EXTENDING THE PRODUCER RESPONSIBILITY UNDER LEGISLATIONS: ECONOMIC IMPACT OF REMANUFACTURING ON AUTOMOTIVE MANUFACTURERS

by

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B.S., Industrial Engineering, Istanbul Technical University, 2003

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in FBE Department of Industrial Engineering
Boğaziçi University
2006

ACKNOWLEDGEMENTS

It’s a pleasure to convey my thanks to my supervisor Assist. Prof. Dr. Aybek Korugan for his belief in me and presenting me the opportunity to begin and complete this study.

I’m deeply grateful to the second committee member, Associate. Prof. Dr. Necati Aras for his precious, constructive and valuable comments to finalize my study.

My gratitude for all members of Department of Industrial Engineering, especially to Prof. Kuban Altınel, for creating a sincere and easy to work in environment for me.

I’m thankful to Mr. Alpin Yıldırım from the domestic bus sales department of Mercedes-Benz Türk A.Ş., for sharing his cooperative comments, information and worthwhile industry experience which has great value for this study.

Most of all, I’m indebted to my family and my love Zeynep, never stopped giving me love, enthusiasm, and support throughout my study.

ABSTRACT

EXTENDING THE PRODUCER RESPONSIBILITY UNDER LEGISLATIONS: ECONOMIC IMPACT OF REMANUFACTURING ON AUTOMOTIVE MANUFACTURERS

Increasing population and consumption drives a common sense for responsible use of resources. Therefore, waste reduction is becoming a major concern in industrialized countries. Legislations that extend producers' responsibility are becoming an element of public environmental policy in these countries. Many countries have introduced legislations giving manufacturers the responsibility for the whole lifecycle of their products. The regulations in countries of the European Union enforce the automotive manufacturers to take back the vehicles at the end of their useful lives returned by the customers.

This study concentrates on the impact of the new legislations extending the producer responsibility on the manufacturers. We analyze the economic effects of remanufacturing on manufacturers by focusing on an automotive manufacturer. We consider a manufacturing, remanufacturing, second hand sales and disposal system with a third party recycler included.

Within this concept, we develop a linear program to model a manufacturer that operates under given capacity and market constraints and aims to maximize its profit. With this model, we are able to analyze the manufacturer by assigning any combination for the remanufacturing, used vehicle sales or recycling functions. We analyze the economic impact for a manufacturer that takes back the returned products and processes them for different purposes including remanufacturing. Throughout the analysis, we gather numerical insight about the manufacturer that adds the take-back function under the pressure of the legal regulations.

ÖZET

ÜRETİCİ SORUMLULUKLARININ GENİŞLEMESİ: YENİDEN İMALÂTIN OTOMOTİV ÜRETİCİLERİ ÜZERİNDEKİ EKONOMİK ETKİSİ

Artan nüfusa bağlı olarak yükselen tüketim, sınırlı kaynakların kullanımı konusunda ortak bir bilinç oluşturmaktadır. Bu sayede, endüstrileşmiş ülkelerde atıkların azaltılması konusunda kaygılar artmaktadır. Üreticilerin sorumluluklarını genişleten yasal düzenlemeler bu tip ülkelerde giderek yaygınlaşmaktadır. Hâl-i hazırda bir çok ülke, üreticileri ürünlerinin bütün yaşam çevriminden sorumlu tutan yönetmelikler yayınlanmıştır. Avrupa Birliği'nde bu yönetmelikler otomotiv üreticilerini, müşterileri tarafından iade edilen ömrünü tamamlamış araçları geri almaya zorlamaktadır.

Bu çalışma, yeni yasal düzenlemeler ile üreticilerin artan sorumluluklarının etkisini incelemektedir. Bu kapsamda, bir otomotiv üreticisi üzerinde analizler yapılarak, yeniden imalatın ekonomik olarak üreticiyi nasıl etkilediği araştırılmaktadır.

Geliştirdiğimiz doğrusal eniyileme modeli ile, belirli kısıtlar altında kârını en iyileyecek şekilde çalışan bir üreticiyi inceliyoruz. Bu model ile üreticiye, yeniden imalât, kullanılmış araç satışı, ve bunlar gibi geri dönüşüm fonksiyonlarının kombinasyonlarından oluşan sorumluluklar yükleyerek ortaya çıkan değerleri izliyoruz. Modele konu olan üreticinin ömrünü tamamlamış veya kullanılmış ürünleri geri alan, bunları, arasında yeniden imalatın da bulunduğu bir takım işlemlerden geçiren karmaşık bir yapıya dönüşmesinin ekonomik etkilerini görüyoruz. Çalışma kapsamında, üreticinin değişen rollerinin sayısal sonuçları sayesinde çeşitli çıkarımlar elde ediyoruz.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

$i = \{0,...,19\}$	Age of product
$j = \{0,...,39\}$	Period/Term
$X0_j$	Number of new products (viz. age 0 products) sold in period j
X_{ij}	Number of used products at age i sold in period j
Y_{ij}	Number of remanufactured products at age i sold in period j
$Zbig_{ij}$	Number of products at age i returned in period j
Zsm_{ij}	Number of accepted products at age i returned in period j
T_{ij}	Number of rejected products at age i returned in period j
W_{ij}	Number of products at age i disposed in period j
w_ul_{ij}	Number of products disposed under legal limit
w_ol_{ij}	Number of products disposed over legal limit
U_{ij}	Number of products at age i sent to recycler in period j
pim_{ij}	Total number of age i products in the market in period j
$sale\_ret_{ij}$	Number of returns at age i in period j occurring from returns
reg_ret_{ij}	Number of regular returns at age i in period j
P_i	Sales price of new or used product at age i
RP_i	Sales price of remanufactured product at age i
PP_i	Purchasing price of used product at age i
PJ_i	Scrap value at age i
RC_i	Unit remanufacturing cost for a product at age i
DC_i	Unit disposal cost for a product at age i
r_i	Willingness of customer to return a product at age i. $r_i \in [0,1]$
q_i	Level of remanufacturability for a product at age i. $q_i \in [0,1]$
dem_X0_j	Demand of new products for period j
dem_XY_{ij}	Demand of remanufactured or used products of age i for period j

wc_X0_i	Warranty cost per product at age i
wc_Y_i	Warranty cost per remanufactured product at age i
e	Effect of sales on return
$prod\_cap$	Production capacity per period
ret_cap	Returned products acceptance capacity per period
rem_cap	Remanufacturing capacity
dir_cap	Direct sales capacity
rec_cap	Capacity of recycler per period
pen_rej	Legal penalty paid for unit unaccepted product return
pen_disp	Legal penalty paid for unit disposal over legal limit
war_cst_{ij}	Total warranty costs for age i products in period j
$disp\_upl$	Upper limit of disposal per production

1. INTRODUCTION

Manufacturers have always been in the effort of finding out easier and less costly techniques for manufacturing products. From the beginning of the industrial revolution, almost every study in the field of manufacturing serves for this unique goal. One of the recent movements in the industry is “remanufacturing”. Remanufacturing is the process of restoring worn-out products to like-new condition [1]. The ultimate goal of remanufacturing is to recover the residual value of used products by reusing components that are still functioning well [2]. Unlike used (second hand) products, remanufactured products are dismantled into components, inspected in detail by the manufacturer and depleted or non-functioning parts are exchanged with new ones. Remanufacturing takes apart the product and reprocesses each component and reassembles it. The manufacturer verifies that the remanufactured product is as functional as the new one.

The remanufacturing gains its value in two aspects. Firstly, it represents an economic advantage for both the producer and the customer. The method makes the product attractive for the customer by offering it for lower prices than its new counterpart. Typically, remanufactured products are sold at 30 to 40 percent lower price than the new ones [3]. It also broadens the market by drawing the consumer who is not willing to pay the full price to purchase the product. As a result of this economic incentive, remanufacturing has been a $53 billion-a-year industry with 73,000 firms and 480,000 employees in the year 1996 [3]. The second basic value of remanufacturing is that it reduces the environmental hazards of industry by decreasing the amount of product disposal. Most of the environmental resources consumed in a production process are not renewable. It is proven that even renewable resources are consumed beyond nature’s ability to renew them [4]. Remanufacturing slows down the consumption of natural resources since it requires less energy and uses fewer materials compared to the manufacturing process by reusing several parts from the used product [4].

Increasing population and consumption drives a common sense for responsible use of resources. Therefore, waste reduction is becoming a major concern in industrialized countries [5]. Legislations that extend producers’ responsibility are becoming an element of public environmental policy in these countries. Many countries have introduced environmental legislations giving manufacturers the responsibility for the whole lifecycle of their products.

The regulations in countries of the European Union enforce the automotive manufacturers to take back the vehicles at the end of their useful lives returned by the customers. Manufacturers have to pay penalties for rejected end-of-life vehicle returns. The networks that are needed to take-back and collect the vehicles have to be set up by manufacturers [6]. Hence, the manufacturers are expected to re-use and recover certain amounts of parts from the returned products. These amounts are set at around 90 of vehicle weight for most of the EU member countries. Therefore, it is clear that remanufacturing business is a must rather than an option for the automotive manufacturers. Under these circumstances, automotive manufacturers have to manage their remanufacturing operations in a profitable and effective manner.

The rest of this thesis is organized as follows. Chapter 2 gives some information about the literature and background information of the remanufacturing concept. Extended producers' responsibility is explained in this section and the legislations in the European Union that enforce automotive manufacturers are explained in detail. Chapter 3 states the main problem that is to be studied in this thesis, and the objectives of the study. Chapter 4 provides a mathematical model. The development of the model is also explained in a logical order. Chapter 5 represents the numerical solution of the model based on real market data obtained from an automotive manufacturer in Turkey. Chapters 6 and 7 provide detailed analysis of the model's results through sensitivity and scenario analysis. These chapters also include some insights obtained from the numbers that are produced throughout the whole analysis. Chapter 8, as the last section, sums up the complete work and wraps up the results and deductions obtained from the analysis.

2. LITERATURE REVIEW AND BACKGROUND INFORMATION

In this chapter, a brief review of the literature related to the topics in our thesis is given. Definitions and information on reverse logistics, remanufacturing, extended producer responsibility and legislations are provided and information on related studies is summarized.

2.1. Reverse Logistics

Before focusing on the concept of remanufacturing, first we introduce an overview of the big picture which is reverse logistics. Brito and Dekker represent a complete framework and introduce the development of definitions about reverse logistics [7]. The formal definition of reverse logistics was put together by the Council of Logistics Management:

"…the term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes all relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal" [8].

This definition is merely originating from a waste management perspective and is quite general. Pohlen and Farris represent another definition giving it a direction insight as follows: "…the movement of goods from a consumer towards a producer in a channel of distribution" [9].

Kopicky et al. [10] represent a broader definition by combining the pervious two as follows: "Reverse logistics is abroad term referring to the logistics management and disposing of hazardous or non-hazardous waste from packaging and products. It includes reverse distribution which causes goods and information to flow in the opposite direction of normal logistics activities".

Rogers and Tibben-Lembke [11] describe reverse logistics stressing the goal and the process as follows: "The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal".

The European Working Group on Reverse Logistics, [12] proposes the following definition: "The process of planning, implementing and controlling backward flows of raw materials, in process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal".

Each of the definitions represented above refer to a different criterion for delineating reverse logistics. Stock and Kopicky et al. emphasize the element of waste reduction and place reverse logistics in the context of environmental management. In contrast, Pohlen and Farris refer to the direction of a goods flow, relative to the supply chain positions of the sender and the receiver. Finally, Rogers and Tibben-Lembke look at the management of goods flows that lead a closed loop in the supply chain [5].

To sum up, the definition of reverse logistics has changed over time. The first definitions include a sense of "reverse direction". The recent definitions incorporate an emphasis on environmental aspects by widening the scope.

2.2. Remanufacturing

Remanufacturing is the process of restoring worn-out products to like-new condition [1]. The ultimate goal of remanufacturing is to recover the residual value of used products by reusing components that are still functioning well [2]. Remanufactured products are obtained by collecting used products and replacing worn-out components with new ones [13].

Remanufacturing begins with the reclamation of used durable products. These products are then disassembled into parts, which are cleaned, inspected, and tested to determine whether they meet acceptable quality standards to be reused. Some parts become waste. Others that do not meet standards can be repaired or reconfigured. These used parts and some new ones are then combined to reassemble the original product from which they were reclaimed, or to build a product with a new identity. Remanufactured products typically have the same or similar performance characteristics and quality standards as new units.

Remanufacturing provides numerous benefits to the environment, the business community, and the consumer. Firstly, it represents an economic advantage for both the producer and the customer. The method makes the product attractive for the customer by bringing lower prices. Remanufacturing broadens the market by drawing the consumer who is not willing to pay the full price to purchase the product.

Remanufacturing reduces the environmental hazards of industry by decreasing the amount of product disposal. Most of the environmental resources consumed in a production process are not renewable. It is proven that even renewable resources are consumed beyond nature’s ability to renew them [4]. Remanufacturing slows down the consumption of natural resources since it requires less energy and uses fewer materials compared to the manufacturing process by reusing several parts from the used product [4]. Hormozi (1997) states that, new products require four to five times more energy than remanufactured parts [1]. Remanufacturing also creates the potential to decrease manufacturing lead times by half [14]. Manufacturers can utilize excess plant capacity with low capital investment and little risk with remanufacturing. Remanufacturing proves beneficial in balancing changes due to the business cycle [1].

2.3. Extended Producer Responsibility

The Organization for Economic Cooperation and Development (OECD) defines Extended Producer Responsibility (EPR) as “an environmental policy approach in which a producer’s responsibility, physical and/or financial, for a product is extended to the post-consumer stage of a product’s life cycle” [15]. This approach maintains that the producers have the greatest ability to realize environmental improvements and to influence changes in the upstream manufacturing and downstream phases of a product’s life [16].

EPR is usually implemented through formal legislations. The motivating factors that have led to the adoption of EPR as a legislative policy include problems with landfill space and contamination, hazardous wastes, and products abandoned in the environment. Minimizing the impact of end-of-life products on the environment is the end goal.

The implementation of EPR demands some type of policy instrument. Forslind summarizes the main policy instruments of EPR in five main areas [17]; (i) Informative responsibility implying the responsibility to provide information about the product and its environmental effects. This responsibility is based both on legal requirements and the producer’s dependence on goodwill. (ii) Physical responsibility stating that the producer is required to physically handle the end-of-life management. (iii) Economic responsibility where the producer covers the whole or an extensive part of the cost associated with the end-of-life management. (iv) Liability implying that the producer is responsible for all damages that a good causes during its life cycle. (v) Owner responsibility defined as of all the other responsibilities. Owner responsibility arises when the producer keeps the legal ownership of the good such as leasing.

The EPR philosophy has already been transferred into a legislation as the European Parliament passed a directive requiring its member countries to institute and EPR program for end-of-life vehicles in 2000 [18].

2.4. Legislations

Several countries, mostly in Europe, have introduced environmental legislation charging manufacturers with responsibility for the whole lifecycle of their products. Take-back and recovery obligations have been enacted or are underway for a number of product categories in the European Union and in Japan, cars in the European Union and in Taiwan, and packaging material in Germany [5].

In the European Union, processing the end-of-life vehicles is prioritized and is managed on the basis of economic extended producer responsibility. In 2000, this was formalized in a directive, where quantified targets and limitations are specified [18].

Forslind [17] summarizes the six main provisions that the directive comprises. (i) Dismantling facilities must be authorized and must fulfill specified requirements. When the last owner of an end-of-life vehicle returns it, he shall receive a certificate of destruction. (ii) Recovery, recycle and reuse ratios are specified both in levels and in time. (iii) Amendments of car type approval regulations shall be prepared to ensure that the vehicles can fulfill the recovery, recycle and reuse ratios. (iv) The use of lead, chromium and mercury is exceptions after July 1, 2003. (v) It shall be possible to return an end-of-life vehicle for dismantling without any cost for the last owner, i.e. free take-back. The producer shall also cover all or a significant part of the costs associated with the dismantling, and (vi) it is possible for member states to implement the directive by means of agreement between national authorities and industries, but the agreements must be enforceable. If industries do not comply, the member state must implement the directive in national legislation.

The member states shall ensure that vehicles sold after July 1, 2002 are covered by extended producer responsibility. The directive also states that the producers shall bear a retroactive economic responsibility starting in January 1, 2007. This part comprises all vehicles on the market. The directive states that returning a vehicle must be free of charge for the owner after this date and that the producer shall cover the whole cost or an extensive part of the cost.

Compared to the different types of responsibilities defined above, the directive implies an informative, physical and economic responsibility. Apart from the main provisions stated above, the producers have an obligation to set up a system for collecting end-of-life vehicles, and to provide the dismantlers with the information needed to dismantle the end-of-life vehicle in an environmentally safe manner.

2.5. Related Work

There are numerous studies in the literature related to the topics that are analyzed in this thesis. The existing studies can generally be classified in three main areas. The first type of studies give general information and some figures or statistics about reverse logistics and/or remanufacturing business. The paper presented by Rogers, D. S., and R. Tibben-Lembke [19] defines reverse logistics and describes reverse logistics practices and barriers to implementing good reverse logistics practices. The result of a survey analysis is represented. In the scope of the survey analysis, the researcher has interviewed approximately 150 managers with reverse logistics responsibilities in US market. Hormozi [20] highlights the importance and structure of new environmental standards. The article explains the environmental benefits of remanufacturing, and suggests reasons why both remanufacturing and environmental standards promote environmentally conscious manufacturing. Giuntini and Gaudette [3] present some general figures like size and scope about remanufacturing business. The benefits of remanufacturing for the industry, consumers, workforce and society are emphasized in the study. The paper also searches for answers about why remanufacturing has a modest success despite of those tremendous benefits. The probable reasons for having a small portion in economy are discussed in detail. Finally, the paper represents some ways to overcome the obstacles and move remanufacturing to a higher and more widespread level. Ferrer and Whybark [4] describe the fully integrated material planning system to facilitate the management of a remanufacturing facility in their article. The system described in the paper is based on material requirements planning logic. This system evaluates the uncertainties in supply of used components (lead times), the good parts in the components (quality of cores), and the demand for remanufactured products. The study addresses the problems of determining the appropriate level of stock, scheduling the disassembly, and managing unique and common parts in the cores in a remanufacturing process. Some of the studies of this type present more specific information about the automotive remanufacturing industry. Hormozi [1] represents an analysis of automotive replacement parts remanufacturing industry. The article represents general figures about remanufacturing industry of automotive parts. The paper introduces the history of automotive parts remanufacturing industry and the current situation as well. Quality and warranty issues of remanufactured parts are also analyzed and the main challenges in planning and control of remanufacturing operations are emphasized. Bellman and Khare [21] analyze the economic issues in recycling end-of-life vehicles in their study. The study identifies the key elements in car scrapping approaches. The paper represents comments about how financial resources could be organized for the end-of-life vehicle recycling systems.

The second type of studies in the literature present analysis throughout mathematical models developed by the analyzers. Krikke et al. [22] develop a quantitative model to support the decision-making process concerning the design structure of a product and its logistics network. The model is applied to a closed-loop supply chain design problem for refrigerators using real life data of a Japanese consumer electronics company. Vorsayan and Ryan [23] represent an open queuing network model of sales, return refurbishment and resale process of a manufacturer. The study examines the optimality conditions for different situations and numerical analysis identifies the characteristics of the market and the manufacturer. Hula et al. [24] represent a model for multi-criteria decision making for optimization of product disassembly. The paper describes a methodology to analyze how product designs and situational variables impact the end of life strategy for a given economic cost or profit. To illustrate the methodology, a case study involving a coffee maker is described. Toktay et al. [25] analyze the procurement of new components for recyclable products. The study seeks an ordering policy that minimizes the total expected procurement, inventory holding, and lost sales cost. The paper presents a model of the system as a closed queuing network and develops a heuristic procedure for adaptive estimation and control. The analysis investigates the effects of various system characteristics with the included case study. Aras et al. [26] represent an approach for assessing the impact of quality-based categorization of returned products. Through the numerical studies on a continuous-time Markov chain model, the paper shows that incorporation of returned product quality in the remanufacturing and disposal decisions can lead to significant cost savings. Inderfurth [27] examines the problem of whether to substitute the new product with the remanufactured one for the same market. In many industries original equipment manufactures are active in the remanufacturing business themselves. In this case coordination problems arise. The paper represents a model for generating an optimal policy for product substitution. Some of the studies of this type focus on the pricing problems specifically. Debo et al. [2] focus on the joint pricing and product technology selection problem faced by a manufacturer who considers introducing a remanufacturable product in a market. The analysis discusses the market and technology drivers of product remanfuacturability and identifies some phenomena of managerial importance that are typical of a remanufacturing environment. In the study represented by Çelebi and Aras [28], a dynamic model is developed in order to determine the optimal pricing and trade-in rebate decisions for a profit maximizing firm selling durable goods which can be remanufactured. The market is divided into two segments as first time buyers and replacement customers. The customer's purchase decisions are modeled using a utility function.

The last type of the studies analyze the extended producer responsibility concept and present discussion about the legislations. Gerrard and Kandlikar [29] question whether the European end-of-life vehicle legislation meets the expectations or not. The study examines the effect of the directive on innovation and vehicle recovery and presents an evaluation of framework based on the anticipated changes that could results from the end-of-life vehicle directive. The study shows that legislative factors and market forces have led to innovation in recycling.

This thesis differs from the previous studies in that we analyze the economic effects of remanufacturing on manufacturers by focusing on an automotive manufacturer. The existing studies in the literature have analyzed either the remanufacturing business or the legislations. The effects of legislations on manufacturers have been presented by some statistics or survey analysis results, but not with a mathematical model yet.

Another specific difference of our thesis is that we analyze an automotive manufacturer with our model. Contrary to the classical definition of remanufacturing, a remanufactured automobile or vehicle cannot be of the same value with the brand new one to the customer because of the model year being older than the brand new.

Throughout the analysis with a mathematical model we gain some insight about the impact of the new legislations on the manufacturers. We develop a linear program to model a manufacturer that works under given constraints and while trying to maximize its profit. With this model, we will be able to analyze the process by assigning any combinations of the remanufacturing, used vehicle sales or recycling functions.

3. PROBLEM DESCRIPTION AND OBJECTIVES

In this chapter, we state the main problem that is to be studied in this thesis, and the objectives of the study. The problems and objectives described in this chapter constructs the base for the model development phase of the study.

3.1. Problem Description

The regulations in countries of the European Union enforce the automotive manufacturers to take back the end-of-life vehicles returned by their customers. Manufacturers have to pay penalties for rejected end-of-life vehicle returns. The networks that are needed to take-back and collect the vehicles have to be set up by the manufacturers due to the regulations [6]. The manufacturers are supposed to re-use and recover certain amounts of parts from the returned products. These amounts are set at around 90 percent of vehicle weight for most of the EU member countries. Therefore, it is clear that remanufacturing business is a must rather than an option for the automotive manufacturers. Under these circumstances, automotive manufacturers have to manage their remanufacturing operations in a profitable and effective manner.

Every new vehicle sales today will result in a return after products life is completed. Also some products will be returned by the customers during their proper lifetime. Therefore the manufacturers should make strategic decisions on planning the capacities of their operations such as manufacturing, remanufacturing, and disposal etc. The questions such as, how many products will be received every year, how many of them are in good condition and how many are non-usable, what proportion of these products are to be remanufactured, what age products bring the most profitable remanufacturing activity, have to be studied by the manufacturers which work under the effect of the above mentioned legal regulations.

Within the framework defined above, there exist some problems for both the manufacturer and the government. The manufacturer should determine how much capacity will be preserved for remanufacturing, used product sales, and recycling. Optimum levels of these capacities can be figured out through detailed analysis of how many products will be remanufactured based on their ages. The manufacturer has to know what the economic impact of collecting used products from the market and selling them as used products or remanufacturing them is. Before going into this business, manufacturers should have some information about how these jobs affect their profit structure. In some cases, the manufacturers may choose to stay away from this business and incur the costs arising from the legal regulations. The cost of this illegal case to the manufacturer also has to be clarified and the economic impact on the manufacturer should be defined. On the other side, the government also should have some information about the market and manufacturers before deploying the legal regulations like described above. The legal penalties determined by the government should be at such a level that they are not as high as to diminish the profit of the manufacturer completely yet not as low as to encourage the manufacturer not to take the responsibility of its products. To determine these penalties accurately, the government needs detailed numerical analysis of the complete concept driven by the legislations.

3.2. Objectives of the Study

In this study, our aim is to develop a mathematical model to come up with solutions to the problems defined in the previous section. Throughout the analysis with a mathematical model we will try to figure out some insight about the impact of the new legislations on the manufacturers. First, we will develop a linear program to model a manufacturer that works under given constraints and aims to maximize its profit. With this model, we will be able to analyze the manufacturer by assigning any combinations of the remanufacturing, used vehicle sales or recycling functions. Thus, we will be able to see the outcome when no legal regulation is enforced on the manufacturer and when legal regulations are imposed. Besides, we will be able to figure out what would be the result if the manufacturer had no concern about obeying the legislations.

Throughout the complete analysis, we will be able to generate some numerical insight about the manufacturers trying to be remanufacturers under the force of the legal regulations by government. We will be able to see the economic impact for a manufacturer to turn into a complex facility that also takes back the returned products and processes them for different purposes including remanufacturing, direct sales of used vehicles, and disposal.

4. MODEL DEVELOPMENT

We consider a manufacturing, remanufacturing, second hand sales and disposal system with a third party recycler included. In our model, the manufacturer has seven basic functions:

- producing and selling new products
- accepting the returned products
- selling non-end-of-life products as used products (without any refurbishing)
- remanufacturing the returned products
- selling remanufactured products
- disposing non-usable products or material
- sending products/material to the recycler

The classical manufacturer accomplishes only the first one of the above listed functions. Production is the only task of a classical manufacturer. Our model will represent a transformation of a manufacturer from the so called classical manufacturing system to a complex facility that also takes back the returned products and processes them for different purposes including remanufacturing (See Figure 5.1).

