STRATEGIC ANALYSIS OF PRODUCT RECOVERY MANAGEMENT BY USING SYSTEM DYNAMICS APPROACH

by

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To my family,

for their love and endless support

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ABSTRACT

STRATEGIC ANALYSIS OF PRODUCT RECOVERY MANAGEMENT BY USING SYSTEM DYNAMICS APPROACH

In this study, by using system dynamics approach, we aim to investigate the profitability of a company engaging in remanufacturing, which is the most advanced form of product recovery. Our motivation is to find out (i) whether investing in remanufacturing is advantageous for a company in terms of long term profitability and (ii) what should be the quality and price levels of the remanufactured and manufactured products. The model shows that a company offering new and remanufactured products in the market generates interesting long term customer-base dynamics endogenously. Different from the studies in the literature that deal with micro level issues, we analyze the effects of being involved in remanufacturing of electronic products on the profitability of the firm in the long term, at macro level, by also taking into account the green image factor and the government incentives for the firms that perform product recovery.

ÖZET

ÜRÜN GERİ KAZANIM YÖNETİMİNİN SİSTEM DİNAMİĞİ YAKLAŞIMI KULLANILARAK STRATEJİK ANALİZİ

Bu çalışmadaki amaç, sistem dinamiği yaklaşımı kullanılarak, ürün geri kazanım yöntemlerinin en gelişmiş türü olan yeniden imalat süreçlerine başlayan bir firmanın kârlılığının analiz edilmesi, uzun vadede yeniden imalata yapılan yatırımların firma gelişimi açısından avantajlı olup olmadığının araştırılması ve eğer kârlıysa, yeni ürün ve yeniden imal edilen ürün için olması gereken fiyat ve kalite değerlerinin incelenmesidir. Çalışmadaki model, yeni ürün üreten ve ürün geri kazanımı yöntemiyle yeniden imalat yapan bir firmanın iç sisteminin, ilginç müşteri tabanı dinamikleri oluşturduğunu göstermektedir. Literatürde yer alan mikro düzeydeki çalışmalardan farklı olarak bu çalışmada, yeniden imalat yöntemiyle elektronik ürün üretmenin kârlılık üzerindeki etkileri devlet teşviği ve çevreci marka imajı da göz önünde bulundurularak uzun dönemli, makro düzeyde analiz edilmektedir.

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1. INTRODUCTION

With the improving technology, some properties like environmental consciousness and thereby product recovery management (PRM) have become more of an issue for a company's brand image, which has an important role in the competitiveness of firms in the market. On the other hand, from the environmental point of view, increase in the production levels leads to an increase in the consumption of natural resources and waste to landfill. This situation also makes PRM a necessity. Therefore, governments enforce the companies for PRM via several legislations in developed countries.

Besides take-back laws, there are some other motives which affect companies for being voluntary for PRM. These are:

- Reducing production costs
- Promoting an image of environmental responsibility
- Meeting customer demands for remanufactured products
- Protecting aftermarkets
- Preempting regulation

Tofel, M. (2004) mention several big companies that are aware of the profitability of PRM:

- Xerox Corporation saves hundreds of million dollars per year by disassembling its end of life (EOL) photocopiers and then cleaning, sorting, and repairing components and recycling residual materials.
- Mercedes-Benz accepts and disassembles EOL Mercedes vehicles to harvest and sell spare parts to both consumers and commercial customers at a significant discount compared to virgin spare parts.
- In 1999, Ford Motor Company began buying salvage yards in the U.S., Canada, the United Kingdom, and Germany to dismantle EOL vehicles to provide a source of spare parts that were cheaper than virgin parts.
- After consumers began referring to Kodak's single-use cameras as "disposables" or "throwaways" and the media reported environmental groups' concerns of their

wastefulness, Kodak and Fuji-Film launched a take-back program to recycle more than 90% of these cameras and reverse the product's poor environmental image.

- Ford's and Mercedes's recent interest in their EOL vehicles can also be viewed as a strategy to preclude independent competitors from accessing their branded spare parts.

While starting to implement PRM, companies may prefer to implement different strategies by considering the company's position and the advantages/disadvantages of the strategies. These strategies can be classified into 5 groups:

- Contracting with recyclers
- Establishing joint ventures with recyclers
- Forming consertia with competitors
- Vertically integrating into product recovery
- Simply promoting the recycling market

The PRM results from the concept of circular economy. Verfaillie H.A. and B. Robin (2000) mention that the purpose of the circular economy is not only contributing to a company in terms of economic development but also in terms of social and environmental development. Therefore, one of the methods to measure company performance is eco-efficiency. That is the ratio of product or service value to the environmental influence. The factors included by product or service value (such as quantity of goods or services produced/provided to customers and net sales) and environmental influence (such as energy consumption, materials consumption, water consumption, greenhouse gas emission and ozone depleting substance emissions) can be chosen optionally.

PRM generally includes remanufacturing, recycling, refurbishing and repairing activities based on the complexity of the process. Repairing is the simplest kind of recovery management processes and includes fixing and/or replacement of broken parts. Reparing usually requires only limited product assembly and reassembly. Refurbishing is a process of replacing outdated modules and parts with technologically superior ones to bring used products up to a specified quality level. Differently, the purpose of remanufacturing is to bring used products up to quality standards that are as rigorious as those for new products. Remanufacturing is the process of disassembly and recovery at the component level. That is, the process of changing some components of a used product with the new components. The last step of PRM is recycling, which is the process of converting the used product to its materials such as paper, plastic, glass, metal and so on as mentioned by M. Thierry et al. (1995). The companies may prefer applying only one type of these PRM options or several of them simultaneously.

Remanufacturing is applied in different kinds of products such as: automotive parts, forklifts and pallets, medical equipments, personal computers, photocopiers, photograph equipments, refrigeration components, telephones, televisions, textile machines and toner cartridges. In academic studies, remanufacturing is generally analyzed for personal computers, photocopiers, telephones, televisions, and toner cartridges.

In developed countries, firms generally apply the PRM due to the government legislations. However, in some developing countries including Turkey, these legislations are not in force yet. The important thing is that PRM is a beneficial method not only for the environment but also for companies since it increases their profits. Therefore, although legislations do not force the companies to apply PRM, it is a good strategy to increase a firm's profit. Although PRM is a profitable strategy, especially high investment costs and inventory issues can have a negative effect on the firms' decisions. Therefore, several academic studies are carried out on this subject area in system dynamics field. However, these studies are in micro level including operational processes of PRM. Generally, operational processes are considered in the literature to analyze the effects of PRM on the environment. Capacity augmentation for remanufacturing or recycling has also been analyzed by considering legislations and green image factor.

In contrast to the former studies, this study aims to investigate the profitability of a company in the long term, if it is engaged in remanufacturing. The model is constructed at a macro level, which does not cover operational processes and aims to help the top management to make a decision about the involvement in remanufacturing. In this study, we are tackling the question of whether investing in remanufacturing in the long term is profitable or not for a firm. We aim to suggest policies for PRM by analyzing the system for a long period of time such as 25 years and the time unit is selected as a quarter year. The model tries to give an answer to the following questions: (i) Can investing in remanufacturing be advantageous compared to manufacturing for a company in terms of long term profitability, (ii) If it is advantageous, under what conditions does it incur more profit in the long term, (iii) What are the effects of the product quality and price on the customer base of remanufactured product and the customer base of new product?

2. LITERATURE SURVEY

Although PRM is analyzed in many studies, there are not many studies conducted by using system dynamics approach. The existing ones consider operational processes to analyze the effects of PRM on the environment. Most of them also include legislations and green image factors. Generally, capacity augmentation for remanufacturing or recycling has been also analyzed by considering operational phases and inventory.

Mont *et al.* (2006) develop a PRM model including leasing and reconditioning scheme. The main goal of the study is to make financial analysis by creating the most suitable scenario including leasing and reconditioning scheme and to test its financial viability. In the study, they choose a specific product, baby pram, to investigate due to its three characteristics: (i) it has a high recovery value at the end of its lifecycle, (ii) it has a large secondary market, and (iii) the lifetimes of its modules are very different. The first improvement in the study is redesigning the product to reduce the time spent and cost by choosing suitable modules. Another improvement is about reconditioning of the system which includes education of retailers and avoiding bottleneck resulting from leasing fee. For the firm in the model, the costs are due to transportation, education, information systems. The factors lead to benefit are leasing fee, price of selling after leasing, interest and indirect revenues. The retailer has a critical role in the model since the increase in the resource productivity and the decrease in the waste flows can be provided by the retailer in the system. At the end of the financial analysis for 48 months, the authors deduce that leasing and reconditioning alternative provides more profit per baby pram comparing to traditional sales.

Kerr and Ryan (2001) aim to quantify the life cycle environmental benefits achieved by incorporating remanufacturing into a product system, based on a study of Xerox photocopiers in Australia. They compare the lifecycles of remanufactured and non-remanufactured Xerox based on five parameters: raw materials consumption, energy consumption, greenhouse gas emission, water consumption, and waste going to landfill. The results show that when the product is designed for disassembly and remanufacturing, economic and environmental savings are increased much more than the case where the product is not designed for disassembly and remanufacturing. They also find out that remanufacturing decreases resource consumption and waste to landfill. As a result, it is deduced that design has a very critical role in increasing the economic and environmental benefits of remanufacturing.

Another study has been done by Kamath and Roy (2007) where they propose to provide necessary information to make a decision about capacity augmentation for the short lifecycle products by using system dynamics approach. Firstly, they find the dominant loops for capacity augmentation. At the end of this step, they plan to make decision about capacity augmentation more efficiently by modifying the loop which includes retail sales and production order. In the next step, they make some tests through what-if analyses:

(i) Test #1: It is made for a capacity management structure in which the manufacturer is able to retire/withdraw part of the capacity.

(ii) Test #2: The effect of the initial capacity is analyzed by giving different values for the initial capacity.

(iii) Test #3: Some variations are tried for the important model parameters.

Consequently, they claim that the information feedback based methodology is general enough to be useful in designing decision support systems for capacity augmentation.

Another study about capacity planning is done by Vlachos *et al.* (2007). They suggest making an efficient capacity planning by considering economic and environmental factors such as the take-back obligation imposed by legislation and the green image effect on customer demand. In their study, there are some assumptions: (i) The variation of remanufacturing demand profit is low, (ii) Many products such as printer toners, single cameras and cell phones have supply chain. They evaluate the total supply chain profit as the measurement of policy effectiveness. They also mention three strategies about capacity planning:

(i) Leading Capacity Strategy: The firm can absorb sudden demand oscillations since the excess capacity is used.

(ii) Trailing Strategy: The capacity is fully utilized since it lags the demand.

(iii) Matching Capacity Strategy: The strategy is to match the demand capacity and demand closely over time.

The results of their study show that the leading capacity expansion strategy is the most suitable one if the aim is to develop reverse channel operations. The important point is that this study is done for the capacity planning of a single product reverse supply chain for product recovery. However, they mention that it can be also used for material recycling systems.

The effect of environmental parameters on PRM is also analyzed by Georgiadis and Vlachos (2004). In this study, they analyze the long term-decisions for collection and remanufacturing activities and the environmental effects on product demand in a single product supply chain. Firstly, they examine the effects of the green image awareness of customer, its effects on demand and the effects of environment legislations on the collection rate. Then they compare capacity planning policies as Vlachos et al. (2007) do. Based on the results of the study, it is deduced that the environmental protection increases the collection rate. The increase in the collection rate increases the green image factor and thereby the product demand. Moreover, the part of the study related to strategy comparison shows that while leading and matching remanufacturing capacity adding strategies increase the green image and demand of the product, the trailing strategy has a negative effect on the green image and demand.

The study which is done by Georgiadis and Besiou (2008) has a same modeling approach with the aforementioned study. The main difference is that recycling is adapted to the model instead of remanufacturing. In this paper, the effects of ecological motivation and technological improvements are investigated on the long term behavior of a supply chain of an electrical equipment in Greece. Since reuse index and green image are dependent on the market behavior, they consider four types of behavior based on the response to average landfill: (i) Proportional, (ii) Quick respond in low levels of average landfill (environmental sensitive), (iii) Quick respond in high levels of average landfill, (iv) Quick respond in low and high levels of average landfill. For empirical testing, the data of a Greece firm called Kozani is used. They examine the effects of different legislations such as take-back obligations, lower limit of recycling and lower limit of recyclability on different variables. The results are evaluated to compare the effects of these legislations on different variables. Finally, it is deduced that the market behavior and the legislation called lower limit of recycling have a significant effect on non-renewable material and only lower limit of recycling legislation has an important influence on *sum_disposal* variable which accumulates the products rejected for recycling, controllable disposal and uncontrollable disposal in the model. For the future work, it is suggested that this model can be improved to investigate of the impact of products' price and the economical profit on the environmental management.

The aim of the study done by Georgiadis and Vlachos (2004) aims is to create an integrated forward/reverse logistics model by using system dynamics approach. In the model, there are two decision points. The first decision is made by the user after the end-of-use of used products if the products will be uncontrollably disposed or properly collected. The second one is made by the manufacturer if a specific item will be reused or not-made by collector based on their profitabilities. The model is constructed under some assumptions: (i) The amount of the demand is constant. (ii) A penalty can be applied due to the environmental legislation. (iii) Manufacturing rate is limited. (iv) The remanufacturing cost is dependent on the capacity. The model is run for 7 different penalty levels, which is expressed as percentage of the production cost, under 9 scenarios for the remanufacturing capacity. Based on the results, it is deduced that the uncontrollable disposal is eliminated when the penalty level is high. Moreover, when the remanufacturing capacity is augmented, the total cost including remanufacturing and production increases due to the initial investment and thereby penalty increased. However, when remanufacturing capacity reaches a certain value, the unit cost decreases. The results are also similar for different penalty levels given in the study.

Poles and Cheong (2009) analyze the relationship between the factors which affect the uncertainty of return rates like return index and residence time since the uncertainty makes optimizing the cost of the operations difficult. Uncertainties in quantity, quality and timing of returns, which negatively affect remanufacturing activities, is defined through the relationships of these factors (residence time and return index) which can provide a correlation between demand and returns. The numerical investigation is done for 6 combinations including 3 different residence time and 2 different remanufacturing batches.

They conclude that total production cost, residence time and return index have more effect on production and stock activities than the effects of firm's strategy. Therefore, the residence time which leads to the lowest production cost should be aimed. Moreover, it is also deduced that the customer behavior and the product characteristics which influence the uncertainty of returns also have an effect on the production cost. Therefore, the incentives such as lease contacts, product service agreements with the customer and marketing/promotion programs for returned products to recover used products, can improve the control on the residence time and the return rate by affecting the customer behavior.

3. OVERVIEW OF THE MODEL

3.1. General Information and Overview of the Model

The model is constructed for company in the electronical industry which is everchanging and has a high competitive environment.

It is assumed that the company is one of the top companies as having 20% marketshare. The marketshares of the other companies which have a corner on the market are also between 10% and 25%. There are two types of products of the company available: new product (NP) and remanufactured product (RP). It has manufactured computers for a long time so it has a huge potential customer base buying its new products. On the other hand, it has just started remanufacturing and it has a small amount of potential customer base for RP with the contribution of its advertisements and its brand image. Therefore, it has a competition in two markets: NP market and RP market.

The companies in these markets have some common characteristics to comply with the rapidly changing technology. All firms are flexible to increase or decrease their capacities to satisfy the demand. On the other hand, all of them collect only their own products for remanufacturing.

In the NP market, the customers are sensitive to the prices and the qualities of the products. In the model, it is assumed that the firm adjusts its NP price to the average NP price in the market. Therefore, the price is not a factor differantiating the company from the others in the new product market in this model. The customers are also sensitive to the qualities of the products in the new product market. Therefore, it has an important role on the competition in the market.

Similarly, the firm adjusts its RP price to the average RP price in the market and the customers are sensitive to the prices and the qualities of the products.

The competition takes place not only between the companies in the market but also between the RP and NP of the company. Therefore, the quality and price of the products also have a significant role in this competition and this competition determines the behavior of the system. The causal loop diagram shown in Figure 3.1 includes the internal system of the company.

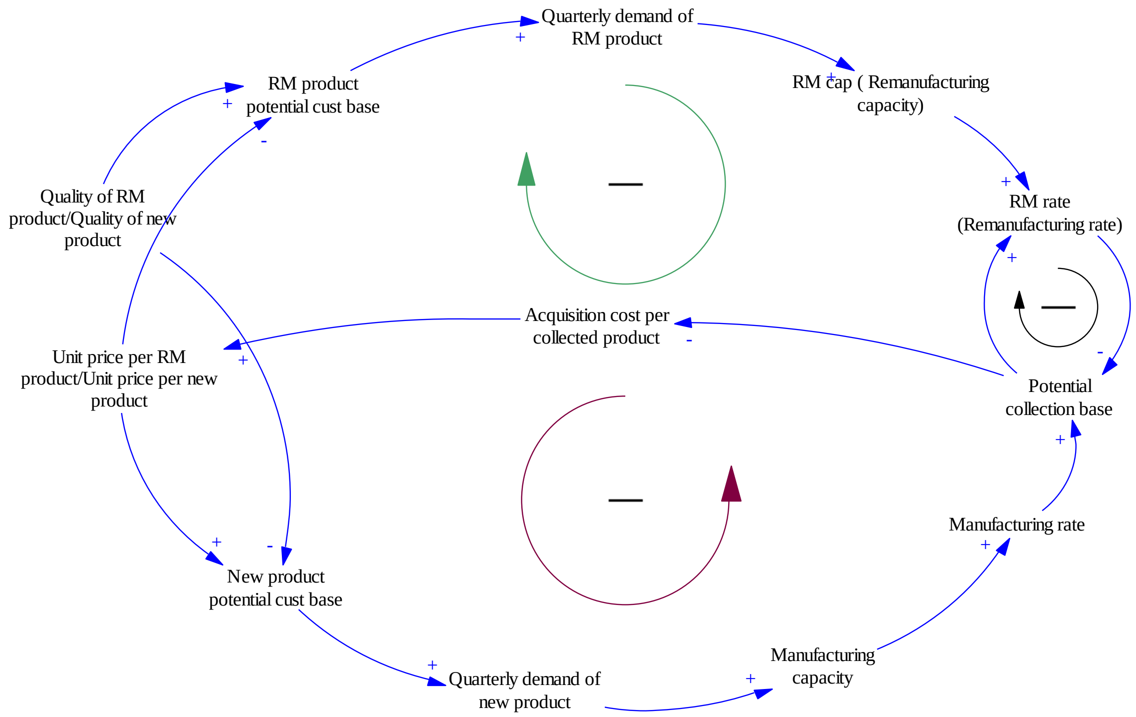

Figure 3.1. Basic causal feedback loop of the firm.

There are two types of customer base of the company: NP potential customer base and RP potential customer base, which show the amount of the customers to prefer those products. The causal loop diagram above explains the behavior of the NP and RP customers of the company in the long term. At the beginning, if one of these products is more advantageous than the other one for the customers of the company, the advantageous product customer base increases while the other one is decreasing due to the migration of the customers to the advantageous product customer base from the other one. For example, when the RP is more advantageous than NP for the customers, customers migrate from the NP potential customer base to the RP potential customer base. The increase in the RP potential customer base leads to an increase in its quarterly demand and remanufacturing capacity, and thus the remanufacturing rate. The increase in the remanufacturing rate results in an increase in the consumption level of the potential collection base. The potential collection base shows the used product base which can be collected by the company for remanufacturing. Therefore, the decrease in the potential collection base increases the acquisition cost per collected product. The acquisition cost is the unit cost per collected product to be used as a raw material for remanufacturing.

If the system is observed from a different perspective, the decrease in the sales of NP as a result of the migration of customers to the RP potential customer base leads to a decrease in its demand, manufacturing capacity and thereby the manufacturing rate. The decrease in the manufacturing rate results in a reduction in the inflow of potential collection base because the decrease in the sales of NP leads to a decrease in the potential collection base after a while. Therefore, although the demand of RP is high, the decrease in the potential collection base starts to restrict the remanufacturing rate. The consequence is that the RP demand cannot be satisfied. Moreover, the decrease in the potential collection base increases the acquisition cost per collected product and the unit price of RP. Thus, purchasing new products becomes more advantageous for the customers and the migration between the NP and RP potential customer bases change in the opposite direction until the potential collection base reaches a sufficient level to enable remanufacturing to meet the RP demand again.

If the system is observed when NP is more advantageous than RP, the NP potential customer base increases while the RP potential customer base is decreasing. Increase in the NP potential customer base also results in an increase in the quarterly demand of NP. Thus, the company increases its NP manufacturing capacity to satisfy the demand. Since the company produces NP and sells much more, after a while the potential collection base symbolizing the collectable used product of the company increases. Increase in the potential collection base results in a decrease in the acquisition cost per collected product. Therefore, the unit cost and the price of the RP decrease. In this situation, the decrease in the unit price of RP may lead to have a priority for the customers while they are making a preference between the product types. Thus, the loops beginning with the RP potential customer base and NP potential customer base are the most important loops of the model determining the system behavior internally as shown in Figure 3.1.

3.2. Methodology

System Dynamics modeling and simulation methodology is used in this study. According to Barlas (2002), *System dynamics discipline deals with dynamic policy problems of systemic, feedback nature. Such problems arise from the interactions between system variables and from the feedbacks between the managerial actions and the system's reactions. The purpose of a system dynamics study is to understand the causes of a dynamic problem, and then search for policies that alleviate/eliminate them.*

System dynamics is an appropriate approach for this study since the aim is to show the simultaneous effects of several factors on the system behavior and analyze the variables such as customer behavior, sales and profit of the firm in the long run for a different number of scenarios. The behavior of the model showing the internal structure of PRM is dynamic. There is a circular causality between the variables and there are time delays between the causes-effects and actions-reactions. Moreover, the dynamics of the system is hard to predict by intuition since it requires mental simulation of interactions of several loops simultaneously. The cause/effect relations between the variables are not linear. Due to the non-linearity, the problem becomes excessively hard to track – mathematically and intuitively.

As a result, due to the large scale, non-linearity and dynamic feedback characteristics of the problem, the system dynamics approach, which is an appropriate method to analyze the dynamics of the system in the long term by considering the causal feedback loops between variables, is applied to analyze this system.

4. DESCRIPTION OF THE MODEL

The model is explained in detail by splitting the stock-flow diagram into several basic sectors since the size of the model is large. The basic stock-flow diagram sectors:

- Customer base sector
- Manufacturing capacity sector
- Remanufacturing capacity sector
- Unit cost and price of NP sector
- Unit cost and price of RP sector
- Company profit sector

4.1 Customer Base Sector

4.1.1. Background Information

Every company has a potential customer base including loyal customers and the customers who are not loyal but interested in the products of the company. Moreover, the potential customer base of remanufactured computers is also increasing day by day with the environmental consciousness of the computer users. The potential customer bases of the products also increase due to some reasons such as population growth and brand awareness.

Apart from the factors mentioned above, an important factor leading to a change in the customer bases is the competition between the products and the brands. The preference criteria of the customers are generally the price and quality of the products. Based on these factors, the customers prefer RP or NP of the same company. There is a competition also between the NPs of different brands in the market and the RPs of different brands in the market separately. Therefore, a company should consider not only the competition between its own products, but also between the products of the companies in the market.

With the increase in the environmental awareness of the customers, remanufacturing has a positive effect on the company's brand image. Therefore, it can lead to an additional increase in the potential customer base of the company and it is called green image factor.

4.1.2. Fundamental Approach and Assumptions

In the model, it is assumed that the firm has 20% market share in the computer sector. Therefore, the initial customer base is calculated based on the Gartner Group data given in Appendix B and 20% market margin assumption.

