, a clear gap in the literature still exists according to the different structures of a CLSC or RSC. For instance, in the content of complex product, after disassembly, different types of components, namely, modules, parts, residues, materials and disposal would be yielded. Therefore different types of disposition options can be considered. In contrary, when a product is simple such as sand, paper, etc. only a limited number of disposition options are possible. The current literature covers only a few of disposition options. For instance, some authors have addressed only one disposition option [1], while others focused on two or three options [1-10], nevertheless, none have investigated all of the possible disposition options in the RSC. Secondly, another important setting to be considered in the RSC and CLSC studies is the alignment with environmental concerns. Hence we expect firms make an effort to acquire used-products from different quality levels in order to reduce the environmental impacts of landfill. While one of the key considerations to minimize the environmental impact in the RSC's is to maximize the acquired used-products among various qualities, to the best of our knowledge, current literature in the RSC tactical planning only investigates the acquisition activities from the economic perspective (profit maximization).

In the literature, it can be observed that some of the contributions developed a setting that returns are from different quality levels. This variation in incoming quality levels are tackled by deterministic and stochastic mathematical programming approaches [2-8]. While most of the works did not study the control over acquisition quality, only a few considered a setting with acquisition decisions of different quality levels [2-4]. Nonetheless, to the best of our knowledge, none of the available contributions considered different quality levels in an integrated tactical planning problem in a RSC, as investigated in this thesis.

Chapter 3 Problem definition and model formulation

In this chapter, we first describe the features of the problem investigated in this thesis. Then, we provide the problem formulation.

3.1 Problem description

In this thesis, we are focused on a RSC corresponding to durable products. Hence, we first elaborate on the main features of such products. Then we provide the characteristics of the corresponding RSC.

3.1.1 Product features

In the underlying research, we considered a complex durable product. Durable products, such as computers, mobile phones, copy machines, washing machine and automobiles, require to be treated differently than other wastes such as papers, containers, etc. EOL durable products are distinguished by their high recoverable value and long product life cycle. They often consist of multiple and various types of components that can be recovered by different methods. The modular structure of the product is shown in figure 3-1. When the durable product is disassembled, it yields modules, parts, residues, some precious materials and other hazardous and non-recoverable components. Modules are units of products which would undergo remanufacturing. Remanufacturing is the highest profitable and at the same time most costly recovery decision among all disposition options. Remanufacturing include disassembly, cleaning, repairing, replacing parts and reassembly and consists of bringing the used product to a common operating and aesthetic standard [25]. Good quality EOL products consist of more remanufacturable modules. On the other hand, poor quality returns include less number of remanufacturable modules. Good quality and poor quality modules are different in terms of remanufacturing costs, as well. Poor quality modules are processed at high cost while good qualities require low cost of remanufacturing. However, both quality levels would be brought up to the same quality level through the remanufacturing processes. Poor quality modules are nominated for remanufacturing at high cost or being sent to bulk recycling. Spare parts are another sub-component of the disassembly process. These spare parts are entities that would undergo the harvesting process if they meet certain criteria for the harvesting. In this process, used parts are recovered to be sold in spare part markets. Each product yields different numbers of a specific part, based on its quality level. Good quality products yield more harvestable parts than poor quality ones. If parts are not qualified for harvesting, they will be sent to bulk recycling. Other disassembly outputs are materials. Materials such as plastic, iron, copper and aluminum are separated after the product is shredded. Some materials could be easily extracted as they exist in solid forms. But a big fraction of materials are combined with other compounds and it is not easy to extract them through simple activities in material recycling's unit. Therefore, the residues remained after removing the hazardous and valuable materials from the product are bulk recycled. In bulk recycling facilities, the remainder of the product is shredded into flakes. Further, different separation methods based on physical properties of materials are used to classify them into different categories of materials. For example, metals are removed by magnets and eddy currents, plastics are separated based on physical properties such as mass, density or particle size [11]. There exist other techniques such as sink-float separation, air classification [26], and ultrasonic methods [27] that could be used in this regard. Bulk recycling is relatively costly comparing to material recycling and it can process large amounts of residues. The remainder of products with no value as well as potentially hazardous components are disposed (e.g. landfilled).

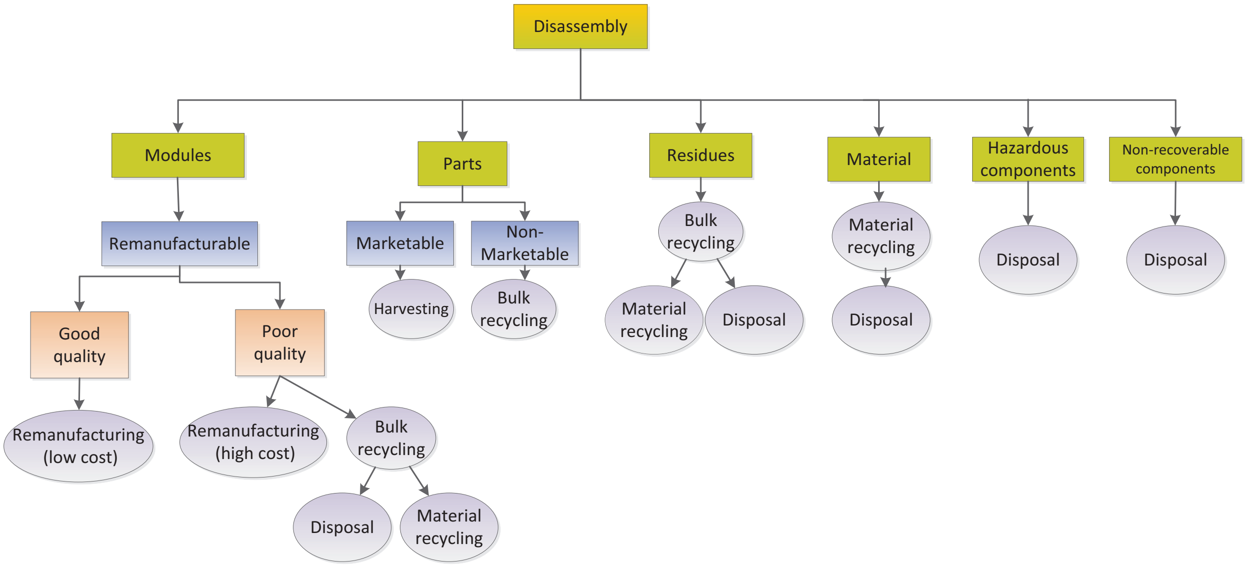

Figure 3-1 Modular structure of a durable product

3.1.2 Reverse supply chain characteristics

Based on the features of the complex durable products, discussed previously, the structure of our reverse supply chain is defined as follows. The reverse supply chain includes different facilities, such as collection, disassembly and inspection, disposition and redistribution ones. End-of-life returns are collected in the collection facility as it can be seen in figure 3-2. These returns are assumed belonging to two different quality levels, good and poor quality. As an example of good quality returns, we can refer to guaranty/warranty returns. In reality, a greater percentage of these returns are from poor quality and the rest are good qualities, as good quality EOL products are scarce and limited. At the collection centers, the firm decides what quantity of EOL products of each quality should be purchased in each period. Good quality products are purchased at high price while we can acquire poor quality products at low cost and in high amount. The purchased amounts of each product are stored in the inventory of acquired products and they are sent to disassembly facilities. All the acquired products are disassembled to their components. Disassembly activities are mostly done manually and are labor intensive. As mentioned before, good quality products yield more useful modules and parts rather than poor quality products. On the other hand, more residues and consequently more materials could be extracted from poor quality products. Disassembled outputs are inspected for assigning to proper disposition categories. In this step, the yielded components are categorized into the good and poor quality modules, harvestable parts, residues for bulk recycling, recyclable materials and both hazardous and non-hazardous disposal. Each category of items is kept in its inventory until they are transferred to their corresponding processing facility. The model also decides if there is a need to transfer some of the low quality modules to the bulk recycling because of the limited capacity. Remanufactured items are raised to the same quality level and they will be sold in the market. Harvestable parts are stored in the inventory until they are transferred to the harvesting facility. Harvested parts are sold to the market at a lower price than the brand new parts. According to the capacity restriction it is not possible to hold all the harvestable parts in inventory, therefore we consider some flows to the bulk recycling from inventory of harvestable parts. Through the disassembly process, some of the targeted materials such as metal and plastic are removed from the product and they only need minor care and repair, which would occur at the material recycling facility. At this facility, a fraction of useless materials are sent to disposal facilities and the rest would be shipped to the recycled material inventory in order to be sold in the market. Material recycling facility is a labor intensive facility where most of the works are done manually. Another recycling facility which is machine intensive is bulk recycling.

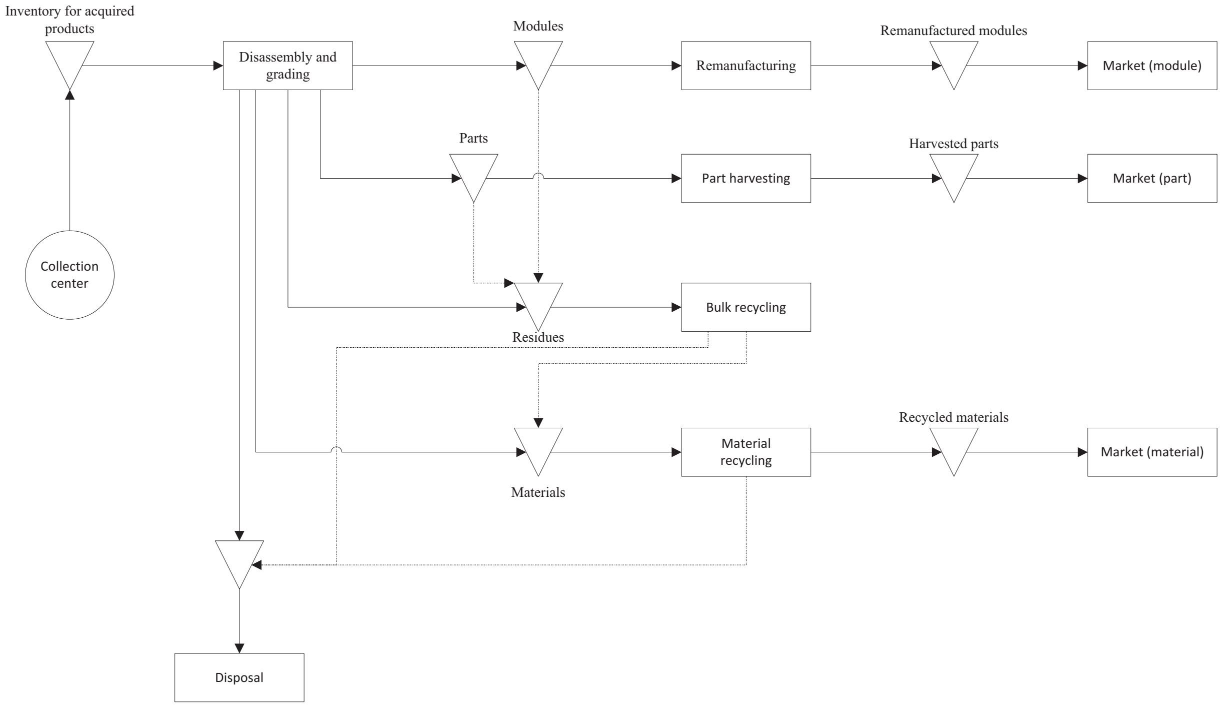

Figure 3-2 Reverse supply chain configuration

3.2 Problem formulation

Under the RSC, described in sub-section 3.1.2, we are looking for a medium-term tactical planning model. More precisely, the following decisions must be taken. We have considered two types of objective functions in this research: the environmental and