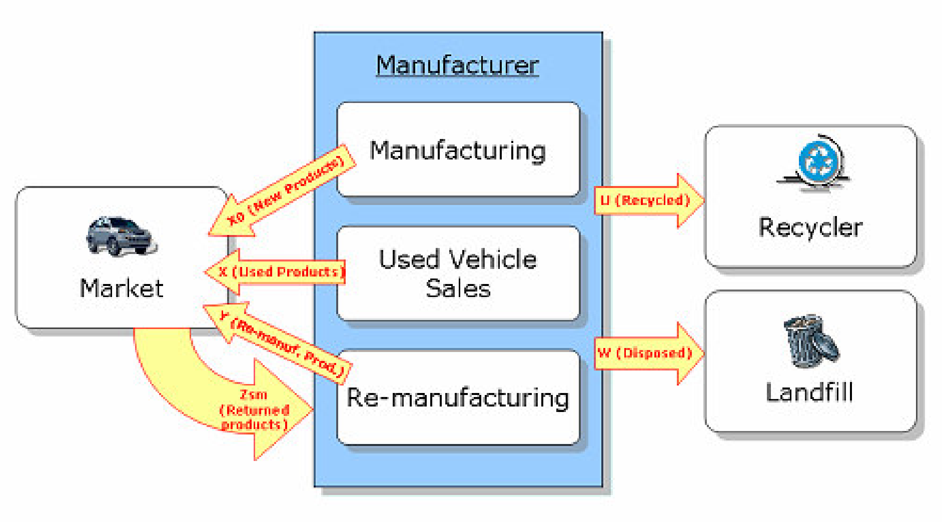

Figure 5.1. The extended roles of the manufacturer

Our manufacturer with extended roles basically manufactures new products ($X0_j$) to fulfill the market demand (dem_X0_j) and sells the products with the new product price (P_i) to the market. The index set i represents the current age of the product and j represents the time period. The total number of products that can be manufactured in every period can be determined ($prod\_cap$). After some time of usage, the product is brought back to the manufacturer by the customer. There are two basic reasons for the customer to bring the product back. Firstly, he may want to trade-in his existing product to buy a newer one ($sale\_ret_{ij}$). Secondly, he may want to stop using the product and sell it as second-hand (reg_ret_{ij}). These two types of returns comprise the total of product returns ($Zbig_{ij}$). If the customer subject to the new product sales is a second-time buyer, then he may want to trade in his existing product. So it can be derived that some of the new product sales may cause a return. This situation is included in our model as the "effect of sales on return" (e). The second type of return is related with the customer's willingness to return the product (r_i). We can expect this willingness to increase as the product gets older. At the end of the proper life of the product, the customer brings the product back certainly. The manufacturer decides on accepting the returned products based on its take back capacity and economic use of the returned product. Since accepting returned items comprises operational activities, the total number of products that can be accepted for each period can be determined (ret_cap). As a result of the manufacturer's decision, the product is either accepted (Zsm_{ij}) and a purchasing price is paid to the customer (PP_i) or rejected (T_{ij}). Note that the manufacturer has to accept the end-of-life products due to the legislations [6]. Rejecting an end-of-life product ends up with a penalty paid to the government (pen_rej). After taking the product back, the manufacturer has alternative ways to process it. The first and the easiest way is to offer the product back to the market as a second hand product (X_{ij}) with a reasonable price (P_i). Since all the customers cannot afford to buy new products, the market –by definition– has demand for these types of used products (dem_XY_{ij}). This sales process includes operational tasks and therefore it is limited with the capacity that the manufacturer determines (dir_cap). So the manufacturer cannot exceed this capacity in each period. Another way to process the product may be to remanufacture it. The remanufactured products (Y_{ij}) can be sold at better prices (RP_i) since they are in better condition. There is also a demand for remanufactured products (dem_XY_{ij}). The remanufacturing process includes disassembling the product, checking every component and replacing the non-functional components with working ones. At the end of the remanufacturing process, the vehicle becomes as good as the new one, but note that the price of the product cannot be equal to the brand new one because the model year of the product stays the same although it is remanufactured. The price of a remanufactured product should be between the used vehicle price of the same age and the new product at age zero. The ratio of re-usable parts in a product is expressed by the level of remanufacturability in our model (q_i). This level gets lower as the age of the product increases. The manufacturer incurs some costs for refurbishing the product (RC_i). Since the remanufactured products are processed by the manufacturer and are considered "as good as new", the manufacturer also declares a warranty period for these types of products like the new ones and expects to fix the mechanical problems of the product during this period. The cost of the warranty repairs (wc_Y_i) are incurred by the manufacturer. The total number of products that can be remanufactured in every period is determined as rem_cap. Another way to process the returned products is to send them to the recycler (U_{ij}). The recycler pays a scrap value for the product (PJ_i). The recycler is also subject to a capacity constraint (rec_cap) and cannot exceed this in each period. The final alternative for processing the returned product is to dispose it of (W_{ij}). The legislation [6] defines the proper way of disposing the products and declares the must-do's for the manufacturers when disposing of the item. This operation is a source of cost for the manufacturer and the manufacturer incurs a disposal cost (DC_i) for each product disposed. The same legislation [6] defines an upper limit ($disp\_upl$) of disposal for the manufacturers. This limit is determined based on the new product sales and is a proportion of the amount of new products sold by the manufacturer. The manufacturer cannot exceed this upper limit when disposing the product. When this limit is exceeded, the manufacturer has to pay a penalty (pen_disp) for its disposal exceeding the limit (w_ol_{ij}).

A linear programming model is developed for solving the problem. The model consists of an objective function representing the total profit to be maximized and constraints due to demand, sales, production, remanufacturing, recycling and disposal capacities etc.

4.1. Assumptions

The following assumptions are made when constructing the linear programming model.

Competitors are not considered in this model. The manufacturer is assumed to be a monopoly in the market. The whole market demand is fulfilled by the manufacturer in consideration.

The prices do not vary between terms due to supply-demand relations. The existing values of the prices are already determined and are kept always the same.

The products are used well until their end of their lives and are brought back to the manufacturer when they complete their life. No product is lost or stolen and dismantled, or becomes scrap because of an accident throughout its useful lifetime. Every product sold by the manufacturer comes back after the end-of-life without any loss during usage.

There are two types of demands in the market. One is for new products and one is for used or remanufactured products. The customers of these two types of supply are separated and there is no demand cannibalization between these two demand types.

The manufacturer declares a warranty period for the new products sold and incurs the cost of mechanical repairs during the warranty period. The remanufactured products are also sold with a warranty period. Although the remanufactured products are as good as new ones, the average warranty cost of a remanufactured product is slightly higher than the new product. The average warranty cost of the remanufactured products is directly proportional to its age. The manufacturer declares one year of warranty period for the remanufactured products. The manufacturer pays the repair cost of mechanical problems occurring in the remanufactured products during this period.

The manufacturer in the model of this study works with zero inventories at all levels of the processes. No inventory of either products or material is considered. So, a product is manufactured with zero lead time when a demand is present.

4.2. Decision Variables and Parameters

The decision variables and parameters of the model are dependent on two basic index sets. The index set i represents the current age of the product. This value can change between 0 and maximum age of product. The index set j represents the time period. The value of j can change between 0 and maximum length of periods defined by the modeler. Both values are incremented with step length 1.

$i = \{0,...,19\}$: Age of product
$j = \{0,...,39\}$: Period/Term

The decision variables of the model are defined to cover all the functions of manufacturing, remanufacturing, second hand sales, disposal and recycling system. The decision variables are defined over indices i and j. The notations and the explanations of the variables are as follows:

$X0_j$: Number of new products (viz. age 0 products) sold in period j
X_{ij} : Number of used products at age i sold in period j
Y_{ij} : Number of remanufactured products at age i sold in period j
$Zbig_{ij}$: Number of products at age i returned in period j
Zsm_{ij} : Number of accepted products at age i returned in period j
T_{ij} : Number of rejected products from the returned products at age i in period j
W_{ij} : Number of products at age i disposed of in period j
w_ul_{ij} : Number of products disposed of under legal limit

w_ol_{ij} : Number of products disposed of over legal limit

U_{ij} : Number of products at age *i* sent to recycler in period *j*

pim_{ij} : Total number of age *i* products in the market in period *j*

$sale\_ret_{ij}$: Number of returns at age *i* in period *j* occurring from trade-ins

reg_ret_{ij} : Number of regular returns at age *i* in period *j*

The model includes the parameters given below. Some of the parameters are defined over sets i or j, and some are independent of the index sets.

P_i : Sales price of new or used product at age *i*

RP_i : Sales price of remanufactured product at age *i*

PP_i : Purchasing price of used product at age *i*

PJ_i : Scrap value at age *i*

RC_i : Unit remanufacturing cost for a product at age *i*

DC_i : Unit disposal cost for a product at age *i*

r_i : Willingness of customer to return a product at age *i*. $r_i \in [0,1]$

q_i : Level of re-manufacturability for a product at age *i*. $q_i \in [0,1]$

dem_X0_j : Demand of new products for period *j*

dem_XY_{ij} : Demand of remanufactured or used products of age *i* for period *j*

wc_X0_i : Warranty cost per product at age *i*

wc_Y_i : Warranty cost per remanufactured product at age *i*

e : Effect of sales on return

$prod\_cap$: Production capacity per period (year)

ret_cap : Returned products acceptance capacity per period

rem_cap : Remanufacturing capacity per year

dir_cap : Direct sales capacity per year

rec_cap : Capacity of recycler per period

pen_rej : Legal penalty paid for unit unaccepted product return

pen_disp : Legal penalty paid for unit disposal over legal limit

war_cst_{ij} : Total warranty costs for age i products in period j

$disp\_upl$: Upper limit of disposal

4.3. Model Components

Before constructing the complete model, it is more practical to formulate the small pieces that will gradually sum up to the ultimate model. Analysis of the manufacturing, remanufacturing, second hand sales, disposal and recycling systems wrap up to some basic formulations represented as follows.

Total number of new products sold in each period must not exceed the demand for new products in every period.

$$X0_j \leq dem\_X0_j \tag{4.1}$$

The total sum of refurbished products sales and second hand product sales cannot exceed the demand for used or remanufactured products for every period.

$$X_{ij} + Y_{ij} \leq dem\_XY_{ij} \tag{4.2}$$

The number of new products sold in each period is lower than or equal to the yearly production capacity of the manufacturer.

$$X0_j \leq prod\_cap \tag{4.3}$$

The total number of used products sold in each period must be lower than the manufacturer's capacity of used product sales.

$$\sum_i X_{ij} \leq dir\_cap \tag{4.4}$$

The total number of products remanufactured in each period is lower than the per-period capacity of manufacturer set aside for remanufacturing.

$$\sum_i Y_{ij} \leq rem\_cap \tag{4.5}$$

The total number of products sold to the recycler in each period cannot exceed the recycler's processing capacity.

$$\sum_i U_{ij} \leq rec\_cap \tag{4.6}$$

Total number of age i products in the market in period j is the subtraction of disposed or recycled products from the new products sold in the $(j-i)$ 'th period.

$$pim_{ij} = X0_{(j-i)} - \left(W_{ij} + U_{ij}\right) \tag{4.7}$$

The total number of products brought back to the customer in each period is the total sum of returns caused by sales and regular returns. The number of sales returns of age i products in period j can be calculated by multiplying the "effect of sales on return" with the total number sales of products at age $i-1$. Here, we assume that the effect of sales on return is valid for one year older products. For example, when a customer buys a product of age four, this may cause him to return a product at age five. The regular returns are the multiplication of the customers willingness to return with the number of products in the market remaining after returns caused by sales.

$$Zbig_{ij} = sale\_ret_{ij} + reg\_ret_{ij} \tag{4.8}$$

$$sale\_ret_{ij} = e \cdot \left(X_{i-1,j} + Y_{i-1,j}\right) \tag{4.9}$$

$$reg\_ret_{ij} = r_i \cdot \left(pim_{ij} - sale\_ret_{ij}\right) \tag{4.10}$$

The manufacturer can accept at most a certain amount of products brought back by the customer. This number is limited by the manufacturer's "returned products acceptance capacity". The number of accepted products cannot exceed the total number of products brought back if the capacity of manufacturer is higher than the number of products brought back.

$$\sum_i Zsm_{ij} \leq ret\_cap \tag{4.11}$$

$$Zsm_{ij} \leq Zbig_{ij} \tag{4.12}$$

The difference of the products brought back and the products accepted gives the number of products rejected by the manufacturer.

$$T_{ij} = Zbig_{ij} - Zsm_{ij} \tag{4.13}$$

The accepted products returned by the customer are either sold as second hand products, or remanufactured, or sold to recyclers or disposed.

$$X_{ij} + Y_{ij} + W_{ij} + U_{ij} = Zsm_{ij} \tag{4.14}$$

The number of products disposed can be divided into two components. One is the number that remains under the pre-defined legal upper limit of disposal for manufacturer, and the other is the part exceeding this upper limit. The part which is under limit can be calculated by multiplying the ratio of disposal upper limit by the number of new products manufactured.

$$W_{ij} = w\_ul_{ij} + w\_ol_{ij} \tag{4.15}$$

$$\sum_i w\_ul_{ij} = disp\_upl \cdot X0_j \tag{4.16}$$

The warranty cost that the manufacturer incurs is the total sum of warranty costs caused by new products and the warranty costs caused by the remanufactured products.

$$war\_cst_{ij} = wc\_X0_i \cdot pim_{ij} + wc\_y_i \cdot Y_{ij} \tag{4.17}$$

The revenues of the manufacturer in this system arise from the sales of new products, used products, refurbished products and scrap sales to recycler.

$$\sum_{i}\sum_{j}\left(P_0 \cdot X0_j + P_i \cdot X_{ij} + RP_i \cdot Y_{ij} + PJ_i \cdot U_{ij}\right) \tag{4.18}$$

The costs of the manufacturer are the purchasing prices paid to customers for returned products, remanufacturing costs, disposal costs, legal penalty paid to government for un-accepted end-of-life products, legal penalty paid to government for over limit disposals and warranty costs.

$$\sum_{i}\sum_{j}\left(PP_i \cdot Zsm_{ij}\right) \tag{4.19}$$

$$\sum_{i}\sum_{j} RC_i \cdot Y_{ij} \tag{4.20}$$

$$\sum_{i}\sum_{j}\left(DC_i \cdot W_{ij} + pen\_disp \cdot w\_ol_{ij}\right) \tag{4.21}$$

$$pen\_rej \cdot \sum_{j} T_{'19',j} \tag{4.22}$$

$$\sum_{i}\sum_{j} war\_cst_{ij} \tag{4.23}$$

The total profit of the manufacturer in the system is the difference between the revenues and the costs. The total profit will form the objective function for our linear optimization model represented in the next chapter.

4.4. Mathematical Model

A linear programming model is developed for solving the problem. The model consists of an objective function representing the total profit to be maximized and constraints due to demand, sales, production, remanufacturing, recycling and disposal capacities etc.

Using the defined index sets, variables, parameters and components, the optimization model for the problem can be formulated as follows:

$$\begin{aligned} \max \quad & \sum_i \sum_j \left(P_0 \cdot X0_j + P_i \cdot X_{ij} + RP_i \cdot Y_{ij} + PJ_{ij} \cdot U_{ij} \right) - \sum_i \sum_j \left(PP_i \cdot Zsm_{ij} \right) \\ & - \sum_i \sum_j RC_i \cdot Y_{ij} - \sum_i \sum_j \left(DC_i \cdot W_{ij} + pen\_disp \cdot w\_ol_{ij} \right) \\ & - pen\_rej \cdot \sum_j T_{'19',j} - \sum_i \sum_j war\_cst_{ij} \end{aligned} \tag{4.24}$$

s.t.

$$X0_j \leq dem\_X0_j \tag{4.25}$$

$$X_{ij} + Y_{ij} \leq dem\_XY_{ij} \tag{4.26}$$

$$X0_j \leq prod\_cap \tag{4.27}$$

$$\sum_i X_{ij} \leq dir\_cap \tag{4.28}$$

$$\sum_i Y_{ij} \leq rem\_cap \tag{4.29}$$

$$pim_{ij} = X0_{(j-i)} - \left(W_{ij} + U_{ij} \right) \tag{4.30}$$

$$sale\_ret_{ij} = e \cdot \left(X_{i-1,j} + Y_{i-1,j} \right) \tag{4.31}$$

$$sale\_ret_{ij} = r_i \cdot \left(pim_{ij} - sale\_ret_{ij} \right) \tag{4.32}$$

$$Zbig_{ij} = e \cdot \left(X0_j + X_{ij} + Y_{ij} \right) + r_i \cdot pim_{ij} \tag{4.33}$$

$$\sum_i Zsm_{ij} \leq ret\_cap \tag{4.34}$$

$$Zsm_{ij} \leq Zbig_{ij} \tag{4.35}$$

$$T_{ij} = Zbig_{ij} - Zsm_{ij} \tag{4.36}$$

$$X_{ij} + Y_{ij} + W_{ij} + U_{ij} = Zsm_{ij} \tag{4.37}$$

$$war\_cst_{ij} = wc\_X0_i \cdot pim_{ij} + wc\_y_i \cdot Y_{ij} \tag{4.38}$$

$$W_{ij} = w\_ul_{ij} + w\_ol_{ij} \tag{4.39}$$

$$\sum_i w\_ul_{ij} \le disp\_upl \cdot X0_j \tag{4.40}$$

$$\sum_i U_{ij} \le rec\_cap \tag{4.41}$$

$$X_{ij} \le pim_{ij} \tag{4.42}$$

$$Y_{ij} \le pim_{ij} \tag{4.43}$$

$$W_{ij} \le pim_{ij} \tag{4.44}$$

$$X0_j \ge 0 \tag{4.45}$$

$$X_{ij} \ge 0 \tag{4.46}$$

$$Y_{ij} \ge 0 \tag{4.47}$$

$$W_{ij} \ge 0 \tag{4.48}$$

$$U_{ij} \ge 0 \tag{4.49}$$

$$pim_{ij} \ge 0 \tag{4.50}$$

$$Zbig_{ij} \ge 0 \tag{4.51}$$

$$Zsm_{ij} \ge 0 \tag{4.52}$$

$$T_{ij} \ge 0 \tag{4.53}$$

$$sale\_ret_{ij} \ge 0 \tag{4.54}$$

$$reg\_ret_{ij} \ge 0 \tag{4.55}$$

$$w\_ul_{ij} \ge 0 \tag{4.56}$$

$$w\_ol_{ij} \ge 0 \tag{4.57}$$

5. NUMERICAL ANALYSIS

The numerical analysis of the model is performed with the information and data obtained from Mercedes-Benz Türk A.Ş. The company manufactures buses (intercity and coaches) in Hoşdere plant (Istanbul, Turkey), trucks in Aksaray plant (Turkey) and imports passenger cars and vans. In this study, we analyze the company's bus production function. Note that Mercedes-Benz Türk A.Ş. has a manufacturing facility for buses but a re-manufacturing or re-conditioning business is not considered yet. The model developed in the previous section will be numerically studied for the company assuming a remanufacturing unit exists. Thus we will be able to see the effect of extending the roles of the manufacturer and analyze the manufacturer's transformation from the so called "classical" production system to a complex facility that also takes back the returned products and processes them for different purposes including remanufacturing (See Figure 5.1).

Since its foundation in 1968 Mercedes-Benz Türk has sold approximately 35,000 buses. Mercedes-Benz Türk, currently produces intercity and municipality buses at Hoşdere and Davutpaşa Plants. The Hoşdere Bus Plant has been completed with an investment of DM 65 million. This plant, comprising of a paint shop, assembling and finishing units, produces in cooperation with the Davutpaşa Plant. The bodies of the intercity and city type buses manufactured at Davutpaşa are conveyed to the Hoşdere Facilities by special transport, where after the painting, assembling and finishing processes, they are ready to be delivered to the customers [30]. The Hoşdere Plant has an initial production capacity of 3,000 buses/year. Mercedes-Benz Türk, currently employs 2,200 personnel for bus manufacturing at the Hoşdere and Davutpaşa Plants [30]. The Hoşdere Plant, presently the most modern bus production facility of the world, has 52,500 m² covered area built on a total of 326,025 m² of land. The combination of conveyor belts and stationary working sites (box) instead of the conventional band production provides the necessary flexibility to the plant to produce different models simultaneously. More-over, time losses during manufacturing can be minimized [30].

Turkey's intercity bus market has demand of 1,200 buses per year. Approximately 700 of these buses are sold by Mercedes-Benz Türk A.Ş. According to the legislations [6] economic lifetime of a bus is 20 years. A bus cannot be used for more than this limit. This lifetime determines the end-of-life product age for our model. The model is run for 40 years with a product lifetime of 20 years ($i = \{0,...,19\}$, $j = \{0,...,39\}$).

5.1. Parameter Estimation

P_i, PP_i, dem_X0_j, wc_X0_i, $prod\_cap$, $disp\_upl$ are the parameters whose exact values are obtained either from the market or the legislations [6]. For the remaining parameters, the values will be decided based on the ones which are already known. To analyze the possible variations of these parameters, a detailed sensitivity analysis will be presented in the upcoming chapters of the study.

The values of P_i (Sales price of new or used product at age *i*) are obtained from the market. P_i represents the price of a new product when $i = 0$ and a used product when $i \geq 1$. The sales price of a new product is €192,000. The price of a used product at age 1 is €170,000 and the value decreases as the age of the product increases. The complete listing of values of P_i can be viewed in Figure 6.1 or Table A.1 of Appendix A.

The values of RP_i (Sales price of remanufactured product at age *i*) is determined based on the values of P_i. The price of a remanufactured product is higher than the price of used product and lower than the price of a brand new product [1]. Based on this information the values of RP_i are set. The values of RP_i is lower than the values of P_i except for $i = 0$. When the product is at age zero, viz. brand new, the value of a remanufactured product is lower than the new one. Figure 6.1 and Table A.1 of Appendix A present detailed information about the values of RP_i.

The values of the parameter PP_i (Purchasing price of used product at age *i*) is obtained from the market. The value PP_i is lower than either the value of P_i or the value

RP_i for any product at any age. Figure 6.1 and Table A.1 of Appendix A represent detailed information about the values of this parameter.

The values of PJ_i (Scrap value at age *i*) is determined based on PP_i. The scrap value of a product is assumed to be the ten percent of its purchasing price (PP_i). To overcome the disadvantage of this rough estimation, the values of PJ_i will be replaced with alternative values in the sensitivity analysis. The values of PJ_i are presented in detail on Figure 6.1 and Appendix A, Table A.1.

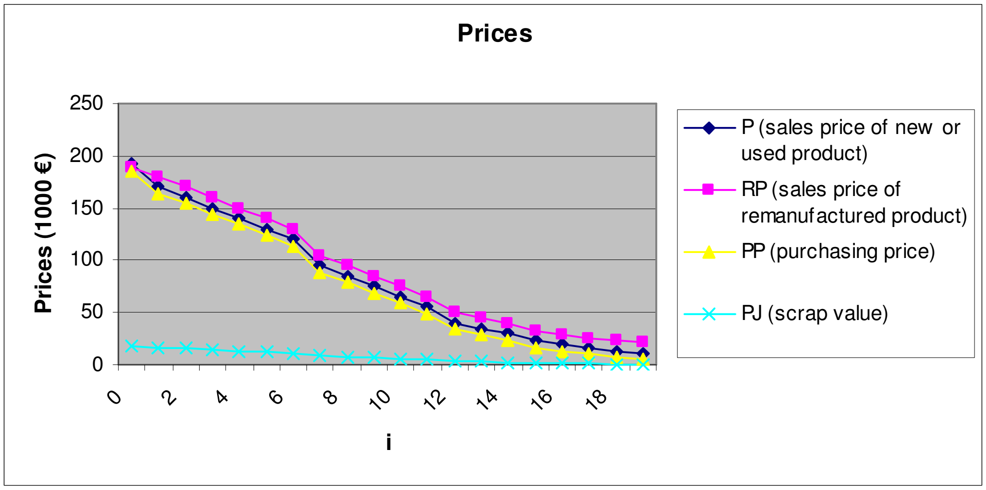

Figure 6.1. Values of the parameters P_i, RP_i, PP_i, and PJ_i

The value of the parameter RC_i (Unit remanufacturing cost for a product at age *i*) should be less than or equal to the difference of RP_i and PP_i. The values of this parameter are set based on this assumption. RC_i should increase as the age of the product increases due increasing operational costs. The values of RC_i are presented in Figure 6.2 and Appendix A, Table A.2.

The parameter DC_i (Unit disposal cost for a product at age *i*) expresses the total cost of disposing of a product with a method that is fully compliant with the rules mentioned in the legislations [6]. The values of the parameter are supposed to increase as the age of product increases because of harder operations in dismantling. The values of

DC_i are presented in Figure 6.2 and Appendix A, Table A.2.

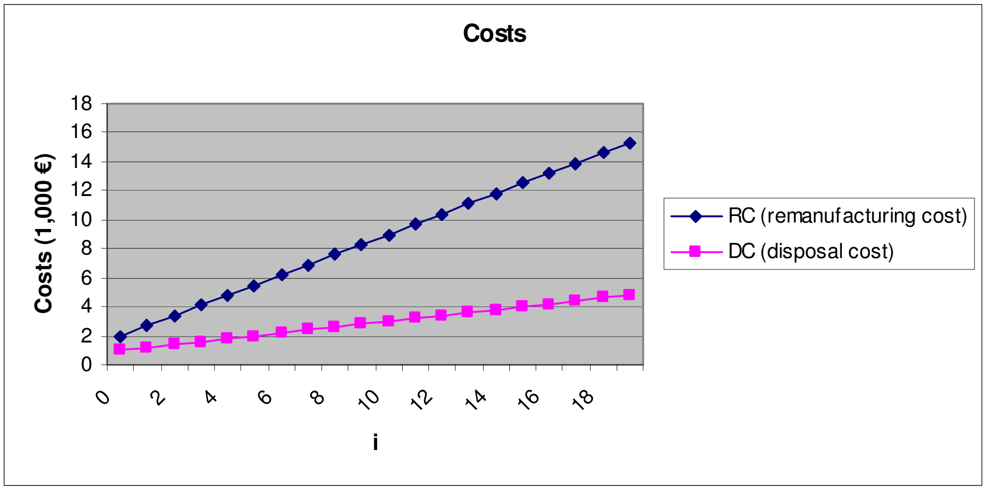

Figure 6.2. Values of the parameters RC_i and DC_i

Willingness of a customer to return a product at age i is represented by the parameter r_i. The values of this parameters change between "0" and "1" ($r_i \in [0,1]$) and increases as the age of the product increases. The value "0" represents that the current owner of the product has no intention to return the product back to the manufacturer. The parameter has this value for brand new products. The value "1" means that the customer definitely wants to return the product to the manufacturer. This is the case when the product is at the end of its proper lifetime, viz. $i = 19$, in our model. The values of r_i are given in Figure 6.3 and Appendix A, Table A.3.

Level of remanufacturability for a product at age i is represented by the parameter q_i. The values of this parameter change between "0" and "1" ($q_i \in [0,1]$) and decrease as the age of the product increases. The value "1" represents that all the components of a product are in good condition and are reused in remanufacturing. This is the ideal case and is possible if the product is either never used or a little used. The value "0" means that none of the parts of the product can be re-used and all are in bad condition. This is the case when the product is at the end of its proper lifetime, viz. $i = 19$, in our model and all the parts of the products are broken or out of order. In physical world, the parameter does not take these extreme end values "0" and "1". None of the parts are as good as new when a product is used even if the customer takes much care. Also at the end of the life, some parts can be obtained from the product such as scrap metal, plastic or glass. Therefore this parameter never has the extreme values “0” and “1” in the numerical analysis. The values of r_i are given in Figure 6.3 and Appendix A, Table A.3.