The main assumption in the model is that the customers are loyal to the company or the product type (NP/RP). Therefore, the customers cannot change their companies and types of the products which they are used to buy at the same time. In the model, the factors such as quality and price determine the migration rate of the loyal customers between NP and RP potential customer base after a while. Therefore, the effects of the factors on customer migration rate are provided with one year information delay. Apart from the factors leading to a change in the customer base, the green image factor also leads to an increase in the customer base of the company which produces RPs. It leads to an increase not only in the RP but also in the NP potential customer base of the company, since RP potential customer base has an effect on the brand image of the company. However, the increase in the NP potential customer base is not as much as the increase in the RP potential customer base. Therefore, in the model, the fraction of the green image factor effect on NP potential customer base growth is given as half of the fraction of green image factor effect on RP potential customer base growth.

Normally, if the values of the factors determining customer preferences are equal for two competitor products, the customers continue to prefer the same product, which means that there is no migration between the potential customer bases. However, if the prices of the NP and the RP are equal, the customers prefer the NP since the quality perception of the customers on the RP cannot be equal to the NP even if the environment awareness increases. The reason is that the customers know that all the components of the

RPs are not new even if they are not eroded. Therefore, the normal migration fraction is assumed as -0.01 which means that even if the qualities and the prices of NP and RP are equal, there exists a bit migration to NP potential customer base direction due to the bias of the potential customers in the market.

4.1.3. Description of the Sector Structure

The diagram of the sector is also separated into two parts to show the detail of the flows of the potential customer bases which can change due to different types of competition.

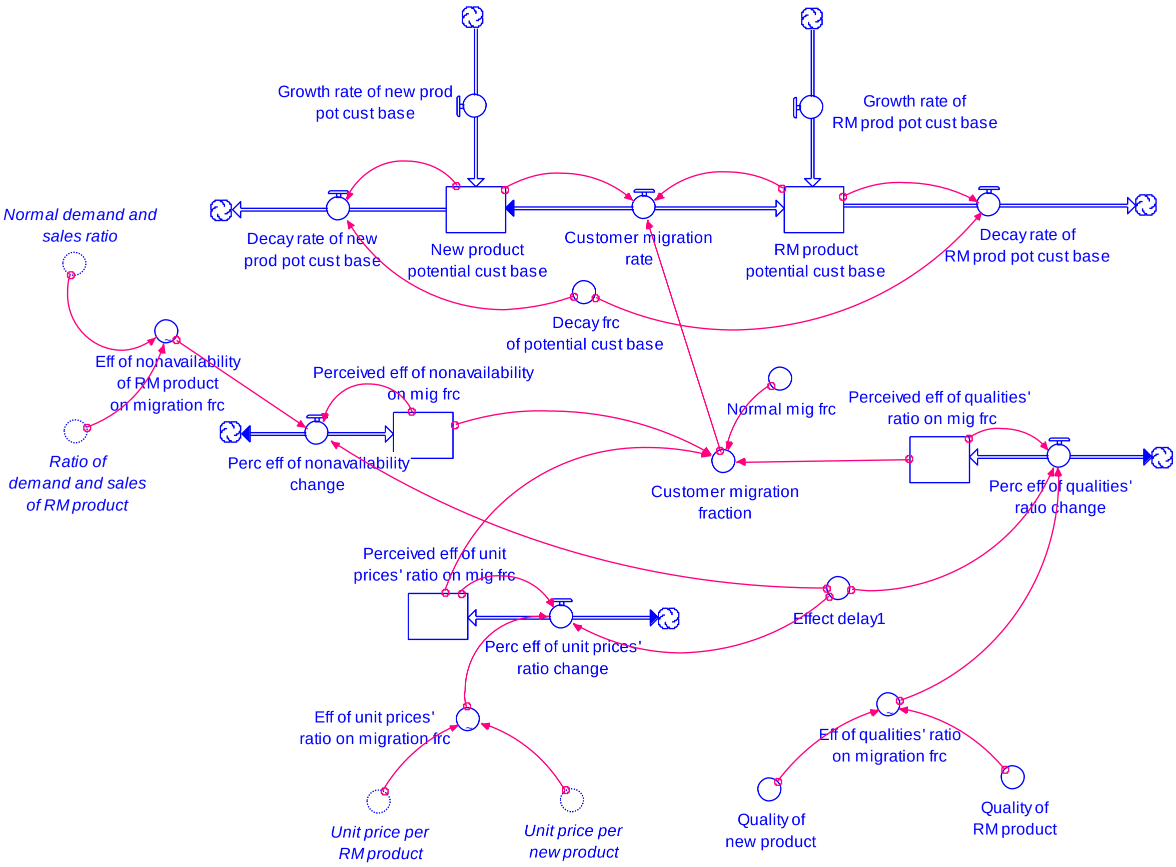

Figure 4.1. Customer migration between the potential customer bases.

In Figure 4.1, based on the assumption that the customers cannot change their companies and types of the products which they are used to buy at the same time, the direct flows are put only between NP and RP potential customer bases and the customer bases of same product types for the firm and market. Although the customers cannot change their firms and products at the same time, the flows provide the migration of the same customer between different firms and types of products potential customer bases in different times.

The migration between the NP potential customer base and the RP potential customer base of the company, which is called *Customer migration rate*, is determined by the additive effects of three factors. These factors resemble the internal competition between the RP and the NP of the same company: (i) the quality ratio of RPs and NPs, (ii) the price ratio of RP and NP, (iii) non-availability of RPs. In the model, the quarterly NP demand can be satisfied, since the company is flexible to increase or decrease its manufacturing capacity. However, although the remanufacturing capacity is also flexible like the manufacturing capacity of the company, quarterly RP demand may not be always satisfied due to the lack of used products which are necessary to produce RPs. Therefore, non-availability of RP is considered as a factor having an effect on the customer migration fraction apart from the quality and price ratios of RPs and NPs. The additive effects determine the customer migration rate indirectly by determining the migration fraction which is called *Customer migration fraction* with a delay since the factors are able to have an effect on the customer behavior after a while. Therefore, the effects of the factors are added after a delay as perceived effects as in Equation 4.1.

$$\begin{aligned}Customer\_migration\_\_fraction = &Perceived\_eff\_of\_qualities'\_\_ratio\_on\_mig\_frc\\ &+Perceived\_eff\_of\_unit\_prices'\_ratio\_on\_mig\_frc\\ &+Perceived\_eff\_of\_nonavailability\_on\_mig\_frc+Normal\_mig\_frc\end{aligned} \qquad (4.1)$$

As given in Equation 4.2, when *Customer migration fraction* which is affected by the quality, price and nonavailability of the RP becomes positive, the customers migrate to the RP potential customer base with a rate determined by the multiplication of *Customer migration fraction* and *New product potential cust base*. On the other hand, when the fraction becomes negative, the RP potantial customers migrate to the NP potential customer base with a rate determined by the multiplication of *Customer migration fraction* and *RM product potential cust base*.

Customer_migration__rate =
New_product_potential_cust_base*MAX(Customer_migration__fraction,0) +
RM_product_potential_cust_base*MIN(Customer_migration__fraction,0) (4.2)

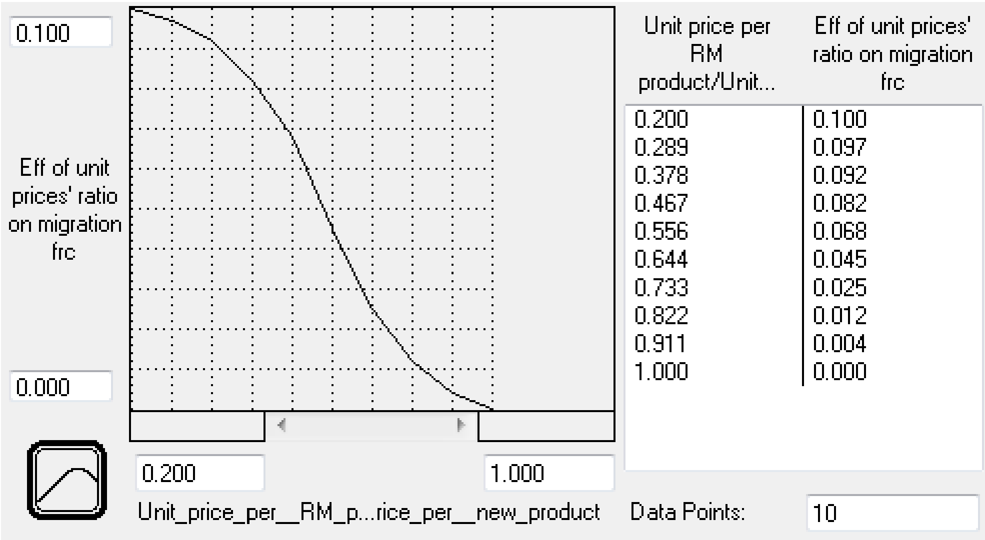

Figure 4.2. Effect of unit price ratio of RP and NP on migration fraction.

Eff_of_unit_prices'_ratio_on_migration_frc =
GRAPH(Unit_price_per__RM_product/Unit_price_per__new_product) (4.3)

As given in Equations 4.3, 4.4 and 4.5, the effects of the factors affecting the customer behavior is generated by nonlinear functions since the sensitivity of the customer behavior is not linear. Based on Figure 4.2 and Equation 4.3, if the unit price per RP is 20% of the unit price of NP, the effect of the unit price ratio on migration fraction is at least equal to 0.1. On the other hand, the price of the RP can be at most equal to the price of the NP to provide the consistency with real life. That is, the unit price of RP cannot exceed the unit price of NP.

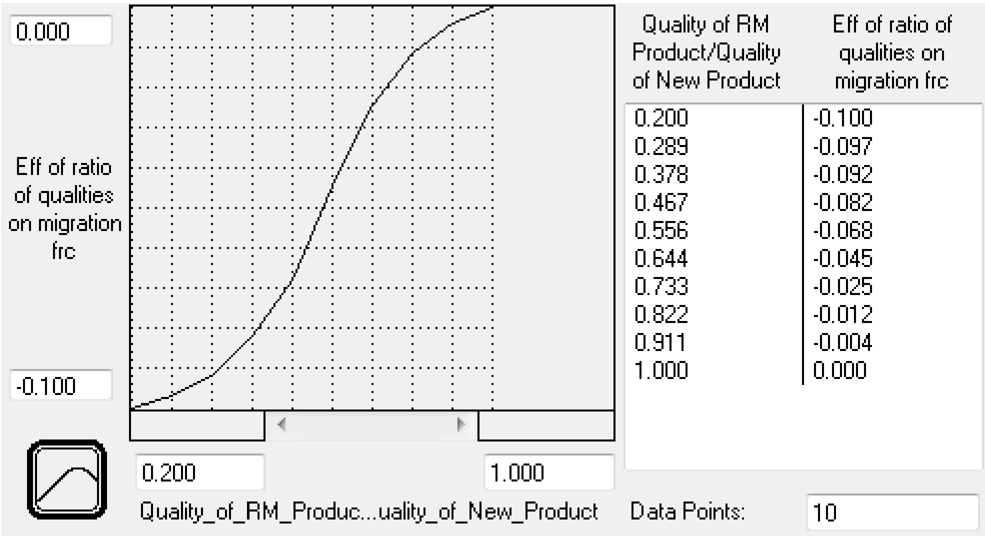

Figure 4.3. Effect of quality ratio of RP and NP on migration fraction.

$$Eff\_of\_qualities'\_ratio\_on\_migration\_frc = GRAPH(Quality\_of\_RM\_product/Quality\_of\_new\_product) \quad (4.4)$$

Based on Figure 4.3 and Equation 4.4, it is provided that the quality of the RP can be at most equal to the quality of the NP. On the other hand, the sensitivity of the customers does not change if the quality of RP is equal to or less than 20% of the quality of the NP. The functions of price and quality effects are exactly the same but opposite of each other since it is assumed that a value of the ratio affects the migration with the same rate but in the opposite direction.

As given in Figure 4.4 depending on Equation 4.5, the non-availability of the RP has a negative effect on the migration fraction when the RP sales is less than the demand, which symbolizes that the demand cannot be satisfied when the RP demand is more than the RP sales. When the demand/sales ratio is one, it shows that the demand can be satisfied. Therefore, in this case, this function does not have an effect on the migration fraction. The ratio can be at least one because the firm aims to satisfy the demand as a goal. Thus, it does not remanufacture more than the demand.

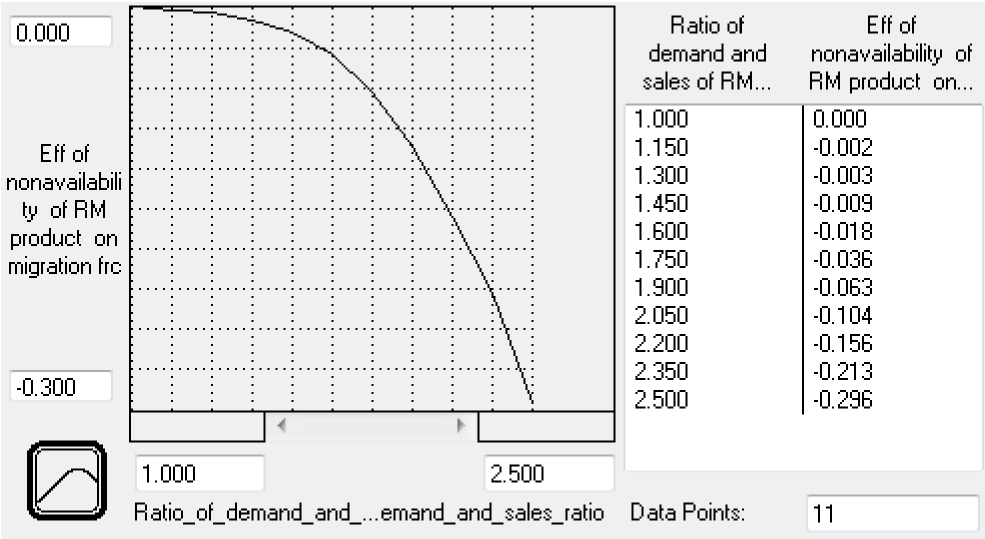

Figure 4.4. Effect of non-availability of RP on migration fraction.

$$Eff\_of\_nonavailability\_\_of\_RM\_product\_\_on\_migration\_frc = GRAPH\ (Ratio\_of\_demand\_and\_sales\_of\_RM\_product/Normal\_demand\_and\_sales\_ratio) \quad (4.5)$$

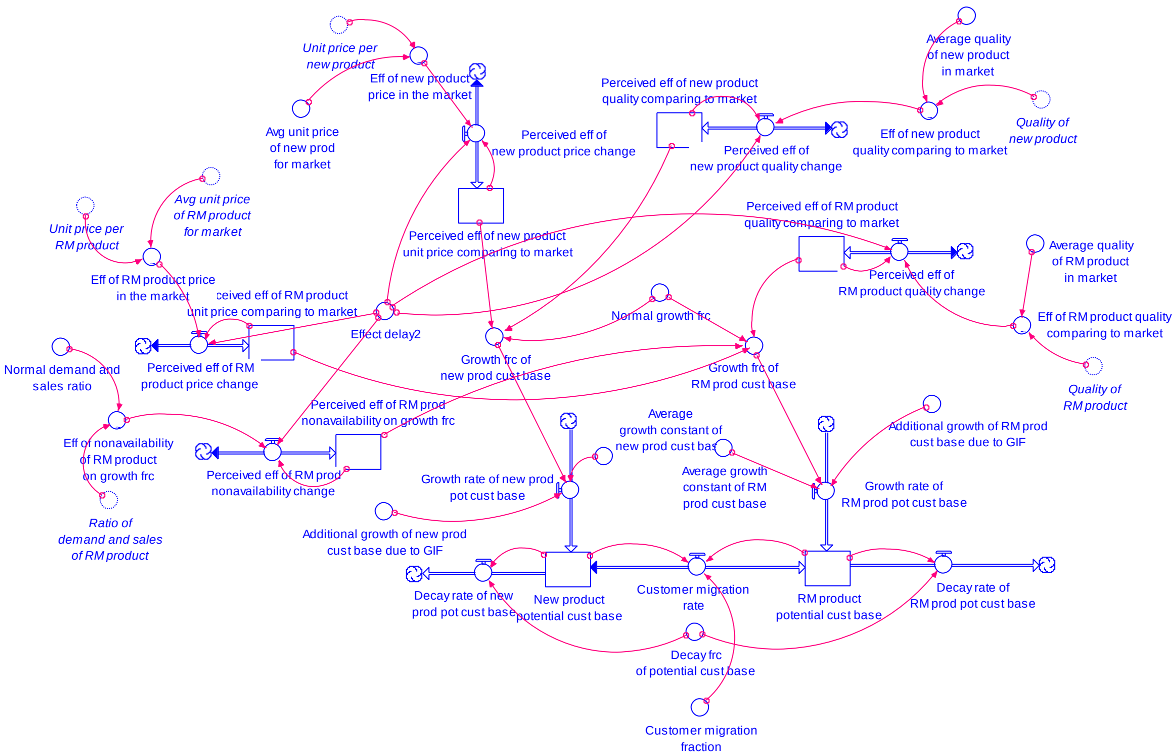

Figure 4.5. The growth rate of NP & RP customer bases.

It is obvious that the competition is not only between RPs and NPs of the same company but also between the RPs and NPs of the company and those of the market. Therefore, the price and quality ratios of NPs of the firm and those in the market determine the migration rate between the NP potential customer base of the firm and that of the market. The customer migration between RP potential customer base of the firm and market is considered in the same fashion as in Figure 4.5.

Growth rate of new prod pot cust base flow includes two types of growth as given in Equation 4.6: (i) a growth due to the effects of the products' characteristics like the quality and the unit price of the products through growth fraction, (ii) an additional growth due to the green image factor effect.

Growth_rate_of_new_prod_pot_cust_base =
Average__growth_constant_of_new_prod_cust_base*Growth_frc_of__new_prod_cust_base+Additional_growth_of_new_prod__cust_base_due_to_GIF (4.6)

The growth due to the product characteristics is shown as Average__growth_constant_of_new_prod_cust_base*Growth_frc_of__new_prod_cust_base. In this case, the additive effects determine the growth fraction of NP potential customer base as perceived effects after a delay as given in Equation 4.7. Then the fraction is multiplied with a constant value, given in Equation 4.8, showing the average growth of the firm per quarter due to having a marketshare in the market.

Growth_frc_of__new_prod_cust_base =
Perceived_eff_of_new_product_unit_price_comparing_to_market+Perceived_eff_of_new_product_quality_comparing_to_market+Normal_growth_frc (4.7)

Average__growth_constant_of_new_prod_cust_base = 100 (4.8)

Similar equations are also created for *Growth rate of RM prod pot cust base* as in Equation 4.9. Additionally, the effect of non-availability of the RP is added when the firm is not able to satisfy the demand of the RP customer (Equation 4.10). Moreover, since the

RP market is not as large as the NP market, the average constant of the RP potential customer base is selected smaller than the constant of the NP as in Equation 4.11.

$$\mathit{Growth\_rate\_of\_RM\_prod\_pot\_cust\_base} = \mathit{Average\_growth\_\_constant\_of\_RM\_\_prod\_cust\_base} * \mathit{Growth\_frc\_of\_RM\_prod\_cust\_base} + \mathit{Additional\_growth\_of\_RM\_prod\_cust\_base\_due\_to\_GIF} \quad (4.9)$$

$$\mathit{Growth\_frc\_of\_RM\_prod\_cust\_base} = \mathit{Perceived\_eff\_of\_RM\_product\_unit\_price\_comparing\_to\_market} + \mathit{Perceived\_eff\_of\_RM\_product\_quality\_comparing\_to\_market} + \mathit{Perceived\_eff\_of\_RM\_prod\_nonavailability\_on\_growth\_frc} + \mathit{Normal\_growth\_frc} \quad (4.10)$$

$$\mathit{Average\_growth\_\_constant\_of\_RM\_\_prod\_cust\_base} = 20 \quad (4.11)$$

As mentioned above, there is also another factor called green image factor which has an effect on *Growth rate of new prod pot cust base* and *Growth rate of RM prod pot cust base* as shown in Figure 4.6.

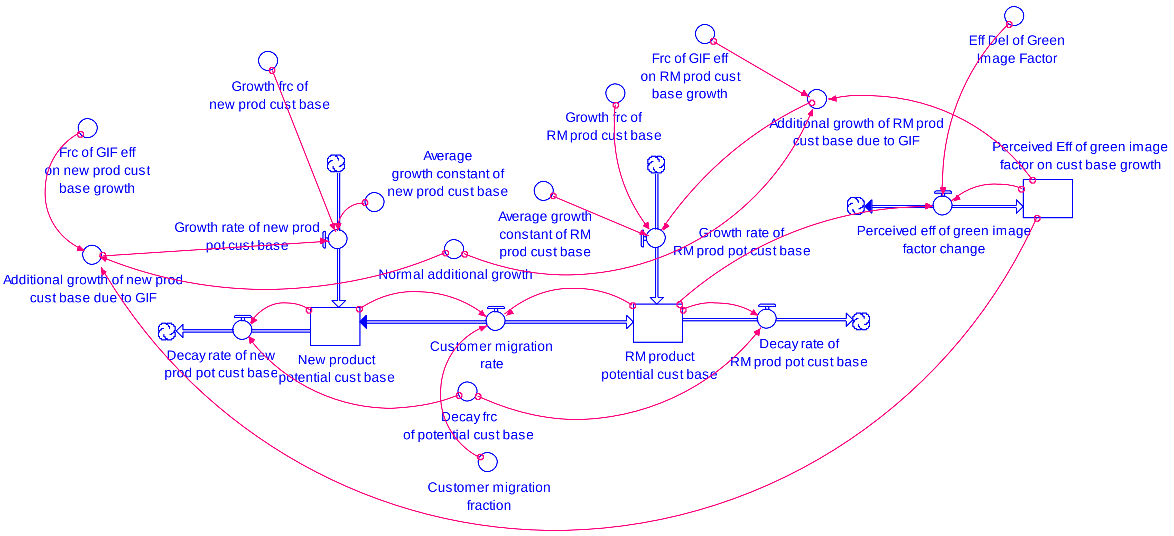

Figure 4.6. The effect of the green image factor on customer base growth.

The green image factor increases not only the RP potential customer base, but also the NP potential customer base of a firm since it has a positive effect on its brand image. Increased awareness of the customers especially makes the green image factor a more significant factor, which increases the migration of the customer rate to the RP potential customer base. However, the green image factor has a larger effect on the increase of the RP potential customer base than the increase of the NP potential customer base of the company. Therefore, the fraction of the green image factor for increasing the inflow of the NP potential customer base is given as nearly half of the fraction for RP potential customer base. The contributions of the green image factor are determined by the multiplication of RP potential customer base with these fractions separately. Then, it increases the inflow rate of the customer bases with an information delay.

For NP, the growth due to the green image factor is shown as *Additional growth of new prod cust base due to GIF* in Equation 4.6. This variable is determined by Equation 4.12. In this equation, *Perceived Eff of green image factor on cust base growth* indicates the effect of the green image factor after a delay. This effect can be named word of mouth. Therefore, the effect of the green image factor is directly shown as the number of the RP potential customer base after a delay. Then it is multiplicated as in Equation 4.12 with the fraction shown in Equation 4.13.

$$\mathit{Additional\_growth\_of\_new\_prod\_\_cust\_base\_due\_to\_GIF} = \mathit{Perceived\_Eff\_of\_green\_image\_\_factor\_on\_cust\_base\_growth} * \mathit{Normal\_additional\_growth} * \mathit{Frc\_of\_GIF\_eff\_on\_new\_prod\_cust\_base\_growth} \quad (4.12)$$

$$\mathit{Frc\_of\_GIF\_eff\_on\_new\_prod\_cust\_base\_growth} = 0.0025 \quad (4.13)$$

The approach is the same for the RP as in Equation 4.14. Differently, the fraction of the green image factor is larger than that of the NP since the green image factor has a larger effect on the potential customers in the RP market when it is compared with the NP market (Equation 4.15). In other words, it can be assumed that the potential customers of RP are more sensitive on the green image of the firm compared with the NP potential customers.

$$\mathit{Additional\_growth\_of\_RM\_prod\_cust\_base\_due\_to\_GIF} = \mathit{Perceived\_Eff\_of\_green\_image\_\_factor\_on\_cust\_base\_growth} * \mathit{Normal\_additional\_growth} * \mathit{Frc\_of\_GIF\_eff\_on\_RM\_prod\_cust\_base\_growth} \quad (4.14)$$

$$Frc\_of\_GIF\_eff\_on\_RM\_prod\_cust\_base\_growth = 0.005 \qquad (4.15)$$

As a result, the potential customer base of each product type determines the quarterly demand of each product type by being multiplied with *Demand per quarter per person*.