Table 3-1 Decision variables

Decision Variable	Description
$X_{k,t}^{prod}$	Number of Products purchased with quality *k* in period *t*
$X_{k,t}^{disa}$	Number of Products disassembled with quality *k* in period *t*
$X_{k,m,t}^{rem}$	Number of module *m* of quality *k* to remanufacturing period *t*
$X_{a,t}^{part}$	Number of part "*a*" of quality k to harvest in period *t*
$X_{l,t}^{recm}$	Mass of material "*l*" to recycle in period *t* (Kg)
X_{t}^{bulk}	Mass of residues sent to bulk recycling facility in period *t* (Kg)
$X_{k,m,t}^{rem-res}$	Number of modules that flow from inventory of modules to residues
$X_{k,a,t}^{part-res}$	Number of parts that flow from inventory of parts to residues
X_{t}^{disp}	Amount to dispose in each period
$I_{k,t}^{prod}$	Inventory level of product with quality *k* in period *t*
$I_{a,t}^{part}$	Inventory level of part *a*, in period *t*
$I_{a,t}^{harv}$	Inventory level of harvested part *a* quality *k* in period *t*
$I_{k,m,t}^{\mathrm{mod}}$	Inventory of module *m* quality *k* in period *t*
$I_{m,t}^{rem}$	Inventory level of remanufactured module *m* in period *t*
I_{t}^{res}	Inventory level of residues in period *t*
$I_{l,t}^{mat}$	Inventory level of material *l* in period *t*
$I_{l,t}^{recm}$	Inventory level of recycled material *l* in period *t*
I_{t}^{disp}	Inventory level of disposal in each period
$S_{m,t}^{\mathrm{mod}}$	Sale amount of module *m* in period *t*
$S_{a,t}^{part}$	Sale amount of part *a* in period *t*
$S_{l,t}^{mat}$	Sale amount of material *l* in period *t*
Y_{t}^{rem}	1, if remanufacturing facility is used during time *t*. 0, otherwise.
Y_{t}^{harv}	1, if harvesting facility is used during time *t*. 0, otherwise.
Y_{t}^{bulk}	1, if bulk recycling facility is used during time *t*. 0, otherwise.

financial ones. Regarding the environmental concerns, we aim to maximize the total quantity of the EOL product acquisition. On the other hand, the financial objective function seeks to maximize the profit. Since these two objective functions are conflicting, improvement in one of them requires degradation in the other. Therefore we apply the epsilon constraint method to find the pareto-front solutions and the trade-off between the two objective functions. The epsilon-constraint method is explained in sub-section 3.3.

The following assumptions are considered in formulating the problem.

- One type of product is considered.
- No back order cost is considered in the model.
- Products of good quality yield good quality modules with less remanufacturing cost.
- Products of poor quality yield poor quality modules with more remanufacturing cost.
- Different quality levels of modules are brought up to one standard quality level after remanufacturing.
- A set-up cost is considered in order to use a facility in each period.
- Each facility consists of a number of machines and workers to process different tasks. The capacity of machines and labors is assumed to be limited.
- Demand is forecasted for the entire time period in a deterministic manner and each time period could be a month.

The mathematical model is explained in the following.

3.2.1 Mathematical model

In this section, we propose an integrated acquisition and recovery production planning model under the context of durable products reverse supply chain. The model integrates the acquisition, disassembly, production, sales and inventory planning decisions. We formulate this multi-period tactical planning problem as a mixed integer linear programming model as follows:

The notions are described in appendix I.

3.2.2 Objective functions

The first financial objective function (3.1) aims at maximizing the total revenue minus the cost of recovery and inventory over the planning horizon. Total revenue is calculated as the income obtained from selling the remanufactured modules, harvested parts and recycled materials.

Objective Function 1:

Max Profit = REV-COR-IHC (3.1)

Revenue (REV) is the income obtained by selling the recovered entities to the market. Cost of recovery activities (COR) consist of the cost of buying used products from both quality levels, disassembly process, remanufacturing as well as set-up fixed costs for remanufacturing in each period, harvesting and refurbishing costs which are mostly labor intensive, besides harvesting set-up cost, material and bulk recycling processing cost. It also includes the cost associated with the disposal of useless residues. Inventory costs (IHC) include the overall cost of keeping the products, modules (before and after remanufacturing), parts (before and after harvesting), materials (before and after recycling), residues and disposal over the entire planning periods.

<u>Cost of recovery activities:</u>

COR:

$$\sum_{k\in K}\sum_{t\in T} C_k^{prod} X_{k,t}^{prod} + \sum_{k\in K}\sum_{t\in T} C_k^{disa} X_{k,t}^{disa} + \sum_{k\in K}\sum_{m\in M}\sum_{t\in T} (C_{fix}^{rem} Y_t^{rem} + C_m^{rem} X_{k,m,t}^{rem}) +$$

$$\sum_{a\in A}\sum_{t\in T} (C_{fix}^{harv} Y_t^{harv} + C_a^{harv} X_{a,t}^{part}) + \sum_{t\in T} (C_{fix}^{bulk} Y_t^{bulk} + C^{bulk} X_t^{bulk}) + \sum_{l\in L}\sum_{t\in T} C_l^{recm} X_{l,t}^{recm} + \sum_{t\in T} C^{disp} X_t^{disp}$$

<u>Inventory holding cost:</u>

IHC:

$$\sum_{k\in K}\sum_{t\in T} h_k^{prod} I_{k,t}^{prod} + \sum_{k\in K}\sum_{m\in M}\sum_{t\in T} h_m^{\mathrm{mod}} I_{k,m,t}^{\mathrm{mod}} + \sum_{m\in M}\sum_{t\in T} h_m^{rem} I_{m,t}^{rem} + \sum_{a\in A}\sum_{t\in T} h_a^{part} I_{a,t}^{part} +$$

$$\sum_{a\in A}\sum_{t\in T} h_a^{harv} I_{a,t}^{harv} + \sum_{t\in T} h^{res} I_t^{res} + \sum_{l\in L}\sum_{t\in T} h_l^{mat} I_{l,t}^{mat} + \sum_{l\in L}\sum_{t\in T} h_l^{recm} I_{l,t}^{recm} + \sum_{t\in T} h^{dis} I_t^{disp}$$

<u>Revenues</u>

REV:

$$\sum_{m\in M}\sum_{t\in T} S_{m,t}^{\mathrm{mod}} p_m^{rem} + \sum_{a\in A}\sum_{t\in T} S_{a,t}^{part} p_a^{harv} + \sum_{l\in L}\sum_{t\in T} S_{l,t}^{mat} p_l^{recm}$$

The second environmental objective function (3.2) ensures that firm has tried to acquire maximum amount of returned products.

<u>Objective function 2:</u>

$$\text{Max } \sum_{k\in K}\sum_{t\in T} X_{k,t}^{prod} \qquad (3.2)$$

3.2.3 Constraints

We consider three categories of constraints, including inventory balance constraints, set-up constraints, and capacity constraints. The capacity constraints include machine capacity, labor capacity and inventory capacity. Each set of constraints are explained in the following.

3.2.3.1 Inventory balance constraints:

Constraint (3.3) ensures that the total inventory of the products for each quality level at the end of period *t* is equal to its inventory in the previous period plus the quantity of products of the same quality level acquired ($X_{k,t}^{prod}$) at the beginning of that period minus the quantity of products that are sent to disassembly ($X_{k,t}^{disa}$), in that period. Constraint (3.4) ensures that the total inventory for each module of quality *k* at the end of period *t* is equal to its inventory in the previous period plus the quantity of the modules of the same quality extracted after disassembly, minus the amount of modules shipped from the inventory to the remanufacturing facility ($X_{k,m,t}^{rem}$) and the bulk recycling ($X_{k,m,t}^{rem-res}$) facility in that period. In this constraint, $\mu_{k,m}$ is the number of module type *m* available in each product quality *k.* Hence, by multiplying this number by the number of product disassembled in each period ($X_{k,t}^{disa}$), we calculate the total number of extracted modules. Constraint (3.5) requires that the total inventory for each part at the end of period *t* is equal to its inventory in the previous period plus the quantity of all the same type parts yielded after disassembly, minus the number of parts shipped out to refurbishing facility ($X_{a,t}^{part}$) and residues inventory ($X_{a,t}^{part-res}$) in that period. In this constraint, $\nu_{a,k,t}$ is the number of part type *a* available in each product quality *k*. By multiplying this number by $X_{k,t}^{disa}$ which is the number of products disassembled the total number of parts yielded after disassembly is calculated. Constraint (3.6) sets the amount of residues in the inventory at the end of period *t* equal to the amount of residues carried over from previous period plus the amount of residues produced after disassembly, as well as amounts of modules and parts coming from modules and parts inventories, minus the amount of residues sent to bulk recycling in that period (X_{t}^{bulk}). In this constraint, λ_{k} is the mass of residues in each product of quality *k* in kg. $\omega_{m}^{\mathrm{mod}}$ and ω_{a}^{part} are weights of each module *m* and part *a,* respectively. Constraint (3.7) ensures that the total inventory for each material at the end of period *t* is equal to its inventory in the previous period plus the amount of the same material extracted from disassembly and bulk recycling in that period minus the amount sent to material recycling ($X_{l,t}^{recm}$). In this constraint, $\kappa_{k,l}$ is the mass of material *l* remained after disassembly of product quality *k* in kg and β_l is the percentage of bulk recycled residues in material *l*. Constraint (3.8) requires that the inventory of remanufactured modules at the end of period *t* is equal to its inventory from previous period plus the amount of remanufactured modules added to the inventory in the same period minus the quantity sold in that period. Constraint (3.9) sets the inventory of harvested parts at the end of period *t* equal to its inventory from previous period plus the amount of harvested parts at the harvesting facility in the same period minus the sale amount. Constraint (3.10) ensures the inventory of recycled materials at the end of period *t* is equal to its inventory from previous period plus a fraction of recycled material at the manual recycling facility minus the amount sold to the market in that period. In this constraint, the fraction of recycled material sent to inventory is calculated by multiplying (1-γ) by the total amount of material type *l* recycled, whereas γ is the percentage of recycled material sent to disposal. Constraint (3.11) balances the inventory of disposal in each period. Disposal inventory in each period is equal to the inventory carried over from previous period plus the disposal generated from different processes such as disassembly, material (γ) and bulk recycling, minus the amount which is disposed from stock in that period. In this constraint, ε_k is the mass of disassembled product of quality *k* sent to disposal in kg, and δ is the percentage of recycled residues sent to disposal. Constraints (3.12) - (3.14) require that the sale amount in each period does not exceed the demand in that period.