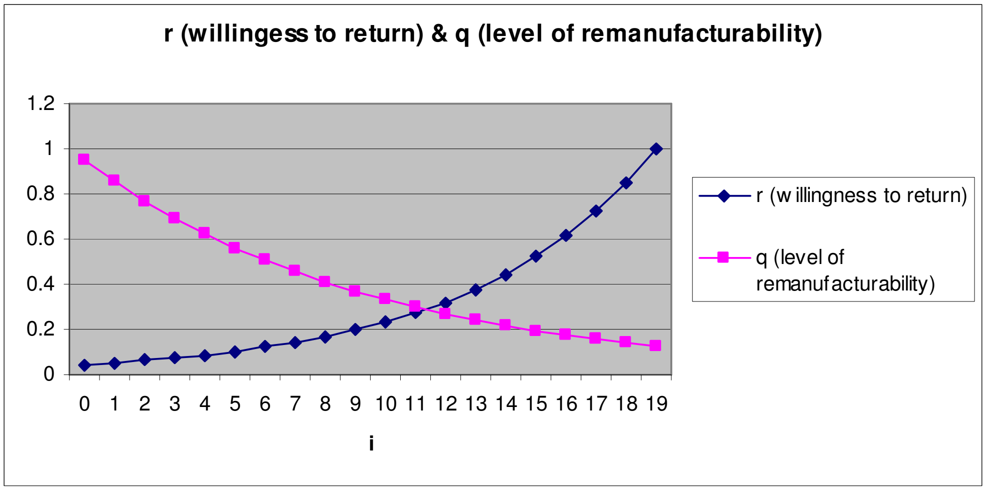

Figure 6.3. Values of the parameters r_i and q_i

Demand for new products in period j is represented by dem_X0_j. The total demand for intercity buses in Turkey market is approximately 1,200 per year. This will be the value of dem_X0_j in our numerical analysis. The values of dem_X0_j are presented in Figure 6.4 and Appendix A, Table A.4.

Demand of remanufactured or used products of age i for period j is represented by the parameter dem_XY_{ij} in our model. The value of this parameter goes down to “0” as the age of the product increases. Theoretically there is no demand for a product when it fulfills the proper lifetime which is equal to “19” for our model. The values of dem_XY_{ij} are presented in Figure 6.4 and Appendix A, Table A.5.

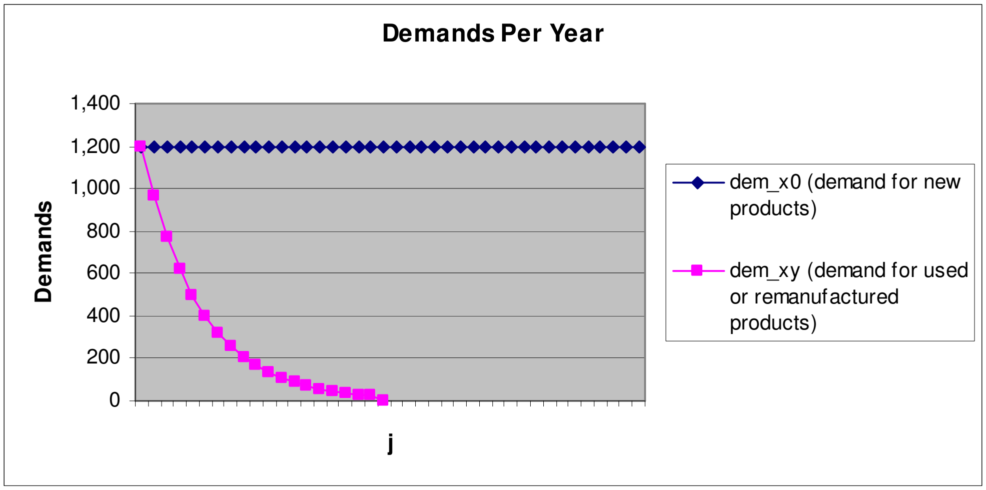

Figure 6.4. Values of the parameters dem_X0_j and dem_XY_{ij}

Warranty costs per product at age *i* is represented by the parameter wc_X0_i in our model. The value of this parameter is obtained from Mercedes-Benz Türk A.Ş. [30]. The company pays yearly € 6,000 on the average for every product in the warranty period. The duration of the warranty period for new buses is 2 years. Beginning from the 3rd year the warranty cost of the product for the company is € 0 practically. The values of wc_X0_i are presented in Figure 6.5 and Appendix A, Table A.6.

Warranty cost per remanufactured product at age *i* is represented by wc_Y_i in the model. In our model we assume that one year of warranty is applied for remanufactured products. The amount of cost for remanufactured products is expected to be a little more than the brand new products. Therefore the value of wc_Y_i should increase as the age of the products increases. Since the value of this parameter is set based on some assumptions mentioned above, the parameter will be replaced by possible alternative values and the outcomes will be observed in the next chapters of the study. The values of wc_Y_i are presented in Figure 6.5 and Appendix A, Table A.6.

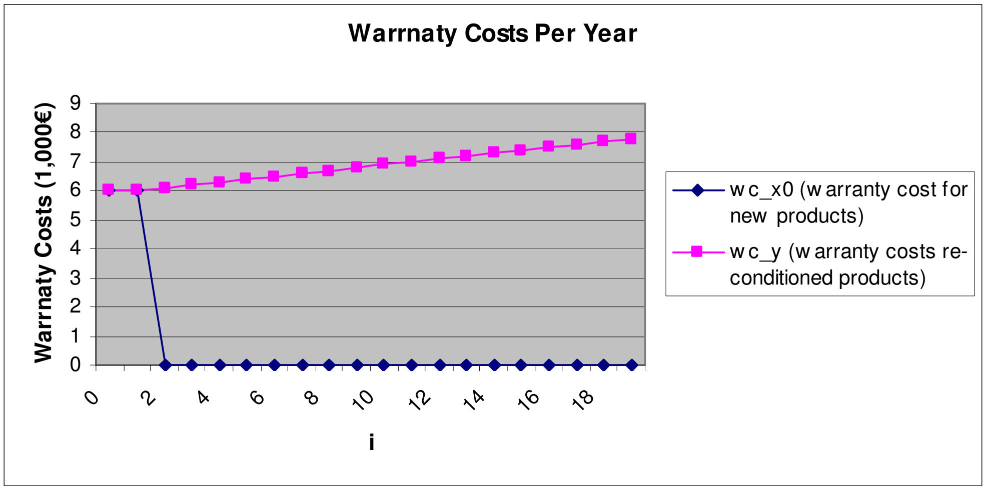

Figure 6.5. Values of the parameters wc_X0_i and wc_Y_i

Effect of sales on return is represented by the term e in our model. If the customer subject to the new product sales is a second-time buyer, than he may want to trade-in his existing product. So it can be derived that some of the new product sales may cause a return. The effect of a product sale on return is represented by this parameter and the value of the parameter is set to 0.20 for numerical analysis. Since the value of this parameter is set based on some assumptions, the parameter will be replaced by possible alternative values and the outcomes will be observed in the next chapters of the study. The value of e is presented in Appendix A, Table A.7.

Production capacity is represented by the parameter $prod\_cap$ in the model and the value of this parameter is 700 products per period. This value is obtained from our manufacturer Mercedes-Benz Türk A.Ş. [30]. $prod\_cap$ is the number of products that the manufacturer can produce per period at most. Returned products acceptance capacity per period is represented by the parameter ret_cap in the model and the value of this parameter is set up as 2,000 products per period. Since accepting returned products involves an operation, there is a maximum capacity for the manufacturer that can accept products by running this process. Remanufacturing capacity is represented by the parameter rem_cap in the model and the value of this parameter is set up as 1,000 products per period. Direct sales capacity is represented by the parameter dir_cap in the model and the value of this parameter is set up as 400 products per period. Capacity of recycler per period is represented by the parameter rec_cap in the model and the value of this parameter is set up as 300 products per period. To overcome the disadvantage of these rough estimations, the values of $prod\_cap$, ret_cap, rem_cap, dir_cap, rec_cap will be replaced with alternative values in the sensitivity analysis study and detailed observations will be performed on the numerical outcomes. The values of these parameters are presented in Figure 6.6 and Appendix A, Table A.8 as well.

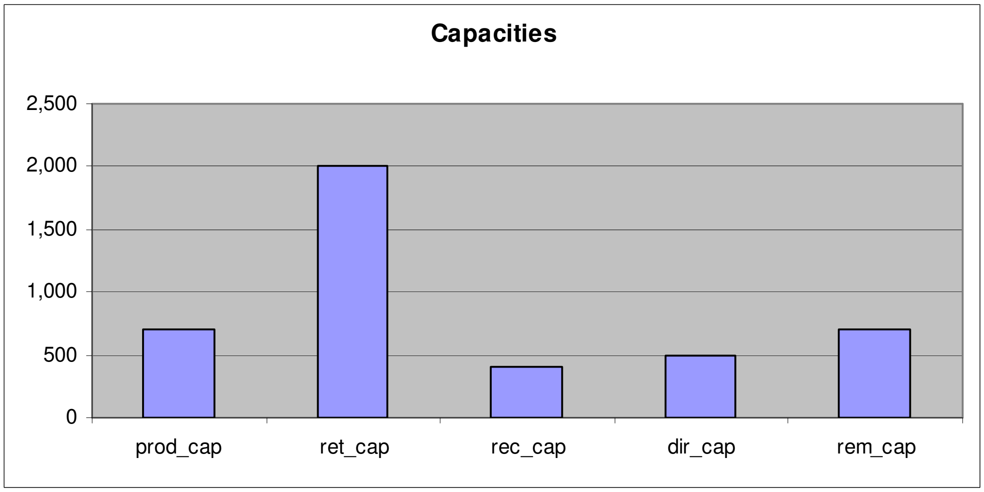

Figure 6.6. Values of $prod\_cap$, ret_cap, rem_cap, dir_cap, rec_cap

Legal penalty paid for unit unaccepted product return by the manufacturer is represented by the parameter pen_rej in our model. The value of this parameter is set to €200,000. Upper limit of disposal per production is represented by $disp\_upl$. The value of this parameter is 0.15 as dictated by the legislation [6]. pen_disp represents the penalty paid for unit disposal over the mentioned legal limit. Our model will be analyzed with this parameter having the value €150.000. The effect of changes in these parameters on the complete model will be presented in the sensitivity analysis section of the study. The values of these parameters are presented Appendix A, Table A.7 and Table A.9.

5.2. Results of Numerical Analysis

The mathematical model presented in Chapter 5 is solved in GAMS [31] with solver BDMLP and computed with the values presented in section 6.1. The model is run for 40 years with a product lifetime of 20 years ($i = \{0,...,19\}$, $j = \{0,...,39\}$). The complete matrix of the optimization model includes 41,081 rows, 10,441 columns, and 140,741 non-zero elements. The results of the analysis indicate that our manufacturer makes a total of € 2,676,711 profit per year (See Table 6.2).

Table 6.2. Annual average figures

Variable	**Value (Yearly Average)**	**Capacity**	**Capacity Usage Ratio**
Z (total profit)	€ 2,676,711	-	-
$X0_j$ (new product sales)	700	700	100%
$\sum_i X_{ij}$ (used product sales)	423	500	85%
$\sum_i Y_{ij}$ (remanufactured product sales)	495	700	71%
$\sum_i U_{ij}$ (sales to recycler)	293	400	73%
$\sum_i W_{ij}$ (disposal)	75	-	-
$\sum_i w\_ul_{ij}$ (disposal under limit)	74	105	70%
$\sum_i w\_ol_{ij}$ (disposal over limit)	1	-	-
$\sum_i Zbig_{ij}$ (total returns)	2,004	-	-
$\sum_i Zsm_{ij}$ (returns accepted)	1,286	2,000	64%
$\sum_i T_{ij}$ (returns rejected)	718	-	-
$\sum_i reg\_ret_{ij}$ (regular returns)	1,820	-	-
$\sum_i sale\_ret_{ij}$ (returns due to sales)	184	-	-

Numbers indicate that the extended roles introduced to our manufacturer play very important roles in the whole business of the manufacturer. Sales volumes of used products and remanufactured products are almost as much as the new product sales. Thus, with the introduction of the extended roles, our manufacturer clearly evolves to a business structure with a mixture of manufacturing and re-manufacturing.

Our manufacturer fully utilizes its production capacity as shown in Figure 6.7. The number new of products sold in each year is 700 (See Appendix A, Figure A.1). The number of used products sold at each period (X_{ij}) is 423 on the average, and 85 percent of the capacity is utilized. Values of X_{ij} variable are represented in detail in Appendix A, Figure A.7.

The number of remanufactured products (Y_{ij}) sold every year is 495 on the average. With this figure, 71 percent of the remanufacturing capacity is utilized (See Figure 6.7). Values of X_{ij} variable are represented in detail in Appendix A, Figure A.8.

The number of products sent to the recycler (U_{ij}) every year is 293 on the average. With this figure, 73 percent of the recycler's capacity is utilized (See Figure 6.7). Values of U_{ij} variable are represented in Appendix A, Figure A.9 in detail.

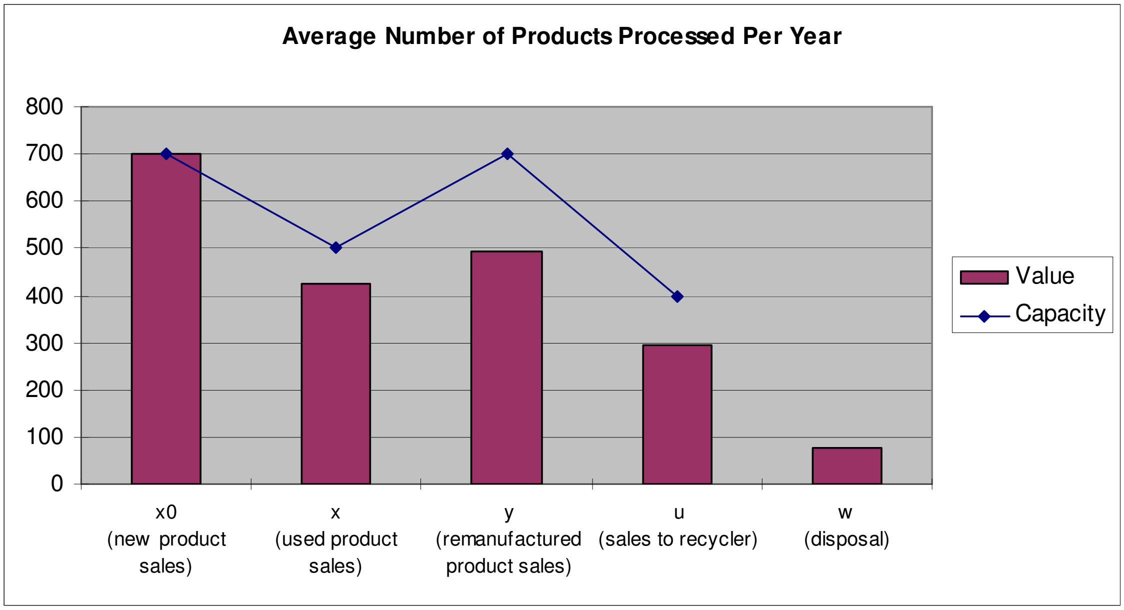

Figure 6.7. Annual average capacity usage ratios

The number of products disposed of every year (W_{ij}) is 75 on the average (See Figure 6.7). Most (98 percent) of the disposals performed every year remain under the legal limits. On the average, 2 percent of the disposals exceed the legal limits determined by legislations [6]. Figure 6.8 represents the ratios of under-limit and over-limit disposals. Values of W_{ij} variable are represented in Appendix A, Figure A.10 in detail.

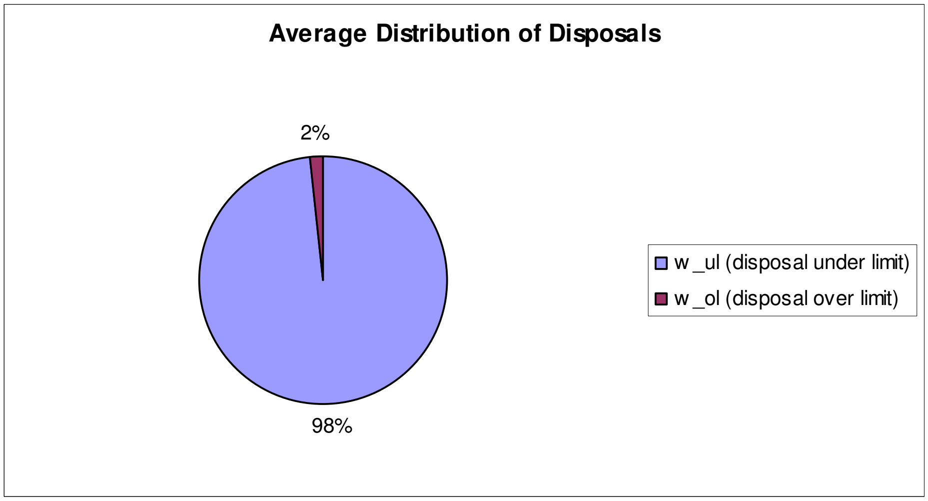

Figure 6.8. Average ratio of w_ul_{ij} and w_ol_{ij} to W_{ij}

On the average, 64 percent of the products brought back by the customers ($Zbig_{ij}$) are accepted. 2,004 products of which 1,286 accepted (Zsm_{ij}) and 718 rejected (T_{ij}), are returned yearly. In Appendix A, more details about the values of retuned products can be seen such as, Figure A.4 representing the number of returned products, Figure A.5 representing the number of accepted products and Figure A.6 representing the number of rejected products.

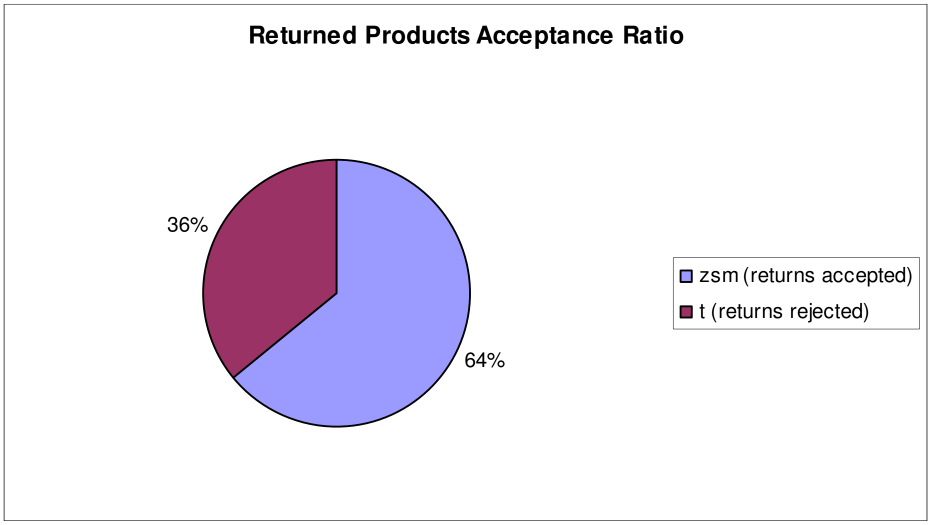

Figure 6.9. Average ratio of returned products acceptance

Regular returns (reg_ret_{ij}) form the 91 percent of the total yearly product returns. Returns from sales ($sale\_ret_{ij}$) do not play a dominant role in product returns.

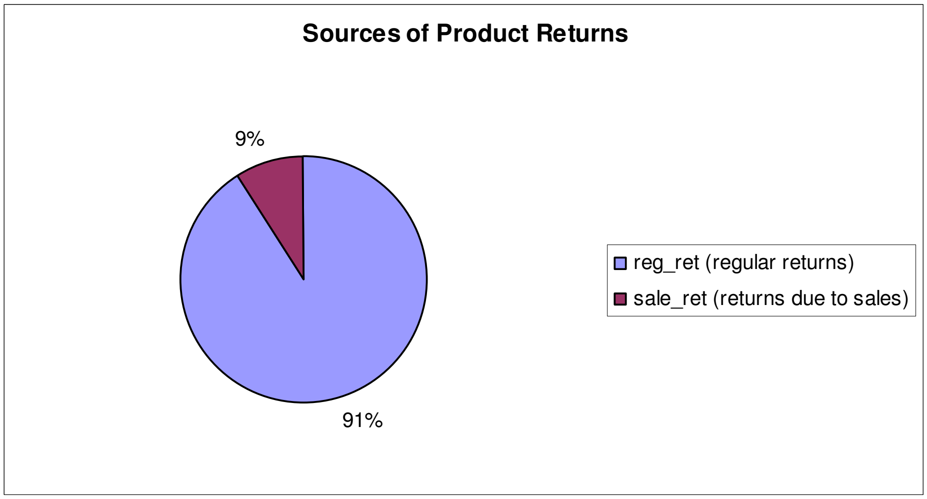

Figure 6.10. Sources of product returns

The values of variables reg_ret_{ij} and $sale\_ret_{ij}$ can be analyzed in detail with the Figures A.11 and A.12 represented in Appendix A.

6. SENSITIVITY ANALYSIS

In this section, some sensitivity analysis is presented to extract inferences about the behavior of the model. The analysis is performed by observing the change in the objective value by changing the parameters.

6.1. Sensitivity Analysis Methodology

The new values assigned to each parameter are presented in Appendix B in detail. The values of the parameters that are used for numerical analysis in the previous section are accepted as the base level, and 4 different levels are created for every parameter of which 2 are smaller and 2 are greater. For example, the value of the parameter e is 0.2 in the base model ($e^* = 0.2$). The four alternative values for this parameter are $e^1 = 0.1$, $e^2 = 0.15$, $e^3 = 0.25$, and $e^4 = 0.3$ (See Figure 7.1). A complete list of the percentage changes in the values of the parameters can be seen in Appendix B Table B.1.

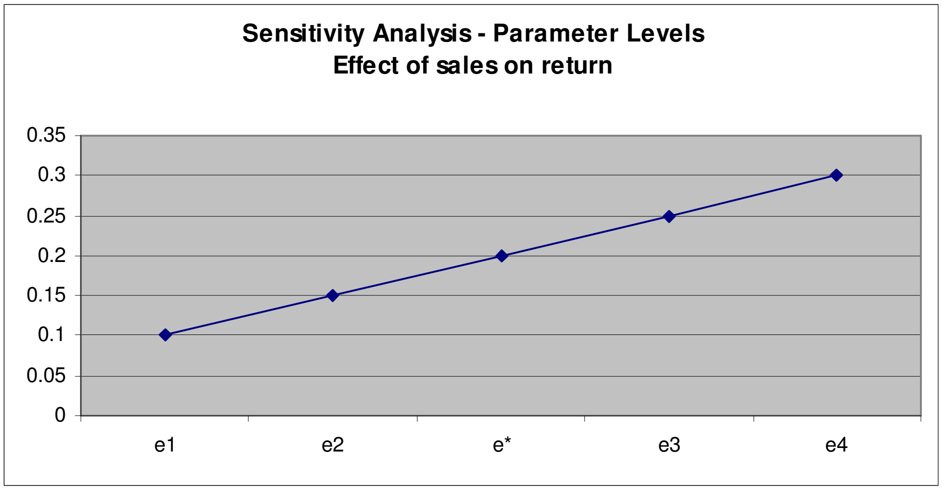

Figure 7.1. Sensitivity Analysis – Levels for parameter e

The values for the alternative levels for all parameters are represented in Figures B.1 to B.1 to B.15 of Appendix B in detail.

6.2. Results of Sensitivity Analysis

The parameters are changed based on the levels determined in the previous section (As explained in Figures B.1 to B.1 to B.15 of Appendix B). One parameter is changed for each observation, and the model is run for each variation of parameters. The change in the objective value is observed and average annual profit of the manufacturer is represented in Appendix B, Table B.2.

The effects of changing the parameter values on objective value are graphed in Figure 7.2. Changing the parameter $prod\_cap$ (Production capacity per period) yields the greatest impact on the objective value of the model. Another parameter which has a big impact on the objective value is P_i (Sales price of new or used product at age *i*).

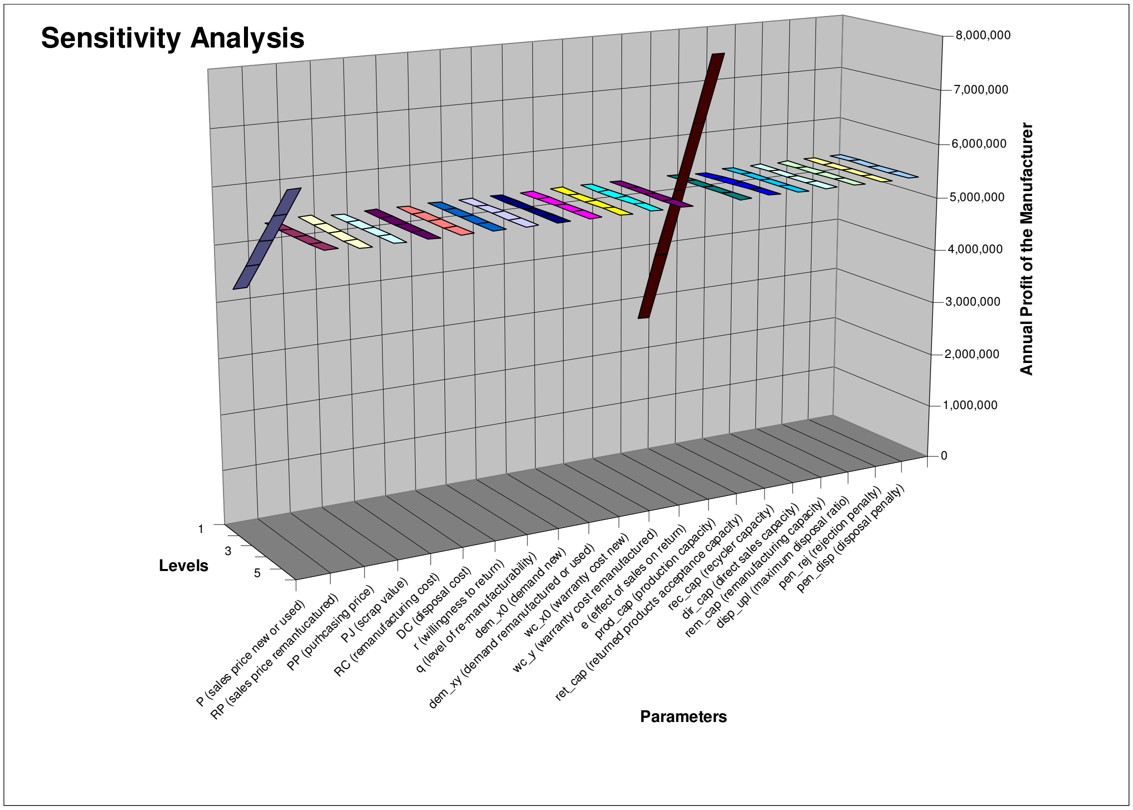

Figure 7.2. Effect of parameters on objective value

The model is also moderately sensitive to the changes in RP_i (Sales price of remanufactured product at age *i*), PP_i (Purchasing price of used product at age *i*), rec_cap (Capacity of recycler per period), wc_X0_i (Warranty cost per product at age *i*), and $disp\_upl$ (Upper limit of disposal per production).