4.2. Manufacturing Capacity Sector

4.2.1. Background Information

The firm is flexible to change its capacity based on demand forecasting. The capacity is increased or decreased by comparing the current capacity with the sales forecasting result. In the model, the demand is forecasted by analyzing the demand amount in the previous periods since the sales are assumed to be equal to the demand.

4.2.2. Fundamental Approach and Assumptions

In real life, the companies do not decide to apply capacity investment/expansion or capacity disposal/reduction decision suddenly. Moreover, the adjustment of the capacity reduction takes longer time than the adjustment of the capacity expansion. Therefore, in the model, the delay order of the capacity reduction adjustment is higher than the delay order of the capacity expansion adjustment.

In the model, the firm aims to satisfy the NP demand. Therefore, the NP manufacturing capacity is arranged based on the demand forecasted. The demand which may not be satisfied in a short time during capacity arrangement is not considered in the model since the capacity reaches the demand in a short time which can be disregarded.

The weekly inventories are not considered in the model since the model is created in macro level and the time intervals are determined as a quarter. Therefore, it is assumed that the manufacturing rate is equal to the sales of the NP. In other words, all the NPs produced are sold in a quarter.

4.2.3 Description of the Sector Structure

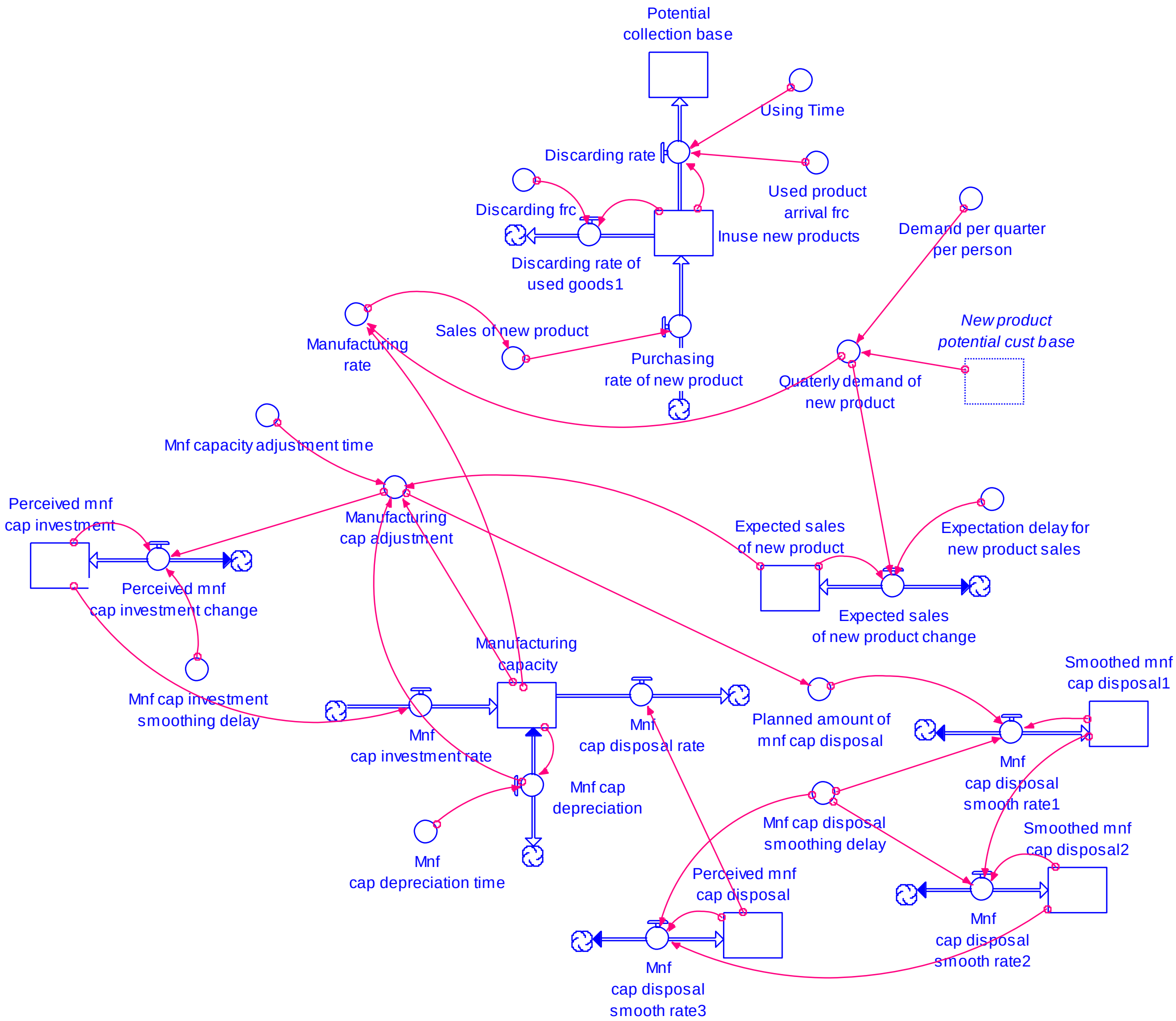

Figure 4.7. Manufacturing capacity sector.

Quarterly demand of the NP, which is determined by the NP potential customer base in Equation 4.16, is used to determine the expected sales of the NP.

$$Quaterly\_demand\_of\_\_new\_product = New\_product\_potential\_cust\_base*Demand\_per\_quarter\_per\_person \quad (4.16)$$

Since the company has a flexible capacity to satisfy the demand, the decision about the capacity change is applied to reach the goal, which is the expected sales of the NP. Then, the depreciation amount of the manufacturing capacity, which shows the decrease in the manufacturing capacity in the last quarter, is added as in Equation 4.17.

$$Manufacturing\_cap\_adjustment = (Expected\_sales\_of\_new\_product - Manufacturing\_capacity)/Mnf\_capacity\_adjustment\_time + Mnf\_cap\_depreciation \quad (4.17)$$

If the expected sales are more than the current manufacturing capacity, the company decides to invest in manufacturing capacity expansion. Thus, it is shown as the inflow of manufacturing capacity stock as *Mnf cap investment rate.* If the expected sales amount is less than the current capacity, it reflects to the outflow of manufacturing capacity as *Mnf cap disposal rate.*

The important point while applying the adjustment for expansion or reduction is that the adjustment of capacity reduction takes more time than the adjustment of capacity expansion since in real life the decision period of the companies for increasing capacity is shorter than the decision period of decreasing it. Therefore, the adjustment time of reduction is assumed longer in the model by adding a higher information delay to the adjustment time for the effect of reduction adjustment. As a result *Manufacturing capacity* is determined as in Equation 4.18.

$$Manufacturing\_capacity(t) = Manufacturing\_capacity(t - dt) + (Mnf\_\_cap\_investment\_rate - Mnf\_cap\_disposal\_rate - Mnf\_cap\_depreciation) * dt \quad (4.18)$$

The minimum of the current manufacturing capacity determined by the expected sales of the NP, and the quarterly demand of NP determines the rate of manufacturing. Therefore, the capacity reaches the demand even though there is a delay. The minimum of *Manufacturing capacity* and *Expected sales of new product* determines *Manufacturing rate* as in Equation 4.19.

$$Manufacturing\_rate = MIN(Manufacturing\_capacity,Quaterly\_demand\_of\_\_new\_product) \quad (4.19)$$

The products sold are used by the customers approximately 3 years and then some of them are transferred to the potential collection base stock as used products while the rest of them are being discarded by the customers without informing the firm. During this residence or usage time, the NPs sold are stocked in *Inuse new products* stock. In real life, when the users change their computers with the new ones, their used computers are discarded by themselves or collected by the company to be used for remanufacturing. Therefore, some percentage of in-use products transferred to *Potential collection base* stock after a usage time by the customers and this percentage is renamed as *Used product arrival frc* as in Equation 4.20.

$$Discarding\_rate = Inuse\_new\_products*Used\_product\_arrival\_frc/Using\_Time \quad (4.20)$$

4.3. Remanufacturing Capacity Sector

4.3.1. Background Information

Comparing to manufacturing, remanufacturing has one more constraint since used product is needed as a raw material. Therefore, firms starting to remanufacture give importance to the PRM to be able to provide raw material to satisfy the demand. In the base case of the model, only the used products of the same firm can be collected for remanufacturing.

4.3.2. Fundamental Approach and Assumptions

Similar to the NP, it is assumed that all RPs are sold in a quarter period. Therefore, the inventory of the goods which will be sold in a quarter is not considered for the RPs. About collecting used products as a raw material, there can be different scenarios such as the firm can collect only its own used products due to a restriction or its preference, or it can collect also other firms’ used products. In this model, it is assumed that the firm can collect only its own used product for remanufacturing in the base case. The reason of this assumption is that using other firms’ products or components can be a risky strategy for big companies which have already proved their qualities to the customers. The other possible reason is that the profitable strategies are eventually started to be used by the companies to continue their existence in the competitive environment. In this case, the priority should be owned by the producer company. Thus, it generates a constraint for the companies especially which have a corner in the market and sell high volume products, since the number of the used products are dependent on the new products sold. Therefore, these reasons restrict the collection availability of the firm. Although this assumption is accepted for the base case, the opposite assumption which is that the firms can collect also other firms’ used products will be analyzed in the study since the raw material problem can restrict the remanufacturing rate considerably.

For remanufacturing, it is assumed that each used product can be used as a raw material for remanufacturing only once since the computer technology improvement is very fast and the components’ versions change fast. Moreover, at the second time, the corrosion in the used product is much more. Therefore, the RPs are not collected again after the usage of the customers.

4.3.3. Description of the Sector Structure

Similar to the manufacturing capacity, the remanufacturing capacity called *RM cap* is also adjusted depending on the current remanufacturing capacity to reach the expected sales of the RP. The depreciation is also considered for the remanufacturing capacity as in Equation 4.21.

$$\mathit{Remanufacturing\_\_cap\_adjustment} = (\mathit{Expected\_sales\_of\_RM\_Product} - \mathit{RM\_cap})/\mathit{RM\_cap\_adjustment\_time} + \mathit{RM\_cap\_\_depreciation} \qquad (4.21)$$

Different from the manufacturing rate, *RM rate* is restricted by *Potential amount of collectable product* additionally. Therefore, the minimum of *RM cap*, *Quarterly demand of*

RM product and *Potential amount of collectable product* determines *RM rate* as in Equation 4.22. The reason is that even if the capacity can satisfy the quarterly demand at that time, if there is no sufficient collectable used product, the firm cannot produce RP to satisfy the demand. Therefore, the expected sales are also determined not only by quarterly demand of RP but also by potential amount of collectable product. By this way, the excessive capacity is also avoided because it avoids the excessive increase in the remanufacturing capacity (Equation 4.23 and Equation 4.24).

$$RM\_rate = MIN(RM\_cap, Potential\_amount\_of\_\_collectable\_product, Quarterly\_demand\_of\_\_RM\_product) \quad (4.22)$$

$$Expected\_sales\_of\_RM\_Product(t) = Expected\_sales\_of\_RM\_Product(t - dt) + (Expected\_sales\_of\_RM\_product\_change) * dt \quad (4.23)$$

$$Expected\_sales\_of\_RM\_product\_change = (MIN(Potential\_amount\_of\_\_collectable\_product, Quarterly\_demand\_of\_\_RM\_product)-Expected\_sales\_of\_RM\_Product)/Expectation\_delay\_for\_RM\_product\_sales \quad (4.24)$$

The ability to collect used products can change from company to company. In other words, each company may not be able to collect all of the potential collection base due to its abilities. Therefore, *Potential amount of collectable product* in the model is found by the multiplication of *Potential collection base* and *Collection ability level* as given in Equation 4.25. In the model, *Potential amount of collectable product* and *Collection rate* symbolize different things. *Potential amount of collectable product* symbolizes the used product amount which can be collected for the remanufacturing rate. However, *RM rate* may be less than *Potential amount of collectable product* since it is determined based on the Equation 4.22. Therefore, *Collection rate* symbolizing the real collection amount is determined by the minimum of the potential amount of collected used product and the estimated remanufacturing rate as in Equation 4.26.

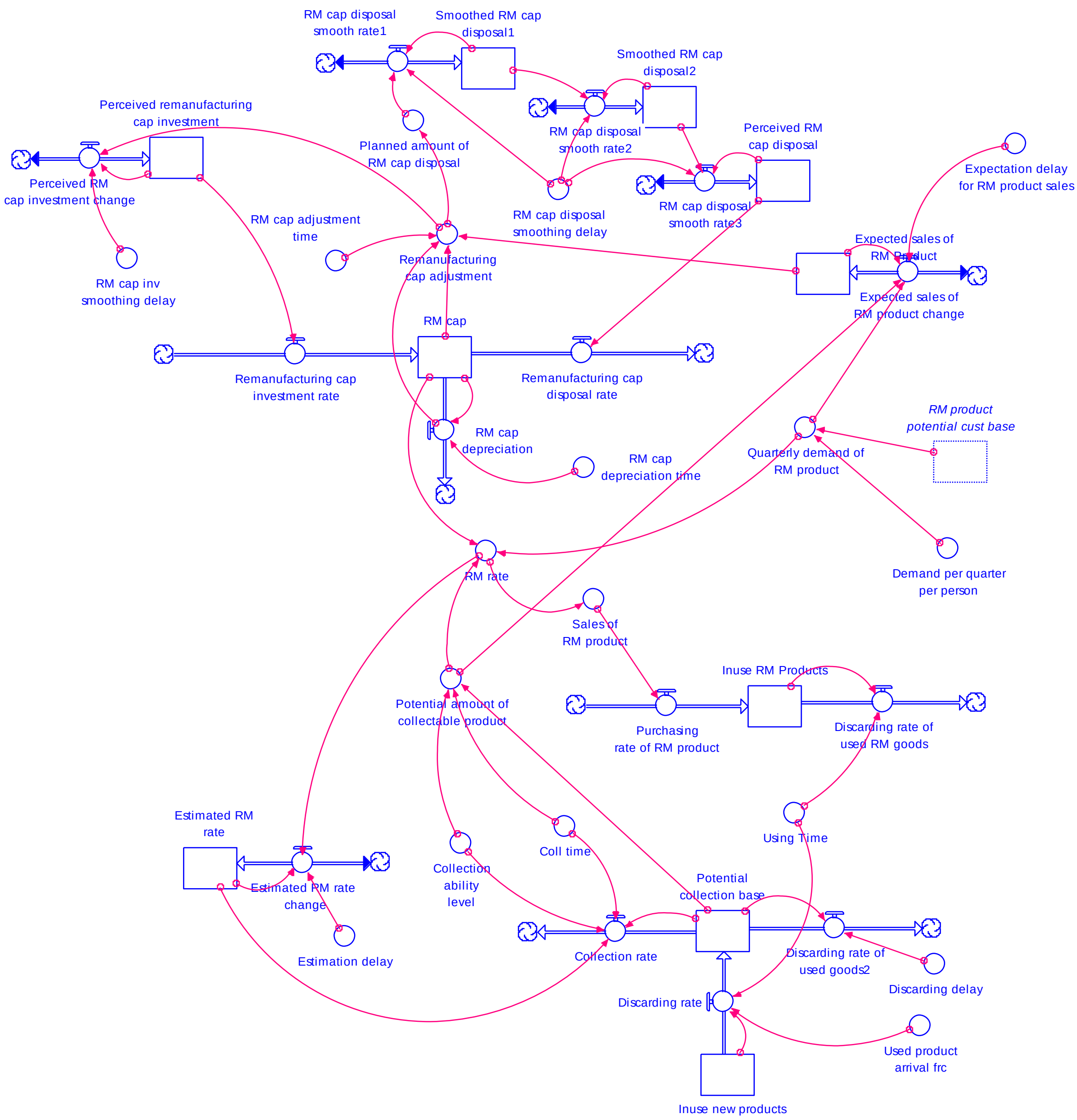

Figure 4.8. Remanufacturing capacity sector.

$$Potential\_amount\_of\_\_collectable\_product = Potential\_collection\_base*Collection\_ability\_level/Coll\_time \quad (4.25)$$

$$Collection\_rate = MIN(Potential\_collection\_base*Collection\_ability\_level/Coll\_time, Estimated\_RM\_\_rate) \quad (4.26)$$

Potential collection base includes the used products which are potential for collection. Therefore, it does not have an inventory cost for the company since the products are not collected. To minimize the inventory cost, the amount of used product which will be collected is determined by estimating the remanufacturing rate. However, due to other constraints of the remanufacturing rate such as quarterly demand of RP and remanufacturing capacity, the amount which will be used can be lower than the amount of estimated. In this case, to avoid waste of used products unnecessarily, *Potential amount of collectable product* is used as a constraint for remanufacturing rate. Then, the estimated remanufacturing rate is determined by the remanufacturing rate identified by the minimum of the remanufacturing capacity, potential amount of collectable product and quarterly demand of RP. Minimum of estimated remanufacturing rate and potential amount of collectable product determines the actual collection rate.

On the other hand, the products which cannot be collected from the potential collection base during a quarter are assumed as invaluable products since they become out of date or depreciate and they don't have the same quality with the products which are just discarded into the potential collection base. Therefore, *Potential collection base* stock has also an outflow called *Discarding rate of used goods2* to symbolize this discard (Equation 4.27).

$$Potential\_collection\_base(t) = Potential\_collection\_base(t - dt) + (Discarding\_rate - Collection\_rate - Discarding\_rate\_of\_used\_goods2) * dt \quad (4.27)$$

It can be observed that the potential amount of collectable used product is an additional constraint determining remanufacturing rate apart from the remanufacturing capacity and the expected sales of the RP. Therefore, the potential amount of collectable used products is a critical constraint for remanufacturing rate. The reason is that even if the demand increases, there are some cases in which the demand cannot be satisfied due to the insufficient amount of collectable used products and/or remanufacturing capacity. In this case, the effect function of non-availability of RP on migration fraction, of which input is ratio of demand and sales of RP, leads to a decrease in the advantage of RP and the customer migration rate in the same direction or it may even change its direction depending on the effects of quality and price ratios, because if the demand is not satisfied, after a while it leads to a customer migration to the other product customer base in real life. Therefore, it is the most important negative loop which balances the system.

4.4. Unit Cost and Price of New Product

4.4.1. Background Information

Unit cost of NP includes fixed manufacturing cost and additional cost. Fixed manufacturing cost in the model includes energy consumption, raw material and collection cost per product. The additional cost changing the unit cost is the reflection of the depreciation of the manufacturing capacity.

The companies generally determine the prices of their products by adding some percent of the cost on the unit cost. Therefore, the price changes when the unit cost of the product changes.

4.4.2. Fundamental Approach and Assumptions

The values of the unit costs in the model are found based on the Gartner Group data for US, 2009 value as given in Figure 4.9.

Generally, for electronic products, the profit margin is nearly 10% of the unit cost. Therefore, the unit cost of the NP is found by considering this percentage.

The additional cost for the NP unit cost is the reflection of the manufacturing capacity depreciation per NP.

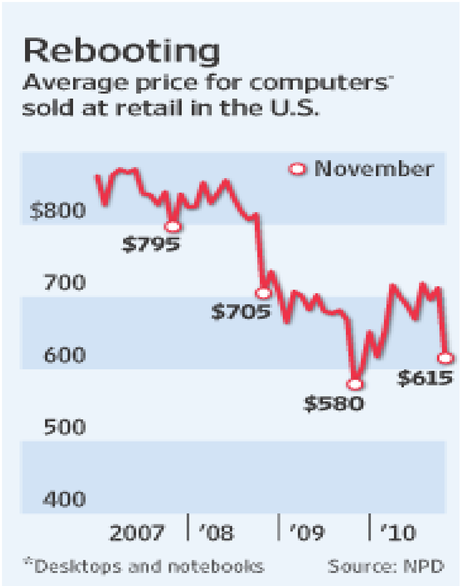

Figure 4.9. Average price of computers sold in the U.S. (2007-2010).

4.4.3. Description of the Sector Structure

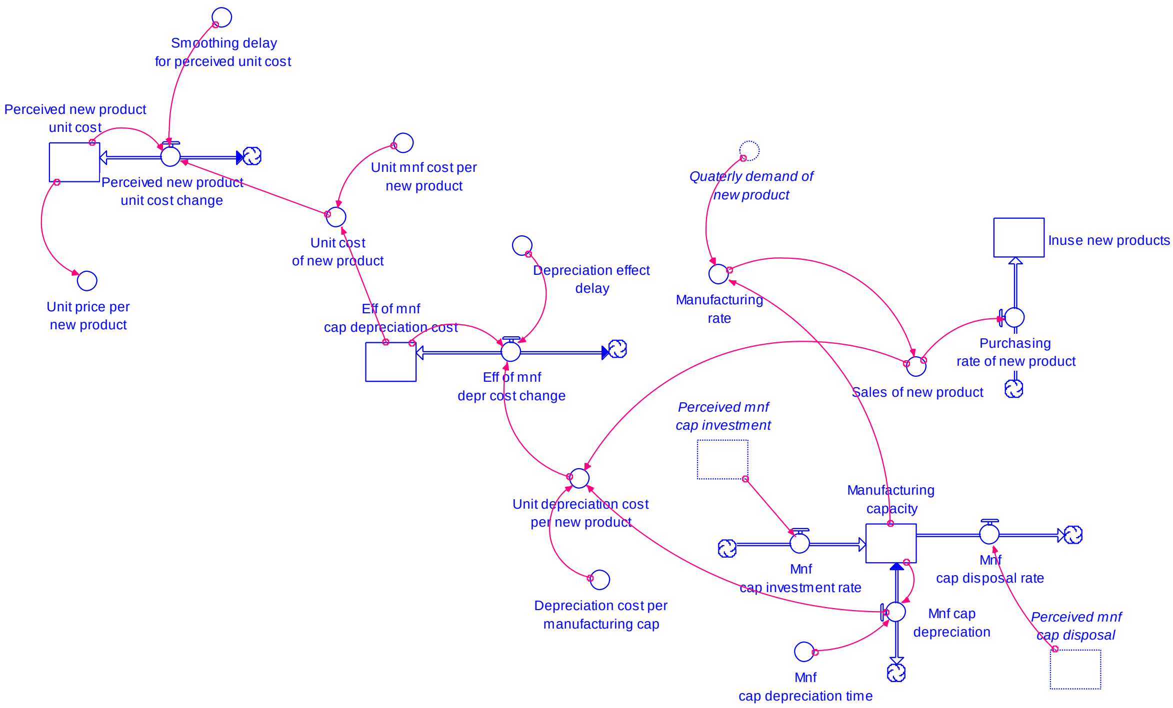

Figure 4.10. Unit cost & price of NP sector.

In Figure 4.10, *Unit cost of new product* is determined by the addition of *Unit mnf cost per new product* and *Eff of mnf cap depreciation cost* which symbolizes the reflection of *Unit depreciation cost per new product* after a delay as given in Equation 4.28, 4.29 and 4.30.

$$Unit\_cost\_of\_new\_product = Unit\_mnf\_cost\_per\_\_new\_product + Eff\_of\_mnf\_cap\_depreciation\_cost \quad (4.28)$$

$$Eff\_of\_mnf\_cap\_depreciation\_cost(t) = Eff\_of\_mnf\_cap\_depreciation\_cost(t - dt) + (Eff\_of\_mnf\_depr\_cost\_change) * dt \quad (4.29)$$

$$Eff\_of\_mnf\_depr\_cost\_change = (Unit\_depreciation\_cost\_\_per\_new\_product - Eff\_of\_mnf\_cap\_depreciation\_cost)/Depreciation\_effect\_\_delay \quad (4.30)$$

The sum of the energy consumption cost and the raw material cost per NP is shown as *Unit mnf cost per new product* as given in Equation 4.28 instead of considering them one by one in detail since their addition is constant.