Returned products:

$$I_{k,t-1}^{prod} + X_{k,t}^{prod} - X_{k,t}^{disa} = I_{k,t}^{prod} \qquad \forall_{k,t} \tag{3.3}$$

Modules:

$$I_{k,m,t-1}^{\mathrm{mod}} + \mu_{k,m} X_{k,t}^{disa} - X_{k,m,t}^{rem} - X_{k,m,t}^{rem-res} = I_{k,m,t}^{\mathrm{mod}} \qquad \forall_{k,m,t} \tag{3.4}$$

Parts:

$$I_{a,t-1}^{part} + \sum_{k \in K} \nu_{k,a} X_{k,t}^{disa} - X_{a,t}^{part} - X_{a,t}^{part-res} = I_{a,t}^{part} \qquad \forall_{a,t} \tag{3.5}$$

Residues:

$$\begin{aligned} & I_{t-1}^{res} + \sum_{k \in K} \sum_{m \in M} \omega_m^{\mathrm{mod}} X_{k,m,t}^{rem-res} \\ & + \sum_{k \in K} \lambda_k X_{k,t}^{disa} + \sum_{k \in K} \sum_{a \in A} \omega_a^{part} X_{a,t}^{part-res} - X_t^{bulk} = I_t^{res} \end{aligned} \qquad \forall_{t} \tag{3.6}$$

Materials:

$$I_{l,t-1}^{mat} + \sum_{k \in K} \kappa_{k,l} X_{k,t}^{disa} + (1-\delta) \beta_l X_t^{bulk} - X_{l,t}^{recm} = I_{l,t}^{mat} \qquad \forall_{l,t} \tag{3.7}$$

Remanufactured products:

$$I_{m,t-1}^{rem} - S_{m,t}^{\mathrm{mod}} + \sum_{k \in K} X_{k,m,t}^{rem} = I_{m,t}^{rem} \qquad \forall_{m,t} \tag{3.8}$$

Harvested parts:

$$I_{a,t-1}^{harv} + X_{a,t}^{part} - S_{a,t}^{part} = I_{a,t}^{harv} \qquad \forall_{a,t} \tag{3.9}$$

Recycled materials:

$$I_{l,t-1}^{recm} + (1-\gamma) X_{l,t}^{recm} - S_{l,t}^{mat} = I_{l,t}^{recm} \qquad \forall_{l,t} \tag{3.10}$$

Disposal:

$$I_{t-1}^{disp} + \sum_{k \in K} \varepsilon_k X_{k,t}^{disa} + \sum_{l \in L} \gamma X_{l,t}^{recm} + \delta X_t^{bulk} - X_t^{disp} = I_t^{disp} \qquad \forall_{t} \tag{3.11}$$

$$S_{m,t}^{\text{mod}} \leq d_{m,t}^{\max \text{mod}} \qquad \forall_{m,t} \tag{3.12}$$

$$S_{a,t}^{part} \leq d_{a,t}^{\max part} \qquad \forall_{a,t} \tag{3.13}$$

$$S_{l,t}^{mat} \leq d_{l,t}^{\max mat} \qquad \forall_{l,t} \tag{3.14}$$

3.2.3.2 Set-up constraints:

Constraints (3.15) - (3.17) represent set-up constraints. The binary variables Y_t^{rem} , Y_t^{harv} and Y_t^{bulk} take 1 if we use the facility and otherwise they take zero. If these variables take 1, the cost of facility set-up is included in the objective function. M is a big positive number.

$$X_{k,m,t}^{rem} \leq M \times Y_t^{rem} \tag{3.15}$$

$$X_{a,t}^{part} \leq M \times Y_t^{harv} \tag{3.16}$$

$$X_t^{bulk} \leq M \times Y_t^{bulk} \tag{3.17}$$

3.2.3.3 Capacity constraints:

Constraints (3.18) and (3.19) require that the remanufacturing quantity does not exceed machine and labor capacities. Constraint (3.20) ensures the refurbishing and harvesting quantity is less than the labor capacity to refurbish the parts. Constraints (3.21) and (3.22) require recycling amounts of the materials are not more than the available labor and machine capacities. Constraints (3.23) and (3.24) represent the capacity constraints for bulk recycling which should not be more than available labor and machine capacities. Similarly constraints (3.25) and (3.26) are regarding the capacity constraints for the disassembly process.

Labor/machine capacity:

$$\sum_{k\in K}\sum_{m\in M} X_{k,m,t}^{rem}\phi_{m,t}^{lab-rem} \le W_t^{lab-rem} \qquad \forall_t \qquad (3.18)$$

$$\sum_{k\in K}\sum_{m\in M} X_{k,m,t}^{rem}\phi_{m,t}^{mach-rem} \le W_t^{mach-rem} \qquad \forall_t \qquad (3.19)$$

$$\sum_{a\in A} X_{a,t}^{part}\phi_{a,t}^{lab-part} \le W_t^{lab-part} \qquad \forall_t \qquad (3.20)$$

$$\sum_{l\in L} X_{l,t}^{recm}\phi_{l,t}^{lab-recm} \le W_t^{lab-recm} \qquad \forall_t \qquad (3.21)$$

$$\sum_{l\in L} X_{l,t}^{recm}\phi_{l,t}^{mach-recm} \le W_t^{mach-recm} \qquad \forall_t \qquad (3.22)$$

$$X_t^{bulk}\phi_t^{lab-bulk} \le W_t^{lab-bulk} \qquad \forall_t \qquad (3.23)$$

$$X_t^{bulk}\phi_t^{mach-bulk} \le W_t^{mach-bulk} \qquad \forall_t \qquad (3.24)$$

$$\sum_{k\in K} X_{k,t}^{disa}\phi_{k,t}^{lab-disa} \le W_t^{lab-disa} \qquad \forall_t \qquad (3.25)$$

$$\sum_{k\in K} X_{k,t}^{disa}\phi_{k,t}^{mach-disa} \le W_t^{machin-disa} \qquad \forall_t \qquad (3.26)$$

Constraint (3.27) ensures that the inventory of products for both quality levels does not exceed the total available space of the stock in each period. In a very similar way constraints (3.28) - (3.35) require that the inventory of disassembled parts, harvested parts, modules, remanufactured modules, residues, material, recycled materials and disposal does not exceed their total available inventory capacity.

Inventory capacity:

$$\sum_{k\in K} I_{k,t}^{prod}\phi_{k,t}^{inv-prod} \le W_t^{inv-prod} \qquad \forall_t \qquad (3.27)$$

$$\sum_{a\in A} I_{a,t}^{part}\phi_{a,t}^{inv-part} \le W_t^{inv-part} \qquad \forall_t \qquad (3.28)$$

$$\sum_{a\in A} I_{a,t}^{harv}\phi_{a,t}^{inv-harv} \le W_t^{inv-harv} \qquad \forall_t \qquad (3.29)$$

$$\sum_{k\in K}\sum_{m\in M} I_{k,m,t}^{\mathrm{mod}}\phi_{m,t}^{inv-\mathrm{mod}} \le W_t^{inv-\mathrm{mod}} \qquad \forall_t \qquad (3.30)$$

$$\sum_{m\in M} I_{m,t}^{rem}\phi_{m,t}^{inv-rem} \le W_t^{inv-rem} \qquad \forall_t \qquad (3.31)$$

$$I_t^{res}\phi_t^{inv-res} \le W_t^{inv-res} \qquad \forall_t \qquad (3.32)$$

$$\sum_{l\in L} I_{l,t}^{mat}\phi_{l,t}^{inv-mat} \le W_t^{inv-mat} \qquad \forall_t \qquad (3.33)$$

$$\sum_{l\in L} I_{l,t}^{recm}\phi_{l,t}^{inv-recm} \le W_t^{inv-recm} \qquad \forall_t \qquad (3.34)$$

$$I_t^{disp}\phi_t^{inv-dis} \le W_t^{inv-dis} \qquad \forall_t \qquad (3.35)$$

3.3 Solution approach

In tackling multi-objective problems, different methods have been developed. The specific attribute of all the multi-objective problems is that, there are more than one objective function and there is no single optimal solution that simultaneously optimizes all the objective functions. The most common method in order to solve these kinds of problems is the epsilon-constraint method, weighting method and goal programming method [30].

In the weighting method, different weights are assigned to each objective function. Then theses objective functions are combined and transferred to one objective function to produce a set of non-dominated solutions.

Goal programming is an effective method to find a definite solution rather than a set of non-dominated solutions. In this method a goal value is set for each objective function and the deviations from the goal value are minimized.

In this research, we applied the epsilon constraint method in order to solve the bi-objective model. In this method, one objective function is optimized while the other objective functions are considered as constraints. These constraints are bounded with some values, and by varying these bounds, a set of "most-preferred" solutions are obtained. The most preferred solutions are the ones that improve at least one of the objective functions; these are also called pareto-optimal, non-dominated and non-inferior solutions. On the other hand, the solutions that do not improve any of the objective functions and are dominated by better solutions would be eliminated [32-33]. To gain a better insight into this method, this method is explained in details for a bi-objective optimization problem, as follows:

First, the optimization model for each objective function is solved individually, X^1 and X^2 are the optimal solutions corresponding to the each objective. $Z_1^*(X^1)$ and $Z_2(X^1)$ are the objective function values associated with solution X^1. Similarly, the objective function value for X^2 are $Z_1(X^2)$ and $Z_2^*(X^2)$.

Second, a pay-off table is constructed as it is shown in table 3-2. The pay-off table values are calculated as follows. In this method, one objective function is chosen as primary objective function, the second objective is transferred into the constraint of the first model. F_d is the feasible region and L_n is the lower bound of $Z_2(X)$. Similarly, by transferring $Z_1^*(X^1)$ into the constraint of the second model, the optimum solution is calculated [30].

Maximize $Z_1(X\ )$

s.t.

$X \in F_d$

$Z_2(X\ ) \geq L_n$

Table 3-2 Pay-off table

	$Z_1(X^k)$	$Z_2(X^k)$
X^1	$Z_1^*(X^1)$	$Z_2(X^1)$
X^2	$Z_1(X^2)$	$Z_2^*(X^2)$

Third, a range should be defined in order to find a set of non-dominated solutions by adapting into the single objective function model. This range (L_n) is generated by taking an arbitrary number γ and using the following formula:

$$L_n = Z_2(X^1) + [h/(\gamma-1)] \times [Z_2^*(X^2) - Z_2(X^1)]$$

Where h=0,1,2,…,$(\gamma-1)$

In other words, the upper bound of L_n is $Z_2^*(X^2)$ and the lower bound of it is $Z_2(X^1)$.

Forth, Solving the single objective function problem for all possible L_n.

Chapter 4 Case study and computational experiment

In this chapter we first provide the details of our case study, and then we present the numerical results of applying the proposed model and solution methodology on the case study. A sensitivity analysis is also conducted for both objective functions at the end of this chapter.

4.1 Case study

It is worth mentioning that finding a case study with representative data was one of the most important challenges in this study. The reason lies behind the fact that none of the existing RSC tactical planning models in the literature are formulated based on a complete bill-of-material similar to the one investigated in this thesis. Consequently, none of them include all recovery options with their corresponding parameters.

The case study considered in this research is an academic case focused on electronic used products. The corresponding data are inspired by the real business case data available in the literature [7, 28, 9, and 6]. Furthermore, they are also validated and tested several times according to some of the real business data available on internet. In the following, the problem data are presented.

4.1.2 Problem data

Returns

Table 4-1 shows the amount of returns for the used products that are collected at the collection site at each period. This table is calculated from data based on the real returns data from the work of Jayaraman [9]. There are two different quality levels of returned products. Good quality and poor quality. We have considered an estimated value of 30% of our returns as good quality products, and the rest (70%) belongs to the poor quality.

Table 4-1 Number of returns for each quality levels of returned products

period	quality 1	quality2	total return
1	171	400	571
2	194	453	647
3	244	570	814
4	202	470	672
5	197	459	656
6	255	594	849
7	184	429	613
8	108	253	361
9	156	364	520
10	113	265	378
11	126	294	420
12	166	388	554

Bill-of-materials

Tables 4-2 and 4-3 illustrate the bill-of-material (BOM) of the product under investigation. These tables indicate the quantities of modules and parts as well as the masses of residues and material in the product. These numbers are different for each quality level of product. The related weights are also calculated based on the disassembly of each product, i.e., the existing numbers of modules and parts. We consider that the product, regardless of its quality level, has a weight of approximately 5 kilograms. According to the calculations, each good quality product contains around 3.1 kilograms of modules and about 0.252 kg of parts. The remaining mass, which has a weight of 1.648 kg, contains residues and materials. Close to 70% of the remaining mass undergo the bulk recycling, around 20% would be sent to material recycling and the rest are sent to the disposal facilities. The amounts of residues/materials that are generated after the disassembly are different for poor quality products. These products include fewer numbers of re-usable modules and parts. The calculated amount of residues/materials after disassembling of a poor quality product is estimated as 3.867 kg. The masses of residues, materials and disposal corresponding to both qualities are illustrated in table 4-3. Based on a study provided by Sodhi and Reimer [11], the percentages of recovered materials in this table are estimated. Hence, in our entire experiment, we set the fractions of the recovered materials to 30% and 70% for plastic and metal, respectively.