The effect of changing the prices (P_i, RP_i, PP_i, and PJ_i) is represented in Figure 7.3a. Sales price of new and used products (P_i) has the greatest impact on the objective value among these parameters. The total profit is increasing due to the increasing price of the products.

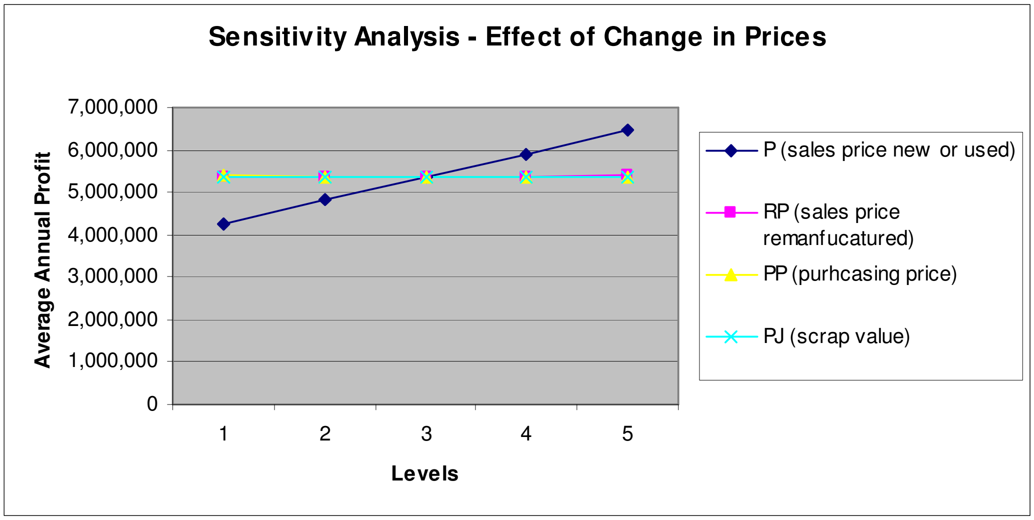

Figure 7.3a. Sensitivity Analysis – Effects of prices on objective value

In order to understand the effects of other price parameters we remove the P_i from the chart which dominated the scale of the graph. The effects of RP_i, PP_i, and PJ_i are represented in Figure 7.3b. The total profit increases as the remanufactured products' sales price (RP_i) increases. Increasing the purchasing price (PP_i) has a negative impact on the total profit. Increasing the scrap value (PJ_i) also yields a minor increase in the profit.

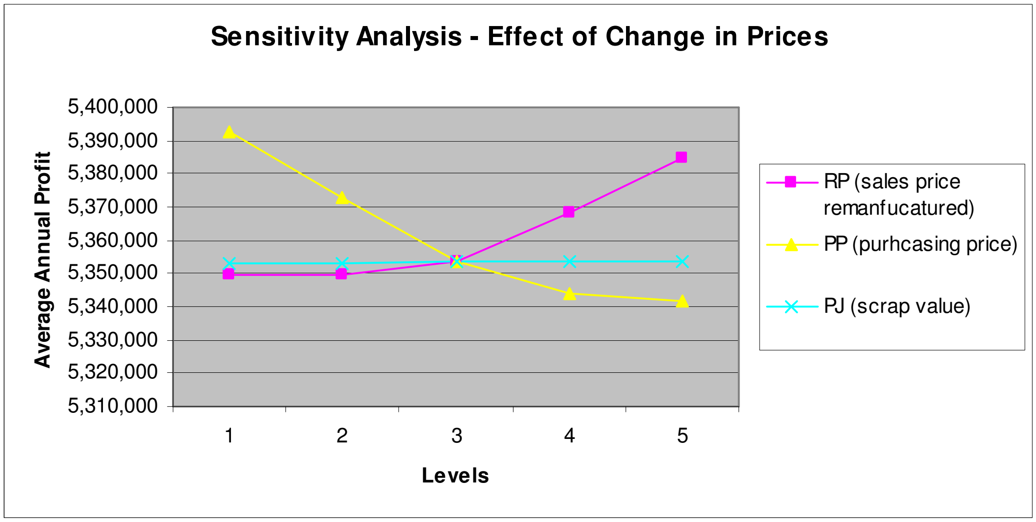

Figure 7.3b. Sensitivity Analysis – Effects of prices on objective value

The effect of changing the cost parameters (RC_i and DC_i) is presented in Figure 7.4. Both parameters have negative impacts on the objective value. The impact of remanufacturing cost (RC_i) is higher than the impact of the disposal cost (DC_i). Thus, one can deduce that studies on cost reduction in this kind of a manufacturer should mostly be concentrated on the remanufacturing costs.

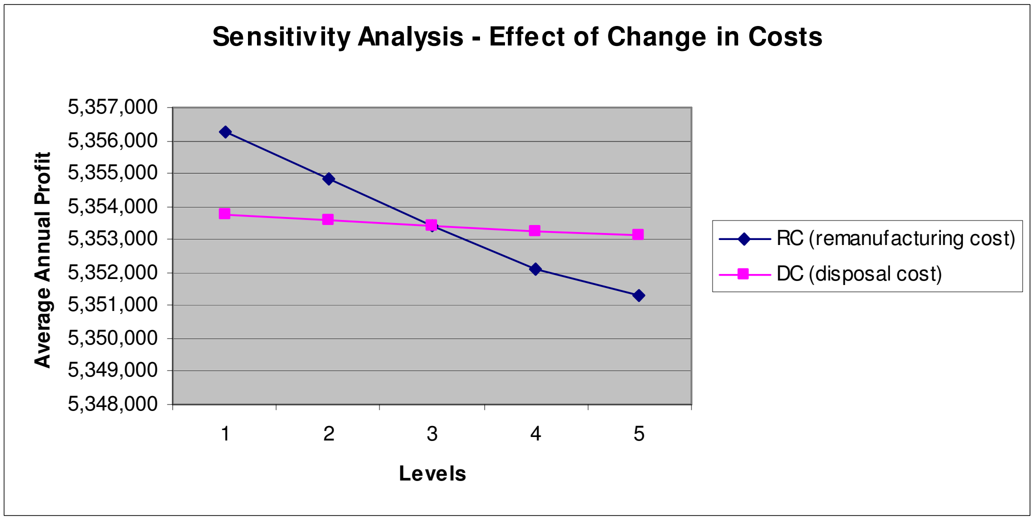

Figure 7.4. Sensitivity Analysis – Effects of costs on objective value

The effect of changing the parameters r_i and q_i is presented in Figure 7.5. While

q_i has no impact on the objective function, the parameter r_i affects the profit in a negative manner. The increase of r_i is generally decreasing the total profit of the manufacturer in our model. This type of behavior basically arises from the increasing rejection penalties that the manufacturer pays.

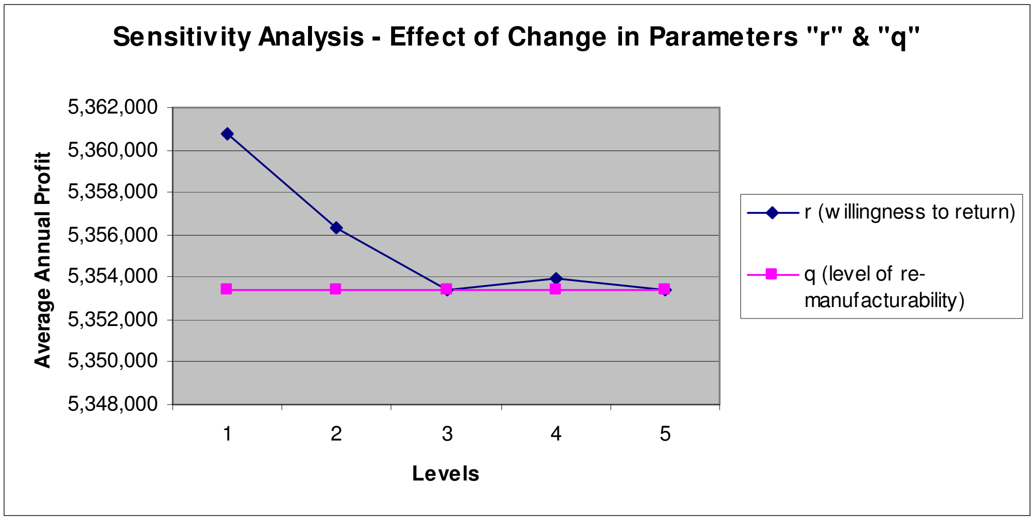

Figure 7.5. Sensitivity Analysis – Effects of r_i and q_i on objective value

The effect of changing the demands (dem_X0_j and dem_XY_{ij}) is presented in Figure 7.6. Demand for new products (dem_X0_j) has practically no impact on the total profit in our model. This behavior occurs since the manufacturer is already utilizing its whole new products manufacturing capacity and cannot respond to any demand changes. Demand for used or remanufactured products (dem_XY_{ij}) has a positive impact on the objective value.

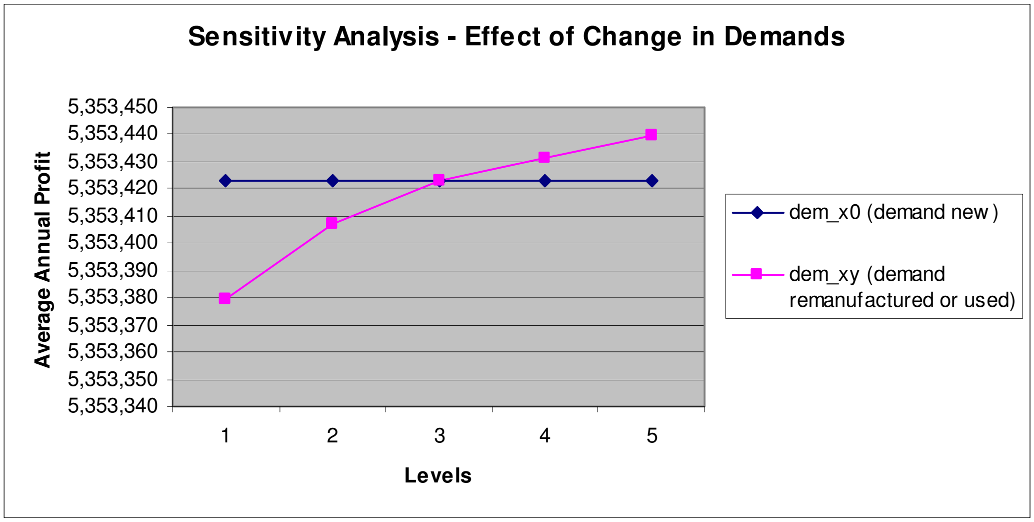

Figure 7.6. Sensitivity Analysis – Effects of demands on objective value

The effect of changing the warranty costs (wc_X0_i and wc_Y_i) is presented in Figure 7.7. Both parameters have negative impacts on the objective value. The impact of warranty cost for new products (wc_X0_i) is higher than the impact of warranty cost for remanufactured products (wc_Y_i). So, reducing the unit warranty cost of new products is more profitable than reducing the unit warranty cost of remanufactured products. Or inversely, promotions offering higher warranty periods or higher per-unit warranty payments of re-manufactured products will be less costly for the company than that of new products.

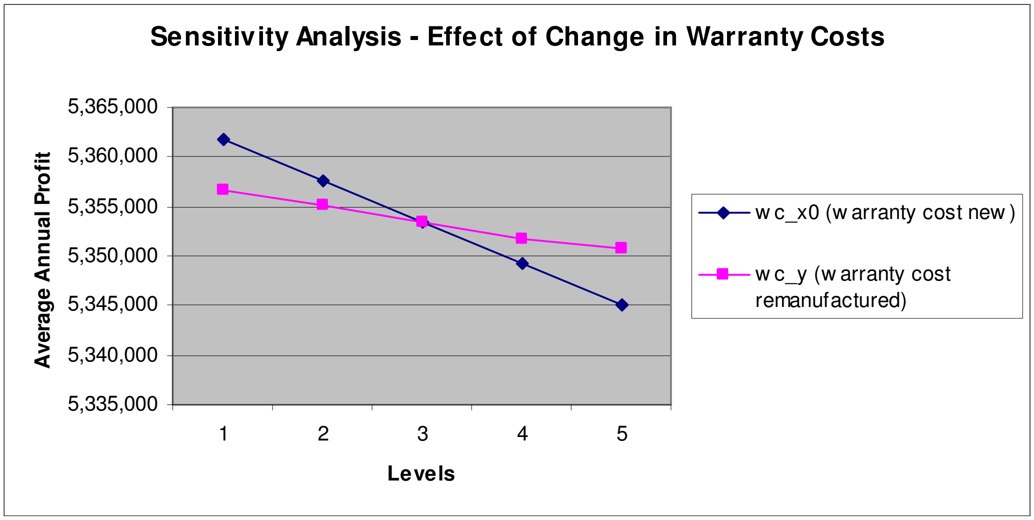

Figure 7.7. Sensitivity Analysis – Effects of warranty costs on objective value

The effect of changing the capacities ($prod\_cap$, ret_cap , rem_cap , dir_cap , rec_cap) is presented in Figure 7.8a. Production capacity ($prod\_cap$) has the greatest impact on the objective value among these parameters. The total profit increases due to the increasing production capacity.

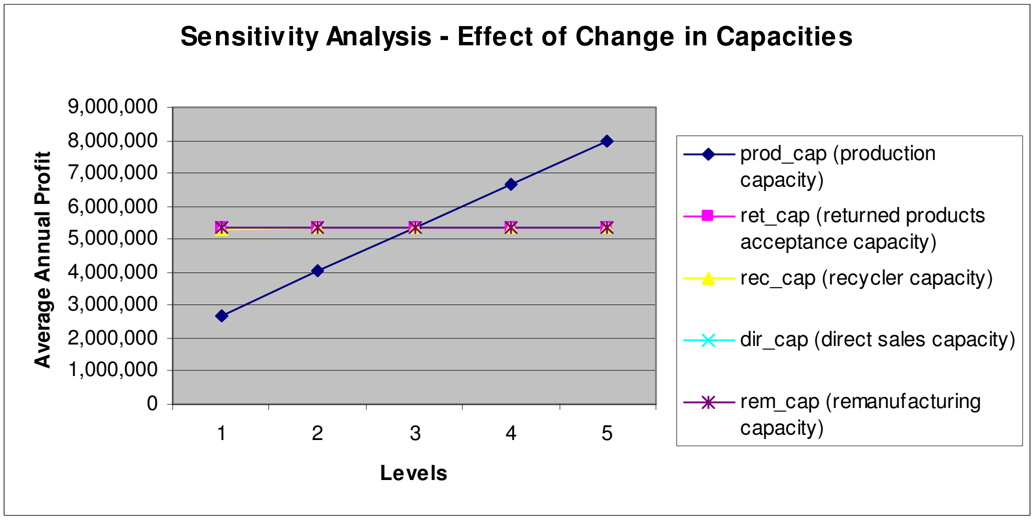

Figure 7.8a. Sensitivity Analysis – Effects of capacities on objective value

To view the effects of other capacity parameters more easily, we remove the $prod\_cap$ from the chart which dominated the scale of the graph. The effects of

ret_cap, rem_cap, dir_cap, rec_cap are represented in Figure 7.8b. The total profit is increasing as the recycler's capacity (rec_cap) increases. Increasing the returned products acceptance capacity (rec_cap) also increases the objective value, but only for the first level. When the value of the parameter is set to its second level, the impact on the objective value diminishes because the capacity goes beyond the total number of returned products. Increasing the rem_cap and dir_cap also yields results similar to the rec_cap.

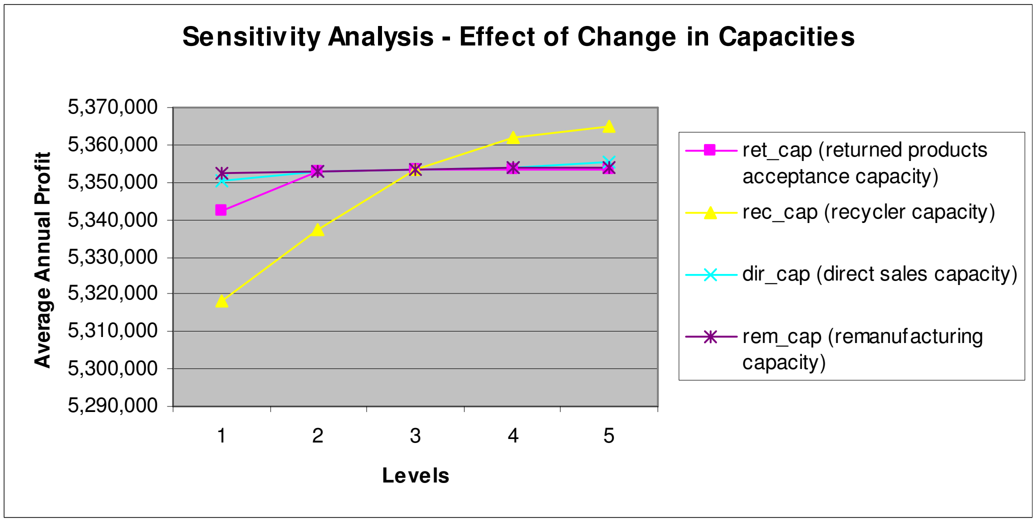

Figure 7.8b. Sensitivity Analysis – Effects of capacities on objective value

The effect of changing the disposal upper limit ($disp\_upl$) is presented in Figure 7.9. This parameter has a positive impact on the objective value because the more capable the manufacturer to dispose items, the less penalty is paid.

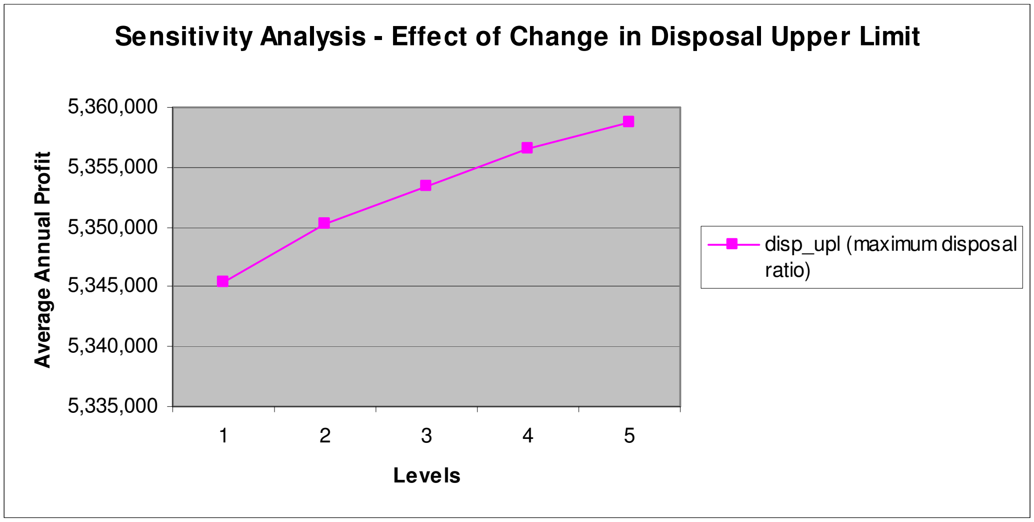

Figure 7.9. Sensitivity Analysis – Effect of disposal upper limit on objective value

The effect of changing the parameter e is shown in Figure 7.10. Increasing the effect of sales on return (e) has a positive impact on the objective value until some point. The total profit increases as the parameter e increases until this point. When the value of the parameter is set to its fourth level, the impact on the objective value turns to negative because the number of returned products starts going beyond the manufacturer's capacities to accept and return the products.

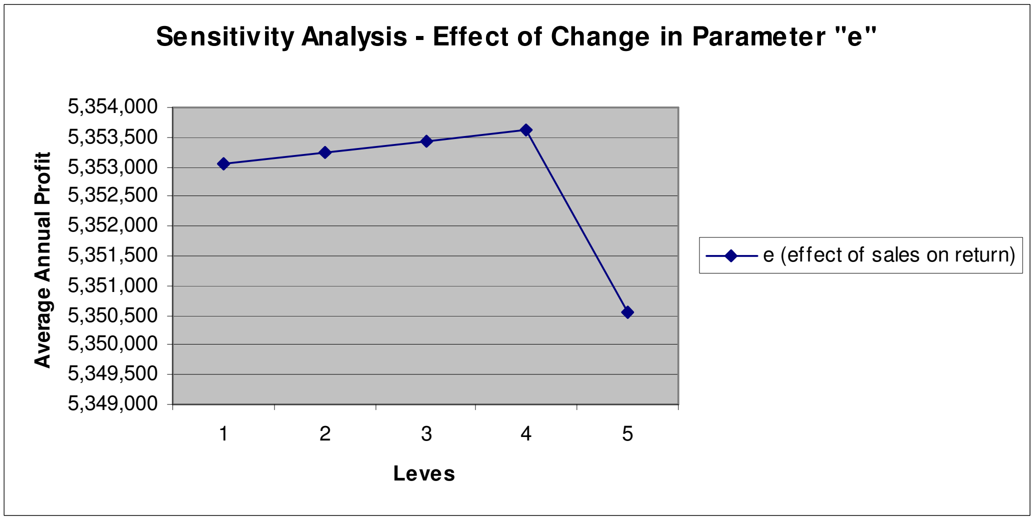

Figure 7.10. Sensitivity Analysis – Effect of e on objective value

The last analysis of this section is performed by changing the penalties (pen_rej and pen_disp) and the results is presented in Figure 7.11. Rejection penalty (pen_rej) has practically no impact on the total profit in our model. This behavior occurs since the manufacturer has never paid a penalty of rejection in our model. Disposal penalty (pen_disp) has a negative impact on the objective value. The total profit decreases as the amount of the penalty increases. When the value of the parameter is set to its third level, the impact on the objective value diminishes because the manufacturer starts disposing the minimum possible number of products and cannot go beyond.

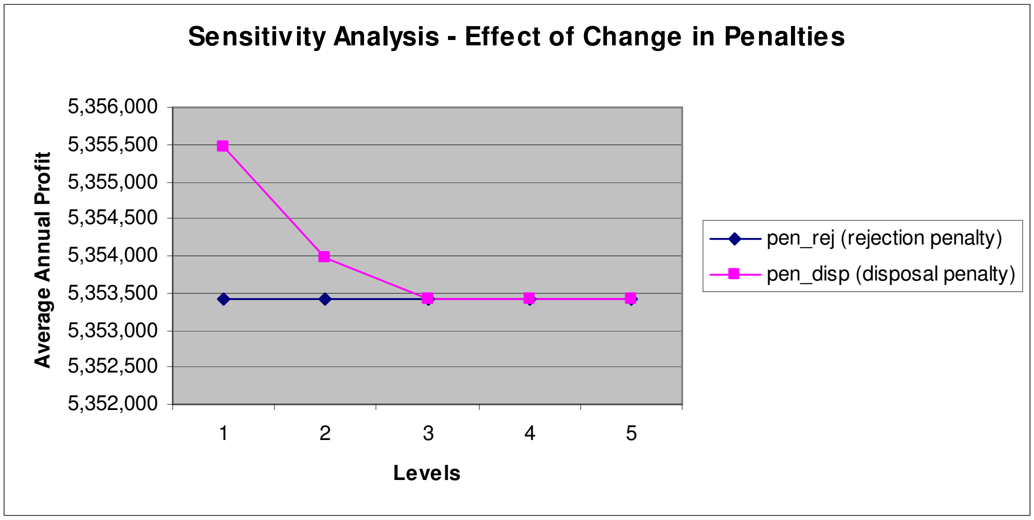

Figure 7.11. Sensitivity Analysis – Effects of penalties on objective value

The legal penalties determined by the government should be at such a level that they are not as high as to diminish the profit of the manufacturer or not as low as to stay far from deterrence. Figure 7.12 presents the change in the annual average production numbers due to the changes in the penalties pen_rej and pen_disp .

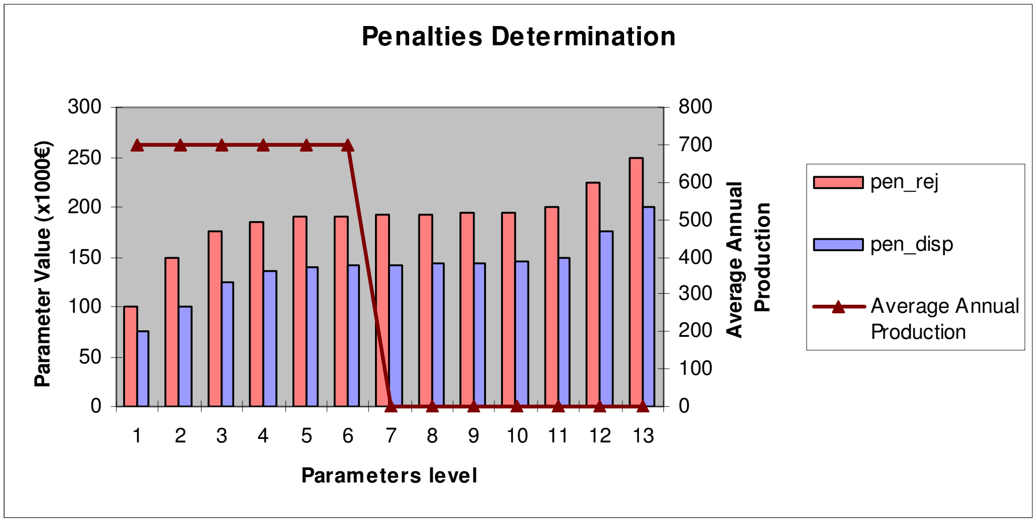

Figure 7.12. Determination of acceptable levels for pen_rej and pen_disp

The manufacturer stops production when pen_rej exceeds €191,000 and pen_disp exceeds €141,000. Beyond these levels, the penalties paid start diminishing the profitability of the business and the manufacturer cannot work with a profit.

The effect of changing the parameter values on the objective value is analyzed in this section. Almost all parameters have some impact on the objective value of our model. The observations indicate that the model is highly sensitive to the changes in the parameters $prod\_cap$ (Production capacity per period) and P_i (Sales price of new or used product at age *i*). The model is also moderately sensitive to the changes in RP_i (Sales price of remanufactured product at age *i*), PP_i (Purchasing price of used product at age *i*), rec_cap (Capacity of recycler per period), wc_X0_i (Warranty cost per product at age *i*), and $disp\_upl$ (Upper limit of disposal per production).

6.3. Interaction Effects

In this section, we analyzed the interaction effect of the most dominant parameters figured out in the previous section. The effects of changing the parameter values on objective value are graphed in Figure 7.2. Changing the parameter $prod\_cap$ (Production capacity per period) yields the greatest impact on the objective value of the model. Another parameter which has a big impact on the objective value is P_i (Sales price of new or used product at age *i*). The model is also moderately sensitive to the changes in RP_i (Sales price of remanufactured product at age *i*), PP_i (Purchasing price of used product at age *i*), rec_cap (Capacity of recycler per period), wc_X0_i (Warranty cost per product at age *i*), and $disp\_upl$ (Upper limit of disposal per production).