The firm determines the unit price per NP by putting 10% profit margin on *Perceived new product unit cost*, which symbolizes *Unit cost of new product* after a delay. Therefore, unit price per NP changes with the change of unit cost of NP after a first order delay as in Equation 4.31.

$$Unit\_price\_per\_\_new\_product = Perceived\_new\_product\_unit\_cost * 1.1 \quad (4.31)$$

4.5. Unit Cost and Price of Remanufactured Product

4.5.1. Background Information

The unit cost of the RP includes the fixed remanufacturing cost, the collection cost per RP and the reflection of depreciation cost per unit RP. The fixed remanufacturing cost in the model includes the energy consumption and the raw material cost. Additionally, the acquisition cost per collected used product and the cost of depreciation per RP are considered while determining the unit cost of the RP.

4.5.2. Fundamental Approach and Assumptions

The unit cost of the RP is assumed by the unit cost of the NP determined based on Gartner Group report as in Figure 4.9. Mitra and Webster (2007) also mention that RP cost is 40-65% lower than NP cost. Based on this information, the average percentage of 40% and 65% is taken and the unit cost of RP is assumed as 50% lower than the unit cost of NP.

It is also mentioned that RP price is 30-40% lower than NP price. Based on the values and percentages taken from these resources, the profit margin of RP is found nearly 30% of the unit cost of RP for the base case.

4.5.3. Description of the Sector Structure

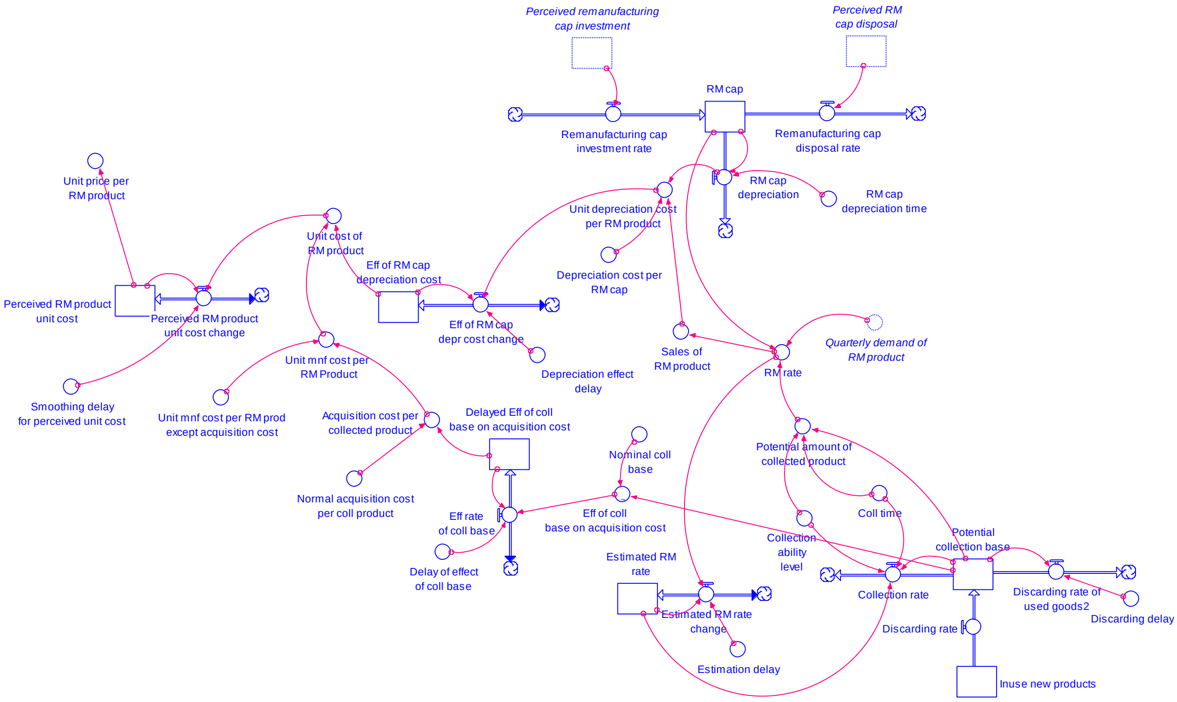

Figure 4.11. Unit cost & price of RP sector.

Unit cost of RM product is determined by the addition of *Unit mnf cost per RM Product* and *Eff of RM cap depreciation cost* as in Equation 4.32. *Unit depreciation cost per RM product* is reflected by dividing the total cost of depreciation per quarter to the sales in that period as in Equation 4.33. A constant value is also given as 30 for the extreme cases since the all depreciation cost is not reflected to the unit cost even if the sales are not so much.

Unit_cost_of__RM_product =
Unit_mnf_cost_per__RM_Product+Eff_of_RM_cap__depreciation_cost (4.32)

Unit_depreciation_cost_per_RM_cap =
*MIN(30,RM_cap__depreciation*Depreciation_cost_per_RM_cap/MAX(Sales_of_RM_product,1))* (4.33)

Unit mnf cost per RM Product is assumed as the sum of the energy consumption cost per RP, the raw material cost per RP and the acquisition cost per collected used product. Although the energy consumption cost and the raw material cost per unit product are constant, the acquisition cost per unit collected used product may change depending on the ratio of *Potential collection base* and *Nominal coll base*. Therefore, *Unit mnf cost per RM prod except acquisition cost* is shown as a constant value symbolizing the sum of the energy consumption cost per RP and the raw material cost per RP. As a result, *Unit mnf cost per RM Product* is calculated as given in Equation 4.34.

Unit_mnf_cost_per__RM_Product =
Unit_mnf_cost_per_RM_prod_except_acquisition_cost+Acquisition_cost_per_collected_product (4.34)

Acquisition cost per collected product increases or decreases based on the assumption that if the potential collection base falls below the nominal collection base, which is assumed as a reference value, the acquisition cost per collected used product increases after a while. If the potential collection base increases and exceeds the nominal collection base, it leads to a decrease in the acquisition cost per collected used product as in Figure 4.12 and Equation 4.35.

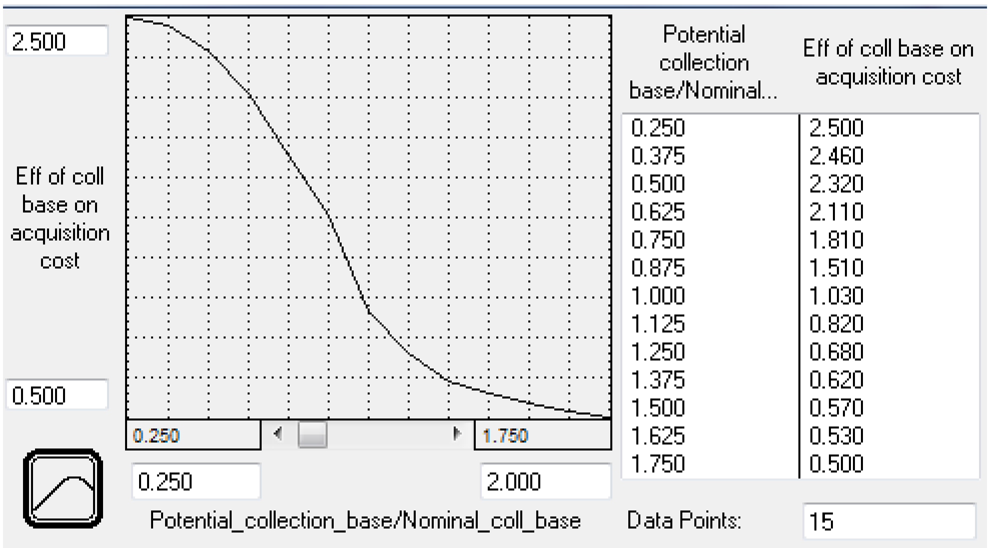

Figure 4.12. The effect function of potential collection base/nominal collection base on acquisition cost per collected product.

$$Eff\_of\_coll\_base\_on\_acquisition\_cost = GRAPH(Potential\_collection\_base/Nominal\_coll\_base) \quad (4.35)$$

The firm determines *Unit price per RM product* by putting 30% profit margin on *Unit cost of RM product* after a first order delay. Therefore, the unit price per RP changes with the change of *Perceived RM product unit cost* (Equation 4.36, 4.37 and 4.38).

$$Unit\_price\_per\_\_RM\_product = Perceived\_RM\_product\_unit\_cost*1.3 \quad (4.36)$$

$$Perceived\_RM\_product\_unit\_cost(t) = Perceived\_RM\_product\_unit\_cost(t - dt) + (Perceived\_RM\_product\_unit\_cost\_change) * dt \quad (4.37)$$

$$Perceived\_RM\_product\_unit\_cost\_change = (Unit\_cost\_of\_\_RM\_product - Perceived\_RM\_product\_unit\_cost)/Smoothing\_delay\_for\_perceived\_unit\_cost \quad (4.38)$$

4.6. Company Profit Sector

4.6.1. Background Information

The profit of the firm is determined by the subtraction of the total expenditures from the incomes of the product sales. Then the total profit of the firm is determined by the subtraction of the corporation tax from the company profit. Moreover, the tax credit, which has been applied as a government incentive for the investment on the remanufacturing capacity expansion, is subtracted from the total profit.

4.6.2. Fundamental Approach and Assumptions

Depending on the government incentive, 20% of the investment cost of the remanufacturing capacity expansion is subtracted from the corporation tax.

4.6.3. Description of the Sector Structure

Based on Equation 4.39 and 4.40 used in Figure 4.13, the total profit of the firm is calculated by the subtraction of the tax credit from the addition of the profit from NPs and RPs.

*Total_profit(t) = Total_profit(t - dt) + (Total_profit_rate_per_quarter) * dt*
INIT Total_profit = 0 (4.39)

Total_profit_rate_per_quarter =
(Profit_rate_of_RM_per_quarter+Profit_rate_of_manufacturing_per_quarter)-
*(((Profit_rate_of_RM_per_quarter+Profit_rate_of_manufacturing_per_quarter)*Tax_percent)-Tax_credit_for_investment)* (4.40)

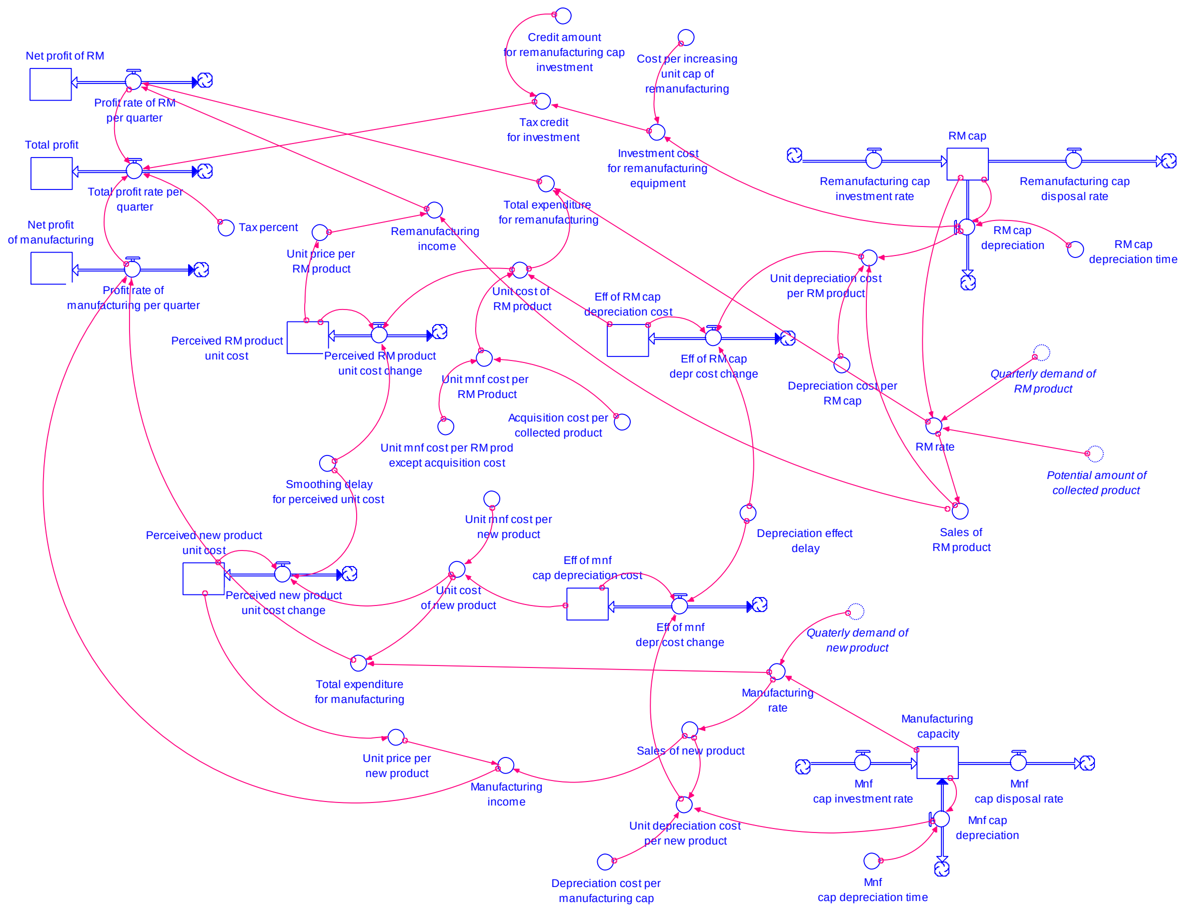

Figure 4.13. Total profit of the firm sector.

*Tax_credit_for_investment = Investment_cost_for_remanufacturing_equipment*Credit_amount_for_remanufacturing_cap__investment* (4.41)

In Equation 4.40, the tax credit and the incentive amount for the remanufacturing are subtracted while calculating the total profit since the tax is subtracted from the total profit of the firm in real life. Therefore, *Net profit of RM* and *Net profit of manufacturing* do not include the subtraction of the tax credit or the government incentive. The profit of manufacturing is calculated as in Equations 4.42, 4.43, 4.44 and 4.45. The profit of remanufacturing is also calculated with same approach.

*Net_profit__of_manufacturing(t) = Net_profit__of_manufacturing(t - dt) + (Profit_rate_of_manufacturing_per_quarter) * dt* (4.42)

$$Profit\_rate\_of\_manufacturing\_per\_quarter = Manufacturing\_income - Total\_expenditure\_\_for\_manufacturing \quad (4.43)$$

$$Total\_expenditure\_\_for\_manufacturing = Manufacturing\_rate * Unit\_cost\_of\_new\_product \quad (4.44)$$

$$Manufacturing\_income = Sales\_of\_new\_product * Unit\_price\_per\_\_new\_product \quad (4.45)$$

5. ANALYSIS AND VALIDATION OF THE MODEL

5.1. Analysis of the Behavior of the Model

In the analysis of the base case, the quality of the NP and RP of the market are set to the same values as those of the firm. The reason is that the customer migration between the customer bases of the firm determines the behavior of the internal system.

As mentioned in the model description, the customer behavior is determined by the effect of quality and price ratios of the RPs and the NPs, and the effect of the non-availability of the RP. The ratios of the qualities are determined as constant values. Therefore, only the change in the unit prices of the RP and the NP, and the non-availability of the RP may result in a fluctuation in the customer bases. The feedback loop in Figure 5.1 indicates the causality between the price and the RP potential customer base.

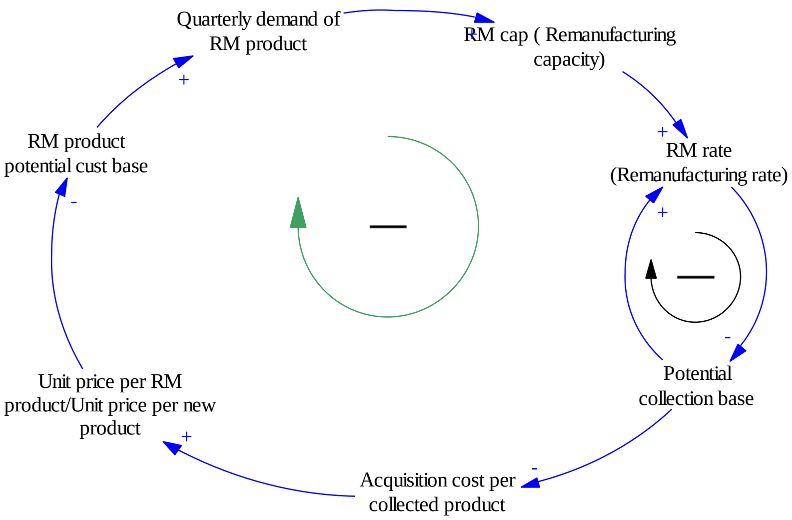

Figure 5.1. The feedback loop of RP potential customer base & unit price of RP.

In the base case, it is assumed that the quality ratio of the RP and the NP is 60%. RP potential customer base increases at the beginning, since the sum of the effects makes RP more advantageous than NP for the customers (Figure 5.2).

Based on the feedback loop in Figure 5.1, when the RP potential customer base increases, the NP potential customer base decreases due to the customer migration from the NP potential customer base to the RP potential customer base. The increase in the RP potential customer base leads to an increase in the quarterly demand of RP and hence an increase in the remanufacturing rate.

As expected from the feedback loop given in Figure 5.1, the increase in remanufacturing rate increases the usage of the used product in the potential collection base. This situation results in a decrease in the potential collection base which is the collectable used product base. Additionally, an excessive decrease in the demand of the NP due to the decrease in the NP potential customer base has a negative effect on the remanufacturing rate since it also leads to a decrease in the potential collection base. As a result, the potential collection base decreases and goes down below the nominal collection base after the 35th quarter as in Figure 5.3.

The unit cost and the price of the RP increase depending on the increase in the acquisition cost per collected used product since the potential collection base goes down below nominal collection base, which is a reference value for the collection base (Figure 5.3 and Figure 5.4).

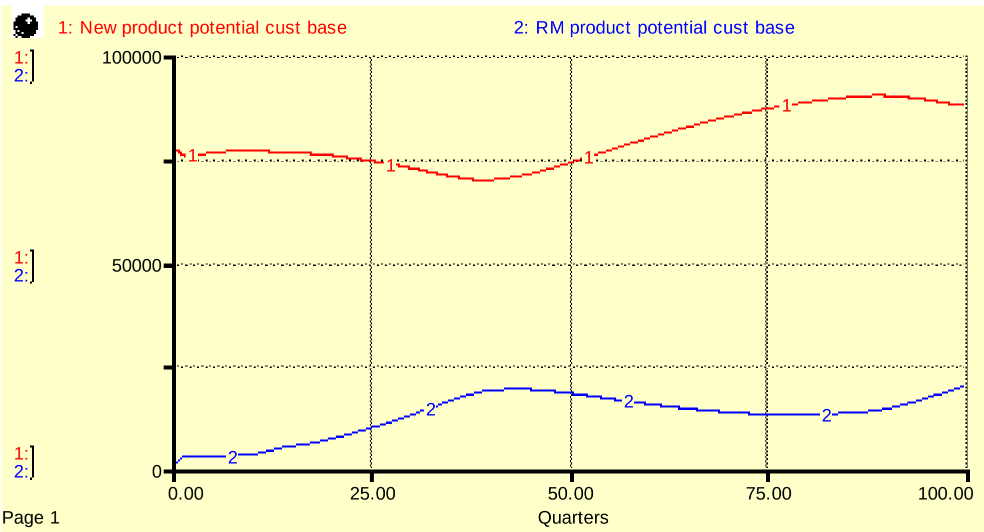

Figure 5.2. The NP & RP potential customer bases in the base case.

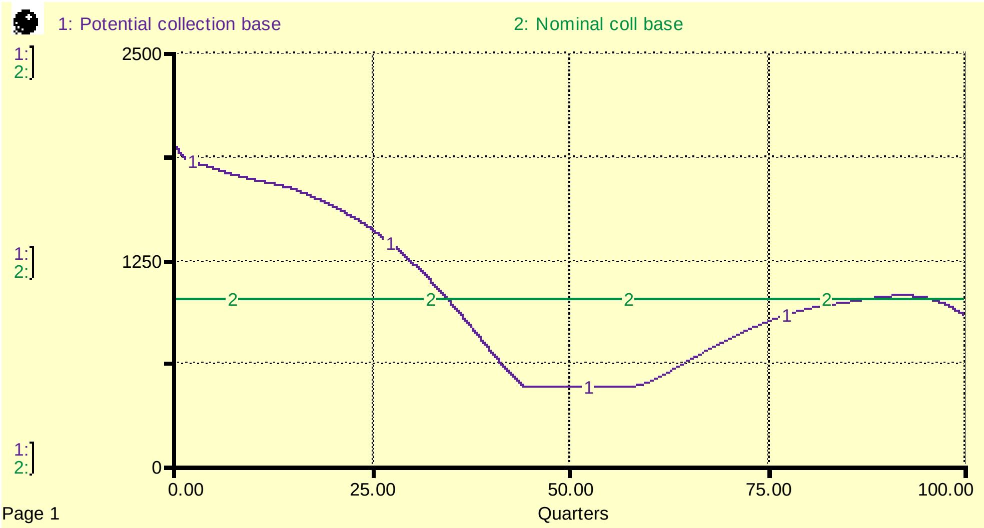

Figure 5.3. Potential collection base versus nominal collection base in the base case.

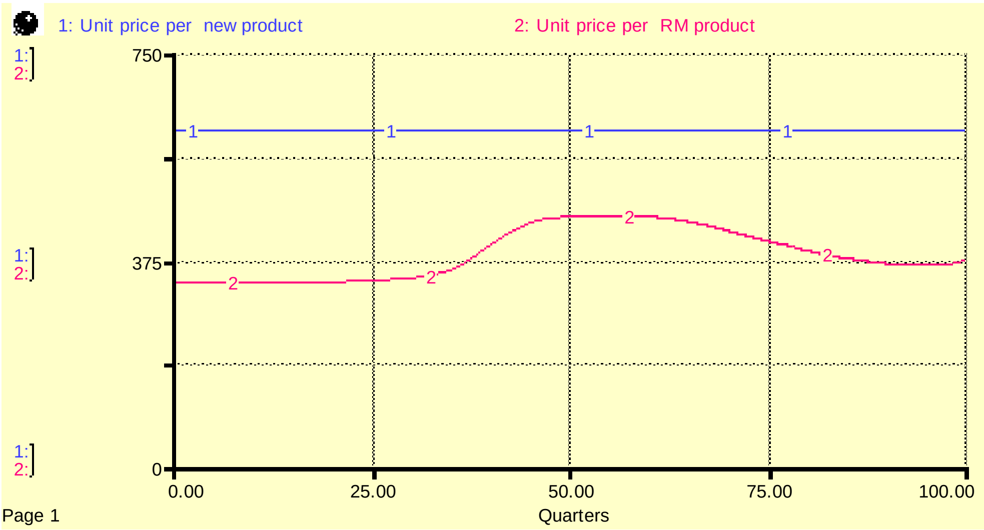

Figure 5.4. Unit prices of NP & RP in the base case.