Table 4-2 The number and weights of parts and modules (BOM)

part	quantity		weight
	quality1	qulity2	
part1	1	1	0.05
part2	3	1	0.05
part3	2	1	0.05
part4	6	5	0.05
part5	2	1	0.05
part6	4	1	0.05
part7	2	1	0.05
part8	3	2	0.05
part9	2	1	0.05
part10	2	1	0.05

module	quantity		weight
	quality1	qulity2	
module1	1	1	0.25
module2	3	1	0.5

Table 4-3 Mass of residues, materials and disposal after disassembly

Quality	Mass of disposal(kg)	Mass sent to material (kg) recycling		Mass sent to bulk recycling (kg)
		metal	plastic	
quality1	0.1648	0.23072	0.09888	1.1536
quality2	0.3867	0.54138	0.23202	2.7069

Prices

The selling prices of the recovered modules and parts are inspired from the work of Srivastava [28]. We also used different internet sources [29], and the work of Sodhi and

Reimer [11] to validate the prices for materials. Table 4-4 illustrates the proposed selling prices for each component of the used product.

Table 4-4 Selling prices

	module1	module2	material1	material2	part1	part2-5	part6-9	part10
price	30	35	9	6	5	6	7	3

Costs

Costs in this study are categorized into three classes: 1) acquisition 2) processing and 3) inventory costs. Acquisition and processing costs are derived from a real case study [28], and holding costs are calculated based on a fraction (10 %) of selling prices adopted from a case study [5]. Unit acquisition costs for good quality and poor quality products are set to be \$200 and \$50, respectively. Processing costs include disassembly, remanufacturing, harvesting, material and bulk recycling cost. The disassembly cost is considered to be \$100 for one entity of product, regardless of its quality level. Remanufacturing set-up fixed cost is set to \$100, and the remanufacturing variable cost is set to be \$5 for good quality modules and for poor quality this value is \$15. Remanufacturing costs are the same for all types of modules. Part harvesting fixed cost is \$50, and part harvesting variable cost for each unit of different parts is illustrated in table 4-5. The costs for material recycling are calculated per kilograms of weight. Recycling 1 kg of plastic will cost \$0.03 while recycling the same amount of metal incurs \$0.02. Fixed cost for bulk recycling is considered to be \$40 and variable cost for each kilogram of residues is \$1.

Table 4-5 Harvesting costs

	part1	part2	part3	part4	part5	part6	part7	part8	part9	part10
harvesting cost	0.03	0.05	0.32	0.04	0.38	0.06	0.37	0.06	0.05	0.19

Table 4-6 indicates the inventory costs for each unit of different parts, modules, material and products. These costs are defined based on the quality and size of each module/part. The Initial inventory for each part is considered to be zero. Holding costs are assumed to be the same for remanufactured modules, harvested parts and recycled materials with modules, parts and materials before being processed.

Table 4-6 Inventory costs

	module1	**module2**	**material1**	**material2**	**Product quality1**	**Product quality2**
holding cost	3	3.5	0.9	0.6	20	5

	part1	**part2**	**part3-5**	**part6-9**	**part10**
holding cost	0.5	0.6	0.6	0.7	0.3

Demand

In order to find the demand for each module/part, we multiplied the number of product demand by the number of modules/parts that exist in that product, based on the BMO of this product. We assume the demand for a (hypothetical) electronic product (e.g., PC) in each period has a uniform distribution ranging between 250-500 units. According to tables 4-2 and 4-3, the demand for each module and part is calculated. In order to find the demand for each material in each period, a fraction of a product's weight is considered. This fraction is 40% and 30% for metal and plastic.

Capacity consumptions are considered not to be the same for different modules. Capacity consumption for poor quality modules are twice as the capacity consumption of good quality modules for both machine and labor. This quantity is 2 units for poor quality modules and 1 unit for good quality modules. Labor and machine part harvesting capacity is assumed to be the same for all the parts and it is set to 1. Labor, machine and inventory consumption for each kg of materials are considered to be 1. We consider a large storage capacity for the inventory of modules, parts and residues (i.e., 10000, 10000 and 20000, respectively).

4.2 Numerical results

4.2.1 Experimental details

Experiments were conducted using computer 2.8 GHz Pentium® Dual-Core Opteron 64-bit processors and 4 GB RAM. The bi-objective mixed integer Linear Programming model is coded and solved with CPLEX OPL version 12.3, 32 bit and we have implemented the sensitivity analysis by the aid of Minitab16.2.3. The bi-objective problem includes 576 inventory balance constraints, 216 capacity constraints and 984 decision variables.

4.2.2 Epsilon-constraint method results

As explained in section 3.3 of this thesis, the epsilon-constraint method is used to solve the bi-objective tactical planning models. In this sub-section we provide the results of the application of the epsilon-constraint method in our case study. For this purpose a payoff table is calculated, as it can be seen in table 4-7.

Table 4-7 Payoff table for two objectives

	$Z_1(X^k)$	$Z_2(X^k)$
X^1	$Z_1^*(X^1)$=247,809	$Z_2(X^1)$=5,723
X^2	$Z_1(X^2)$=188,972	$Z_2^*(X^2)$=7,055

The payoff table is calculated by finding the individual optimum of each objective function. Further, by adding the other objective function as a constraint to the primary objective function we find the upper and lower bounds for the second objective function.

In table 4-7, $Z_2(X^1)$=5723 and $Z_2^*(X^2)$=7055 are the lower and upper bounds of the second objective function, respectively. By picking 20 as the value for γ and using the following equation, we divided the range of the second objective to 20 equivalent intervals.

$$L_n = Z_2(X^1) + [h/(\gamma_1 - 1)] \times [Z_2^*(X^2) - Z_2(X^1)]$$

By plugging different values of each L_n as the lower bound of the corresponding constraint (i.e., second objective function) into the bi-objective model, we generated 20 non-dominated solutions. Table 4-8 illustrates the range of both objective function values over the range of non-dominated solutions. It can be observed that while moving from one pareto solution to the other, one objective is improved and the other is degraded. The last two columns in table 4-8, represent the deviation (%) from the optimal objective value for each non-dominated solution.

Table 4-8 Payoff table for gamma=20

Z2	Z1	Z2 %	Z1%
7055	188972	100	76.25712
6985	194882	99.0063	78.64202
6915	200010	98.01261	80.71135
6845	205052	97.01891	82.74599
6775	209847	96.02522	84.68094
6704	214408	95.03152	86.52147
6634	218517	94.03782	88.17961
6564	222401	93.04413	89.74694
6494	226070	92.05043	91.22752
6424	229418	91.05673	92.57856
6354	232798	90.06304	93.94251
6284	236178	89.06934	95.30647
6214	239131	88.07565	96.49811
6144	241462	87.08195	97.43875
6074	243573	86.08825	98.29062
6003	245486	85.09456	99.06258
5933	246804	84.10086	99.59445
5863	247508	83.10717	99.87854
5793	247809	82.11347	100
5723	**247809**	81.11977	100

4.2.3 Analysis of the results

The decision maker has to choose the best compromise solution among the set of pareto-optimal non-dominated solutions. In order to facilitate the process of decision making, we have shown the results in terms of the percentage of deviation from optimal objective value for each objective function in figure 4-1. This figure illustrates the relationship between the two competing objective functions. The top left point represent the optimum acquisition quantity (second objective) and the bottom right point indicates the optimum profit (first objective).

Generally, good quality returned products are all purchased due to their low recovery cost, more recoverable modules and high profitability. High quality returned products are also scarce and limited, comparing to the poor quality products. Hence, the maximization of our environmental objective function would target the acquisition of poor quality products. With the same reasoning, it would be able to prevent the high penalties that the producer is charged by legislation due to landfilling of the EOL products. Based on the experimental results, it can be concluded that if the decision maker aims for maximum profit, he is lacking 18% of maximum acquisition which mainly include poor quality products. Furthermore, by increasing the acquisition quantity to 8%, the firm's profit would be decreased by 6% from its optimal value. Therefore, it is crucial to utilize the tradeoffs between both objectives prior to make decisions on acquisition amounts of returned products. Due to the fact that firms are required to participate in environmentally friendly activities, acquiring more amounts of used product not only decreases the landfill amounts of EOL's, but also prevents the firm from paying high penalties to governments. By using figure 4-1, the manager would be able to choose the best solution according to the profit and acquisition amounts that the firm is willing to obtain.

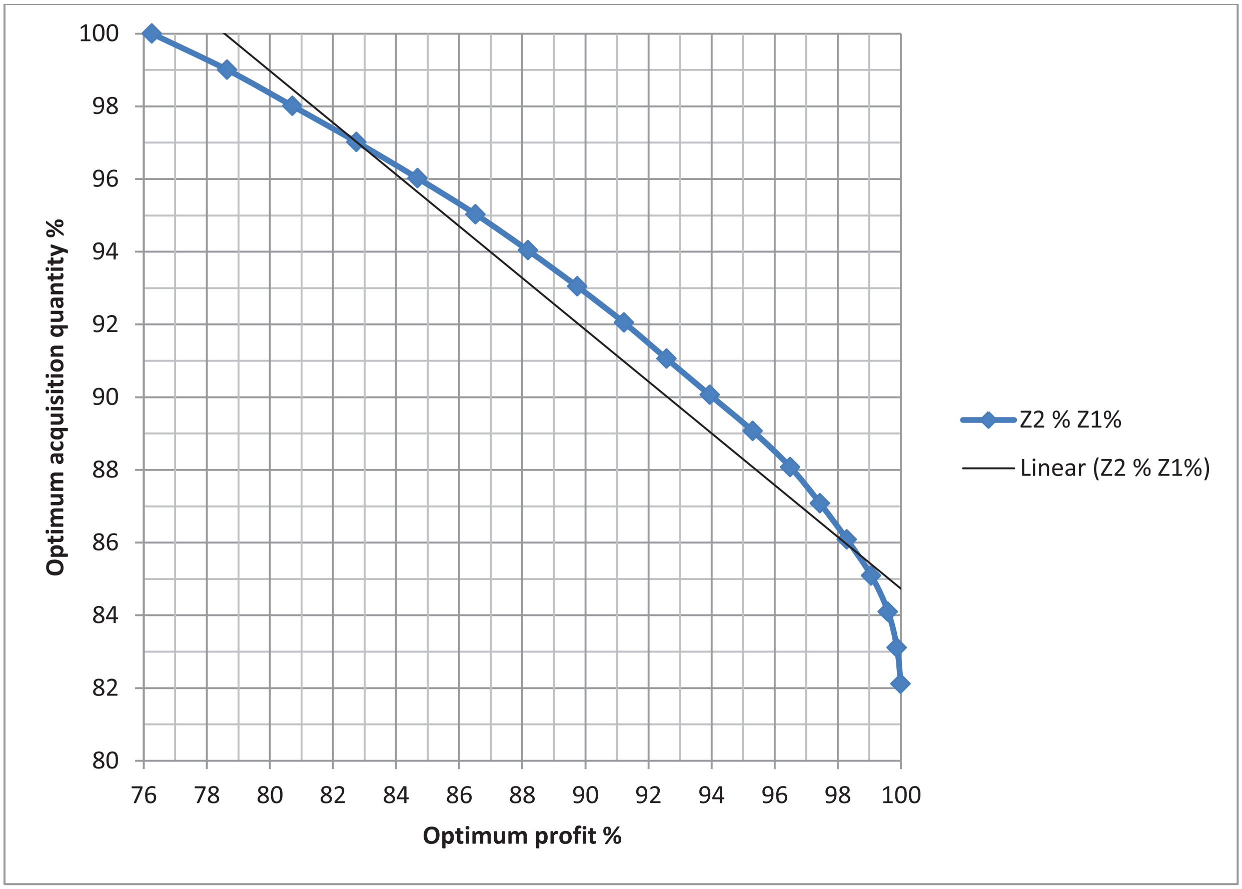

Figure 4-1 Trade-off graph for two objective functions

4.3 Sensitivity analysis

In order to determine how different model parameters affect each objective function, a set of sensitivity analysis tests are conducted. In the present work, we are interested into studying the simultaneous influence of several parameters on the both objective functions. Therefore, we have used the full factorial design for this purpose.