In the previous section, we analyzed the effects of these parameters by changing the values one at a time. Figure 7.13 presents the combined effect of the parameters $prod\_cap$ (Production capacity per period) and P_i (Sales price of new or used product at age *i*) on the average annual profit of the manufacturer.

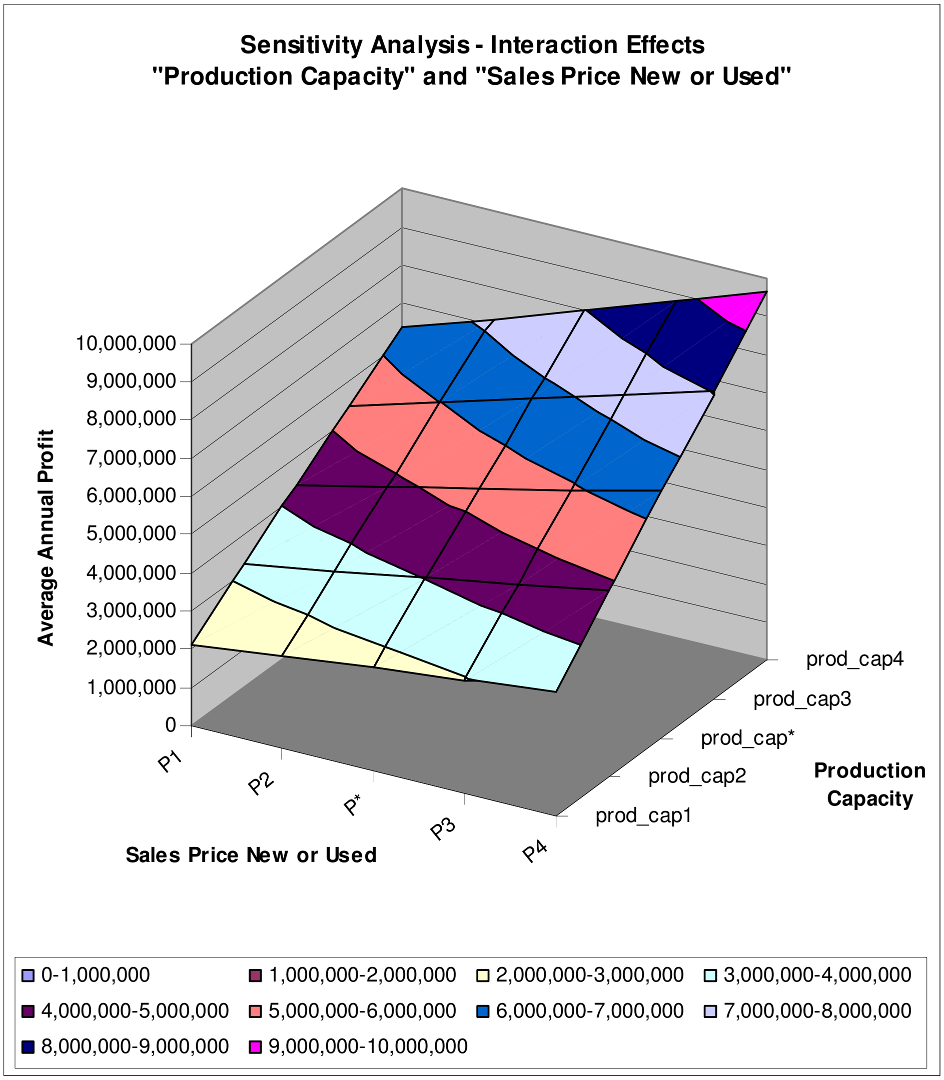

Figure 7.13. Sensitivity Analysis – Interaction effects of $prod\_cap$ and P_i

The resulting figure is not much different than the effects of these parameters analyzed one at a time. The average annual profit of the manufacturer increases as either one of the parameters increases. Increasing both of the parameters results in a tremendous increase in the average profit. Based on the figures obtained, we can say that the manufacturer can obtain five times more of its current profit by increasing the prices by 20 percent and the production capacity 50 percent together.

Figure 7.14 represents the combined effect of the parameters RP_i (Sales price of remanufactured product at age *i*) and PP_i (Purchasing price of used product at age *i*) on the average annual profit of the manufacturer.

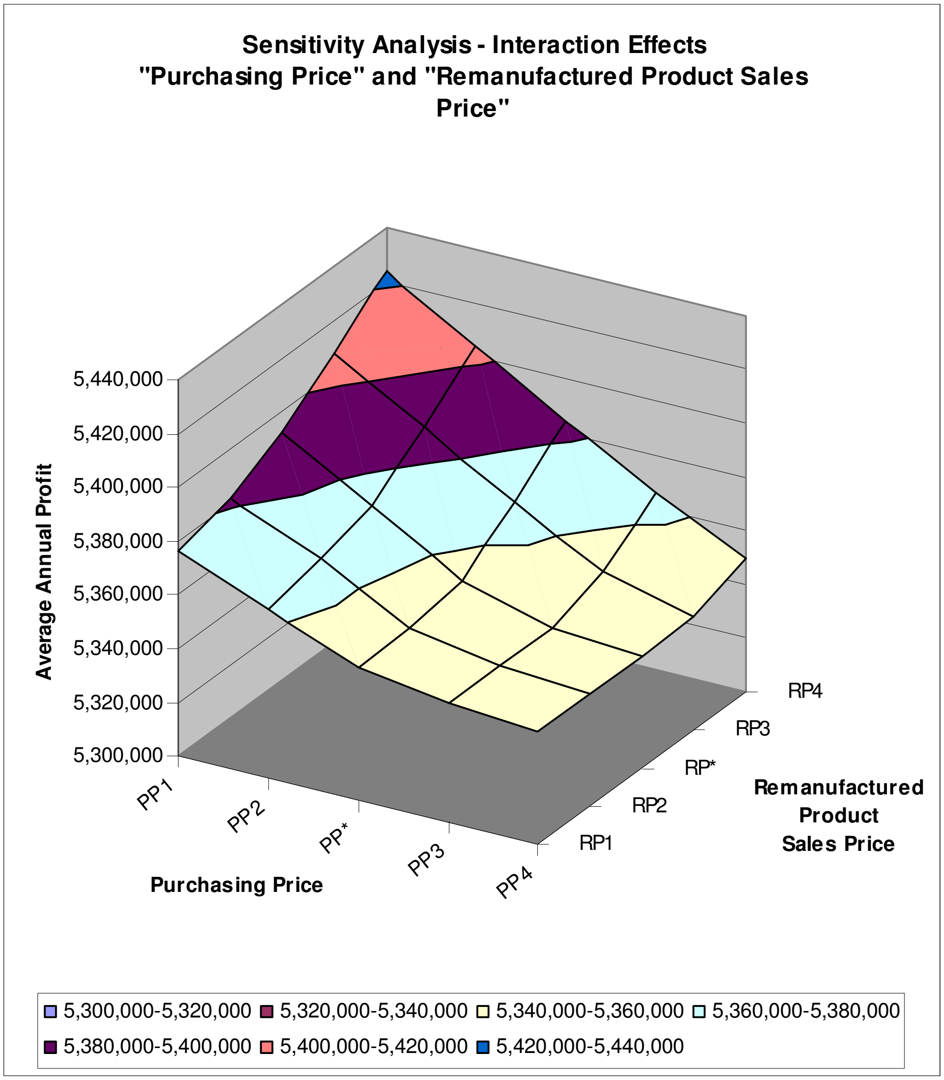

Figure 7.14. Sensitivity Analysis – Interaction effects of RP_i and PP_i

The average annual profit of the manufacturer increases as either the remanufactured sales price increases or purchasing price decreases. Note that the slope of the graph changes dramatically among varying values for the parameter PP_i. The effect of RP_i on the profit is high when the PP_i is at its lowest level. The effect of RP_i diminishes when the PP_i is set to its highest level. The manufacturer can obtain the most profitable figure by setting the parameter PP_i to a low value and RP_i to a high value at the same time.

The interaction effects of the other parameters are not discussed here because the effects obtained are not different than the effects of each parameter alone. The reason of this behavior is that some parameters have big impact on the objective value while others have very tiny effects. Analyzing the interaction effect of one strong and one weak parameter ends up with a result highly dominated by the strong one. Therefore, only the interaction of equally strong parameters have an effect.

7. SCENARIO ANALYSIS

In this section, scenario analysis is presented to deduce some implication from model's behavior and gain some notion for real life applications. The scope of the analysis is to observe the change in the objective value by differentiating the parameters related with manufacturer's roles and legal regulations.

The manufacturer subject to this study is an automotive manufacturing facility. In the previous sections, we introduced a model representing the transformation of the manufacturer from the classical production system to a complex facility that also takes back the returned products and processes them for different purposes including remanufacturing (See Figure 4.1). In this section, we will create some scenarios by which we will be able to see how profitable this transformation is.

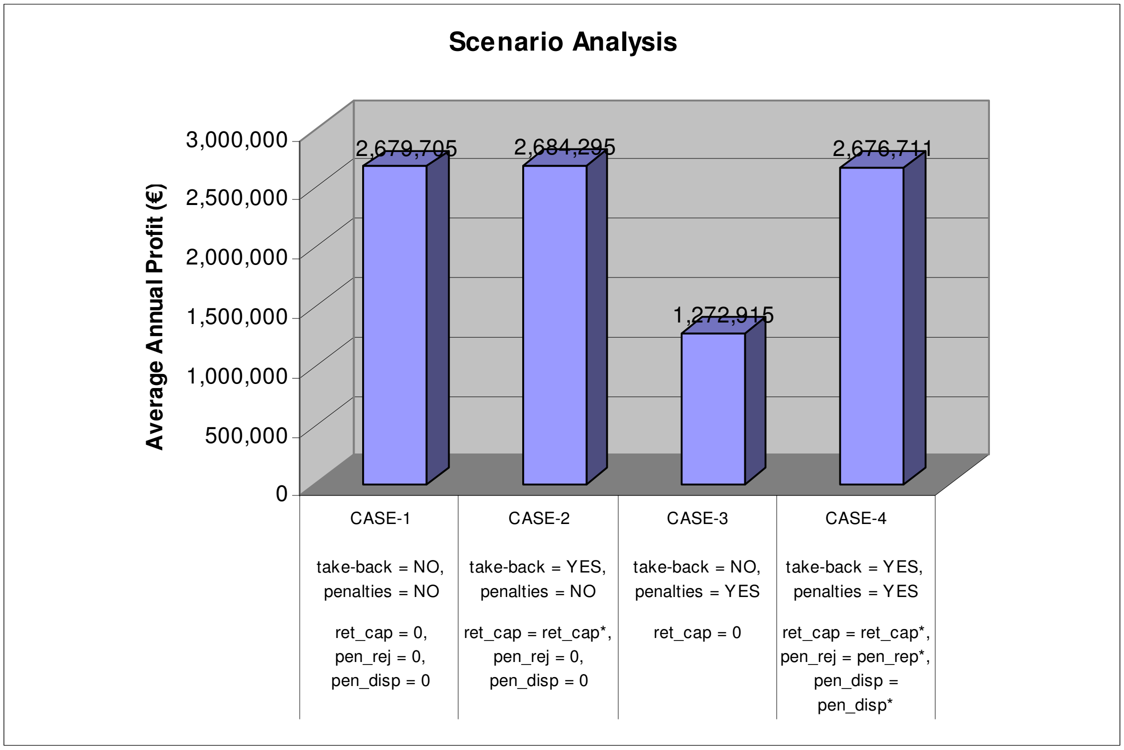

Figure 8.1. Effects of manufacturer's roles and legal regulations on profit

Figure 8.1 illustrates some probable scenarios for the manufacturer. Case-1 represents the annual total profit of the manufacturer if no product is taken back and no legal penalties are applied for not performing the collection of end-of-life products. In this case, the manufacturer has built up and currently running its production system and selling the products to the market. No products are brought by the customers back to the manufacturer and the manufacturer has no obligation to take back the end-of-life products. The manufacturer has also no business functions such as selling used products, or performing remanufacturing tasks, or properly disposing end-of-life products, or transmitting any material to the recycler. This case is valid for markets with no legal regulation about extending producers responsibilities or end-of-life vehicles. In this environment, our manufacturer obtains an amount of € 2,679,705 profit per year on the average. Annual average figures of the manufacturer and capacity usage ratios are presented in Appendix C, Table C.2 and Figure C.1 respectively.

Case-2 represents the same legal environment as in case-1, but this time the manufacturer is in the business of used vehicles sales and remanufacturing. The legal environment does not enforce the manufacturer for taking back end-of-life products or paying any penalties for improper disposals. In this case, the average annual profit of the manufacture is € 2,684,295. Thus we can claim that, the used vehicle sales and remanufacturing is not profitable for our manufacturer in this scenario. Annual average figures of the manufacturer and capacity usage ratios for this case are presented in Appendix C, Table C.3 and Figure C.2 respectively.

In case-3, the legal regulations enforce our manufacturer to take-back the end of life vehicles but the manufacturer does not have an infrastructure to collect these products and remanufacture, recycle, or properly dispose them. Under these circumstances, the manufacturer pays penalties for the rejected end-of-life vehicles. The manufacturer also pays penalties for improper disposal of materials. This is the case in which the manufacturer has not been able to adapt to the legal regulations. Our manufacturer makes a total of € 1,272,915 profit annually in this case. This means a big loss of almost half of the profit compared to the previous cases. Annual average figures of the manufacturer and capacity usage ratios for this case are represented in Appendix C, Table C.4 and Figure C.3 respectively.

In case-4, our manufacturer adapts to the enforcing legal environment and builds up systems for taking back the returned end-of-life vehicles. The used vehicles are bought from customers at any age and they are either sold as used vehicles, or remanufactured, or recycled or disposed properly. The legal penalties for rejecting end-of-life vehicles or improper disposals are still in case, but the manufacturer avoids paying these penalties since the corresponding business units are in operation. In this case, our manufacturer makes a total of € 2,676,711 profit annually. Thus, we can say that our manufacturer can recover the lost profit in case-3 by adapting the legal environment dictated by the regulations.

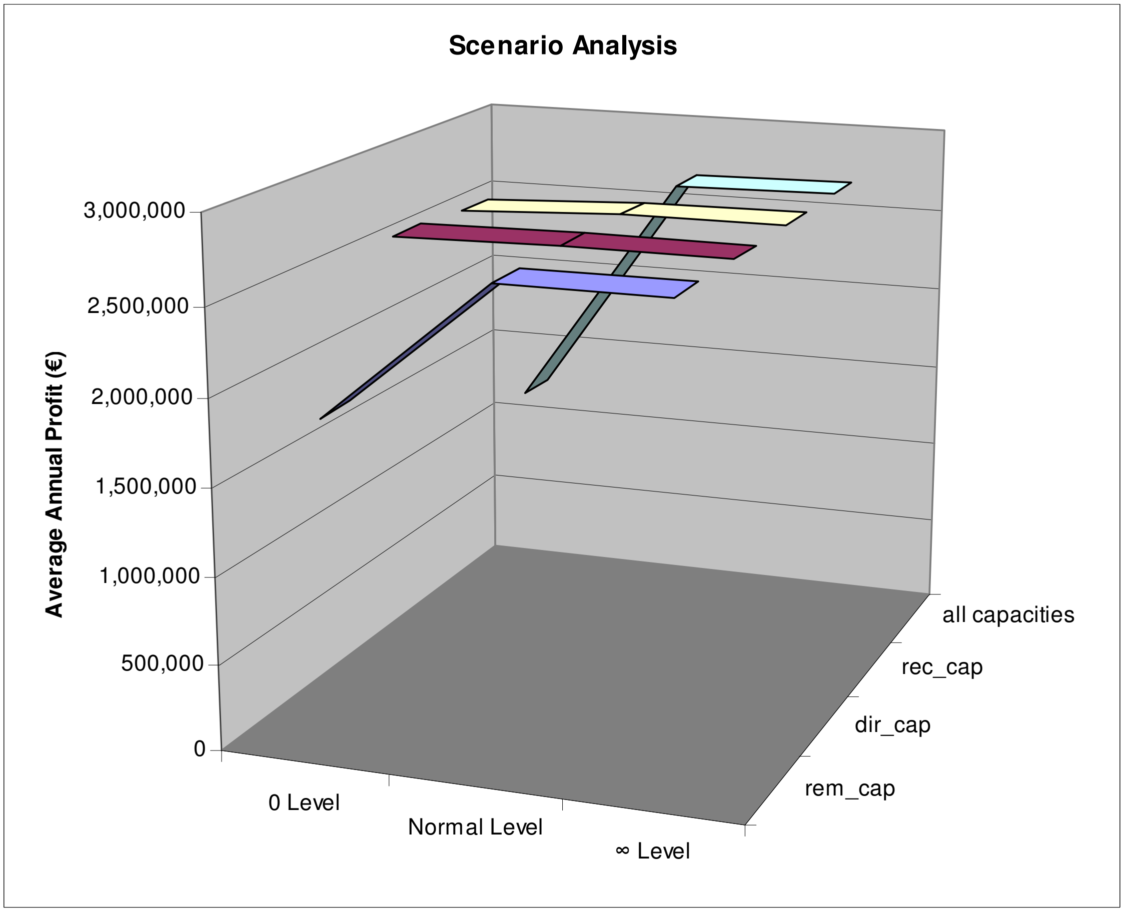

Figure 8.2. Scenarios with extreme values of capacities

Figure 8.2 illustrates the effects of capacities at extreme values on the profit of the manufacturer. We see that diminishing the remanufacturing capacity (rem_cap) or all capacities (rem_cap, dir_cap, rec_cap, ret_cap) has a big negative effect on the profit. Increasing any parameter to the infinite does not affect the profit since the limited demands (dem_X0_j, dem_XY_{ij}) stops manufacturer to make high sales volumes.

8. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this study, we analyzed the economic effects of remanufacturing on manufacturers by focusing on an automotive manufacturer. The regulations in countries of the European Union enforce the automotive manufacturers to take back the end-of-life vehicles returned by their customers [6]. Every new vehicle sales today will result in a return after products life is completed. Also some products will be returned by the customers during their proper lifetime. Therefore the manufacturers should make strategic decisions on planning the capacities of their manufacturing, remanufacturing, and disposal etc. operations. These operations have to be studied by the manufacturers which work under the effect of the above mentioned legal regulations.

Within the framework defined above, some questions have to be answered for both manufacturers, and government. The manufacturer should determine how much capacity to allocate for remanufacturing, used product sales, and recycling. Optimum levels of these capacities can be figured out through detailed analysis based on how many products will be brought back at which stage of their lifetimes. The manufacturer has to know what would be the economic impact of collecting the used products from the market and selling them as used products or remanufactured ones. Before going into this business, the manufacturer should have some information about how these operations affect its profit structure. In some cases, the manufacturer may choose to stay away from this business and incur the costs arising from the legal regulations. The cost of this illegal case to the manufacturer also has to be clarified and the economic impact on the manufacturer should be defined. On the other side, the government also should have some information about the market structure and manufacturers before deploying the legal regulations as described above. The legal penalties determined by the government should be at such a level that they do not diminish the profit of the manufacturer completely but still impose a convincing penalty. To determine these penalties, the government needs detailed numerical analysis of the complete concept driven by the legislations. In this study, we developed a mathematical model that offers solutions to these problems.

At first, we developed a profit maximizing optimization model for the manufacturer. The manufacturer subject to our modeling is a complex structure that includes manufacturing, remanufacturing, used vehicle sales and disposal functions with a third party recycler included. Then, the numerical analysis is performed with the model developed. The numerical analysis is carried out with the information and data obtained from Mercedes-Benz Türk A.Ş. [30]. Through the numerical analysis we were able to see the transformation of the manufacturer from the classical production system to a complex facility that also takes back the returned products and processes them for different purposes including refurbishing.

The results of the numerical analysis indicate that the extended roles introduced to our manufacturer play important roles in the business of the manufacturer. Sales volumes of used products and remanufactured products are almost as much as the new product sales. Thus, with the introduction of the extended roles, our manufacturer clearly evolves to a business structure with a mixture of manufacturing and remanufacturing functions. Throughout the sensitivity analysis we found out the most dominant factors that affect the total profit of the company in the model. Almost all parameters have some impact on the objective value of our model. The observations indicate that the model is highly sensitive to the changes in the parameters $prod\_cap$ (Production capacity per period) and P_i (Sales price of new or used product at age *i*). The model is also moderately sensitive to the changes in RP_i (Sales price of remanufactured product at age *i*), PP_i (Purchasing price of used product at age *i*), rec_cap (Capacity of recycler per period), wc_X0_i (Warranty cost per product at age *i*), and $disp\_upl$ (Upper limit of disposal per production). The manufacturer stops production when pen_rej exceeds €191,000 and pen_disp exceeds €141,000. Beyond these levels, the penalties paid eliminate the profitability of the business. Based on the figures obtained in the sensitivity analysis, we can say that the manufacturer can obtain the 5 times of its current profit by increasing the prices by 20 percent and production capacity 50 percent together.

In the scenario analysis, we created some imaginary cases through observing the change in the objective value by differentiating the parameters related with manufacturer's roles and legal regulations. So we were able to deduce some implication from model's behavior and obtain some insight for real life applications.

In the first case we analyzed the annual total profit of the manufacturer if no product is taken back and no legal penalties are applied for not performing this collection of end-of-life products. In this case, the manufacturer has built up and currently running its production system and selling the products to the market. No products are brought by the customers back to the manufacturer and the manufacturer has no obligation to take back the end-of-life products. The manufacturer has also no business functions such as selling used products, or performing remanufacturing tasks, or properly disposing end-of-life products, or transmitting any material to the recycler. This case is valid for markets with no legal regulation about extending producers responsibilities or end-of-life vehicles. In this environment, our manufacturer obtains an amount of € 2,679,705 profit per year on the average.

The second case represents the same legal environment with the first case but, this time the manufacturer is in the business of used vehicles sales and remanufacturing. The legal environment does not enforce the manufacturer for taking back end-of-life products or paying any penalties for improper disposals. In this case, the average annual profit of the manufacture is € 2,684,295. Thus we can claim that, the used vehicle sales and re-manufacturing is not profitable for our manufacturer if legal environment is not enforcing.

In the third case, the legal regulations enforce our manufacturer to take-back the end of life vehicles but the manufacturer has not built-up systems to collect these products and remanufacture, recycle, or properly dispose them. Under these circumstances, the manufacturer pays penalties for the rejected end-of-life vehicles. The manufacturer also pays penalties for improper disposal of materials. This is the case in which the manufacturer has not been able to adapt to the legal regulations. Our manufacturer makes a total of € 1,272,915 profit annually in this case. This means a big loss of almost half of the profit compared to the previous cases.

In the last case, our manufacturer adapts the enforcing legal environment and builds up systems for taking back the returned end-of-life vehicles. The used vehicles are bought from customers at any age and they are either sold as used vehicles, or remanufactured, or recycled or disposed properly. The legal penalties for rejecting end-of-life vehicles or improper disposals are still in case, but the manufacturer avoids paying these penalties since the corresponding business units are being run. In this case, our manufacturer makes a total of € 2,676,711 profit annually, which is almost the same amount as in the initial case where take-back regulations are not enforced.

Throughout the complete analysis, we figured out some numerical insight about the manufacturers trying to be remanufacturers with extended responsibility under the force of the legal regulations. We analyzed the economic impact for a manufacturer to turn into a complex facility that also takes back the returned products and processes them for different purposes including refurbishing.

This study can be further improved by either some additions to the model or by including alternative types of analysis. For example, competitors can be added into the model to understand a more complex market structure. The status of the manufacturer can be analyzed under fluctuating demand. Break even point and ROI (return on investment) can be analyzed after figuring out the total cost of building and starting a remanufacturing plant. An option of buying cheap raw materials from recyclers can be studied. The operation of extracting spare parts from the returned products can be implemented in the model. The impact of selling remanufactured spare parts instead of new spare parts can be analyzed. The demand of used products and remanufactured products can be separated by differentiating the customers.

APPENDIX A: NUMERICAL ANALYSIS

Appendix A presents tables and figures related to numerical analysis, such as the values of parameters used in the model or the values of decision variables obtained.