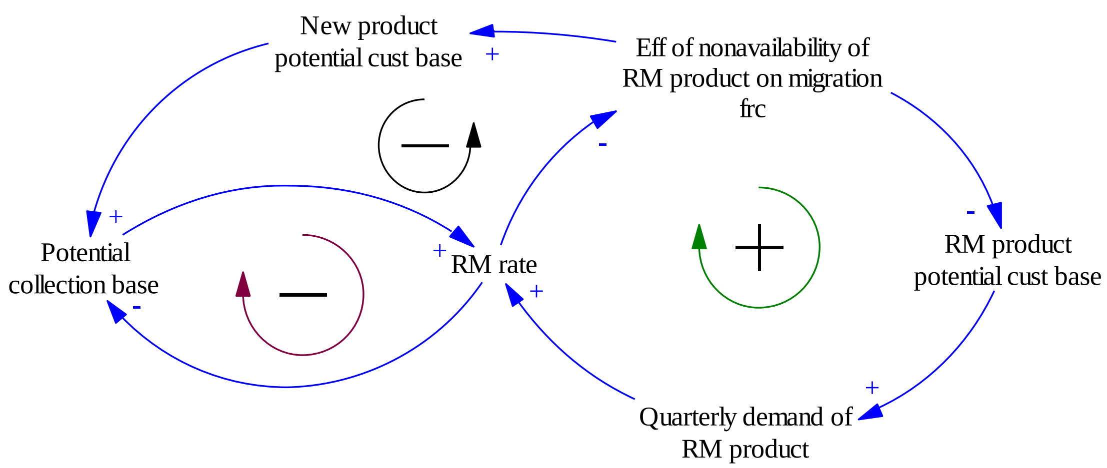

Figure 5.5. The feedback loop of RP Potential customer base & the non-availability effect on customer migration.

Additionally, after a while, the potential collection base starts to restrict the remanufacturing rate since the remanufacturing rate is determined based on the minimum of the remanufacturing capacity, the quarterly demand of the RP and the potential amount of the collected used products. The restriction in the remanufacturing rate results in an increasing gap between the sales and the demand as in Figure 5.6 and this gap, showing the decreasing demand satisfaction, leads to an increase in the rate of the non-availability of the RP. Then, the effect of the non-availability of the RP on the customer migration fraction increases since the customers do not wait to buy a product forever, if the product does not exist in the market (Figure 5.5). This situation may change the customer behavior if the quality ratio of the NP and the RP does not have a dominant effect on the customer behavior comparing to the disadvantage of the unit price and the non-availability of the RP.

The RP potential customer base decreases until the potential collection base reaches the sufficient amount to satisfy the RP demand (Figure 5.2, 5.3 and 5.5). After it reaches the sufficient amount, the RP potential customer base starts to increase while the NP potential customer base is decreasing because of the migration to the RP potential customer base (Figure 5.2). Another reason leading to an increase in the RP potential customer base is the decrease in the unit price of the RP depending on the potential collection base (Figure 5.4). Therefore, it can be deduced that the potential collection base has an indirect effect on the customer migration rate through its effect on the unit price and the non-availability of the RP which symbolizes the meeting rate of the quarterly demand of the RP and thereby the customer migration fraction (Figure 5.7).

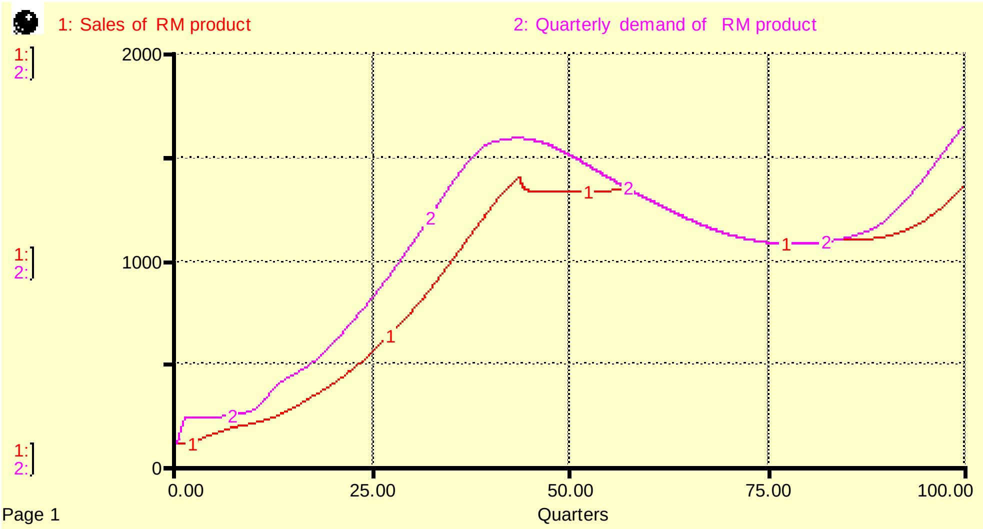

Figure 5.6. Sales & quarterly demand of RP in the base case.

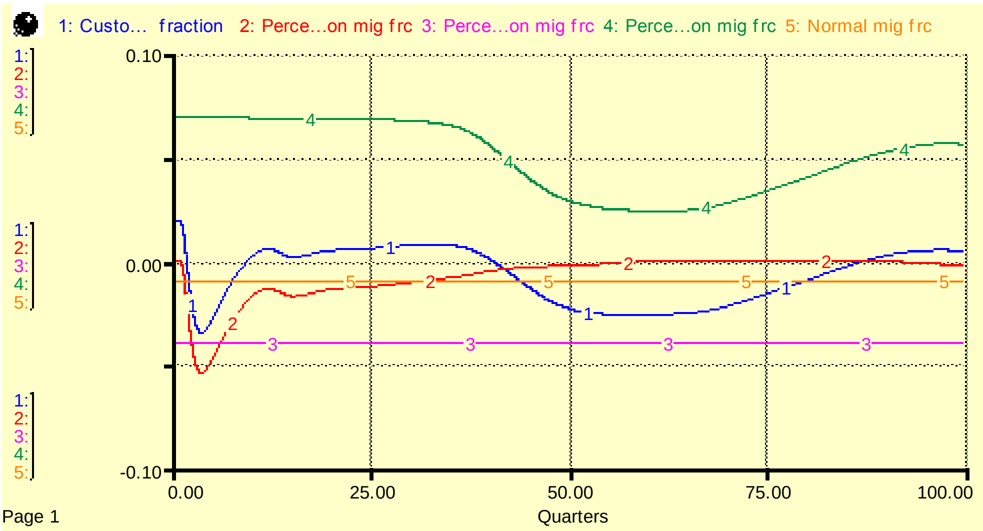

Figure 5.7. Customer migration fraction, effect of non-availability of RP, effect of quality ratio, effect of price ratio on migration fraction and normal fraction in the base case.

The most important result obtained from the analysis is that when the RP is much more advantageous than the NP, its demand increases for a while. However, the RP cannot maintain its advantage forever, since the firm needs a sufficient potential collection base to remanufacture, but the sales of the NP decreases and it cannot provide the used products sufficiently. Therefore, the system balances itself through two ways: (i) the increasing acquisition cost per collected used product and so the unit price of the RP, (ii) backlogged quarterly demand of the RP.

5.2. Structure Validity

Structure test is to check whether the structure of a model is a meaningful description of the real relations that exist in the problem or not. There are two types of structure tests: Direct structure tests and structure-oriented behavior tests (Barlas, 1996).

5.2.1. Direct Structure Tests

Direct structure tests assess the validity of the model structure, by a direct comparison with the knowledge about the real system structure. The parameter and variable confirmation, dimensional consistency and extreme condition tests are included in direct structure testing (Barlas, 1996). In the model, all the parameters, variables and delays have real life counterparts. The dimensions of the equations are consistent and the dimensions of the parameters and variables are shown in Appendix D. All the model equations are valid under extreme conditions.

5.2.2. Indirect Structure Tests

Extreme condition test and behavior sensitivity tests are included in the indirect structure test.

5.2.2.1. Extreme Condition Test. In extreme condition test, some extreme values are assigned to the selected parameters and the model-generated behavior is compared to the observed behavior of the real system under the same extreme condition via simulation (Barlas, 1996). Some extreme conditions are tested in the study.

Extreme Condition 1: The used product arrival fraction is set to 0%.

The remanufacturing rate and sales are determined by the minimum of remanufacturing (RM) capacity, potential amount of collected used product and quarterly demand of RP. Moreover, the RM capacity is increased or decreased by referring the expected sales determined by the minimum of potential amount of collected used product and the quarterly demand of the RP. Therefore, when the used product arrival fraction is 0%, after the usage of potential collection base for remanufacturing, it is expected that firstly potential amount of collected used product and thereby the sales of the RP becomes zero. After a delay, RM capacity goes to zero due to the expected sales. Moreover, the demand cannot be satisfied due to zero sales and it also goes to approximately zero. Even if the RP sales amount is zero, the quarterly demand of the RP is not zero and stable due to the new potential customers of the RP coming from the market (Figure 5.8). The reason is that even if the sale is zero, new customers in the market do not know the situation until they prefer and think to buy RP product. After a waiting time, while they are also migrating to the NP potential customer base or preferring another brand in the market due to the lack of RP of the company, other new customers prefer its RP product. Consequently, the potential customer base and quarterly demand of RP do not become zero due to the market share of the company and so the new customers coming from the market.

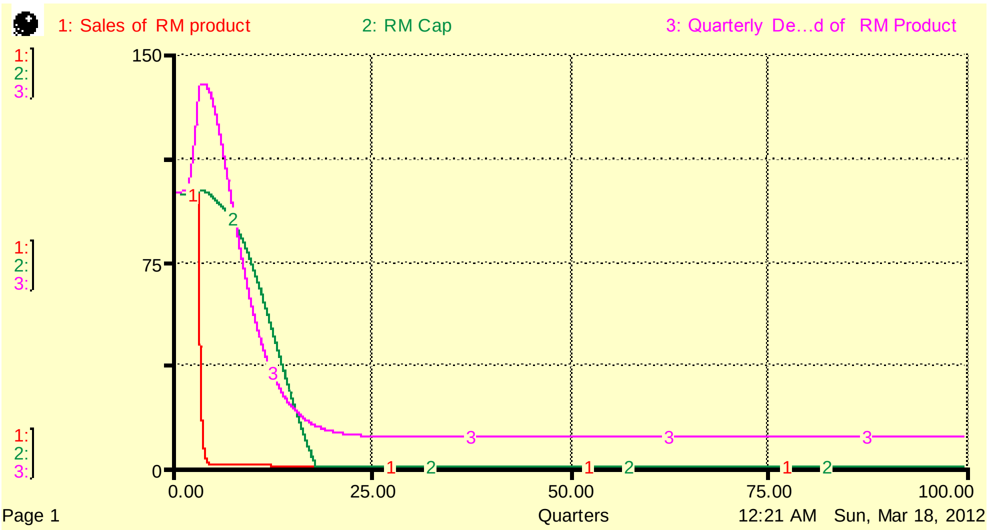

Figure 5.8. The behavior of the RP sales & RM capacity in extreme condition 1.

Extreme Condition 2: The used product arrival fraction is set to 100%.

Even if the *potential amount of collected product* is high due to the 100% arrival fraction and it does not restrict the remanufacturing rate since when the *RM Cap* is lower than the potential amount of collected used product and the quarterly demand of the RP, the sales amount of RP is determined by the *RM Cap* as in Figure 5.9.

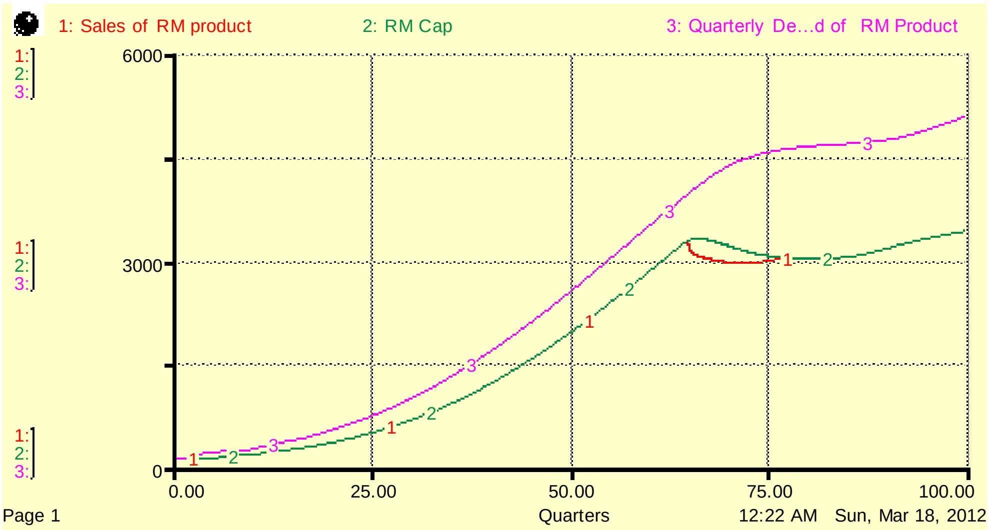

Figure 5.9. The behavior of the RP sales, RM capacity & quarterly demand of RP in extreme condition 2.

Extreme Condition 3: The effects of all factors on customer behavior are zero.

Normally, it is nearly impossible in the real life that the qualities and the customer perception both on the NP and RP are equal. Moreover, a firm having a marketshare has at least some increase since the customer amount in PC market increases due to the population growth and the firm loses some customers since they give up PC usage. If the inflow including the customer increase due to the market growth and outflow are set to zero, which is that the customer migration takes place only between the NP potential customer base and the RP potential customer base and the effects are equal, it is expected that the migration is not zero and its direction occurs from the RP potential customer base to the NP potential customer base because people have a bias about the RP. Figure 5.10 and Figure 5.11 show this bias and customer behavior exists as expected.

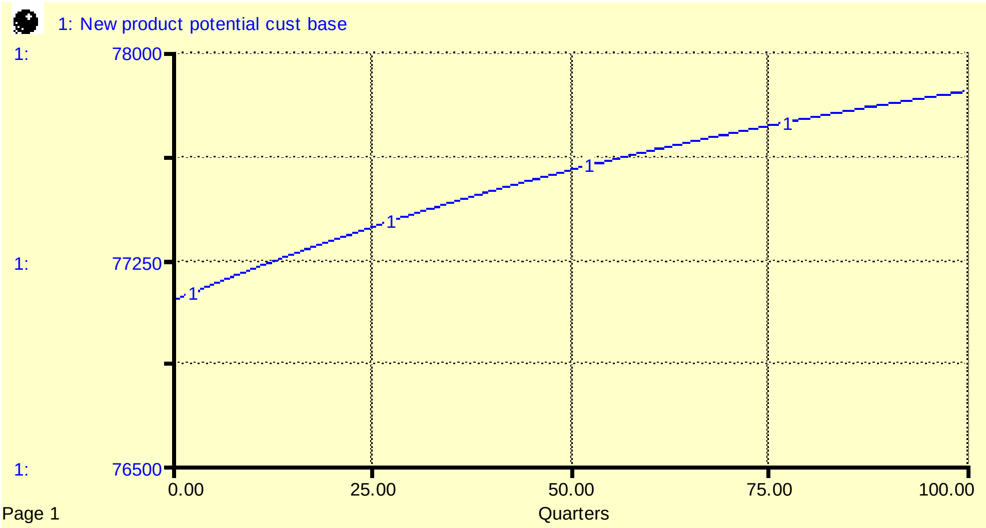

Figure 5.10. The behavior of the NP potential customer base in extreme condition 3.

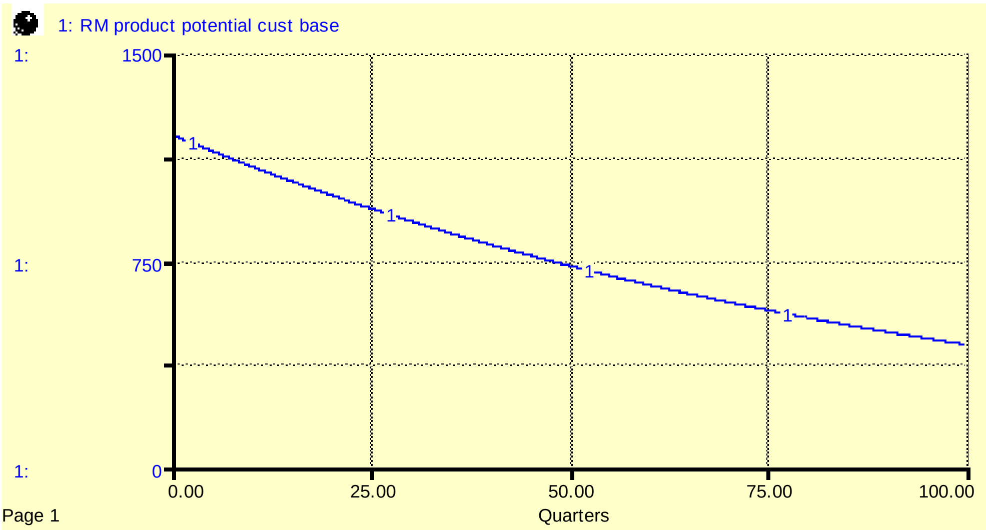

Figure 5.11. The behavior of the RP potential customer base in extreme condition 3.

5.2.2.2. Behavior Sensitivity Test. Behavior sensitivity tests consist of determining those parameters to which the model is highly sensitive, and asking if the real system would exhibit similar high sensitivity to the corresponding parameters (Barlas, 1996). Sensitivity test is mentioned in Section 6.1.

5.3. Behavior Validity

Since the model is hypothetic, in other words there is a very limited real data, behavior validity test cannot be applied to check whether the structure of the model is a meaningful description of the real relations that exist in the system. Some parameters' values and the initial values are estimated as mentioned in the previous sections.

6. SCENARIO ANALYSIS

In this section, the results of the scenario analysis will be evaluated in two steps. The first step includes the analysis of the change in the customer bases and the behavior of the whole system depending on the given quality values and the changing unit prices of the products. The second step includes the analysis of the total profit of the firm for these scenarios.

6.1. Analysis of the Dynamic Behaviors

In Section 5.1, the system behavior is analyzed by assuming the base case that the RP quality is 60% of the NP quality. In this section, the system behavior is analyzed for some scenarios also including different quality values of the products and compared with the base case.

Scenario 1: The RP quality is 50% of the NP quality.

When the RP quality is half of the NP quality, the NP becomes more advantageous than the RP. On the other hand, both of the customer bases increase with a little rate because the firm has a normal growth rate due to the market growth. Therefore, the RP customer base increases a little due to the market growth. However, the customer migration from the RP potential customer base to the NP potential customer base continues and the NP potential customer base increases due to two inflows: (i) the growth rate of the NP potential customer base and (ii) the customer migration rate from the RP potential customer base to the NP potential customer base (Figure 6.1).

Based on the customer bases, the quarterly demand of the NP increases while the quarterly demand of the RP is increasing with a very few rate. Therefore, although the *potential collection base* decreases with a few rate due to the RP demand, since the increase in the quarterly demand of NP is much more than the increase in the quarterly demand of RP, the *potential collection base* starts to increase after a while and it does not go down below the nominal base (Figure 6.2). Because, the NP quarterly demand and thereby the NP sales amount becomes high and it leads to an increase in the *potential collection base*.

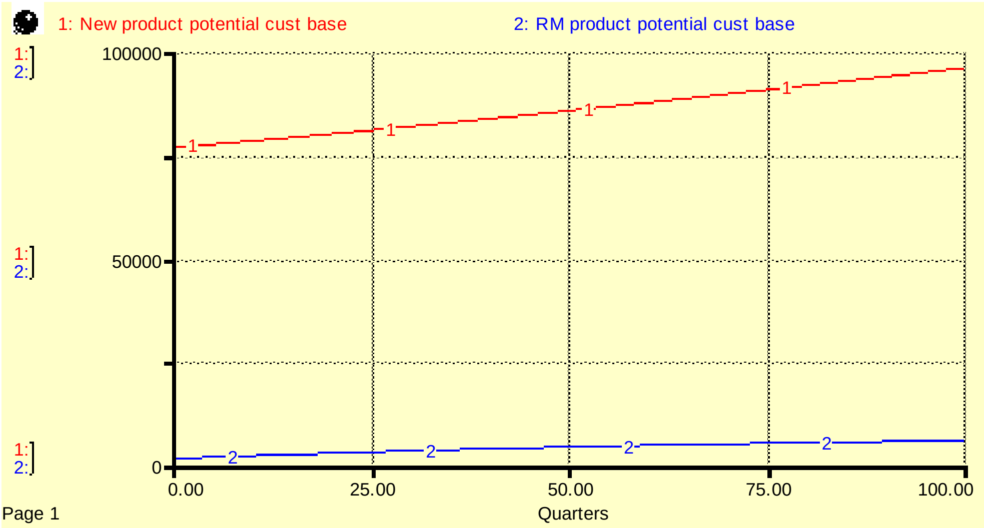

Figure 6.1. The NP & the RP customer bases in scenario 1.

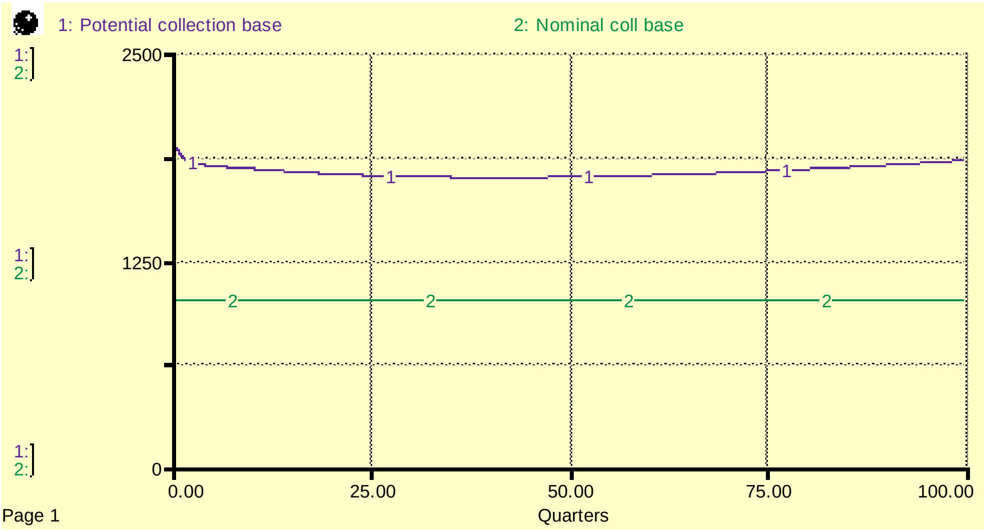

Figure 6.2. Potential collection base versus nominal collection base in scenario 1.

Since the amount of the used product is sufficient and it is not under the nominal collection base, it does not lead to an increase in the acquisition cost per collected used product and thereby the unit cost and unit price of the RP as shown in Figure 6.3.

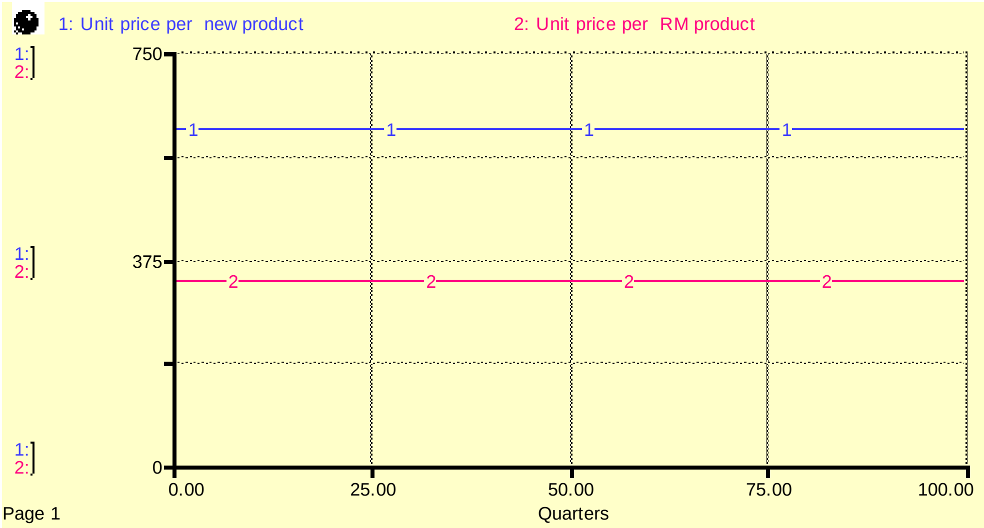

Figure 6.3. Unit prices of NP & RP in scenario 1.