Factorial design

Factorial experiments involve the analysis of two or more factors on a response variable. A full factorial design allows for studying of the effect of each factor and their interaction on the response variable [20].

The sensitivity analysis, on both models is conducted based on factorial design, where the factors are fixed at two levels, and two replications for each set of experiments are run. Inspired by the common practice in the literature and also according to the order of magnitude of nominal values of different parameters, variations of parameters (factors) have been considered as +20% and -20% of their nominal values. In total there are 2^k different combinations of factors in the experiment. By considering two replications for each experiment we ran $2^6\times 2=128$ different experiments. Each replication is generated based on a random demand that follows a uniform distribution ranging between [250,500]. Hence, in each replication we generate a new demand profile based on the uniform distribution.

4.3.1 Sensitivity analysis on the financial objective function- Profit maximization

In this experiment, we study six different factors, such as total demand, quantity of returns, price, acquisition costs, holding costs and the ratio of good to poor quality return. We are interested to investigate the influence of mentioned factors on the two key performance indicators (KPIs). These KPIs are profit and total acquisition amount.

4.3.1.1Factors effect on profit (KPI 1)

According to figure 4-2 and table 4-9 (ANOVA table), following conclusions are made:

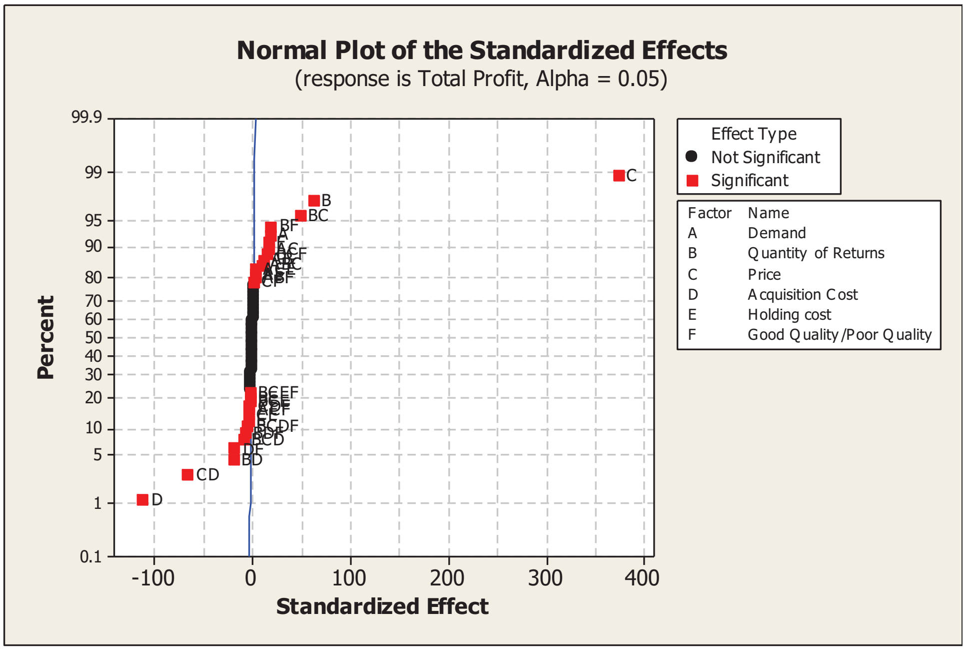

Figure 4-2 Normal plot of the effect on Total profit

Table 4-9 ANOVA table for profit

Term	Effect	Coef	SE Coef	T	P
Constant		291,951	635.7	459.26	0.000
Demand	23,054	11527	635.7	18.13	0.000
Quantity of returns	79,756	39878	635.7	62.73	0.000
Price	475,795	237897	635.7	374.23	0.000
Acquisition Cost	-142,090	-71045	635.7	-111.76	0.000
Holding cost	-5,181	-2591	635.7	-4.08	0.000
Good quality/ Poor quality	21,445	10723	635.7	16.87	0.000

- The most influential factors affecting the profit are selling price of recovered items, quantity of returns and the acquisition cost.

- Price and quantity of returns have a positive effect while acquisition cost has a negative influence on the profit.

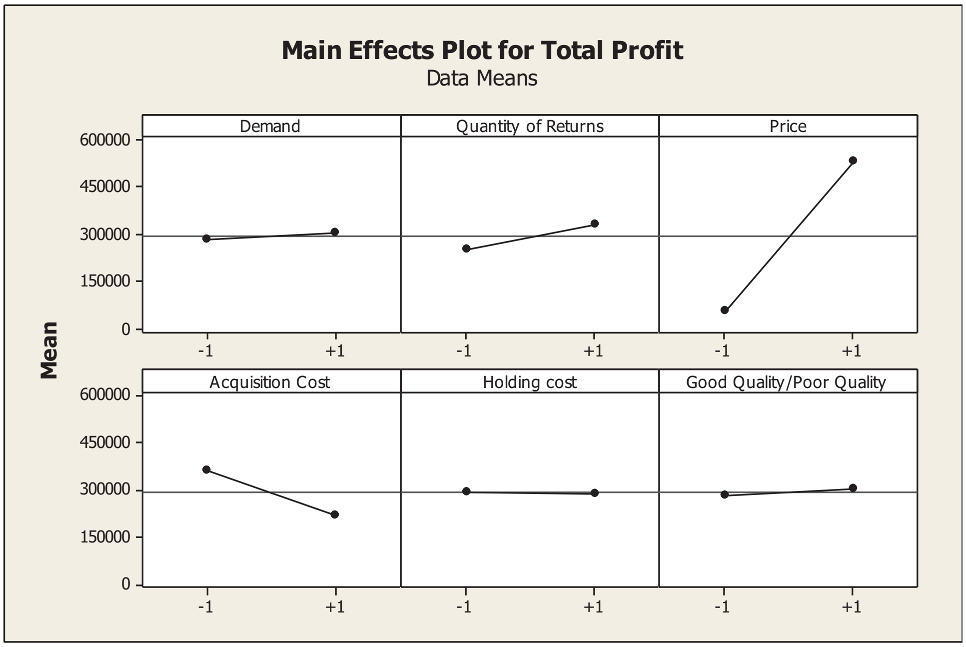

Figure 4-3 Main effect plot for total profit

According to the main effects plot for total profit (figure 4-3), it is worth to discuss the effects of price, quantity of returns and acquisition costs more thoroughly.

Based on figure 4-3 and table 4-9, it can be concluded that by increasing the selling prices of recovered items, profit would be increased significantly, this is due to the fact that increase in price lead to the revenue increase while the costs remain the same.

Figure 4-3 also indicates that by increasing the quantity of returns, profit is increased. However, this effect is relatively small comparing to the effects of changes in the selling price.

Unlike selling price and quantity of returns, acquisition cost has a negative impact on the profit. By increasing the acquisition price, the profit would be decreased and vice versa.

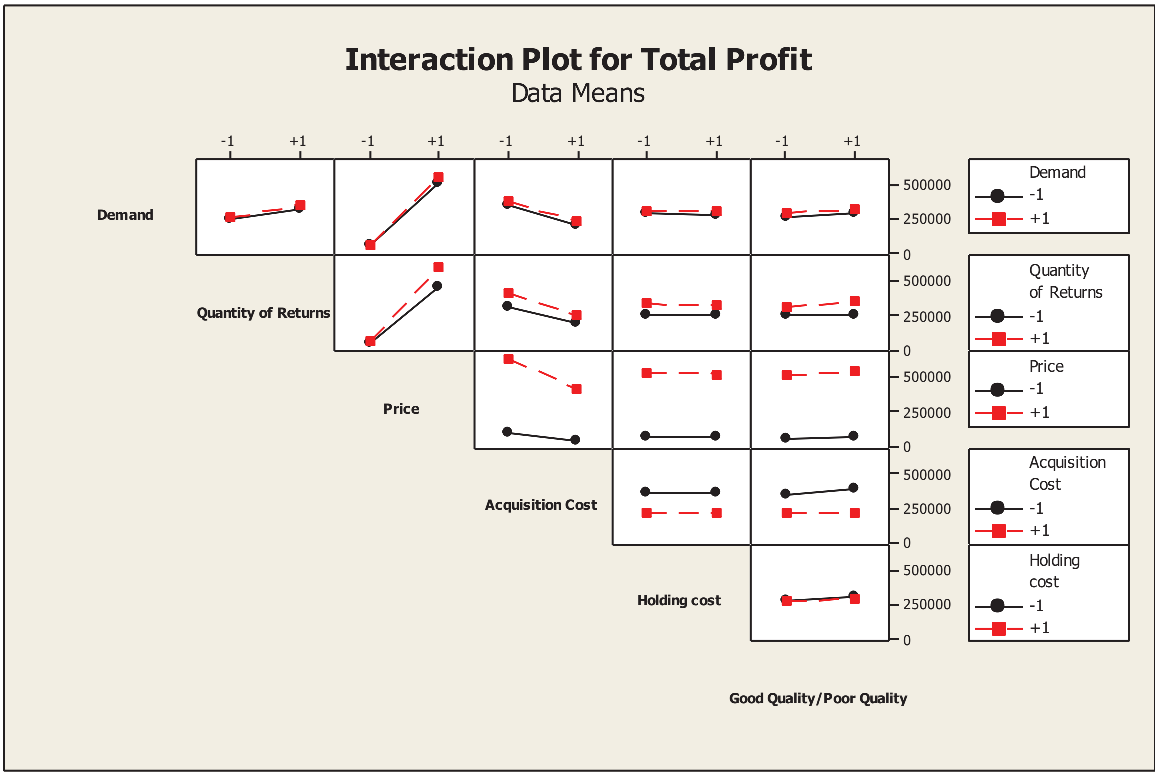

Figure 4-4 Interactions plot for total profit

An interesting finding from the interaction plot in figure 4-4, shows that some factors such as price and holding cost or price and ratio of good to poor quality returns are totally independent. Parallel graphs prove that changes in one factor could not affect the objective function resulted by other factor. In contrary, some factors such as return quantity and price happen to have an interaction. More precisely, when the price is low, changes in the quantity of returns do not affect the profit. But when the price is increased, profit will increase for more amounts of returns.

According to the same plot in figure 4-4, it can be concluded that the quantity of returns has no interaction with other factors in affecting the profit except for the ratio of qualities. In other words, for low level of returns, changes in the ratio of good to poor quality of returns do not affect the profit. Whereas for larger amounts of returns the profit would be increased significantly by increasing the ratio of good to poor quality. Moreover, when the price is low, changes in the ratio of good quality to poor quality would not affect the total acquisition of poor quality returns but for a higher price it may decrease the poor quality return acquisition to some extent.

4.3.1.2Factors Effect on total acquisition amount (KPI2)

According to the normal plot for total acquisition which is shown in figure 4-5 and the ANOVA table 4-10, important factors affecting the total acquisition incorporate price and quantity of returns positively and acquisition cost and ratio of good to poor quality returns negatively.