Table A.1. Values of the parameters P_i, RP_i, PP_i, and PJ_i

i (Age of product)	**P_i (Sales price of new or used product)**	**RP_i (Sales price of remanufactured product)**	**PP_i (Purchasing price)**	**PJ_i (Scrap value)**
0	192.0	188.0	186.0	18.6
1	170.0	180.0	164.0	16.4
2	160.0	170.0	154.0	15.4
3	150.0	160.0	144.0	14.4
4	140.0	150.0	134.0	13.4
5	130.0	140.0	124.0	12.4
6	120.0	130.0	114.0	11.4
7	95.0	105.0	89.0	8.9
8	85.0	95.0	79.0	7.9
9	75.0	85.0	69.0	6.9
10	65.0	75.0	59.0	5.9
11	55.0	65.0	49.0	4.9
12	40.0	50.0	34.0	3.4
13	35.0	45.0	29.0	2.9
14	30.0	40.0	24.0	2.4
15	23.0	33.0	17.0	1.7
16	19.0	29.0	13.0	1.3
17	16.0	26.0	10.0	1.0
18	13.0	23.0	7.0	0.7
19	11.0	21.0	5.0	0.5

Table A.2. Values of the parameters RC_i and DC_i

i **(Age of product)**	RC_i **(Remanufacturing cost)**	DC_i **(Disposal cost)**
0	2.0	1.0
1	2.7	1.2
2	3.4	1.4
3	4.1	1.6
4	4.8	1.8
5	5.5	2.0
6	6.2	2.2
7	6.9	2.4
8	7.6	2.6
9	8.3	2.8
10	9.0	3.0
11	9.7	3.2
12	10.4	3.4
13	11.1	3.6
14	11.8	3.8
15	12.5	4.0
16	13.2	4.2
17	13.9	4.4
18	14.6	4.6
19	15.3	4.8

Table A.3. Values of the parameters r_i and q_i

i **(Age of product)**	r_i **(willingness of customer to return a product at age *i*)**	q_i **(level of remanufacturability at age *i*)**
0	0.05	0.95
1	0.05	0.86
2	0.06	0.77
3	0.07	0.69
4	0.09	0.62
5	0.10	0.56
6	0.12	0.50
7	0.14	0.45
8	0.17	0.41
9	0.20	0.37
10	0.23	0.33
11	0.27	0.30
12	0.32	0.27
13	0.38	0.24
14	0.44	0.22
15	0.52	0.20
16	0.61	0.18
17	0.72	0.16
18	0.85	0.14
19	1.00	0.13

Table A.4. Values of the parameter dem_X0_j

j **(Period)**	dem_X0_j **(demand for new products in period *j*)**
j = {0,...,39}	1,200

Table A.5. Values of the parameter dem_XY_{ij}

i **(Age of product)**	dem_XY_{ij} **(demand for used or remanufactured products at age *i* in period** $j = \{0,...,39\}$**)**
0	0
1	963
2	774
3	622
4	499
5	401
6	322
7	259
8	208
9	167
10	134
11	108
12	86
13	69
14	56
15	45
16	36
17	29
18	23
19	0

Table A.6. Values of the parameters wc_X0_i and wc_Y_i

i **(Age of product)**	wc_X0_i **(warranty costs for new products)**	wc_Y_i **(warranty costs for reconditioned products)**
0	6.0	6.0
1	6.0	6.0
2	0.0	6.1
3	0.0	6.2
4	0.0	6.3
5	0.0	6.4
6	0.0	6.5
7	0.0	6.6
8	0.0	6.7
9	0.0	6.8
10	0.0	6.9
11	0.0	7.0
12	0.0	7.1
13	0.0	7.2
14	0.0	7.3
15	0.0	7.4
16	0.0	7.5
17	0.0	7.6
18	0.0	7.7
19	0.0	7.8

Table A.7. Values of the parameters e, $disp\_upl$

Parameter	**Value**
e	0.20
$disp\_upl$	0.15

Table A.8. Values of $prod\_cap$, ret_cap, rem_cap, dir_cap, rec_cap

Parameter	**Value**
$prod\_cap$	700
ret_cap	2,000
rec_cap	300
dir_cap	400
rem_cap	1,000