Additionally, since the quarterly demand of the RP can be satisfied by the firm, it does not restrict the remanufacturing rate and so the sales of the RP (Figure 6.4) and the non-availability effect of the RP continues to be nearly zero (Figure 6.5).

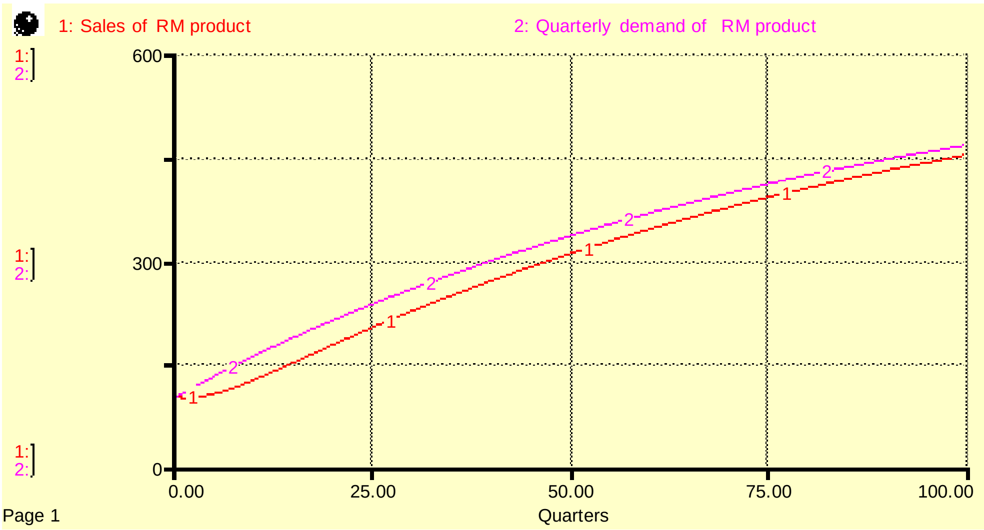

Figure 6.4. The sales & quarterly demand of the RP in scenario 1.

In Figure 6.4, the small gap between the quarterly demand and the sales amount is allowable since it means that there are some customers having tolerance for waiting to buy a RP.

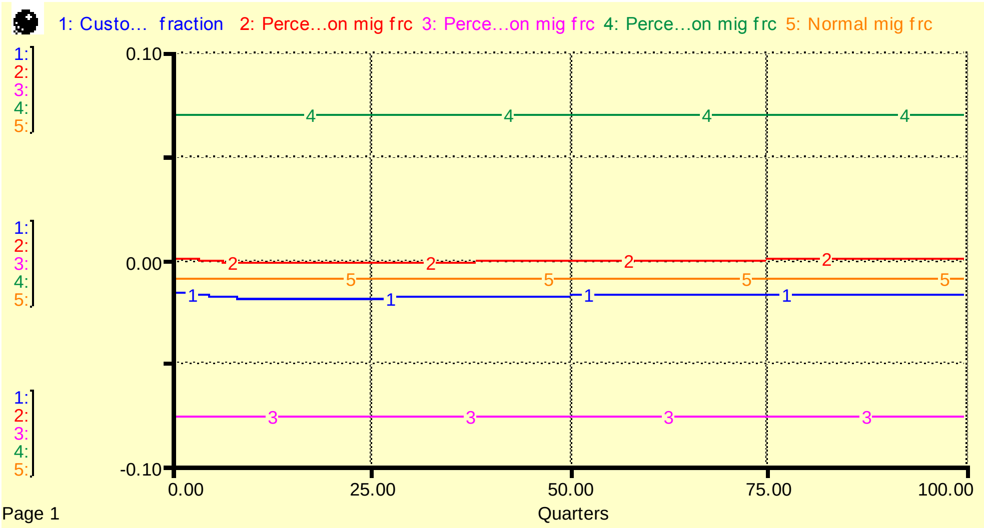

Figure 6.5. Customer migration fraction, effect of non-availability of RP, effect of quality ratio, effect of price ratio on migration fraction and normal fraction in scenario 1.

As a result, since the effect of non-availability of the RP on migration fraction is zero, it can be deduced that since the advantageous price of RP cannot dominate the sum of the negative effect of the quality and the normal migration fraction, which reflects the people bias to the NP, as shown in Figure 6.5, the customer migration exists from the RP potential customer base to the NP potential customer base during the whole period.

Scenario 2: The RP quality is 75% of the NP quality.

In similar to the base case, the RP potential customer base increases at the beginning since the customers' evaluation shows that the RP is more advantageous than the NP as in Figure 6.6. However, the increase rate of the RP potential customer base at the beginning is higher than the base case, since the NP quality is higher than that in the base case. It makes the decrease in the customer base of NP faster and the decrease in the potential collection base also is faster and earlier than the decrease in the base case (Figure 6.7). The unit cost of the RP and thereby the unit price of the RP increases depending on the decrease in the potential collection base (Figure 6.8). Moreover, since the potential collection base decreases faster, it leads to an increase in the gap between the quarterly demand and the sales of the RP much more and it shows that satisfying the demand of the RP customer becomes harder (Figure 6.9). Since the RP demand cannot be satisfied and the price of the RP increases, the direction of the customer migration changes and some of the customers start to migrate to the NP potential customer base from the RP potential customer base as in Figure 6.6. The increase in the NP potential customer base and the decrease in the RP potential customer base start to decrease until the end of the period as in Figure 6.6 due to the increase in the potential collection base as in Figure 6.7. Thus, the gap between the quarterly demand and the sales of the RP decreases as shown in Figure 6.9. It can be observed also from the Figure 6.10, because, the effect of the non-availability of the RP, which fluctuates at the beginning of the period, converges to a value near zero due to the decrease in the gap between the sales and the quarterly demand of the RP. Moreover, the effect of the unit price ratio decreases since the unit price per RP decreases due to the increase in the potential collection base. As a result, the customer migration fraction, which is affected by the addition of these effects, approaches to a very small value which is nearly zero as in Figure 6.10.

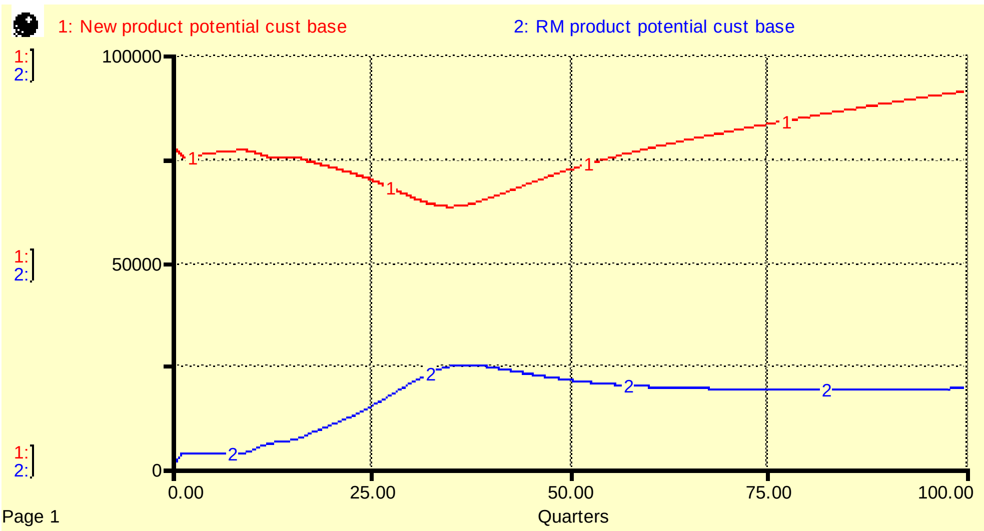

Figure 6.6. The new product & the RP customer bases in scenario 2.

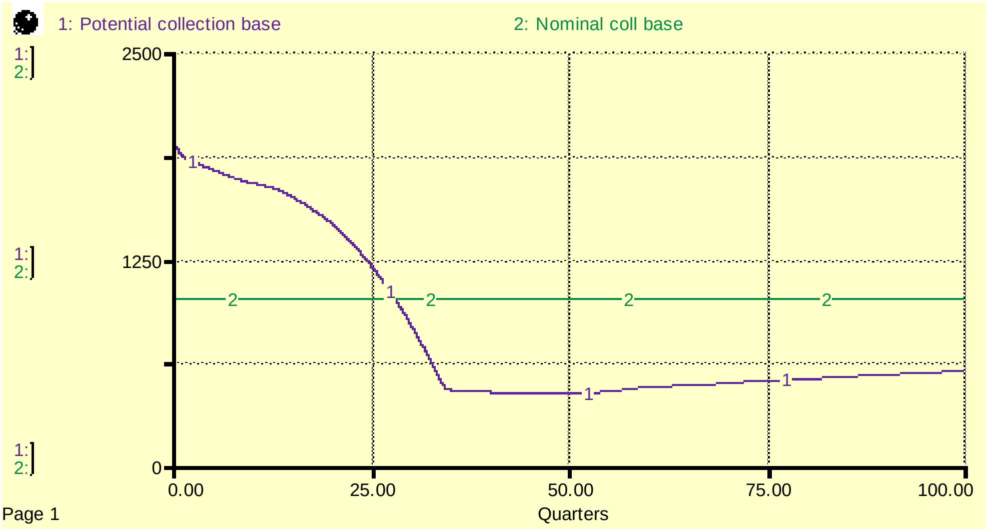

Figure 6.7. Current collection base versus nominal collection base in scenario 2.

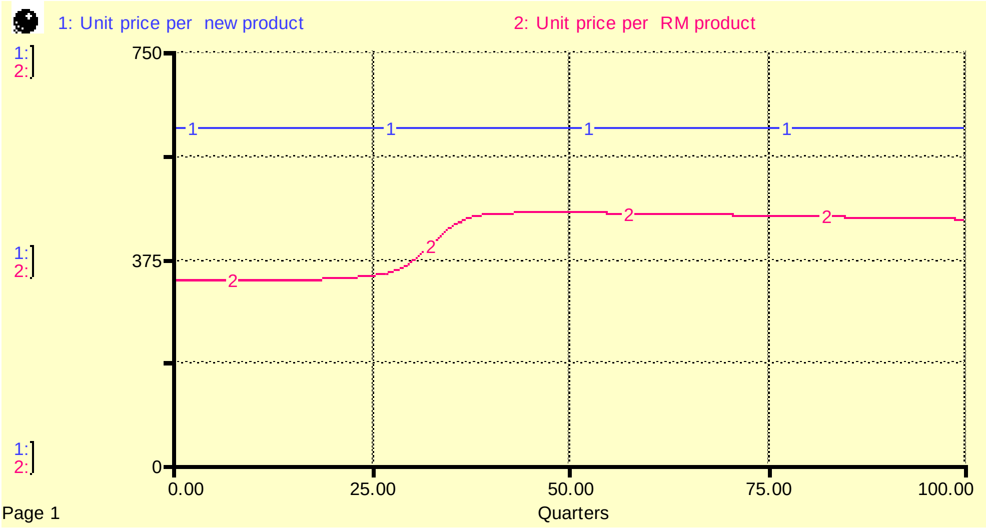

Figure 6.8. The unit prices of NP & RP in scenario 2.

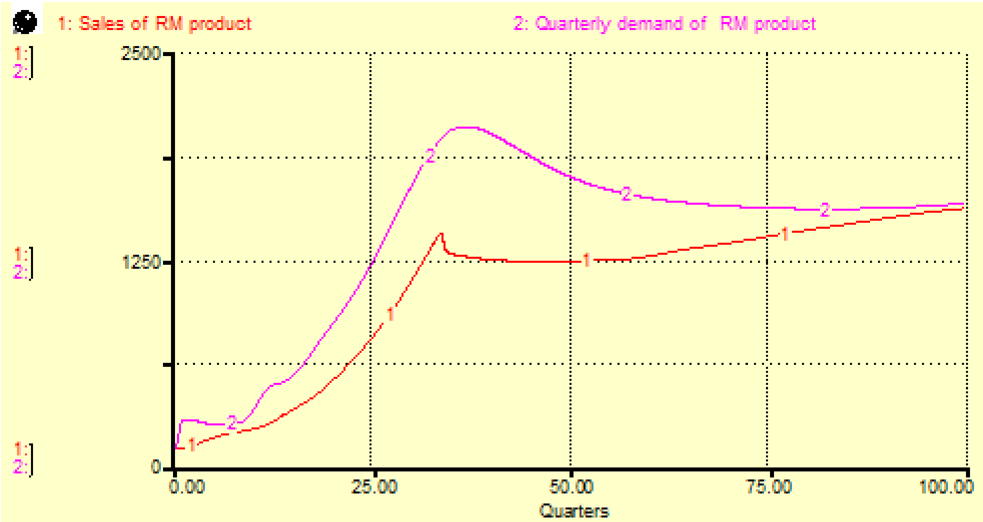

Figure 6.9. The sales & quarterly demand of the RP in scenario 2.

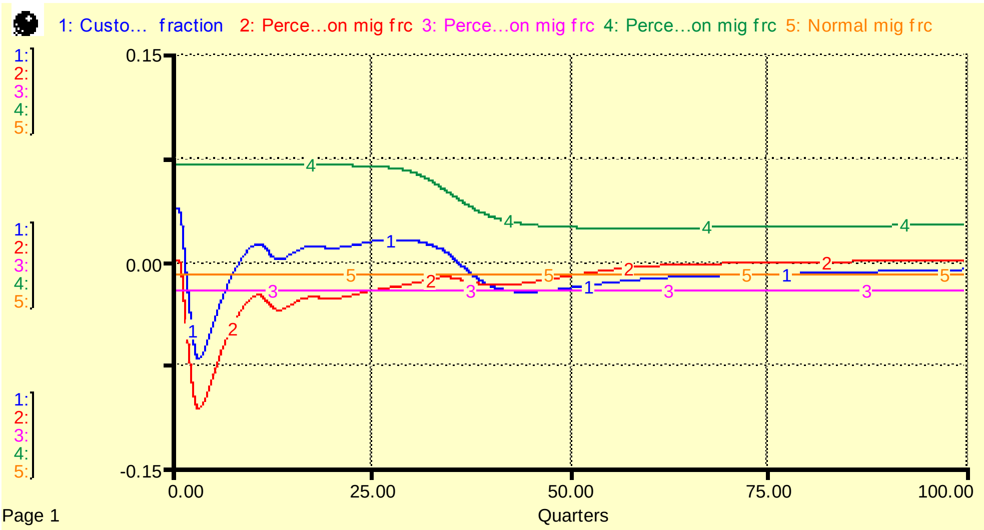

Figure 6.10. Customer migration fraction, effect of non-availability of RP, effect of quality ratio, effect of price ratio on migration fraction and normal fraction in scenario 2.

Scenario 3: The RM product quality is equal to the new product quality.

Since the normal migration fraction is set to a negative value, it can be assumed that the gap between the NP quality and the RP quality can be very small that is nearly equal. Therefore, this case where the quality values are set to the same values is a case in which the qualities of both of the products are nearly same.

It is deduced that the system behavior is nearly same with Scenario 2 since the RP is more advantageous than the NP as in that scenario. Differently, since the quality value is set to nearer to the NP quality than that in Scenario 2 when all other values are same with Scenario 2, the increase in the RP potential customer base is higher than that in Scenario 2 (Figure 6.6 and Figure 6.11). Therefore, the decrease in the potential collection base is quicker than Scenario 2 (Figure 6.7 and Figure 6.12).

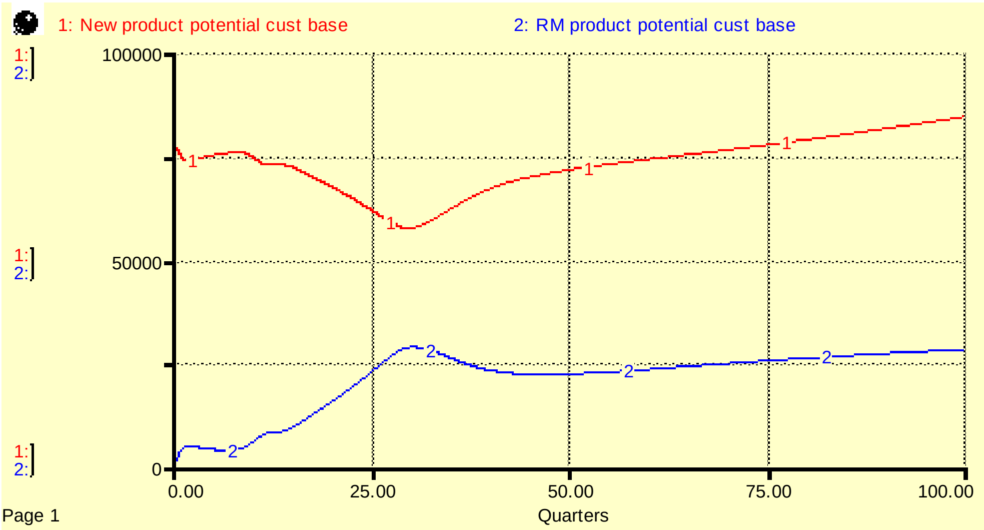

Figure 6.11. The NP & RP customer bases in scenario 3.

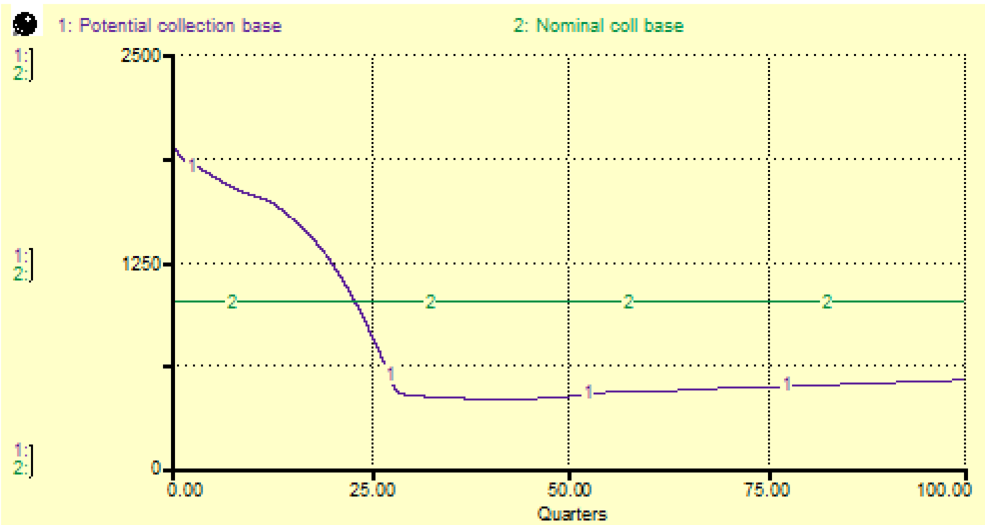

Figure 6.12. The potential collection base versus the nominal collection base in scenario 3.

In summary, the difference of the system behavior from the behavior in Scenario 2 is that in the last quarters of the period, there is a very small increase in the *potential collection base* as given in Figure 6.12 and thereby a very small decrease in *unit price per RM product* as in Figure 6.13. It affects the gap between the sales and the quarterly demand of the RP as in Figure 6.14. However, differently from the Scenario 2, the RP quality is equal to the NP quality, and it has a positive effect on the customer tolerance for waiting to buy the RP than in Scenario 2. Moreover, the gap between the sales and the quarterly demand of the RP continues in a tolerance range. Therefore, in the last quarters, the effects neutralize each other as in Figure 6.15 and the system behavior reacts similar with the system in Scenario 2.

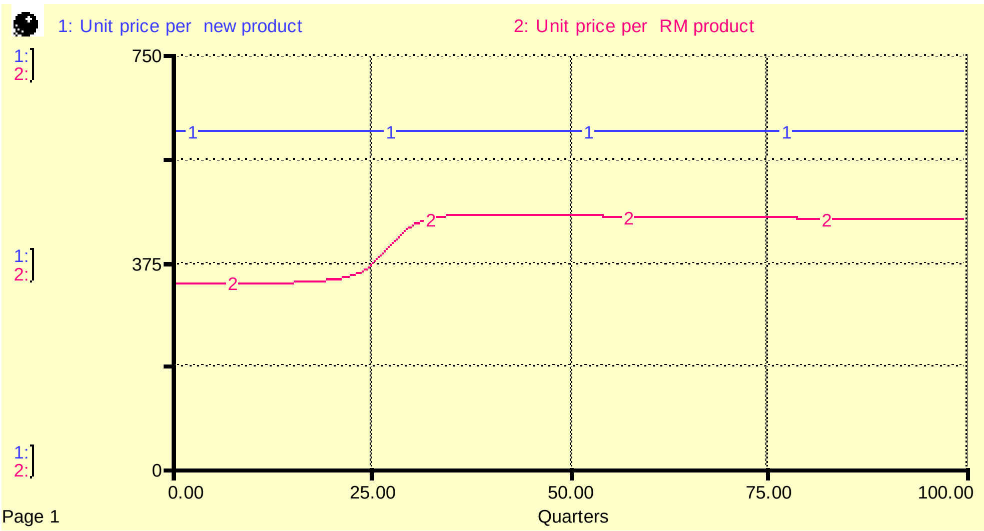

Figure 6.13. The unit prices of NP & RP in scenario 3.

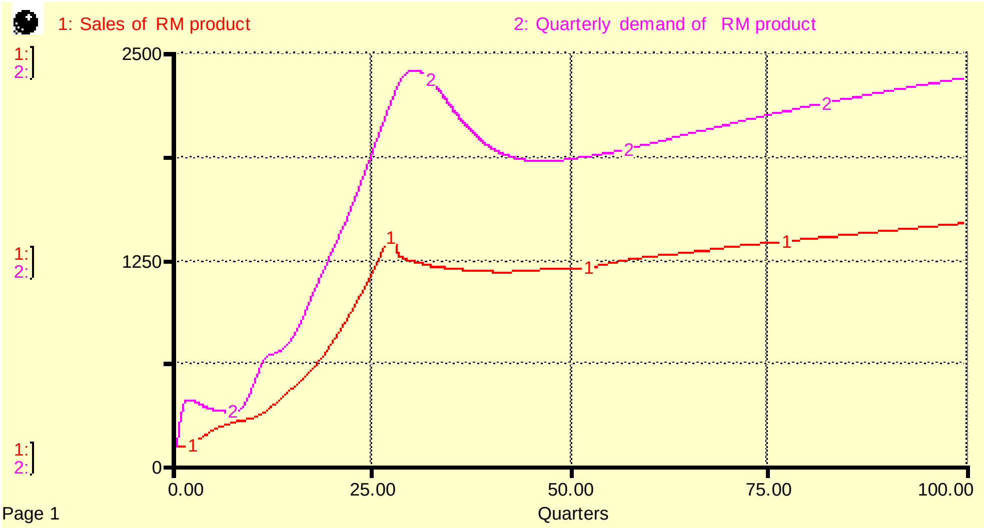

Figure 6.14. The sales & quarterly demand of the RP in scenario 3.

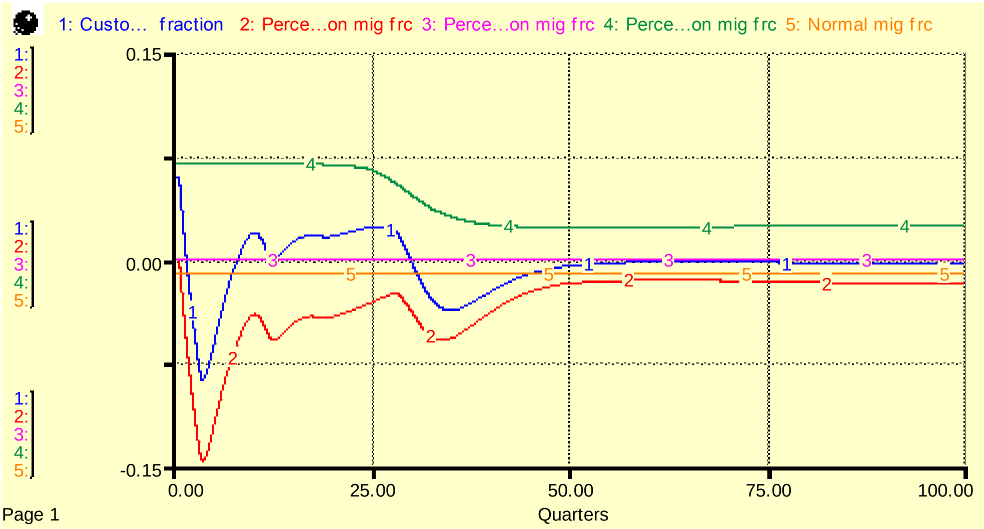

Figure 6.15. Customer migration fraction, effect of n-availability of RP, effect of Quality ratio, effect of price ratio on migration fraction and normal fraction in Scenario 3.