As it is shown in figure 4-6 and 4-7, increasing the price of recovered items would increase the acquisition amounts of both poor and good quality. The reason is that by acquiring more returned items higher revenue is expected due to higher prices of recovered items.

By analyzing the main effect plots in figures 4-6 and 4-7, it can be observed that by increasing the quantity of products return, the acquisition quantity of good quality products is increased while the acquisition of poor qualities does not change. An important key point could be concluded that by increasing the quantity of returns, the model tends to acquire more of good quality rather than poor quality. This is based on the fact that recovering good quality products are more profitable. In other words, the model does not tend to acquire poor quality ones because of their high processing cost and low value.

Another finding from the normal plot (figure 4-5) and table 4-10 is that by increasing the ratio of good to poor quality, total acquisition would be decreased. This is due to the fact that by increasing the ratio of qualities while the total amount is fixed, there would be more amounts of good quality which produce more recovered items and fewer amounts of poor quality products which are more costly. Therefore, the model does not need to acquire high amounts of returns when the ratio of good to poor quality is high.

Another observation regarding total acquisition, is that increasing the acquisition cost, remarkably decrease the good quality acquisition amount but it does not change the acquisition of poor quality ones significantly. It could be interpreted based on the considerable difference between the acquisition price of good and poor qualities.

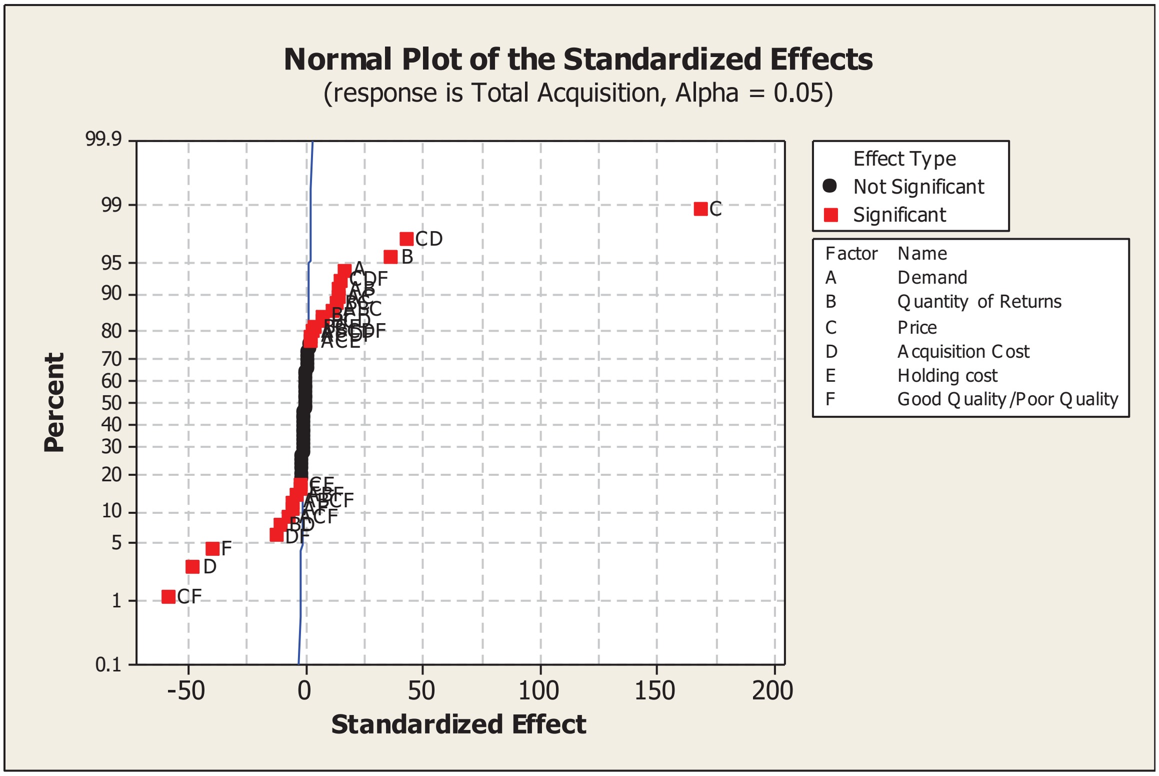

Figure 4-5 Normal plot for total acquisition

Table 4-10 ANOVA table for total acquisition

Term	Effect	Coef	SE Coef	T	P
Constant		3162.5	10.55	299.75	0.000
Demand	342.9	171.4	10.55	16.25	0.000
Quantity of returns	768.7	384.4	10.55	36.43	0.000
Price	3,560.7	1780.1	10.55	168.71	0.000
Acquisition Cost	-1015.6	-507.8	10.55	-48.13	0.000
Holding cost	-45.9	-23.0	10.55	-2.18	0.033
Good quality/ Poor quality	-836.8	-418.4	10.55	-39.65	0.000

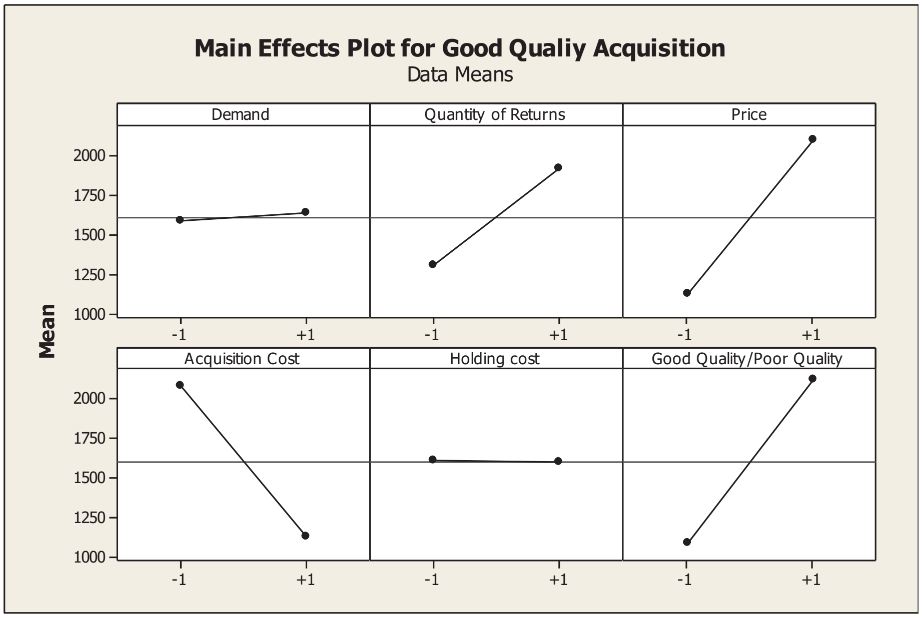

Figure 4-6 Main effects plot for good quality acquisition

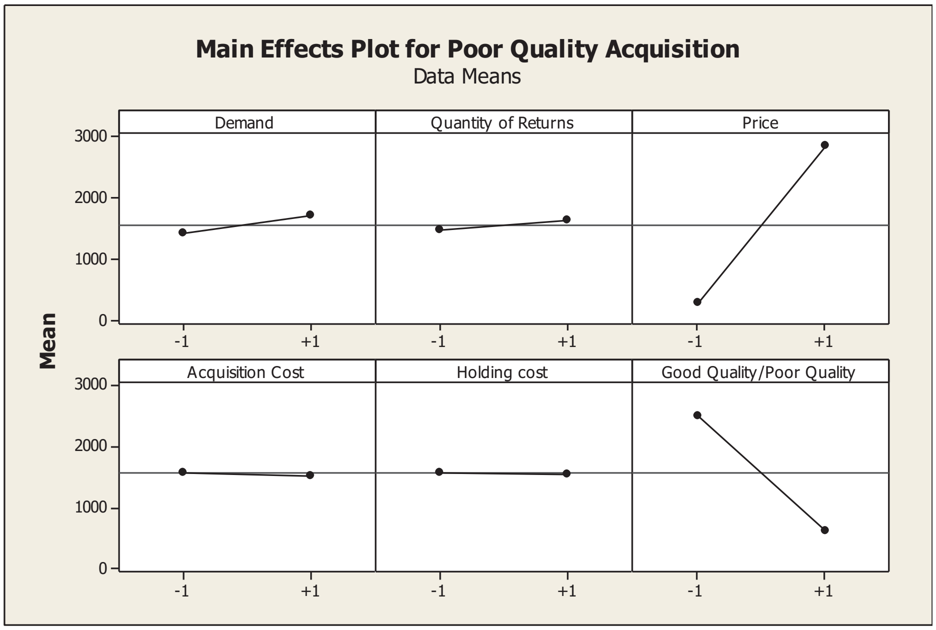

Figure 4-7 Main effects plot for poor quality acquisition

4.3.2 Sensitivity analysis on the environmental objective function- acquisition amount maximization

In this set of experiment, we consider total acquisition amount as the only objective function and we are only interested to investigate the effects of three factors on the total acquisition. These factors include quantity of returns, demand and ratio of good to poor quality products.

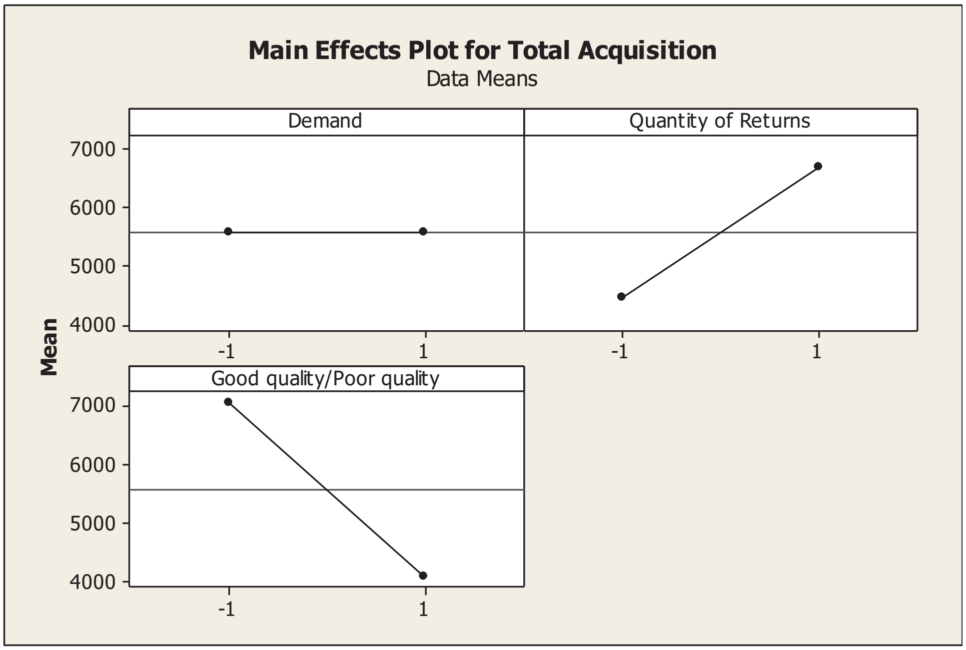

Figure 4-8 Main effects plot for total acquisition

According to the figure 4-8, it can be concluded that only the quantity of returns and the ratio of good to poor quality returns are affecting the amount of acquisition.

Since total acquisition is the summation of both good and poor quality returns, we are going to explain the effects of each factor on each quality level separately. Figures 4-9 and 4-10, indicate that by increasing the quantity of returns, the acquisition amount of both good and poor qualities would be increased. More importantly, by increasing the ratio of good to poor quality, the model tends to acquire more from the better quality products. On the other hand, this increase would result in a decrease in the acquisition amounts of poor quality returns. But according to the main plot effect (figure 4-8), poor quality returns are more influential by this ratio comparing to the good quality returns. This fact suggests increasing the ratio of poor over good quality returns will result in a higher total acquisition amount. While the profit element is excluded in this section, this could be explained according to capacity consumptions, inventory and demand constraints.