Table A.9. Values of the parameters pen_rej, pen_disp

Parameter	**Value (thousand €)**
pen_rej	200
pen_disp	150

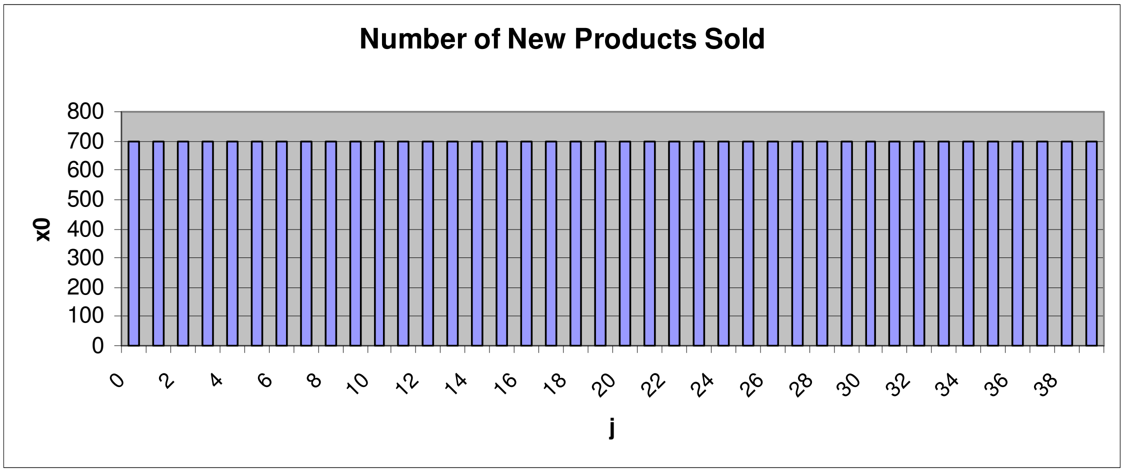

Figure A.1. Number of new products sold at each period

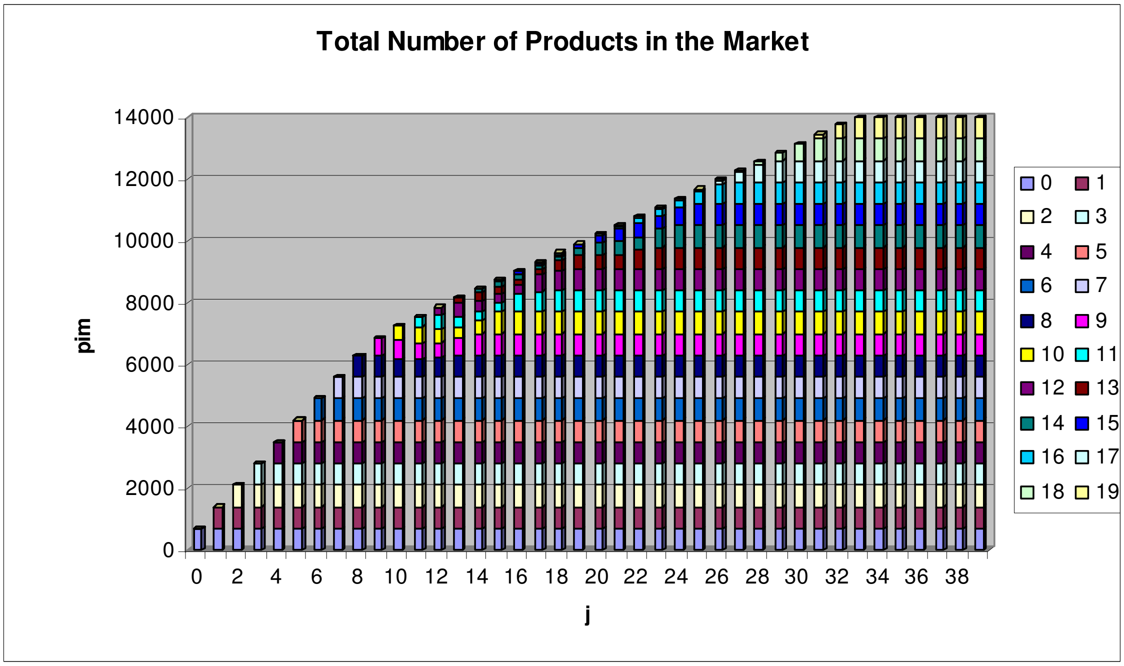

Figure A.2. Total number of products in the market at each period

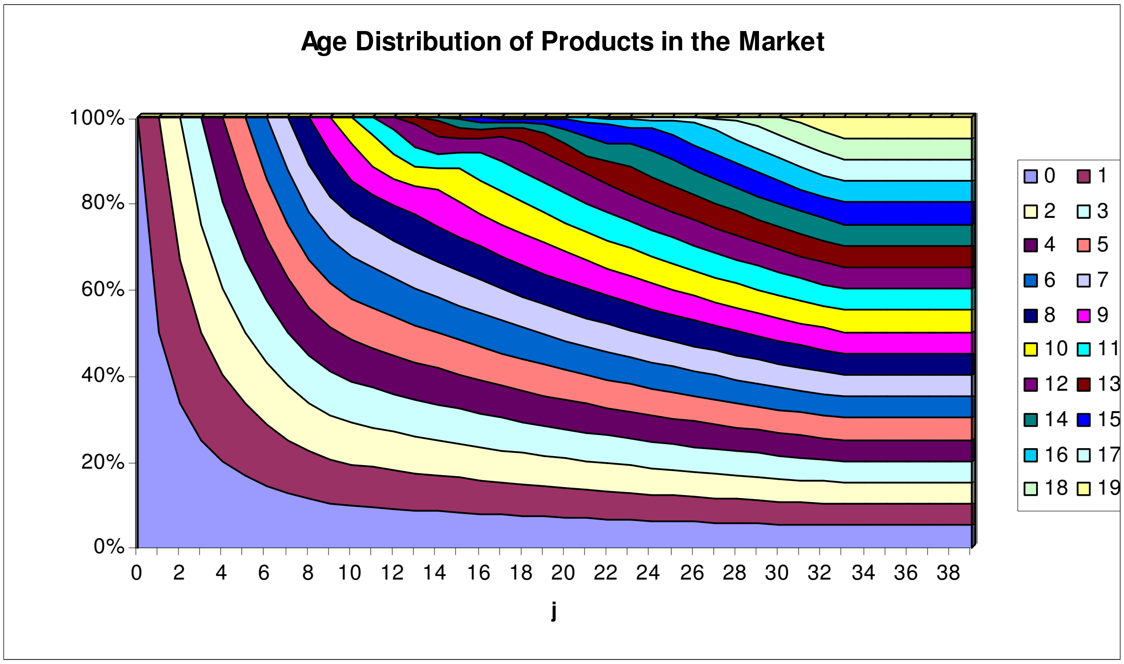

Figure A.3. Age distribution of products in the market

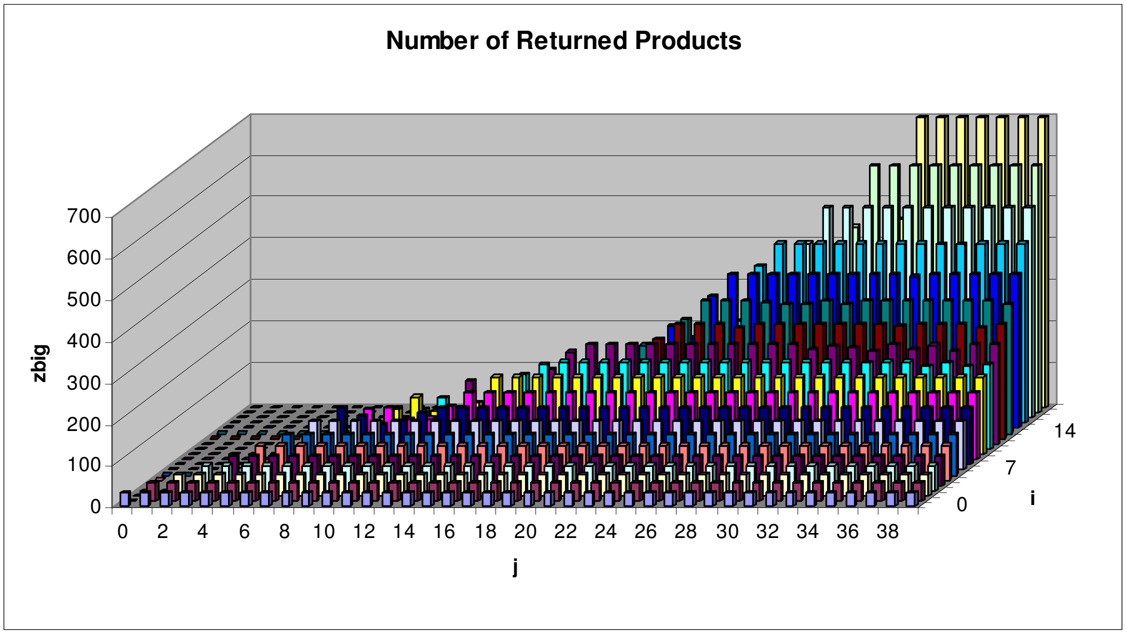

Figure A.4. Number of returned products

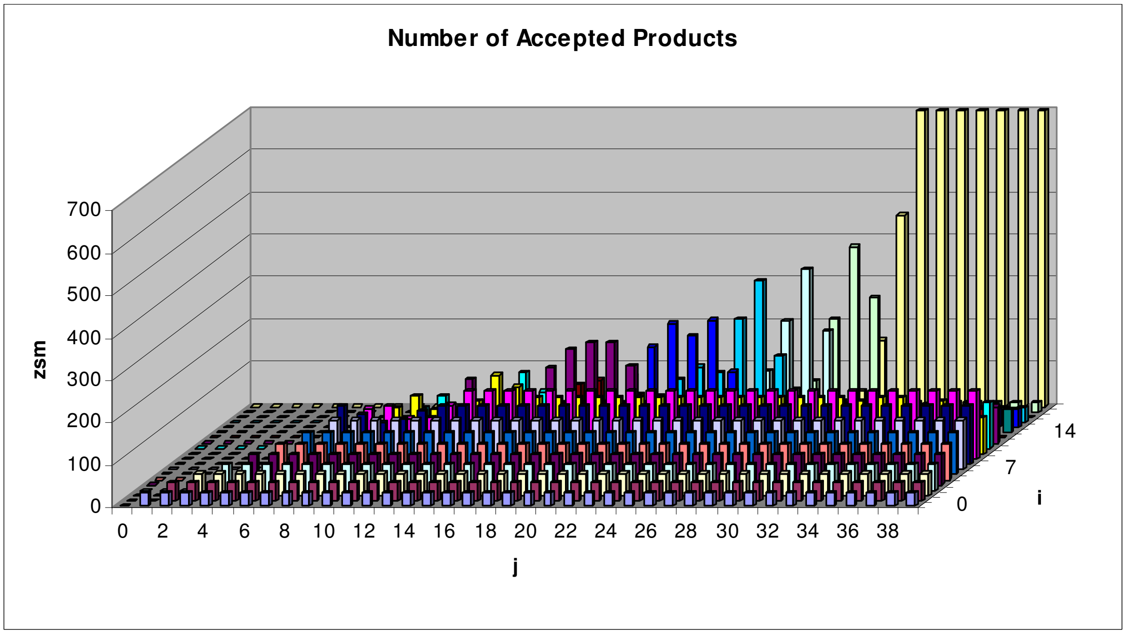

Figure A.5. Number of accepted products

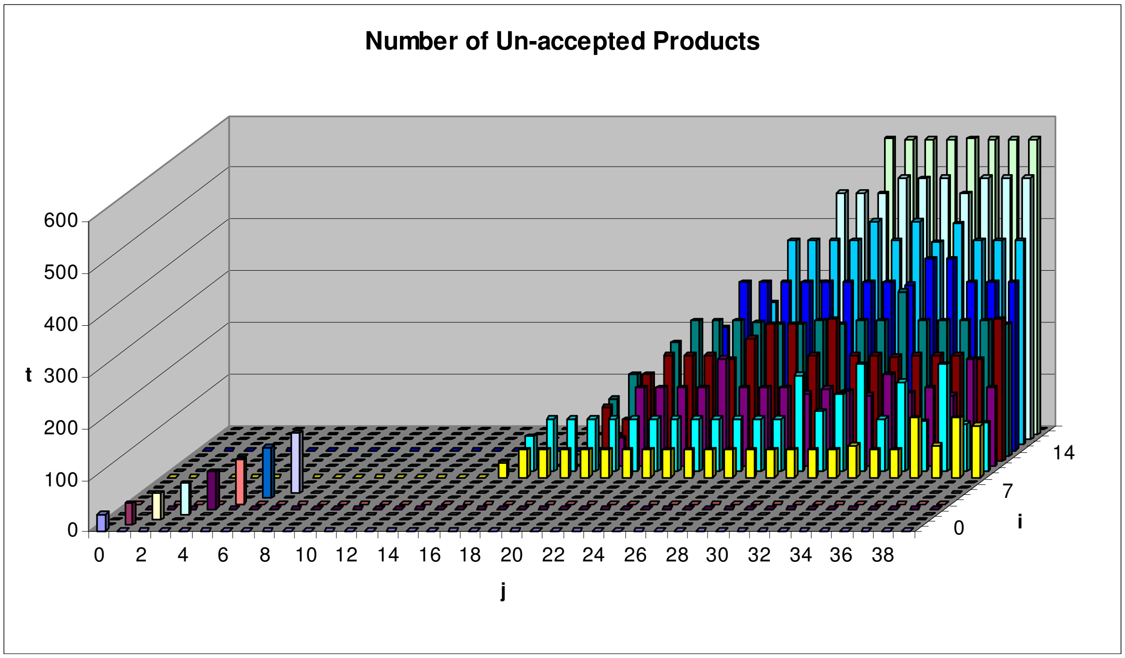

Figure A.6. Number of unaccepted products

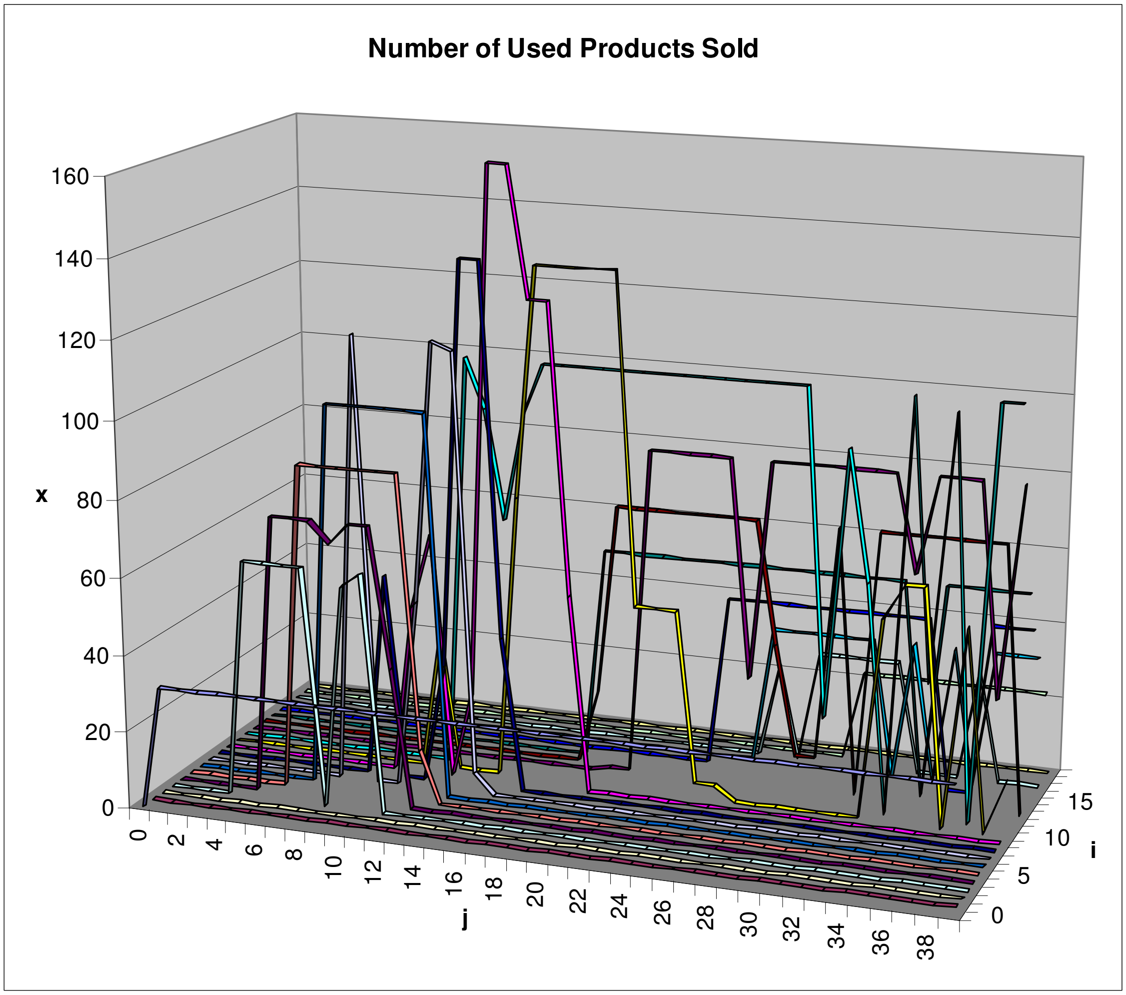

Figure A.7. Number of used products sold

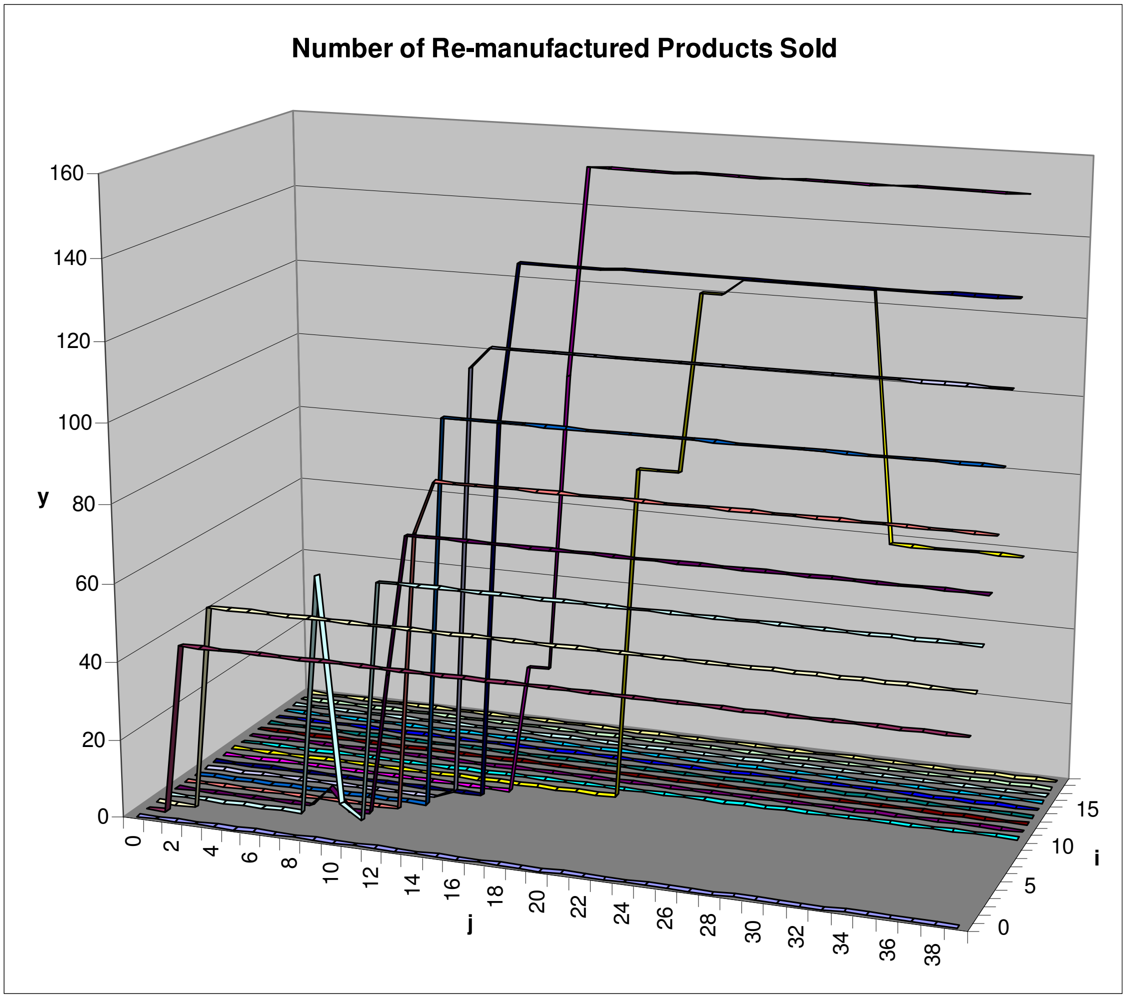

Figure A.8. Number of re-manufactured products sold

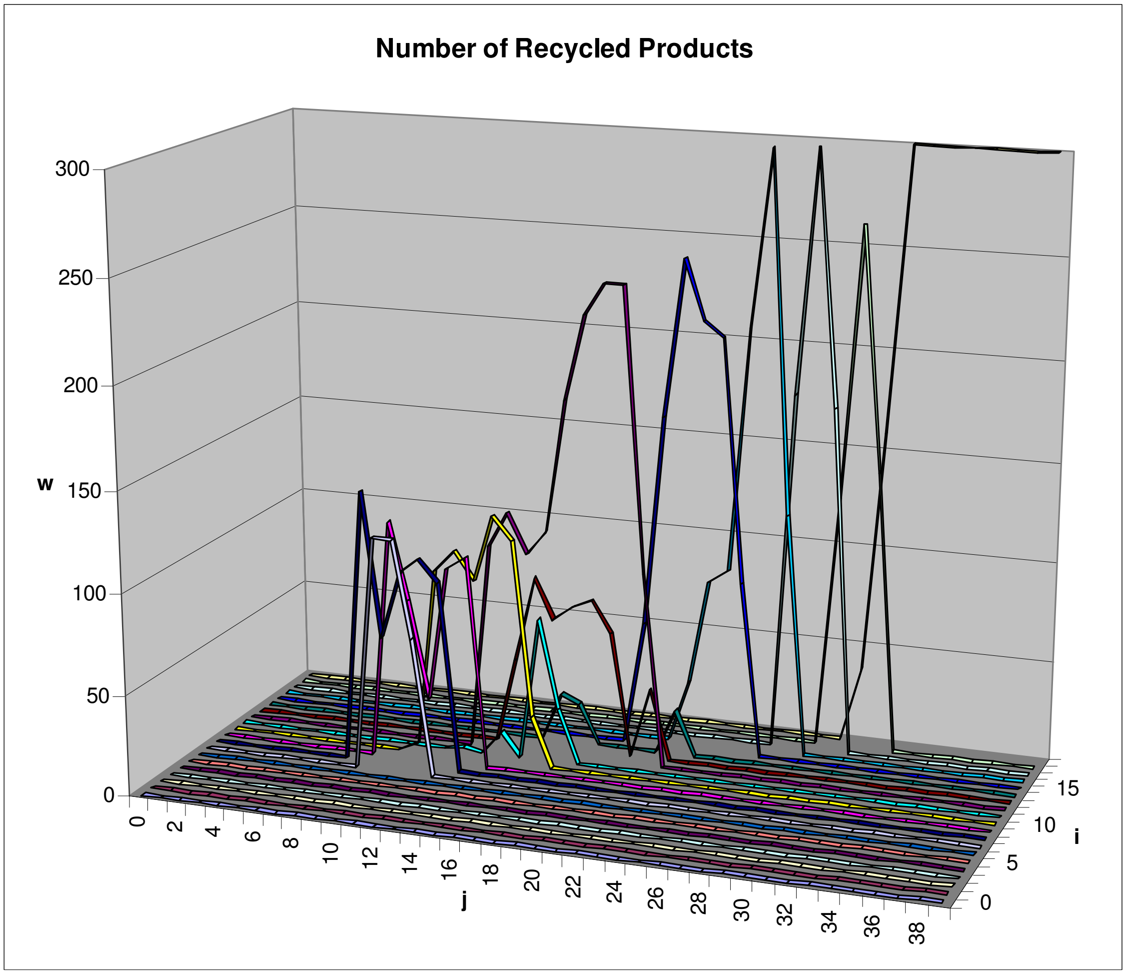

Figure A.9. Number of recycled products

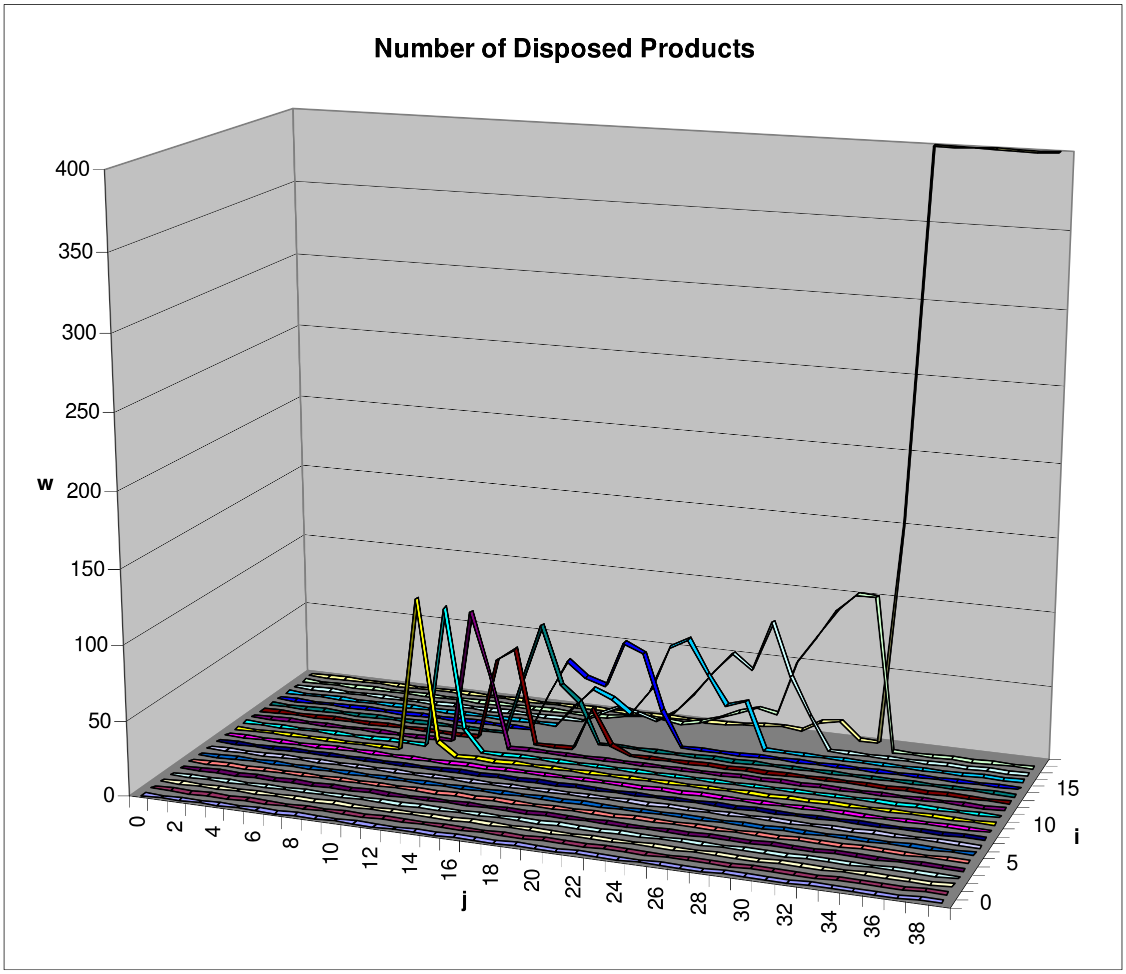

Figure A.10. Number of disposed products

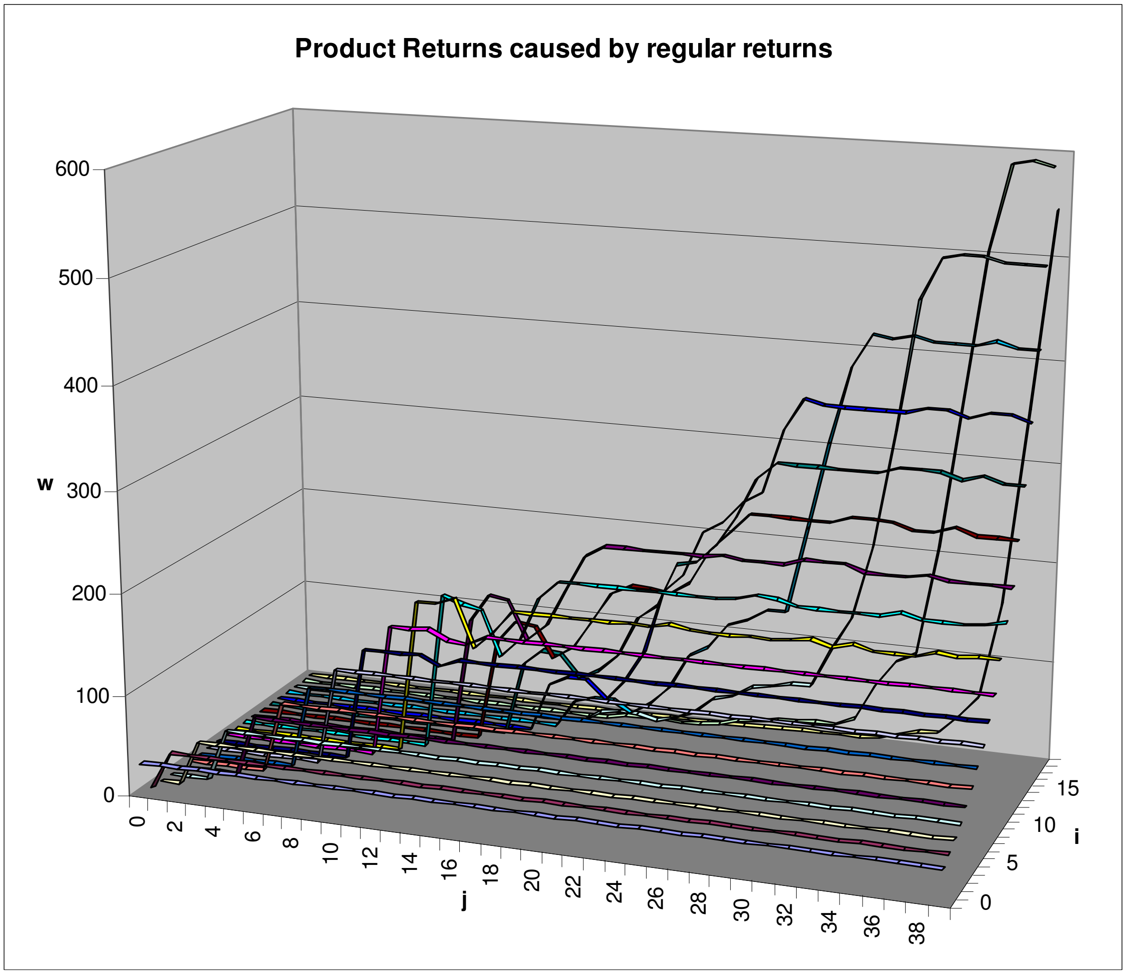

Figure A.11. Product returns caused by regular returns

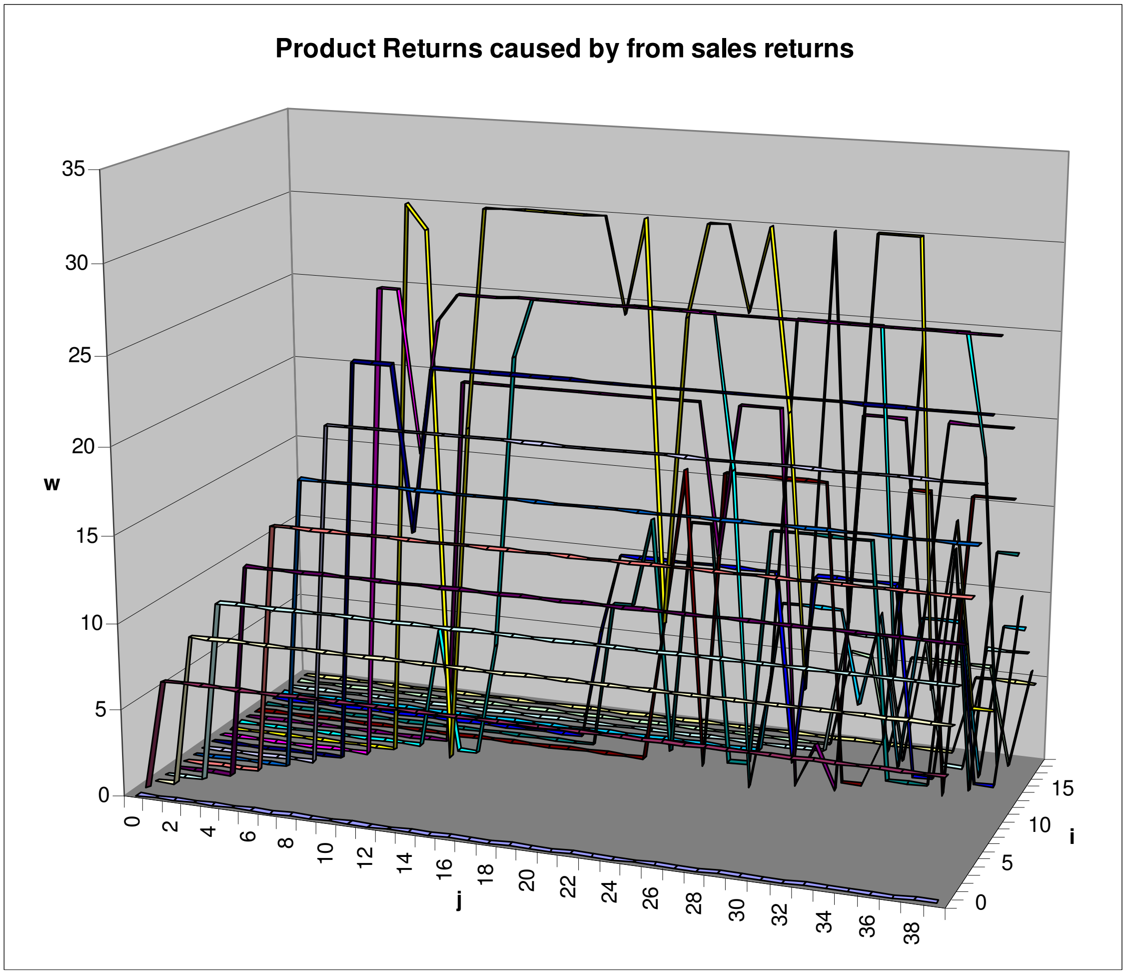

Figure A.12. Product returns caused by sales returns

APPENDIX B: SENSITIVITY ANALYSIS

Appendix B presents tables and figures related to sensitivity analysis, such as the levels of parameters used in the model or the variation in the objective value obtained during the analysis.

Table B.1. Sensitivity Analysis – Percentage change in parameter levels

Parameter	Levels				
	1	2	3	4	5
P_i	-20%	-10%	-	+10%	+20%
RP_i	-20%	-10%	-	+10%	+20%
PP_i	-20%	-10%	-	+10%	+20%
PJ_i	-20%	-10%	-	+10%	+20%
RC_i	-50%	-25%	-	+25%	+50%
DC_i	-50%	-25%	-	+25%	+50%
r_i	-20%	-10%	-	+10%	+20%
q_i	-20%	-10%	-	+10%	+20%
dem_X0_j	-20%	-10%	-	+10%	+20%
dem_XY_{ij}	-20%	-10%	-	+10%	+20%
wc_X0_i	-50%	-25%	-	+25%	+50%
wc_Y_i	-50%	-25%	-	+25%	+50%
e	-50%	-25%	-	+25%	+50%
$prod\_cap$	-50%	-25%	-	+25%	+50%
ret_cap	-50%	-25%	-	+25%	+50%
rec_cap	-50%	-25%	-	+25%	+50%
dir_cap	-50%	-25%	-	+25%	+50%
rem_cap	-50%	-25%	-	+25%	+50%
$disp\_upl$	-50%	-25%	-	+25%	+50%
pen_rej	-50%	-25%	-	+25%	+50%
pen_disp	-50%	-25%	-	+25%	+50%

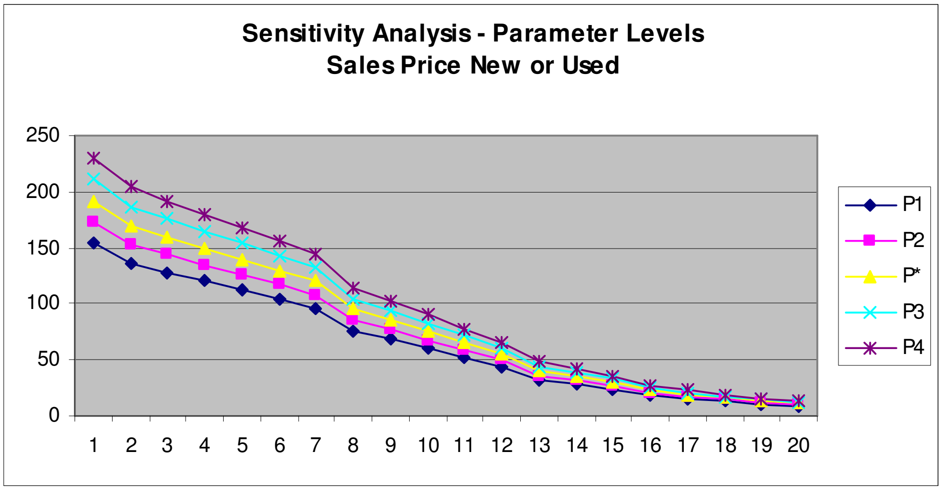

Figure B.1. Sensitivity Analysis – Levels for parameter P_i

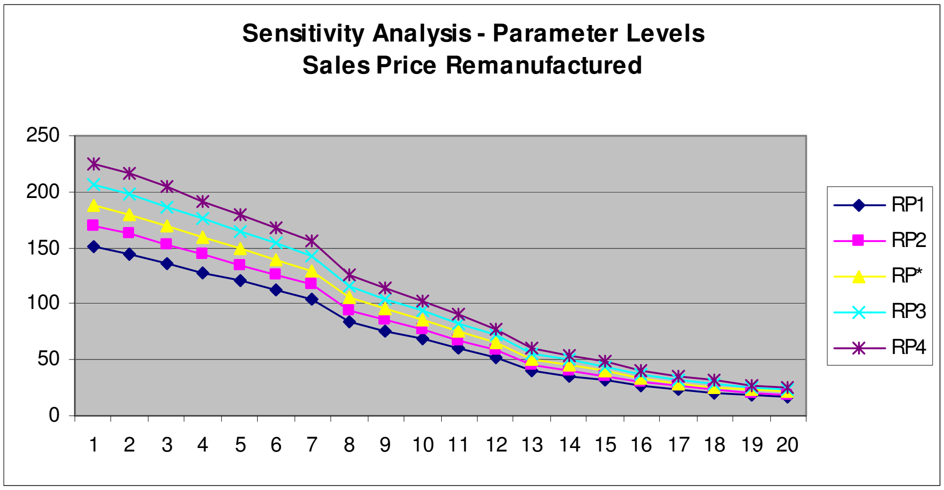

Figure B.2. Sensitivity Analysis – Levels for parameter RP_i

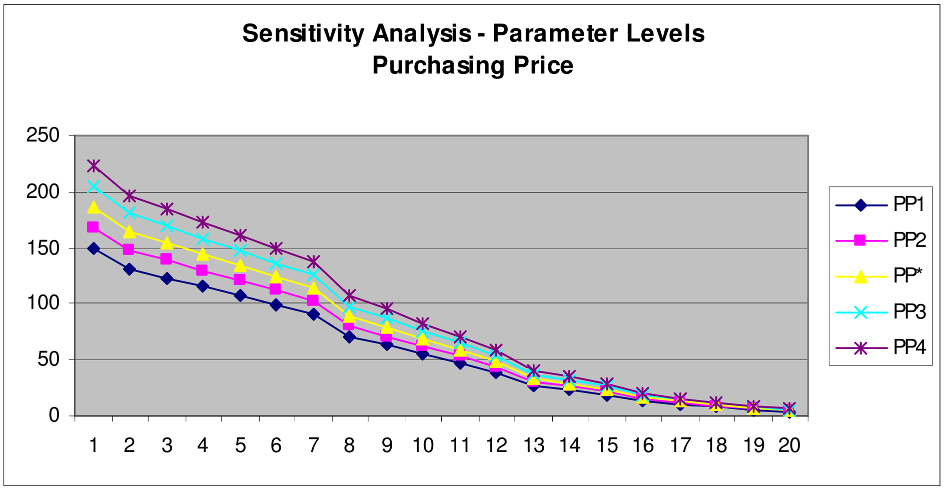

Figure B.3. Sensitivity Analysis – Levels for parameter PP_i

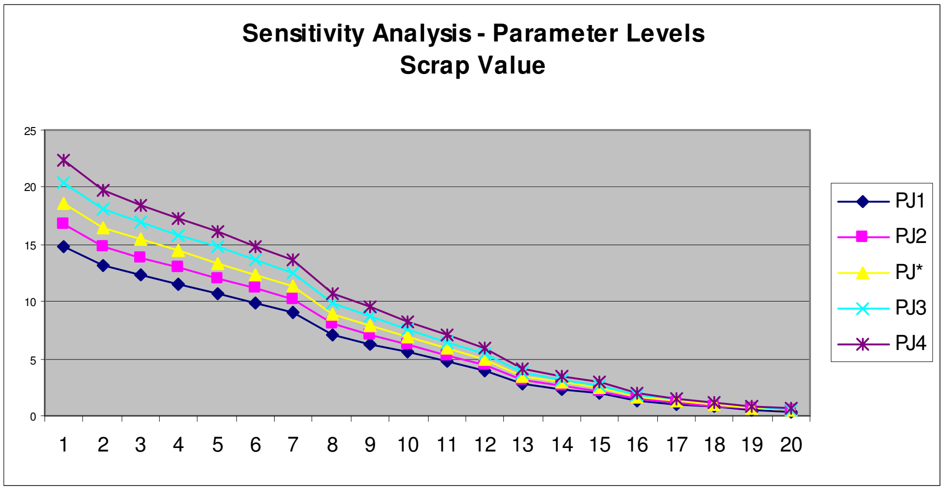

Figure B.4. Sensitivity Analysis – Levels for parameter PJ_i

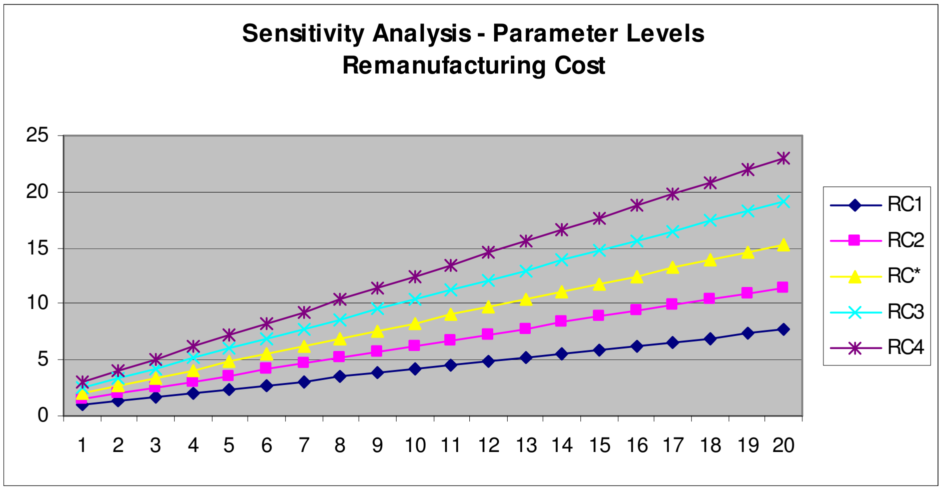

Figure B.5. Sensitivity Analysis – Levels for parameter RC_i

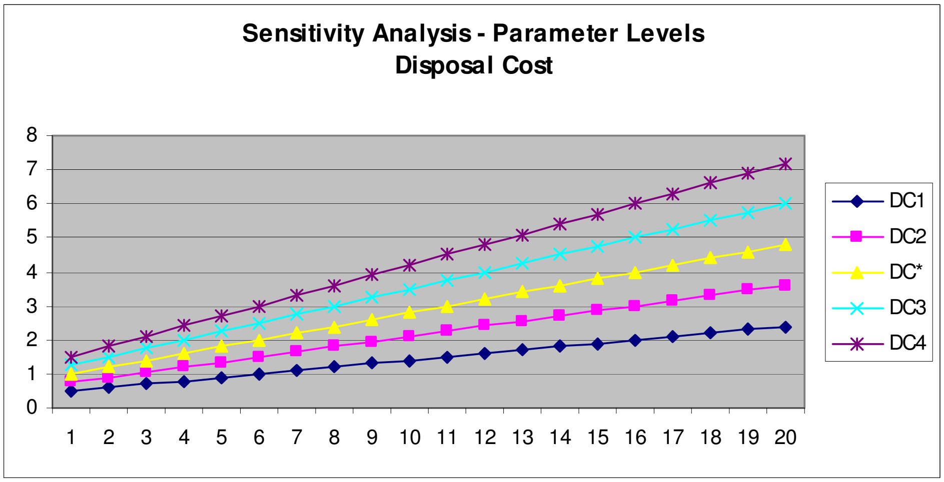

Figure B.6. Sensitivity Analysis – Levels for parameter DC_i

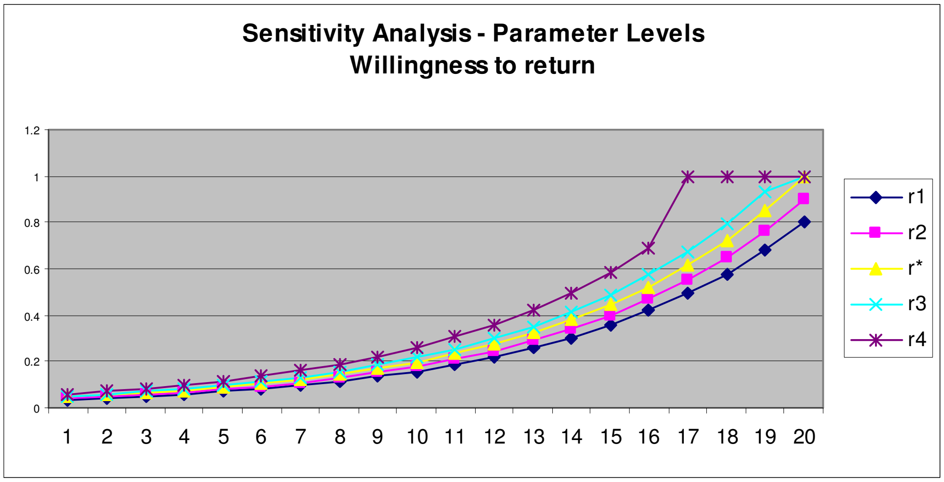

Figure B.7. Sensitivity Analysis – Levels for parameter r_i

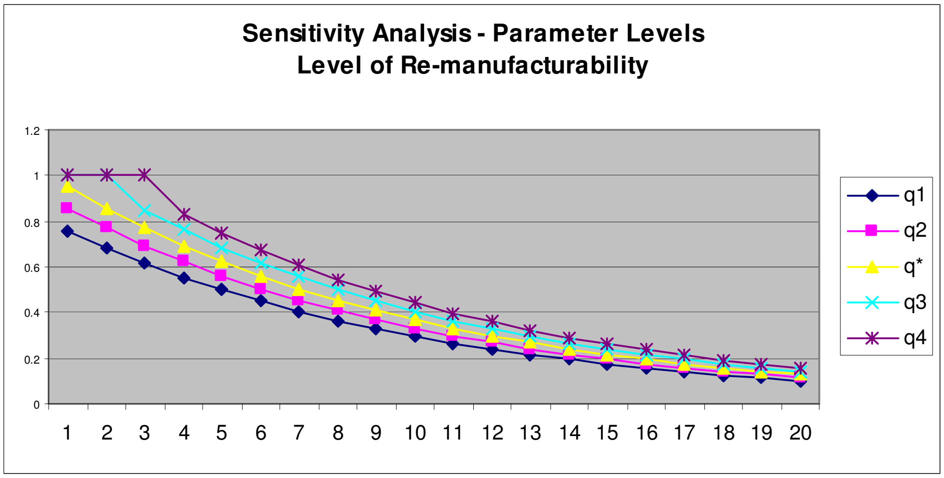

Figure B.8. Sensitivity Analysis – Levels for parameter q_i

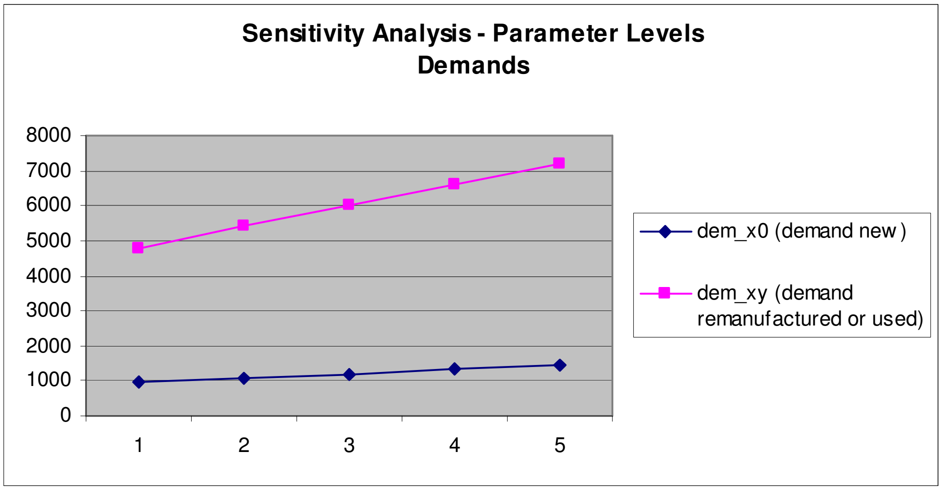

Figure B.9. Sensitivity Analysis – Levels for parameters dem_X0_j and dem_XY_{ij}