Scenario 4: The used product arrival fraction is 70% in the base case.

The used product arrival fraction is one of the most important factors affecting the system behavior. Therefore, in this case, it is assumed that the used product arrival fraction is 70% instead of 30%. In this case, it is assumed that the quality of the RP is 60% of the new product quality as in the base case. When it is compared with the base case given in Section 5.1, since the *used product arrival fraction* is higher, the *potential collection base* can satisfy the demand for a longer time and does not decrease below the nominal collection base so much as in the base case (Figure 6.16). Moreover, since the *potential collection base* is much more than that in the base case as in Figure 6.17, the price of the product does not become high soon as in the base case. Therefore, the increase in the RP potential customer base exists for a longer time as in Figure 6.16. However, after a while, the RP potential customer base starts to decrease since the quarterly demand of the RP increases until the price of the RP becomes high as the NP. Moreover, the demand of the RP cannot be satisfied, since the manufacturing capacity and the manufacturing rate decrease due to the low demand. Therefore, it can be deduced that the change in the direction of the customer migration is a dispensable result.

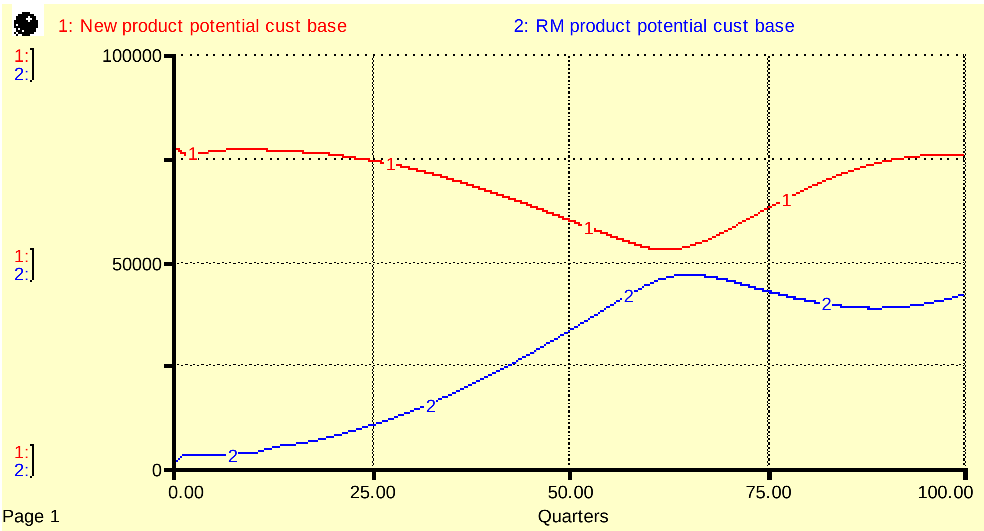

Figure 6.16. The NP & RP potential customer bases in scenario 4.

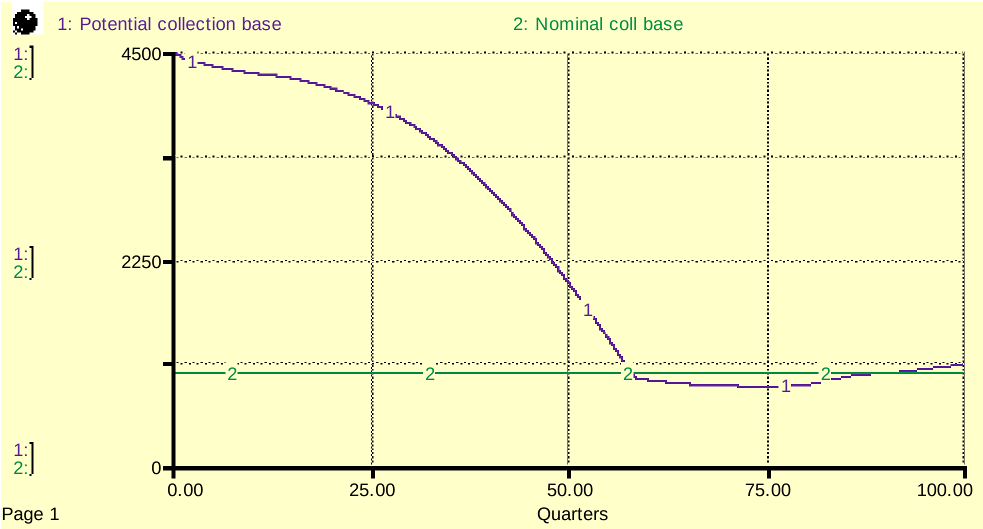

Figure 6.17. The potential collection base versus the nominal collection base in scenario 4.

Scenario 5: The used product arrival fraction is 70% when the RP quality is nearly 80% of the NP quality.

In this case, it is assumed that the *used product arrival fraction* is 70% instead of 30% when the RP quality is nearly 80% of the NP quality.

Comparing to Figure 5.2, although the increase in the RP potential customer base is faster than the base case due to the higher RP quality, the RP quarterly demand can be satisfied by the firm for a longer time due to the higher used product arrival fraction. Therefore, the increase in the RP potential customer base continues longer as given in Figure 6.18. However, even if the *used product arrival fraction* is increased to 70% from 30%, the demand cannot be satisfied after a period since the NP potential customer base and thereby the quarterly demand of the NP and the manufacturing rate decrease.

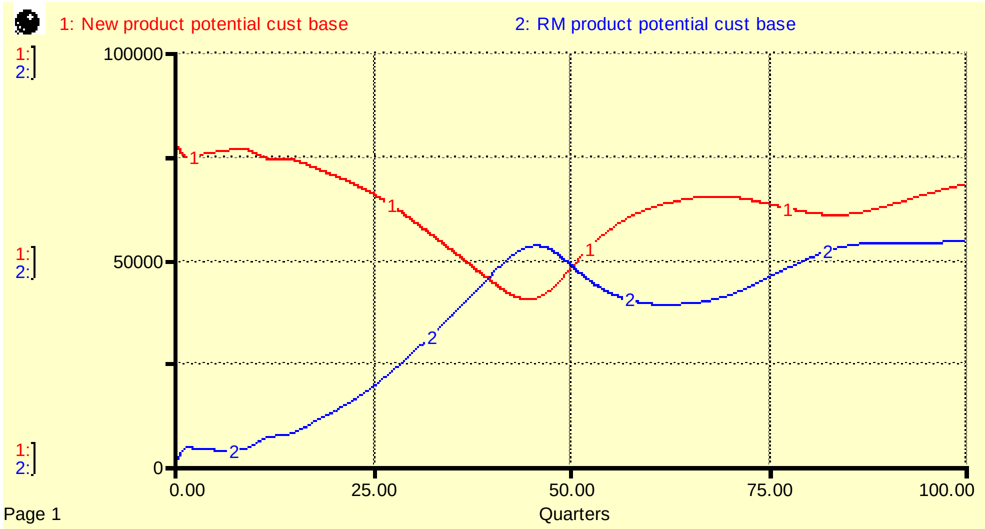

Figure 6.18. The NP & RP customer bases in scenario 5.

The decrease in the manufacturing rate also decreases the sales of the NP and the *potential collection base* necessary for the remanufacturing (Figure 6.19). With the decrease in the *potential collection base*, the unit price of the RP and the non-availability effect of the RP increase and the RP potential customer base starts to decrease until the *potential collection base* reaches a sufficient level for the quarterly demand of the RP(Figure 6.18 and 6.19).

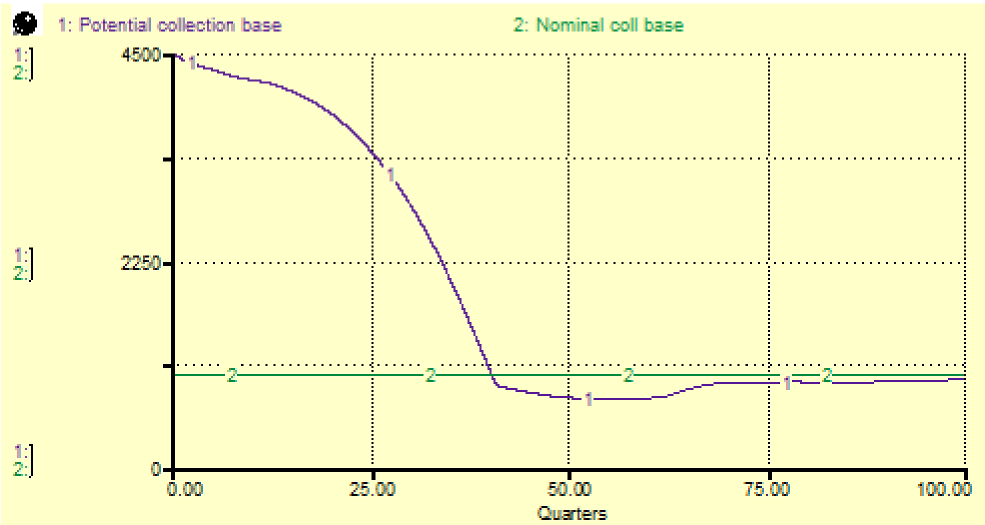

Figure 6.19. The potential collection base versus the nominal collection base in scenario 5.

Scenario 6: The used product arrival fraction is 10% in the base case.

In this case, the system is analyzed when the *used product arrival fraction* of the RP is 10% when the quality of the RP is nearly 60% of the NP quality as in the base case. In this situation, even if the RP is more advantageous than the NP, the RP potential customer base cannot increase due to the insufficient *potential collection base*. It is also analyzed that although the NP potential customer base increases during the whole period, the potential collection base cannot increase due to the low used product arrival fraction, since the *potential collection base* cannot be fed with the used product sufficiently during the whole period (Figure 6.20 and Figure 6.21).

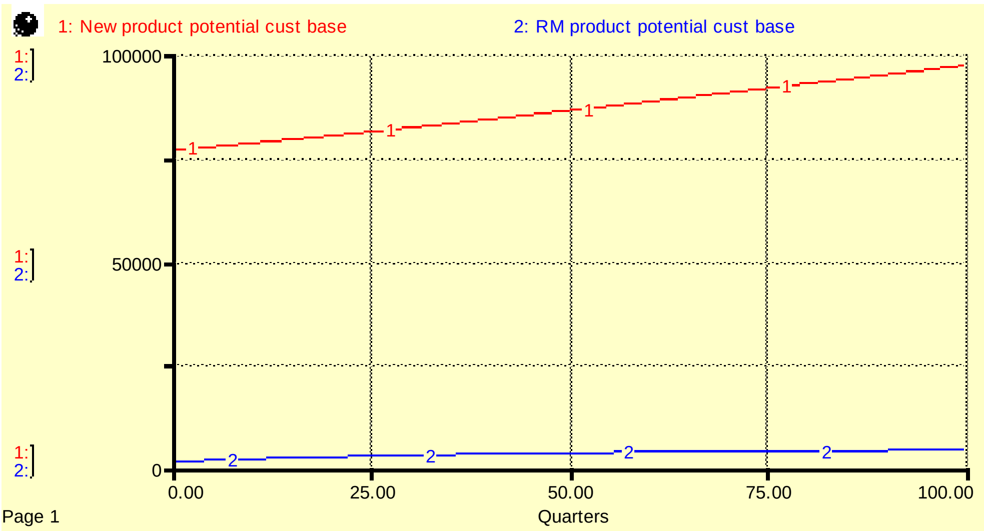

Figure 6.20. The NP & the RP customer bases in scenario 6.

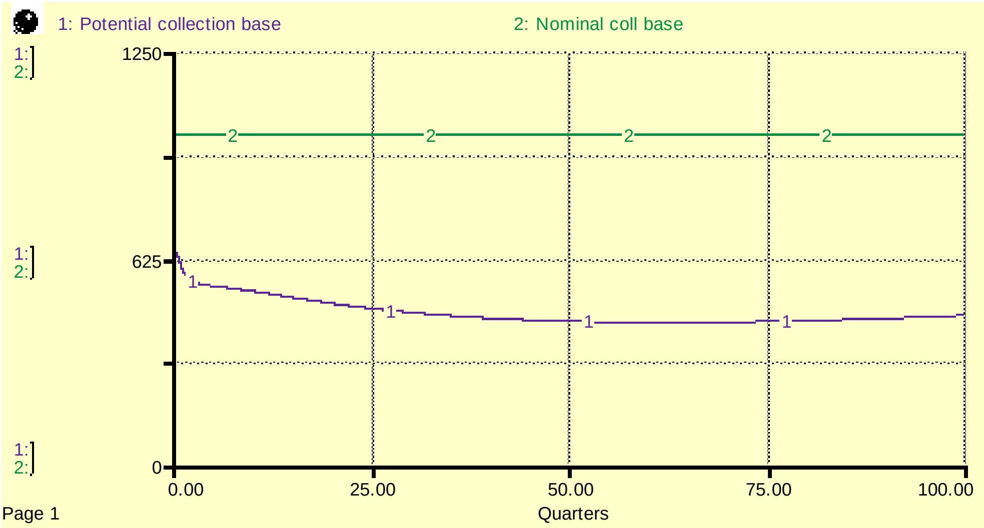

Figure 6.21. The potential collection base versus the nominal collection base in scenario 6.

Scenario 7: The used product arrival fraction is 10% when the quality of the RP is nearly 80% of the NP quality.

In this case, it is assumed that the quality of the RP is nearly 80% of the NP's quality when the *used product arrival fraction* remains 10% as in Scenario 6. However, it is analyzed that although the RP potential customer base has a small increase, it leads to a huge decrease in the *potential collection base* since the *used product arrival fraction* is only 10% (Figure 6.22 and Figure 6.23) and the potential collection base cannot be fed sufficiently. Then, when the potential collection base continues nearly at the same level, the RP potential collection base becomes nearly stable.

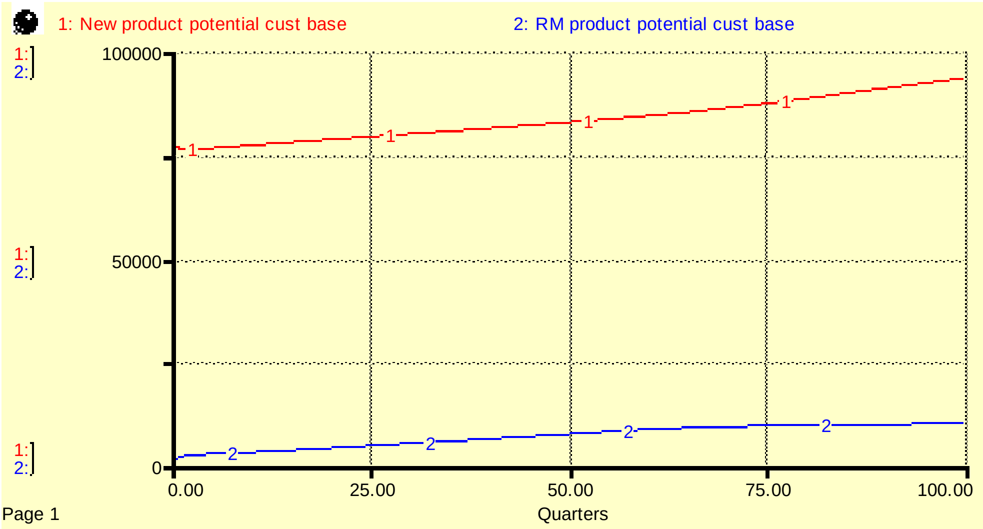

Figure 6.22. The NP & the RP customer bases in scenario 7.

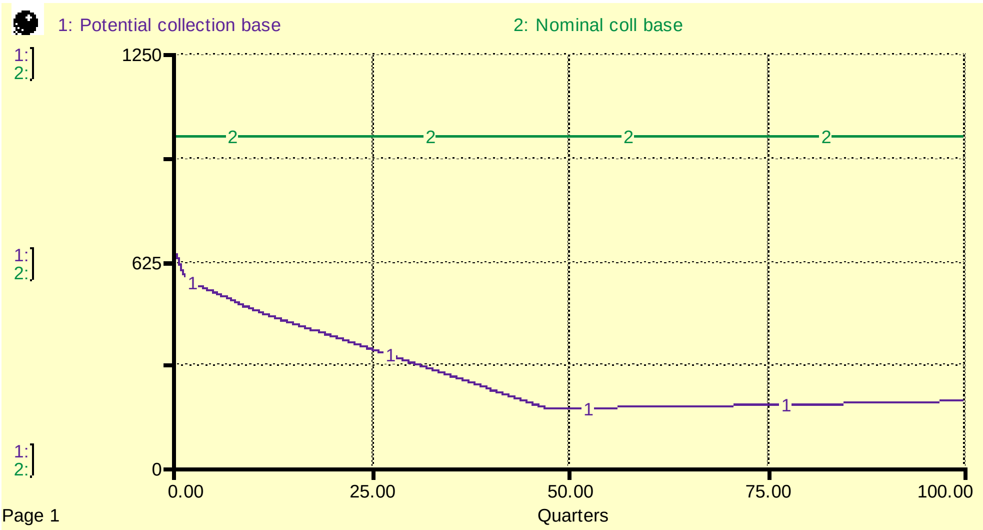

Figure 6.23. The potential collection base versus the nominal collection base in scenario 7.

6.2. Profit Analysis of the Firm

In this chapter, the profit analysis is done for different scenarios including various values of the green image factor and the product qualities including customer perception and the real quality of the product since they are critical parameters for the profit of the firm. In this section, the aim is to determine the profitable case for each scenario.

Base Case: The firms determine the profit per NP as 10% of the unit cost of the NP. However, for the RP, the profit percentage is higher than that of the NP. Therefore, in the base case of the model, 30% of the unit cost of the RP is added to its unit cost while determining its unit price. On the other hand, for the unit price of the NP, 10% of the unit cost is added to the unit cost of the NP. Under this assumption, the profit analysis is done for different quality values.

Table 6.1. Profit of the firm based on the quality ratio for the base case.

Quality Ratio (RP/NP)	Net Profit of RP (Billion $)	Net Profit of NP (Billion $)
0.5	2.243	39.323
0.55	2.754	39.024
0.6	4.254	38.169
0.65	7.908	36.555
0.7	9.635	35.630
0.75	10.633	34.728
0.8	10.695	34.107
0.85	10.747	33.709
0.9	10.785	33.427
0.95	10.809	33.268
1	10.827	33.139

If the firm does not start to remanufacture, the profit of the firm is 30.853 Billion $. When it is compared with the profits in Table 6.1, it is deduced that remanufacturing is a profitable strategy in all cases. However, this strategy can be more efficient if the most suitable quality values are determined for the products. Based on the analysis for the different values of RP Quality/NP Quality ratio in Table 6.1, the profit of the firm increases while the RP quality is getting near the NP quality. However, when the given value exceeds 0.75, the profit of the firm starts to decrease while it is getting near 1 (Figure 6.24). To find the reason why the profit has an increasing trend until a quality ratio and decreasing trend when the quality ratio is between 0.75 and 1, the demands and sales are compared.

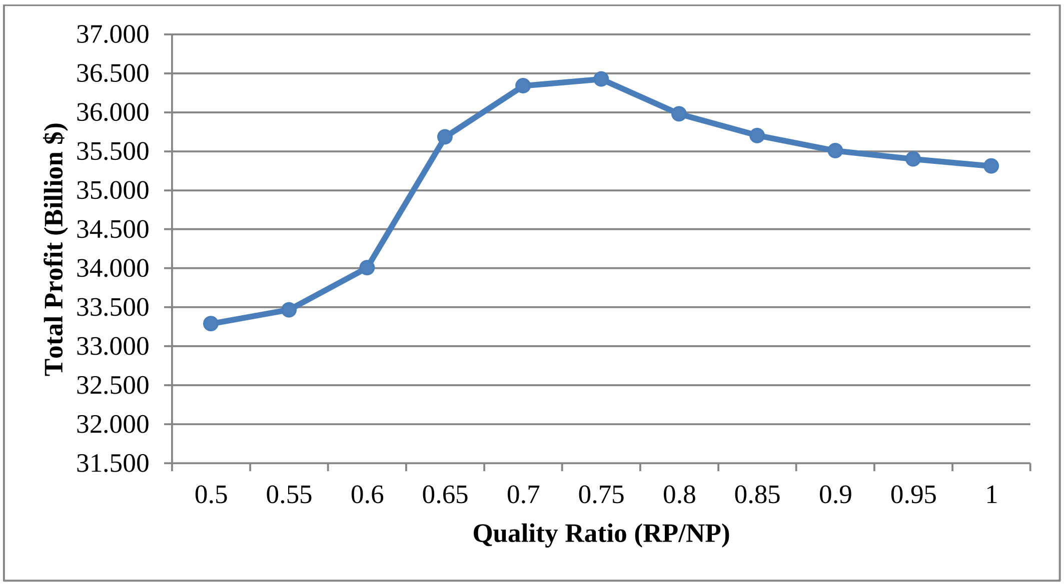

Figure 6.24. Total profit of the firm based on the quality ratio.

Table 6.2. The sales and the demands of the RP in the base case.

Quality Ratio (RP/NP)	Total Sales of RP (Million Units)	Total Demand of RP (Million Units)
0.5	28.980	31.437
0.55	35.488	39.085
0.6	54.157	61.091
0.65	87.714	99.556
0.7	99.837	118.811
0.75	107.361	139.000
0.8	107.623	154.069
0.85	107.901	163.458
0.9	108.114	170.019
0.95	108.257	173.723
1	108.364	176.744

In Table 6.2 and Figure 6.26, until 0.75 value for the ratio of the RP quality and the NP quality, the demand and sales of the RP increase. However, after the quality ratio exceeds 0.75, the increase in the sales of the RP is restricted comparing to the increase in the demand of RP. On the other hand, the decrease in the NP sales is proportional with the demand of the NP decrease (Table 6.3 and Figure 6.25).

Table 6.3. The sales and the demands of the NP in the base case.

Quality Ratio (RP/NP)	Total Sales of NP (Million Units)	Total Demand of NP (Million Units)
0.5	706.935	718.722
0.55	701.560	712.503
0.6	686.192	694.646
0.65	657.157	668.320
0.7	640.501	655.293
0.75	624.252	639.660
0.8	613.087	627.342
0.85	605.935	619.864
0.9	600.858	614.725
0.95	598.002	611.845
1	595.673	609.494

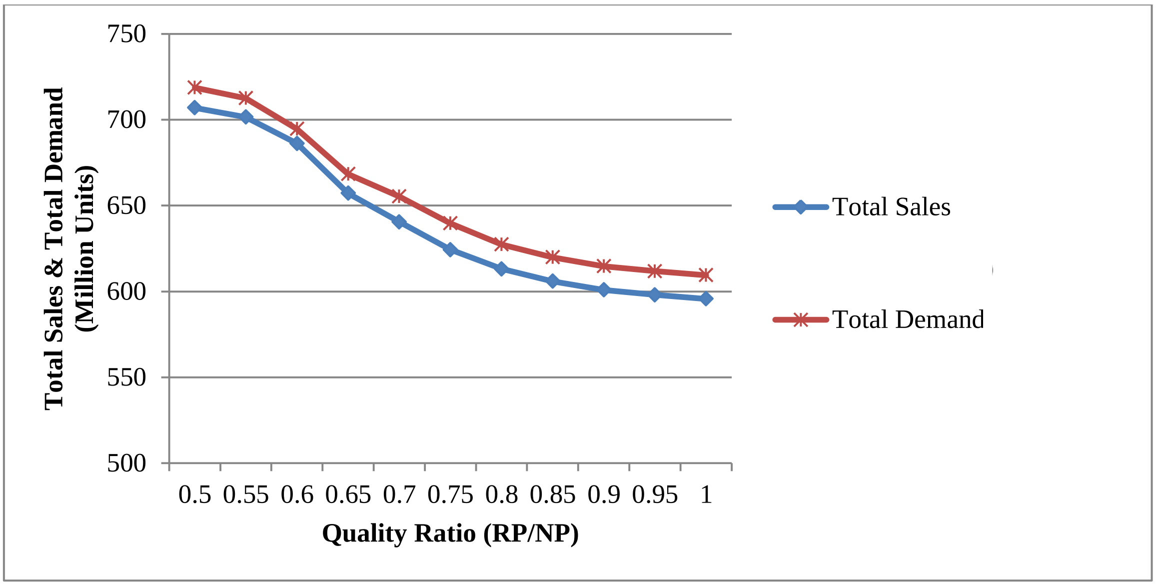

Figure 6.25. The sales and the demand of the NP in the base case.