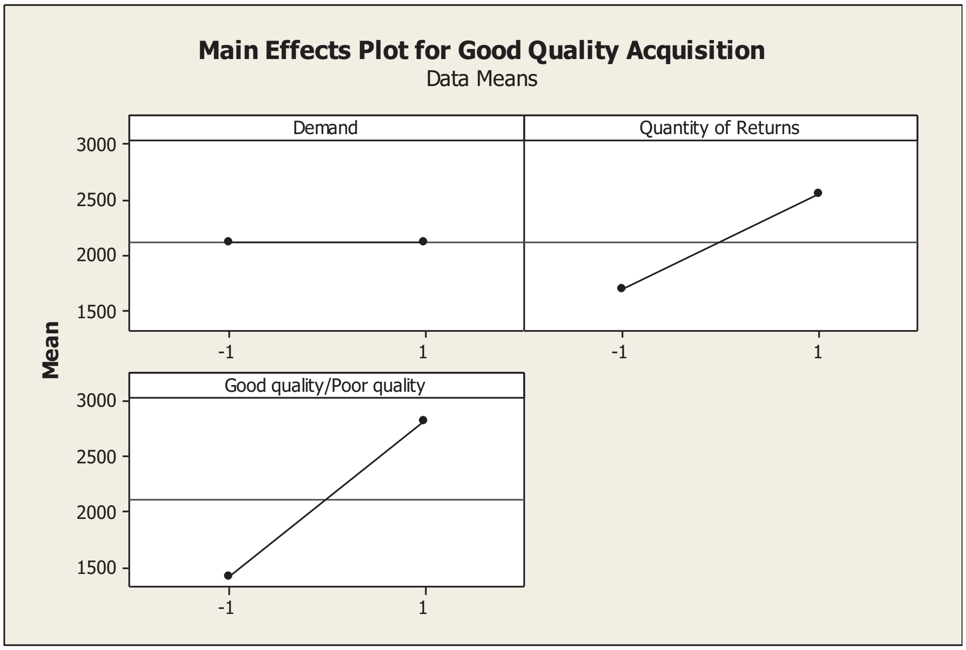

Figure 4-9 Main effects plot for good quality acquisition

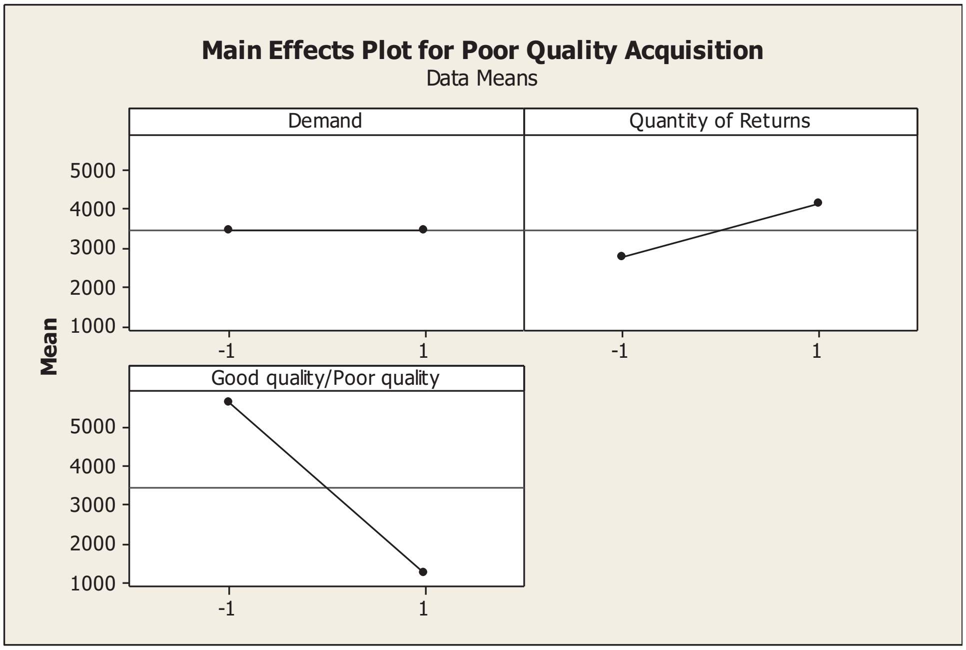

Figure 4-10 Main effects plot for good quality acquisition

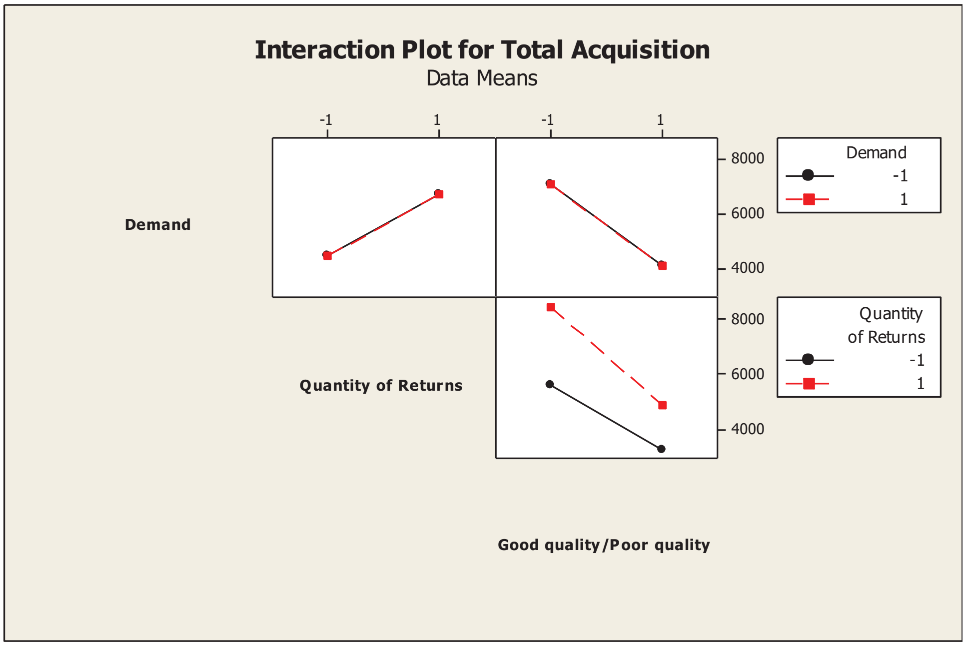

Figure 4-11 Interaction plot for total acquisition

According to the interaction plot in figure 4-11, it can be concluded that there is no relation between changes in demand with both quantity of returns and ratio of qualities. Moreover, there is a relation between quantity of returns and ratio of good to poor quality in such a way that when the quantity of returns is at its high level, having more poor quality than good quality products (bigger ratio of poor to good quality) will increase the acquisition amount.

Chapter 5 Conclusions and future research

In this chapter, we present a summary of the thesis. We also provide several concluding remarks based on the problem solution and sensitivity analysis. Future research in this area is discussed at the end.

5.1 Conclusion

In this research, we developed a bi-objective, multi-period mixed integer linear programming model for tactical planning in a RSC. We considered two objective functions, including profit maximization as well as total acquisition amount maximization. In this problem, the returns are assumed to be durable products which consist of multiple and various types of components that can be recovered by different recovery methods. The modular structure of durable products makes them subject to the all disposition options, such as remanufacturing, harvesting, material and bulk recycling, and disposal. The proposed model decides on the integrated tactical level decisions such as acquisition, disassembly and grading, and production planning of different disposition activities as well as, sales and inventory planning in the reverse supply chain.

The multi-indenture structure of durable products which leads to a complex RSC network increases the complexity of the proposed model. The model incorporates numerous decision variables and constraints which are formulated based on a complex bill of material corresponding to a durable product. In order to validate and test the model, it is applied on an EOL electronic device. Nevertheless, the model is applicable to similar RSC networks corresponding to durable products.

Furthermore, the bi-objective model is solved by the aid of the epsilon-constraint method. A set of non-dominated solutions are presented for the decision maker and the following conclusions were obtained:

- The good quality acquisition amount reaches 100% in all the solutions, because of the profitability of the recovery of good quality products.
- By increasing the acquisition quantity, more poor quality products are acquired, consequently the recovery cost is increased and profit is decreased.
- The profit reaches its maximum value while the total acquisition takes the lowest amount among all the possible solutions. Keeping the acquisition at lower quantities protect the company against high costs of poor quality products recovery.
- The acquisition amount reaches it maximum by scarifying the profit around 25% of its optimal value. In return, acquiring poor quality products help the company to get aligned with the legislations and environmental concerns, particularly, when the company is obliged to reach a certain amount of EOL recovery.
- By the aid of the non-dominated solutions, the decision maker would be able to choose the best solution according to the profit and acquisition amounts that the firm is willing to obtain. The latter also depends on the legislation regarding the target amount of EOL recovery.

In order to determine how different model parameters affect each objective function and other KPIs, a set of sensitivity analysis tests are conducted. The following conclusions are derived for the problem with profit maximization objective:

- The most influential factors affecting the profit are selling price of recovered items and quantity of returns positively, and the acquisition cost negatively.
- When the price is low, changes in the quantity of returns do not affect the profit. But when the price is increased, profit will increase for more amounts of returns.
- For low amounts of returns, changes in the ratio of good to poor quality of returns do not affect the profit, whereas for large amount of returns the profit would be increased significantly.
- When the price is low, changes in the ratio of good to poor quality would not affect the total acquisition of poor quality returns but for a higher price it may decrease the poor quality return acquisition to some extent.
- Considering the total acquisition amount as the second KPI, we observed that increasing the price would increase the acquisition amounts of both poor quality and good quality
- Another key point could be concluded that by increasing the quantity of returns, the model tends to acquire more of good quality rather than poor quality returns. This justifies the fact that recovering good quality products are more profitable.

The following conclusions were obtained based on the sensitivity analysis regarding the environmental objective function (acquisition amount maximization):

- Increasing the ratio of poor over good quality products will result in a higher total acquisition amount. While the profit element is excluded in this section, this could be explained according to capacity consumptions, inventory and sales constraints.

- When the total quantity of returns is at its highest level, having more poor quality than good quality products (bigger ratio of poor to good quality) results in larger acquisition amounts, comparing to the low levels of returns quantity.

The key considerations in this study that contribute to the existing literature are as follows:

- An integrated tactical planning model including acquisition, grading and disposition (remanufacturing, harvesting, recycling and disposal) decisions in the context of a durable product RSC is proposed.
- A multi-indenture structure is considered for the EOL products. Consequently, all possible recovery options are taken into account.
- Two objective functions addressing both financial and environmental criteria are proposed.
- Two quality levels for returns are considered. They differ in the acquisition price, recovery and processing costs, and the amounts of recoverable components.

5.2 Future research

There are several directions to extend the model presented in this study. Our suggestions for future research in this area are as follows:

- To consider the uncertainty in the quality of returns. More precisely, considering the proportions of reusable modules, parts and materials in a returned item of a given quality level as a random variable instead of a deterministic one, as we did in the current study.
- To reformulate the problem as a stochastic program or a robust optimization model while considering the uncertain quality of returns.

- To integrate the return acquisition pricing problem into the current RSC tactical planning model. The latter will lead to a non-linear optimization problem.
- To integrate the proposed RSC tactical planning model with the forward supply chain planning model in the context of a closed-loop supply chain. The idea is to align the forward and backward flow decisions in such a network.
- To address the RSC tactical planning model in a multi-product setting.

Refrences

[1] Atasu and Cetinkaya, “Lot Sizing for Optimal Collection and Use of Remanufacturable Returns over a Finite Life-Cycle”, *Production and Operations Management,* 15(4), 473–487, 2006.