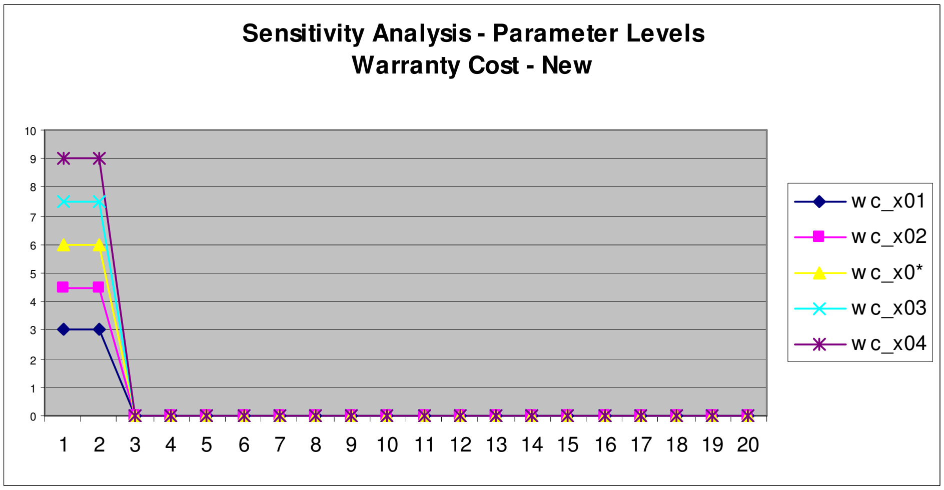

Figure B.10. Sensitivity Analysis – Levels for parameter wc_X0_i

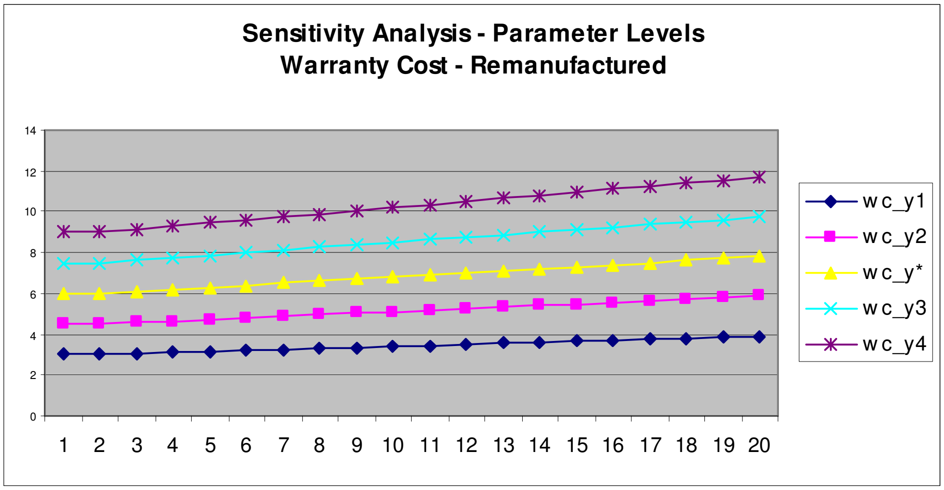

Figure B.11. Sensitivity Analysis – Levels for parameter wc_Y_i

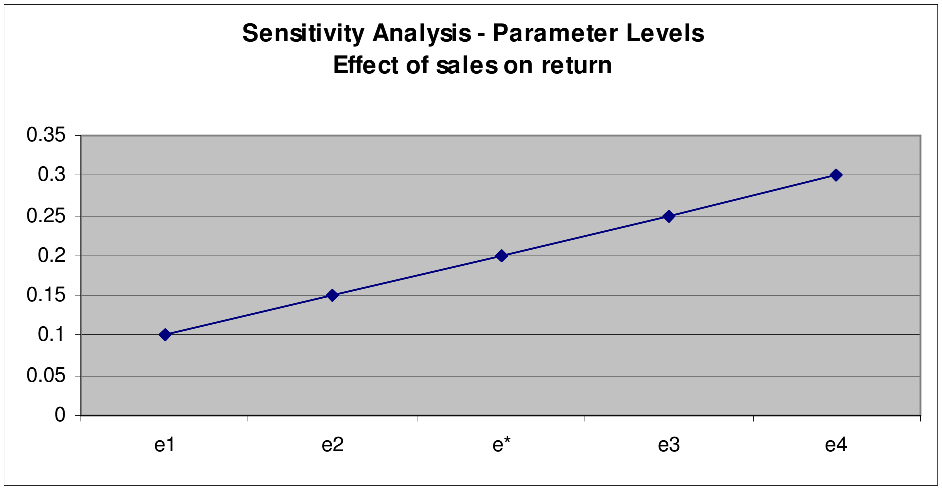

Figure B.12. Sensitivity Analysis – Levels for parameter e

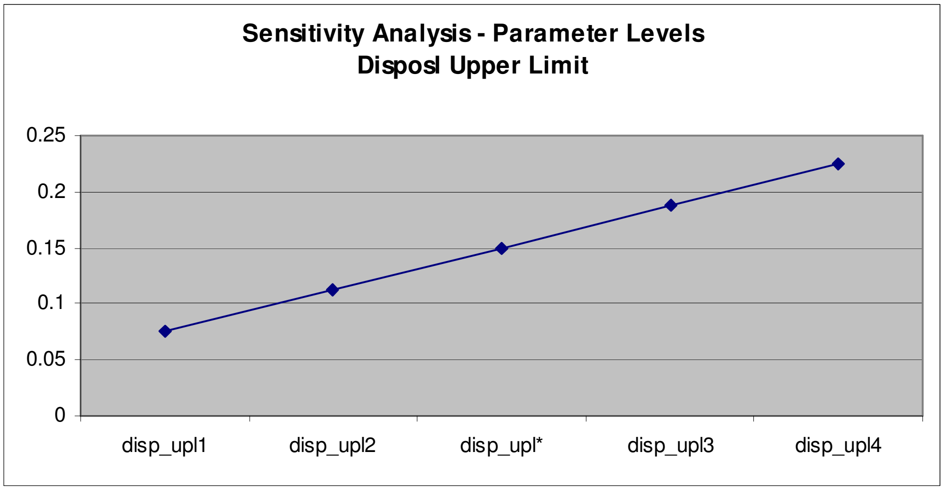

Figure B.13. Sensitivity Analysis – Levels for parameter $disp\_upl$

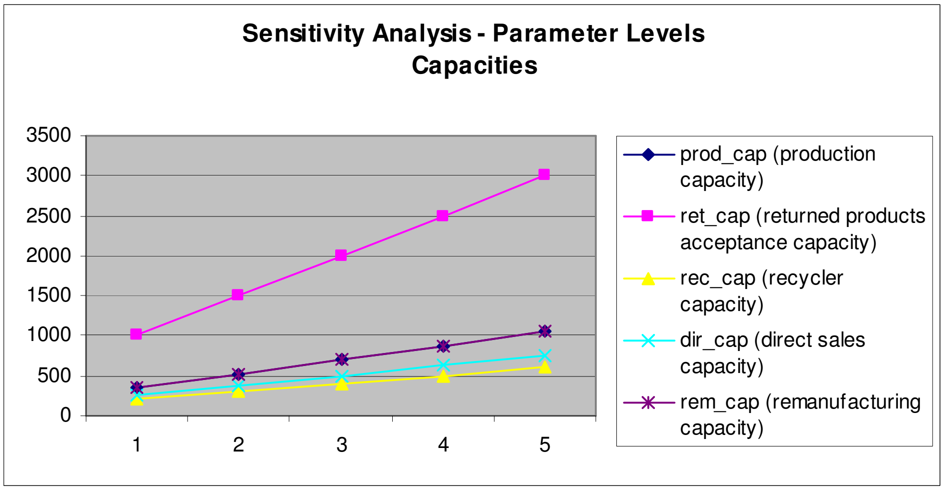

Figure B.14. Levels for $prod\_cap$, ret_cap, rec_cap, dir_cap, and rem_cap

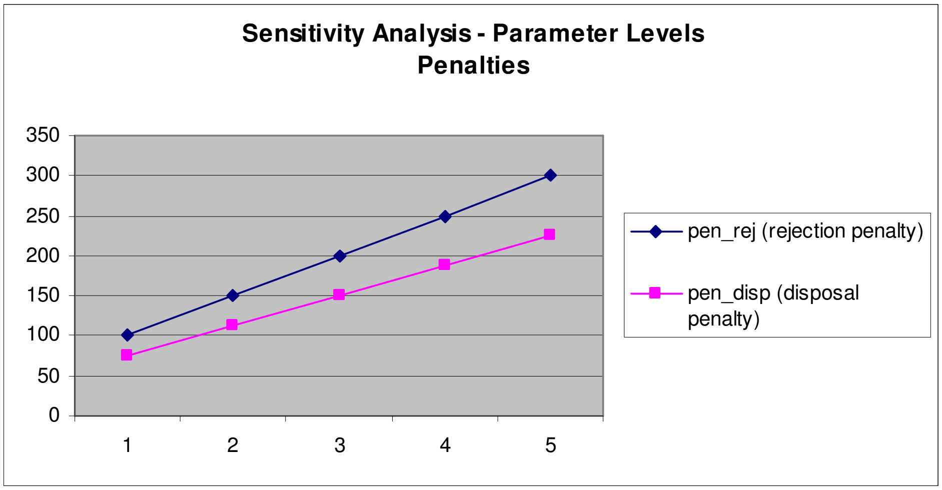

Figure B.15. Sensitivity Analysis – Levels for parameters pen_rej and pen_disp

Table B.2. Sensitivity Analysis – Objective values

PARAMETER	**LEVELS**	**AVERAGE ANNUAL PROFIT (€)**
P (sales price new or used)	P1	4,273,762
	P2	4,812,190
	P*	5,353,423
	P3	5,900,322
	P4	6,449,256
RP (sales price remanfucatured)	RP1	5,349,648
	RP2	5,349,648
	RP*	5,353,423
	RP3	5,368,497
	RP4	5,384,614
PP (purhcasing price)	PP1	5,392,424
	PP2	5,372,899
	PP*	5,353,423
	PP3	5,344,226
	PP4	5,341,902
PJ (scrap value)	PJ1	5,353,160
	PJ2	5,353,291
	PJ*	5,353,423
	PJ3	5,353,562
	PJ4	5,353,701
RC (remanufacturing cost)	RC1	5,356,286
	RC2	5,354,826
	RC*	5,353,423
	RC3	5,352,127
	RC4	5,351,276
DC (disposal cost)	DC1	5,353,752
	DC2	5,353,587
	DC*	5,353,423
	DC3	5,353,265
	DC4	5,353,107

Table B.2. (Cont'd) Sensitivity Analysis – Objective values

PARAMETER	LEVELS	AVERAGE ANNUAL PROFIT (€)
r (willingness to return)	r1	5,360,720
	r2	5,356,344
	r*	5,353,423
	r3	5,353,965
	r4	5,353,381
q (level of re-manufacturability)	q1	5,353,423
	q2	5,353,423
	q*	5,353,423
	q3	5,353,423
	q4	5,353,423
dem_x0 (demand new)	dem_x01	5,353,423
	dem_x02	5,353,423
	dem_x0*	5,353,423
	dem_x03	5,353,423
	dem_x04	5,353,423
dem_xy (demand remanufactured or used)	dem_xy1	5,353,380
	dem_xy2	5,353,407
	dem_xy*	5,353,423
	dem_xy3	5,353,432
	dem_xy4	5,353,439
wc_x0 (warranty cost new)	wc_x01	5,361,718
	wc_x02	5,357,570
	wc_x0*	5,353,423
	wc_x03	5,349,275
	wc_x04	5,345,128
wc_y (warranty cost remanufactured)	wc_y1	5,356,732
	wc_y2	5,355,044
	wc_y*	5,353,423
	wc_y3	5,351,682
	wc_y4	5,350,759

Table B.2. (Cont'd) Sensitivity Analysis – Objective values

PARAMETER	LEVELS	AVERAGE ANNUAL PROFIT (€)
e (effect of sales on return)	e1	5,353,044
	e2	5,353,226
	e*	5,353,423
	e3	5,353,633
	e4	5,350,558
prod_cap (production capacity)	prod_cap1	2,684,814
	prod_cap2	4,023,535
	prod_cap*	5,353,423
	prod_cap3	6,674,388
	prod_cap4	7,993,171
ret_cap (returned products acceptance capacity)	ret_cap1	5,342,298
	ret_cap2	5,352,975
	ret_cap*	5,353,423
	ret_cap3	5,353,423
	ret_cap4	5,353,423
rec_cap (recycler capacity)	rec_cap1	5,318,259
	rec_cap2	5,337,094
	rec_cap*	5,353,423
	rec_cap3	5,361,847
	rec_cap4	5,364,753
dir_cap (direct sales capacity)	dir_cap1	5,350,164
	dir_cap2	5,353,095
	dir_cap*	5,353,423
	dir_cap3	5,353,751
	dir_cap4	5,355,172
rem_cap (remanufacturing capacity)	rem_cap1	5,352,471
	rem_cap2	5,353,108
	rem_cap*	5,353,423
	rem_cap3	5,353,738
	rem_cap4	5,354,053

Table B.2. (Cont'd) Sensitivity Analysis – Objective values

PARAMETER	**LEVELS**	**AVERAGE ANNUAL PROFIT (€)**
disp_upl (maximum disposal ratio)	disp_upl1	5,345,368
	disp_upl2	5,350,229
	disp_upl*	5,353,423
	disp_upl3	5,356,617
	disp_upl4	5,358,678
pen_rej (rejection penalty)	pen_rej1	5,353,423
	pen_rej2	5,353,423
	pen_rej*	5,353,423
	pen_rej3	5,353,423
	pen_rej4	5,353,423
pen_disp (disposal penalty)	pen_disp1	5,355,468
	pen_disp2	5,353,965
	pen_disp*	5,353,423
	pen_disp3	5,353,422
	pen_disp4	5,353,422

APPENDIX C: SCENARIO ANALYSIS

Appendix C presents tables and figures related to scenario analysis, such as average capacity usage ratios or average values of decision variables obtained.

Table C.1. Scenario analysis criterias and objective values

Scenario #	**Criteria**	**Explanation**	**Objective Value (€)**
0	ret_cap = ret_cap*, pen_rej = pen_rep*, pen_disp = pen_disp*	Base	107,068,455
1	ret_cap = 0, pen_rej = 0, pen_disp = 0	take-back = NO, penalties = NO	107,188,200
2	ret_cap = 0	take-back = NO, penalties = YES	50,916,600
3	ret_cap = ret_cap*, pen_rej = 0, pen_disp = 0	take-back = YES, penalties = NO	107,371,817
4	rem_cap = 0	No remanufacturing	74,435,726
5	dir_cap = 0	No direct sales of used products	106,689,481
6	rec_cap = 0	No recycling	105,501,761
7	rem_cap = 0, dir_cap = 0, rec_cap = 0, ret_cap = 0	All capacities zero	50,916,600
8	rem_cap = ∞, ret_cap = ∞	Infinite take-back capacity, infinite remanufacturing capacity	107,046,562
9	dir_cap = ∞, ret_cap = ∞	Infinite take-back capacity, infinite used sales capacity	107,138,937
10	rec_cap = ∞, ret_cap = ∞	Infinite take-back capacity, infinite recycling capacity	107,305,667
11	rem_cap = ∞, dir_cap = ∞, rec_cap = ∞, ret_cap = ∞	All capacities infinite	107,389,121

Table C.2. Annual average figures for Case-1

Variable	**Value (Yearly Average)**	**Capacity**	**Capacity Usage Ratio**
Z (total profit)	€ 2,679,705	-	-
$X0_j$ (new product sales)	700	700	100%
$\sum_i X_{ij}$ (used product sales)	0	500	0%
$\sum_i Y_{ij}$ (remanufactured product sales)	0	700	0%
$\sum_i U_{ij}$ (sales to recycler)	0	400	0%
$\sum_i W_{ij}$ (disposal)	0	-	-
$\sum_i w\_ul_{ij}$ (disposal under limit)	0	105	0%
$\sum_i w\_ol_{ij}$ (disposal over limit)	0	-	-
$\sum_i Zbig_{ij}$ (total returns)	2,900	-	-
$\sum_i Zsm_{ij}$ (returns accepted)	0	0	-
$\sum_i T_{ij}$ (returns rejected)	2,900	-	-
$\sum_i reg\_ret_{ij}$ (regular returns)	2,900	-	-
$\sum_i sale\_ret_{ij}$ (returns due to sales)	0	-	-

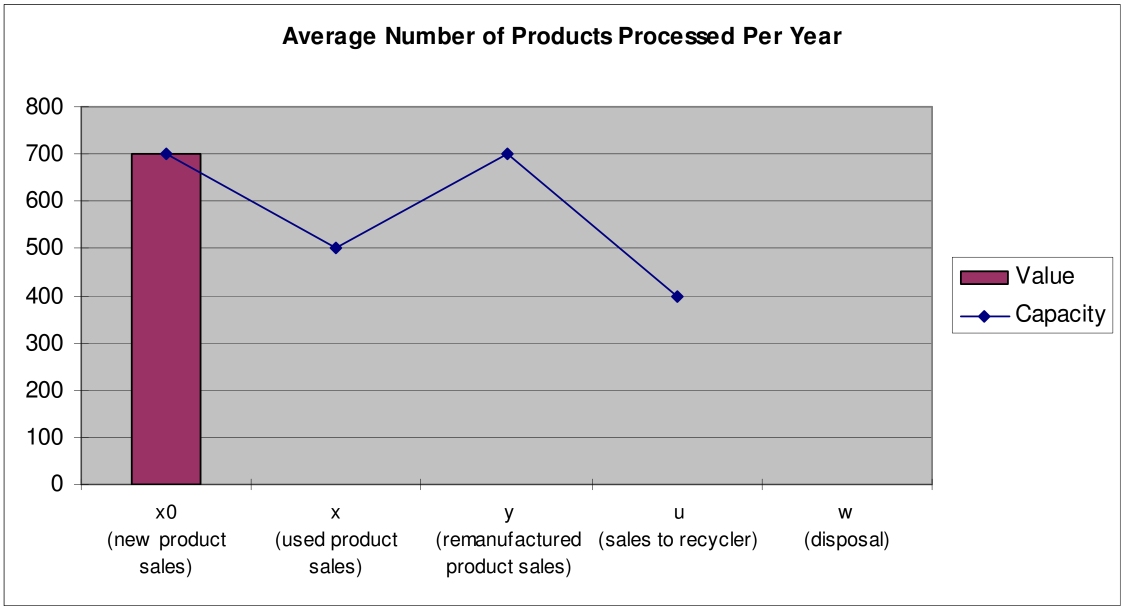

Figure C.1. Annual average capacity usage ratios for Case-1

Table C.3. Annual average figures for Case-2

Variable	Value (Yearly Average)	Capacity	Capacity Usage Ratio
Z (total profit)	€ 2,684,295	-	-
$X0_j$ (new product sales)	700	700	100%
$\sum_i X_{ij}$ (used product sales)	423	500	85%
$\sum_i Y_{ij}$ (remanufactured product sales)	529	700	76%
$\sum_i U_{ij}$ (sales to recycler)	0	400	0%
$\sum_i W_{ij}$ (disposal)	0	-	-
$\sum_i w\_ul_{ij}$ (disposal under limit)	0	105	0%
$\sum_i w\_ol_{ij}$ (disposal over limit)	0	-	-
$\sum_i Zbig_{ij}$ (total returns)	3,046	-	-
$\sum_i Zsm_{ij}$ (returns accepted)	952	2,000	48%
$\sum_i T_{ij}$ (returns rejected)	2,094	-	-
$\sum_i reg\_ret_{ij}$ (regular returns)	2,856	-	-
$\sum_i sale\_ret_{ij}$ (returns due to sales)	190	-	-

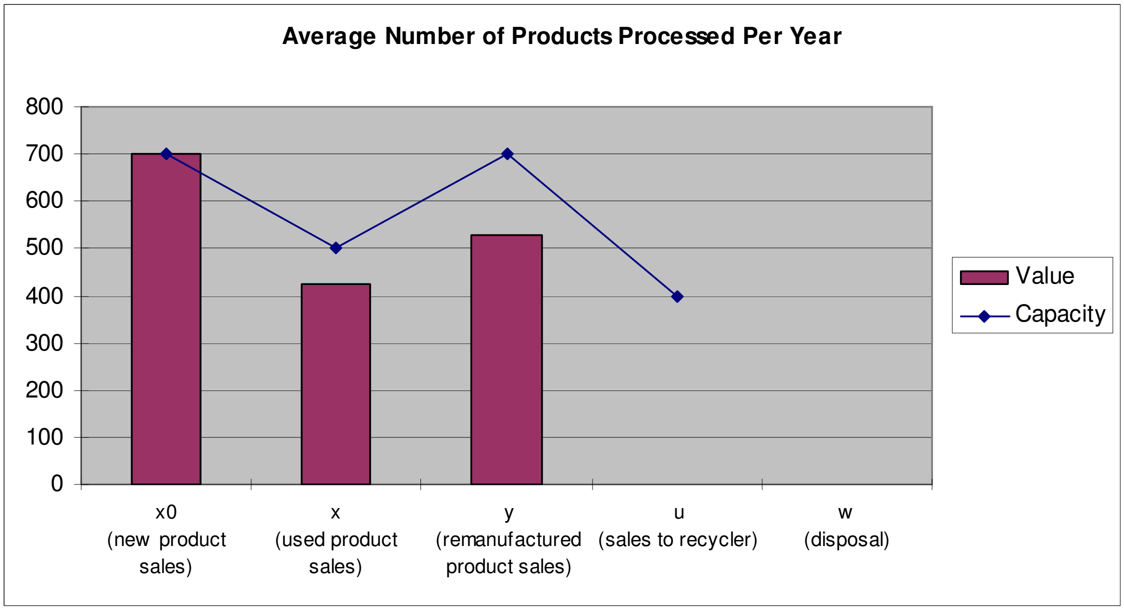

Figure C.2. Annual average capacity usage ratios for Case-2

Table C.4. Annual average figures for Case-3

Variable	Value (Yearly Average)	Capacity	Capacity Usage Ratio
Z (total profit)	€ 1,272,915	-	-
$X0_j$ (new product sales)	333	700	48%
$\sum_i X_{ij}$ (used product sales)	0	500	0%
$\sum_i Y_{ij}$ (remanufactured product sales)	0	700	0%
$\sum_i U_{ij}$ (sales to recycler)	0	400	0%
$\sum_i W_{ij}$ (disposal)	0	-	-
$\sum_i w\_ul_{ij}$ (disposal under limit)	0	105	0%
$\sum_i w\_ol_{ij}$ (disposal over limit)	0	-	-
$\sum_i Zbig_{ij}$ (total returns)	545	-	-
$\sum_i Zsm_{ij}$ (returns accepted)	0	0	-
$\sum_i T_{ij}$ (returns rejected)	545	-	-
$\sum_i reg\_ret_{ij}$ (regular returns)	545	-	-
$\sum_i sale\_ret_{ij}$ (returns due to sales)	0	-	-

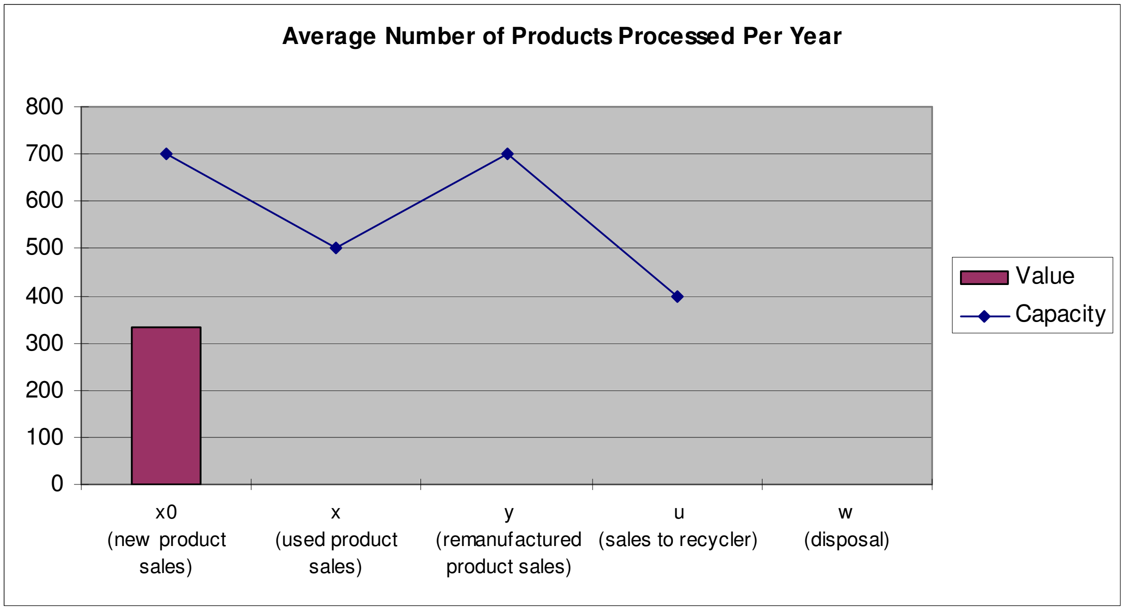

Figure C.3. Annual average capacity usage ratios for Case-3

Table C.5. Annual average figures for Case-4

Variable	Value (Yearly Average)	Capacity	Capacity Usage Ratio
Z (total profit)	€ 2,676,711	**-**	-
$X0_j$ (new product sales)	700	700	100%
$\sum_i X_{ij}$ (used product sales)	423	500	85%
$\sum_i Y_{ij}$ (remanufactured product sales)	495	700	71%
$\sum_i U_{ij}$ (sales to recycler)	293	400	73%
$\sum_i W_{ij}$ (disposal)	75	-	-
$\sum_i w\_ul_{ij}$ (disposal under limit)	74	105	70%
$\sum_i w\_ol_{ij}$ (disposal over limit)	1	-	-
$\sum_i Zbig_{ij}$ (total returns)	2,004	-	-
$\sum_i Zsm_{ij}$ (returns accepted)	1,286	2,000	64%
$\sum_i T_{ij}$ (returns rejected)	718	-	-
$\sum_i reg\_ret_{ij}$ (regular returns)	1,820	-	-
$\sum_i sale\_ret_{ij}$ (returns due to sales)	184	-	-

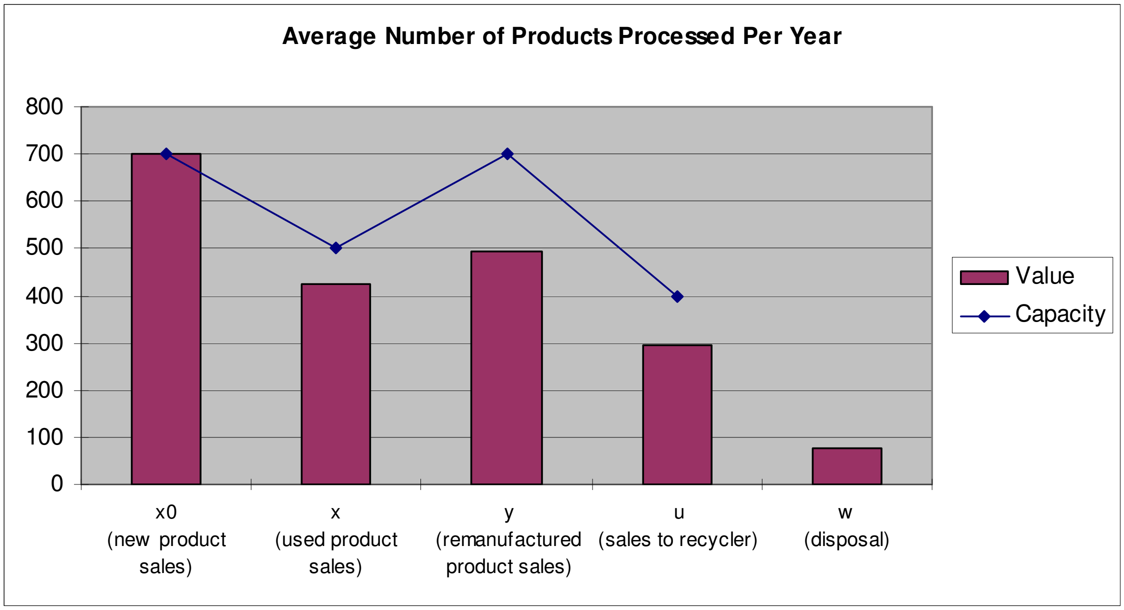

Figure C.4. Annual average capacity usage ratios for Case-4

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