[2] Galbreth and Blackburn,“Optimal Acquisition Quantities in Remanufacturing”, *Production and Operations Management*,19(1), 61–69, 2009.

[3] Robotis Andreas Robotis, Shantanu Bhattacharya, Luk N. Van Wassenhove, “The effect of remanufacturing on procurement decisions for resellers in secondary markets”, *European Journal of Operational Research,* 163, 688–705, 2005.

[4] C. Zikopoulos, G. Tagaras, “Production, Manufacturing and Logistics Impact of uncertainty in the quality of returns on the profitability of a single-period refurbishing operation”, *European Journal of Operational Research,* 182, 205–225, 2007.

[5] M. Denizel, M. Ferguson, and G. Souza, “Multi-period remanufacturing planning with uncertain quality of inputs,”*, IEEE Transactions on Engineering Management*, 57(3), 394–404, 2010.

[6] M. Ferguson, V. D. Guide Jr, E. Koca, and G. C. Souza, “The value of quality grading in remanufacturing,” *Production and Operations Management*, 18(3), 300–314, 2009.

[7] Kibum Kim , Iksoo Song, Juyong Kim, BongjuJeong, “ Supply planning model for remanufacturing system in reverse logistics environment”, *Computers & Industrial Engineering*, 51, 279–287, 2006.

[8] H-H Doh and D-H Lee, “Generic production planning model for remanufacturing systems”, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 224(159), 2010.

[9] Vaidyanathan Jayaraman, “Production planning for closed-loop supply Chains with product recovery and reuse”, *International Journal of Production Research*, 44(5), 981-998, 2006.

[10] J. B. Sheu, Y. H. Chou, and C. C. Hu, “An integrated logistics operational model for green-supply chain management”, *Transportation Research Part E: Logistics and Transportation Review*, 41(4), 287–313, 2005.

[11] Manbir S. Sodhi and Bryan Reimer, “Models for recycling electronics end-of-life products”, *ORSpektrum*, 23, 97-115, 2001.

[12] Grit Walther, Thomas Spengler, "Impact of WEEE-directive on reverse logistics in Germany", *International Journal of Physical Distribution & Logistics Management*, 35(5), 337–361, 2005.

[13] Ehrgott, M. “Multi-criteria optimization”. Berlin, Springer, 2005.

[14] M. E. Ferguson and G. C. Souza, “Commentary on Closed-loop supply chains”, *in Closed-loop supply chains: new developments to improve the sustainability of business practices*, 1st ed., M. E. Ferguson and G. C. Souza, Ed. New York: CRC Press, 99-118, 2010.

[15] Chopra, S., & Meindl. Supply chain management: strategy, Planning and operation, Upper saddle River, NJ: Prentice-Hall. 2001.

[16] Guide Jr., V.D.R. and L.N. Van Wassenhove. Managing product returns for remanufacturing, *Production and Operations Management,* 10(2), 142–155, 2001.

[17] Necati Aras, Tamer Boyaci, and VedatVerter, “Designing the reverse logistic network”, *in Closed-loop supply chains: new developments to improve the sustainability of business practices*, 1st ed., M. E. Ferguson and G. C. Souza, Ed. New York: CRC Press, 99-118, 2010.

[18] http://www.un-documents.net/unchedec.html, *Report of the United Nations Conference on the Human Environment*, Stockholm, June 1972.

[19] Guide Jr., V.D.R., R. Teunter, and L.N. Van Wassenhove, “Matching demand and supply to maximize profits from remanufacturing”, *Manufacturing & Service Operations Management,* 5(4), 303–316, 2003.

[20] Diouglas, C.Montgomery, “Design and Analysis of Experiments”, 2005.
Karakayali, I., H. Emir-Farinas, and E. Akcali, “An analysis of decentralized collection and processing of end-of-life products”, *Journal of Operations Management*, 25(6),1161–1183, 2007.

[21] Bakal, I.S. and E. Akcali, “Effects of random yield in remanufacturing with price-sensitive supply and demand”,. *Production and Operations Management,* 15(3), 407–420. 2006.

[22] Ray, S., T. Boyaci, and N. Aras, “Optimal prices and trade-in rebates for durable, remanufacturable products”, *Manufacturing & Service Operations Management* 7(3), 208–228, 2005.

[23] Blackburn, J.D., V.D.R. Guide Jr., G.C. Souza, and L.N. Van Wassenhove, “Reverse supply chains for commercial returns”,. *California Management Review,* 46(2), 6–22, 2004.

[24] Moritz Fleischmann, Michael R. Galbreth, and George Tagaras, “product acquisition, grading, and disposition tagaras”, *in Closed-loop supply chains: new developments to improve the sustainability of business practices*, 1st ed., M. E. Ferguson and G. C. Souza, Ed. New York: CRC Press, 99-118, 2010.

[25] Gilvan C .Souza, “production planning and control for remanufacturing”, *in Closed-loop supply chains: new developments to improve the sustainability of business practices*, 1st ed., M. E. Ferguson and G. C. Souza, Ed. New York: CRC Press, 99-118, 2010.

[26] Stessel RI, Pelz S, “Air classification of mixed plastics”, *In: National Waste Processing Conference Procedings ASME*, 333–339, 1994.

[27] Hull JB, Langton CM, Jones AR, “An ultrasonic method for identifying polymeric materials/components for reclamation and recycling”, *Macromolecular Reports*, 31, 1191–1199, 1994.

[28] Samir K. Srivastava, Rajiv K. Srivastava,"Managing product returns for reverse logistics", *International Journal of Physical Distribution & Logistics Management*, 36(7), 524 – 546, 2006.

[29] http://www.recycleinme.com. Scrap and recycle market news.

[30] George Mavrotas, “Effective implementation of the e-constraint method in Multi-Objective Mathematical Programming problems”, *Applied Mathematics and Computation,* 213, 455–465, 2009.

Appendix I

Notions of the mathematical model.

Indice	Description
a:	Part, a = {1… A}
m:	Modules, m = {1… M}
k:	Quality level, k = {1… K}
t:	Time period, t = {1… T}
l :	Material, l = {1… L}

Parameter	Description
$Q_{k,t}$	Quantity of collected products of quality *k* period *t*
h_k^{prod}	Unit holding cost of product quality *k*
h_a^{part}	Unit holding cost of part *a*
h_a^{harv}	Unit holding cost of harvested part *a*
h_m^{mod}	Unit holding cost of module *m*
h_m^{rem}	Unit holding cost of remanufactured module *m*
h^{res}	Holding cost of residues (/kg)
h_l^{mat}	Holding cost of material *l*
h_l^{recm}	Holding cost of recycled material *l*
h^{dis}	Holding cost for disposal (/kg)
$D_{m,t}^{rem}$	Demand for remanufactured module *m* in period *t*
$D_{a,t}^{part}$	Demand for harvested part *a* in period *t*
$D_{l,t}^{recm}$	Demand for recycled material *l* in period *t*
p_m^{rem}	Price of selling remanufactured module *m*

Parameter	Description
p_a^{harv}	Price of selling harvested part *a*
p_l^{recm}	Price of selling recycled material *l*
$\mu_{k,m}$	Number of module type *m* available in each product quality k
$v_{k,a}$	Number of part type *a* available in each product quality k
λ_k	Mass of residues in each product of quality *k* (kg)
$\kappa_{k,l}$	Mass of material *l* remained after disassembly of product quality k (kg)
ε_k	Mass of disassembled product of quality *k* sent to disposal (kg)
ω_m^{mod}	Weight of each module *m* (kg)
ω_a^{part}	Weight of each part *a* (kg)
β_l	Percentage of bulk recycled residues that is material *l*
γ	Percentage of recycled material sent to disposal
δ	Percentage of recycled residues sent to disposal
c_k^{prod}	Cost of purchasing product with quality *k*
c_k^{disa}	Cost of disassembly each product quality *k*
c^{bulk}	Cost of bulk recycling of residues (/Kg)
c_m^{rem}	Unit cost of remanufacturing of module *m*
c_a^{harv}	Cost of harvesting of part *a*
c_l^{recm}	Cost of recycling material *l*
c^{disp}	Cost of dispose (/Kg)
C_{fix}^{rem}	Fixed cost for setting up and using remanufacturing facility in each period
C_{fix}^{harv}	Fixed cost for setting up and using harvesting facility in each period
C_{fix}^{bulk}	Fixed cost for setting up and using recycling facility in each period
$W_t^{lab-disa}$	Total labor hours available for disassembly
$W_t^{machin-disa}$	Total machine hours available for disassembly

Parameter	Description
$W_t^{lab-recm}$	Total labor hours available for material recycling
$W_t^{mach-recm}$	Total machine hours available for material recycling
$W_t^{lab-bulk}$	Total labor hours available for bulk recycling
$W_t^{lab-part}$	Total labor hours available for harvesting parts
$W_t^{lab-rem}$	Total labor hours available for remanufacturing
$W_t^{mach-rem}$	Total machine hours available for remanufacturing
$W_t^{mach-bulk}$	Total machine hours available for bulk recycling
$W_t^{inv-prod}$	Total Inventory capacity for product (sqft)
$W_t^{inv-\mathrm{mod}}$	Total inventory capacity for modules (sqft)
$W_t^{inv-rem}$	Total inventory capacity for remanufactured modules
$W_t^{inv-part}$	Total inventory capacity for parts (sqft)
$W_t^{inv-res}$	Total inventory capacity for residues (kg)
$W_t^{inv-harv}$	Total inventory capacity for harvested parts (sqft)
$W_t^{inv-dis}$	Total inventory capacity for disposal (kg)
$W_t^{inv-mat}$	Total inventory capacity for materials
$W_{l,t}^{inv-recm}$	Total inventory capacity for recycled materials
$\phi_{m,t}^{lab-rem}$	Labor hour needed to remanufacture module *m*
$\phi_{m,t}^{mach-rem}$	Machine hour needed to remanufacture module *m*
$\phi_{a,t}^{lab-part}$	Labor hour needed to harvest part *a*
$\phi_t^{lab-bulk}$	Labor hour required to bulk recycle residues
$\phi_t^{mach-bulk}$	Machine hour required to bulk recycle residues
$\phi_{l,t}^{lab-recm}$	Labor hour required to recycle material *l*
$\phi_{l,t}^{mach-recm}$	Machine hour required to recycle material *l*
$\phi_{k,t}^{lab-disa}$	Labor hour needed to disassemble product of quality k
$\phi_{k,t}^{mach-disa}$	Machine hour needed to disassemble product of quality k

Parameter	Description
$\phi_{t}^{inv-prod}$	Inventory area occupation by each product (sqft)
$\phi_{k,m,t}^{inv-\mathrm{mod}}$	Inventory area occupation by each module m quality *k* (sqft)
$\phi_{m,t}^{inv-rem}$	Inventory area occupation by each remanufactured module *m*
$\phi_{a,t}^{inv-part}$	Inventory area occupation by each part a (sqft)
$\phi_{a,t}^{inv-harv}$	Inventory area occupation by each harvested part *a* (sqft) Could be same as $\phi_{a,t}^{inv-part}$)
$\phi_{t}^{inv-res}$	Inventory occupation by each kg of residues
$\phi_{t}^{inv-dis}$	Inventory occupation by each kg of disposal
$\phi_{l,t}^{inv-mat}$	Inventory occupation by each kg of material *l*
$\phi_{l,t}^{inv-recm}$	Inventory occupation by each kg of recycled
$d_{m,t}^{\max \mathrm{mod}}$	Demand upper bound for module *m*
$d_{a,t}^{\max part}$	Demand upper bound for part *a*
$d_{l,t}^{\max mat}$	Demand upper bound for material *l*