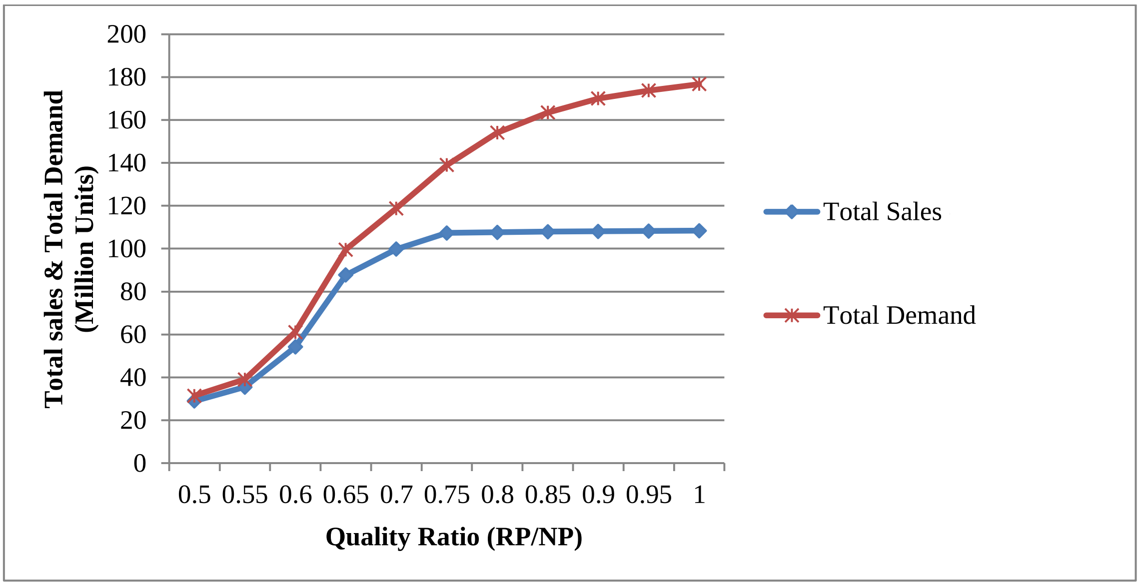

Figure 6.26. The sales and the demand of the RP in the base case.

The difference between the sales and demand for NP is due to the time delay for the manufacturing capacity determining the manufacturing rate band and thereby sales of the NP. As a result, while NP demand and thereby the sales are decreasing with the same ratios, RP sales cannot increase as much as expected although the demand of the RP increases (Figure 6.26).

The restricted increase in the sales of the RP also leads to a decrease in the total sales of the firm. Since the increase in the sales of the RP cannot be as much as the decrease in the NP sales, the total sales start to decrease after the quality ratio exceeds 0.65 as in Table 6.4.

Table 6.4. The total sales and the total demand of the firm in the base case.

Quality Ratio (RP/NP)	Total Sales of the Firm (Million Units)	Total Demand of the Firm (Million Units)
0.5	735.915	750.159
0.55	737.048	751.588
0.6	740.349	755.737
0.65	744.871	767.876
0.7	740.338	774.104
0.75	731.613	778.660
0.8	720.710	781.411
0.85	713.836	783.322
0.9	708.972	784.744
0.95	706.259	785.568
1	704.037	786.238

The analysis indicated in the extreme case shows the main reason why the demand of the RP decreases although the RP demand increases in the same case.

Extreme Case: Based on the system behavior analysis in section 6.1, the main factor restricting the remanufacturing rate and thereby the RP sales is the potential amount of the collected used products. Therefore, it is checked whether the main reason of the case that the sales of the RP cannot increase although the demand of the RP increases.

To check whether the collectable used products restrict the sales, the model is run when the firm can also collect the used products of the other firms when its used product amount is not enough to satisfy the demand. In this case, it is assumed that the firm gives the priority to its own used products in the potential collection base. However, it starts to collect other firms' used products when its potential collection base is exhausted. While it is collecting other firms' used products, the acquisition cost per collected used product is assumed as high as the case when the potential collection base is very low. Therefore, the only difference with the base case is cancelling the restriction of the potential collection base. In this case, the new equation for the remanufacturing rate:

$$\textit{Remanufacturing Rate} = \textit{MIN (RM Capacity, Quarterly Demand of RM Product)} \tag{6.1}$$

This equation shows that there is also a possibility that the quarterly demand of the RP may not be satisfied just in time due to the time delay for the capacity decision. Therefore, the demand can be satisfied after a time delay even if the used product is enough to satisfy the quarterly demand.

Table 6.5. Comparison of the base case and the extreme case for the sales of the RP.

	Base Case	Extreme Case
Quality Ratio (RP/NP)	Total Sales of RP (Million Units)	Total Sales of RP (Million Units)
0.5	28.980	28.980
0.55	35.488	35.488
0.6	54.157	54.157
0.65	87.714	87.935
0.7	99.837	110.377
0.75	107.361	150.679
0.8	107.623	190.764
0.85	107.901	237.983
0.9	108.114	280.992
0.95	108.257	306.026
1	108.364	325.580

After the comparison of the total sales for different quality ratios of the RPs and the NPs for two cases as in Table 6.5, it is deduced that when the potential amount of collected used product is not scarce, the sales gets larger if the quality of the RP becomes nearer the NP quality. The results also support that if the quality ratio is 0.65 or more than it, the potential collection base starts to restrict the remanufacturing capacity and remanufacturing rate separately in the base case. Therefore, the sales in case I cannot be as much as those in the extreme case if the quality ratio is equal or much more than 0.65.

For Figure 6.27, showing the demand behavior for different quality ratios; in Figure 6.28, the sales can be nearly satisfied by the firm and the reaction of the sales is consistent with the demand behavior.

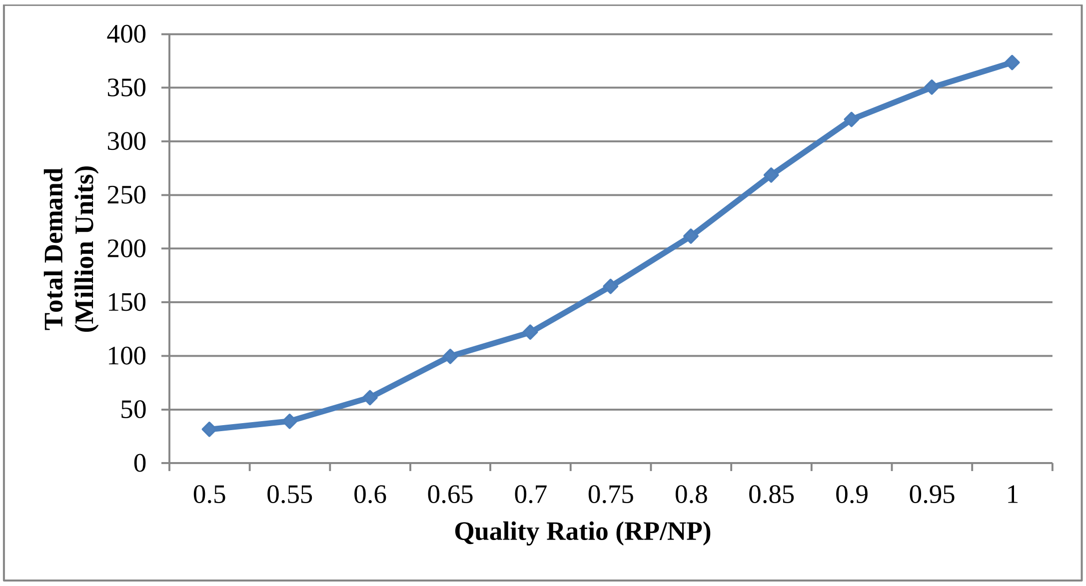

Figure 6.27. The total demand of the RP for different quality ratios for the extreme case.

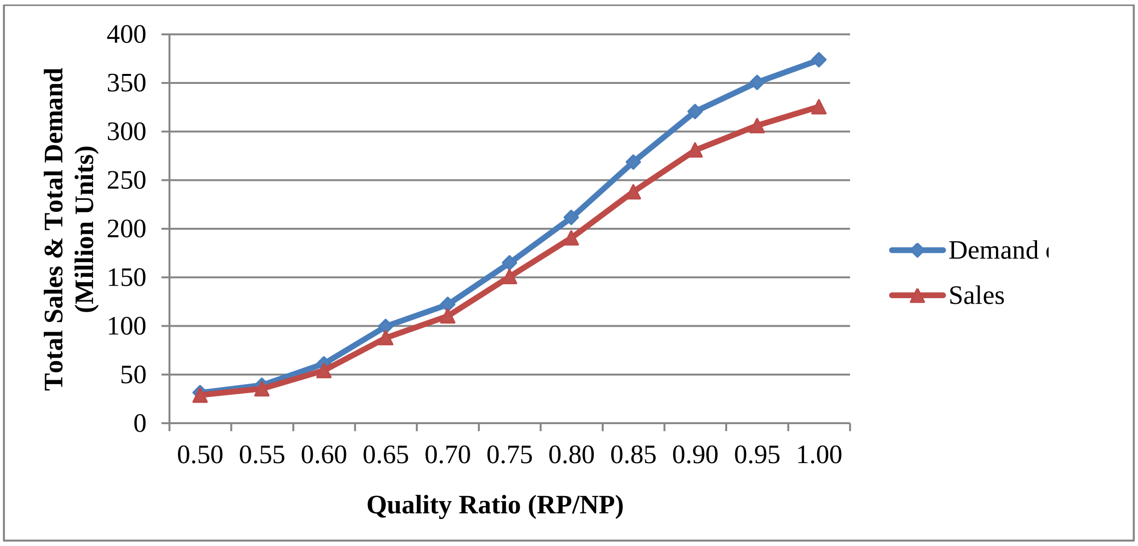

Figure 6.28. The sales and the demand of the RP for the extreme case.

The profits of the firm for the base case and the extreme case are compared in Figure 6.29:

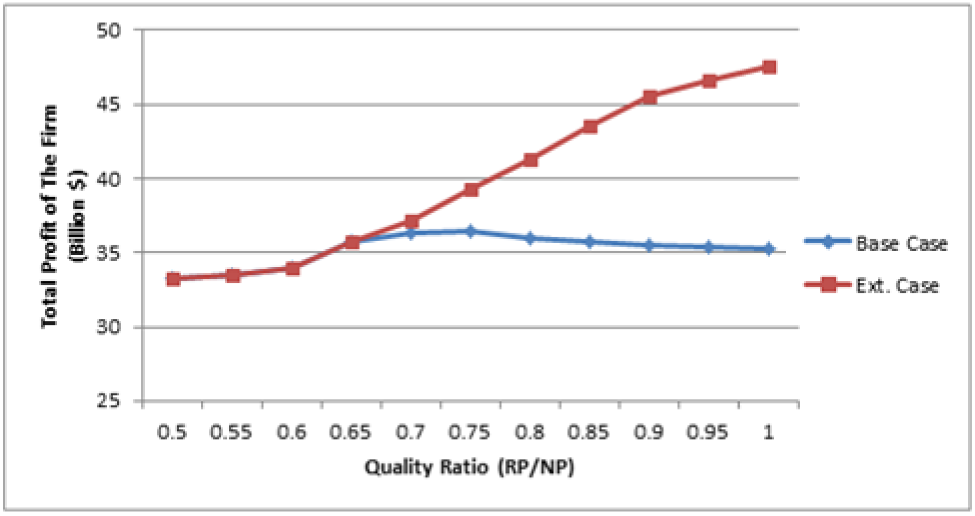

Figure 6.29. The comparison of the total profit of the firm for the base case and extreme case.

As in Figure 6.29 and Table 6.6, while the profit has a decreasing trend after an increasing trend in the base case, the profit has an increasing trend in the extreme case, since there is no restriction in remanufacturing rate due to the potential collection base.

Table 6.6. The comparison of the total profit of the firm for the base case and the extreme. case.

Quality Ratio (RP/NP)	Total Profit of the Firm -Base Case (Billion $)	Total Profit of the Firm-Extreme Case (Billion $)
0.5	33.289	33.289
0.55	33.467	33.467
0.6	34.007	34.007
0.65	35.684	35.703
0.7	36.340	37.173
0.75	36.425	39.292
0.8	35.979	41.247
0.85	35.702	43.537
0.9	35.507	45.543
0.95	35.400	46.635
1	35.311	47.504

Case I: In this case, it is assumed that the firm can also collect the other firms' used products when its potential collection base is not enough to satisfy the demand of the RP. But it is also assumed that the unit collection cost of the other firms' used products is same with the unit collection cost of the firm's used products. For this case, the profits are analyzed with the low and high feeding rates of the other firms' used products separately. The difference of this case from the extreme case is that the feeding rate is limited instead of unlimited used product as in the extreme case. As shown in Table 6.7, when the feeding rate is low, the increase in the profit is more than it in the base case as long as the used product satisfies the RP demand. However, if the demand increases very much, the profit starts to decrease as in the base case since the RP demand cannot be satisfied. If the feeding rate of the potential collection base is high, the profit increases if the quality of the RP increases since the potential collection base is always enough to satisfy the RP demand (Figure 6.30). It is observed that if the feeding rate is very low, even if the used products of the other firms can be collected, the amount of the used product is not enough to satisfy the RP demand.

Table 6.7. The comparison of the total profit of the firm for the base case and Case I.

		Low Feeding Rate	High Feeding Rate
Quality Ratio (RP/NP)	Total Profit of the Firm-Base Case (Billion $)	Total Profit of the Firm -Case I (Billion $)	Total Profit of the Firm -Case I (Billion $)
0.50	33.289	33.284	33.284
0.55	33.467	33.456	33.456
0.60	34.007	34.267	34.263
0.65	35.684	36.062	37.077
0.70	36.340	36.510	38.922
0.75	36.425	36.347	40.354
0.80	35.979	35.970	41.330
0.85	35.702	35.703	42.055
0.90	35.507	35.523	42.602
0.95	35.400	35.415	42.926
1.00	35.311	35.339	43.186

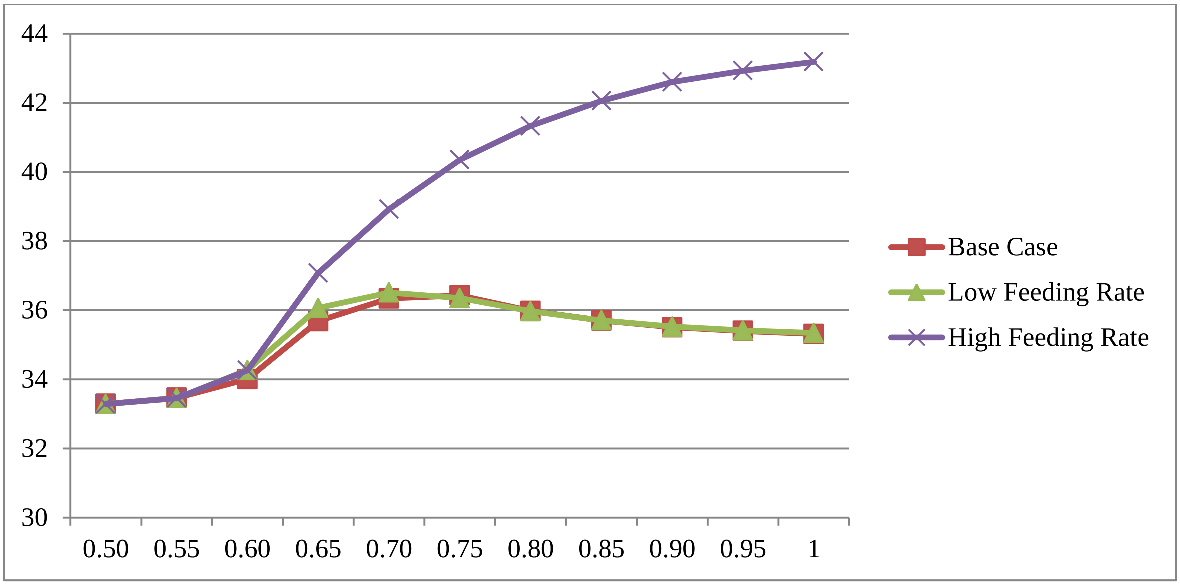

Figure 6.30. The comparison of the total profit of the firm for the base case and Case I.

Case II: In this case, the firm can collect the used products of the other firms as in Case I but differently, the unit collection cost of the other firms' used product is higher than the cost of the firm's used product.

Table 6.8. The comparison of the total profit of the firm for the base case and Case II.

		Low Feeding Rate	High Feeding Rate
Quality Ratio (RP/NP)	Base Case	Case II	Case II
0.50	33.289	33.284	33.284
0.55	33.467	33.459	33.459
0.60	34.007	34.088	34.088
0.65	35.684	35.650	35.650
0.70	36.340	37.063	37.063
0.75	36.425	39.111	39.111
0.80	35.979	40.608	40.973
0.85	35.702	39.506	43.153
0.90	35.507	38.748	45.062
0.95	35.400	38.421	46.108
1	35.311	38.202	46.944

The results of Case II are so similar with Case I. When the feeding rate is high, the profit gets higher if the quality of the RP increases. If the feeding rate is not high, the profit starts to decrease if the used product amount is not enough to satisfy the RP demand as shown in Table 6.8 and Figure 6.31.

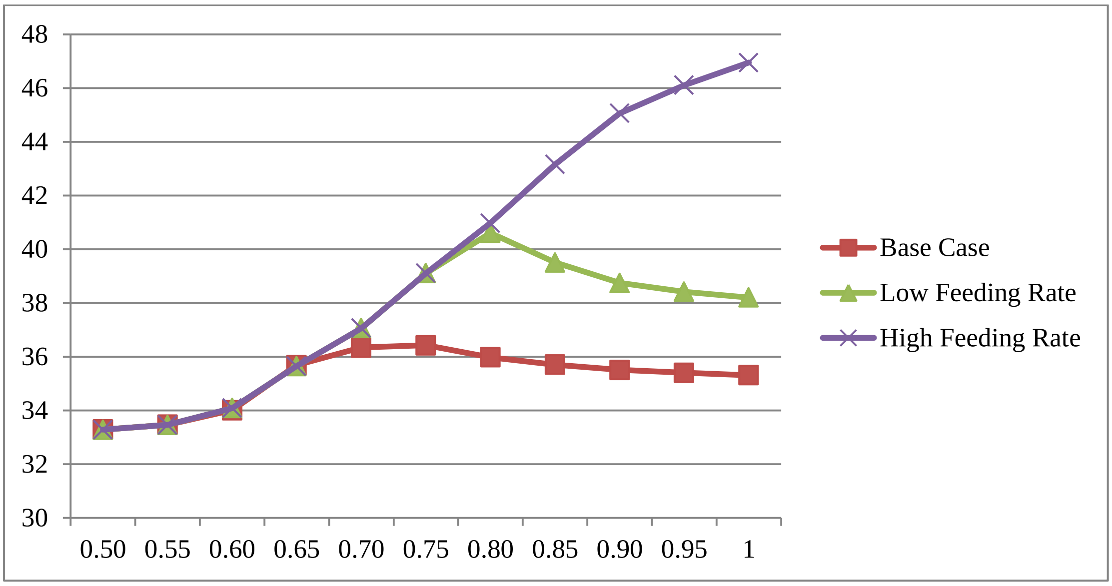

Figure 6.31. The comparison of the total profit of the firm for the base case and Case II.

If Case I and Case II are compared when the feeding rate of the used product is high, it is observed that the profit is higher when the unit collection cost of the other firms' used product is higher. The reason is that the unit price and the unit profit per product is higher when the unit collection cost of the used product is higher. The unit price cannot dominate the customers' behavior when the RP demand is satisfied and the quality of the RP is so near to the quality of the NP.

Case III: One of the main factors which make the remanufacturing advantageous for the firms is the green image factor showing the environmental image of the firm. Especially with the increasing consciousness of the customers about the environment, it is obvious that the green image factor has a positive effect on the customer behavior while preferring the product. In the base case, the model also includes the green image factor which is affecting the increase in the amount of the RP potential customer base and thereby the NP potential customer base. In case III, the green image factor effect is made higher, which means that the RP supports the increase in the customer bases more efficiently than it does in the base case.

Table 6.9. The comparison of the total profit of the firm for the base case and case III.

Quality Ratio (RP/NP)	Total Profit of the Firm -Base Case (Billion $)	Total Profit of the Firm-Case III (Billion $)
0.5	33.289	35.582
0.55	33.467	36.324
0.6	34.007	38.693
0.65	35.684	42.241
0.7	36.340	43.010
0.75	36.425	43.273
0.8	35.979	43.482
0.85	35.702	43.681
0.9	35.507	43.843
0.95	35.400	43.942
1	35.311	44.026

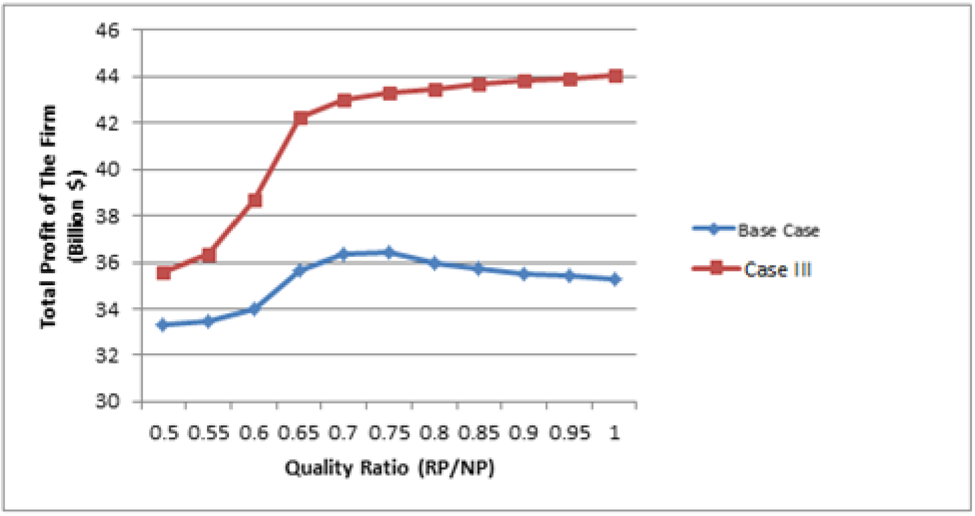

Figure 6.32. The comparison of the total profit of the firm for the base case and case III.

As shown in Table 6.9 and Figure 6.32, the profit of the firm gets higher when the quality gap between the RP and the NP becomes narrower. On the other hand, in the base case, the behavior of the profit of the firm is different. In the base case, it has been deduced that when the quality gap between the RP and the NP gets narrower until a value, the remanufacturing increases the profit. However, if the gap becomes so narrow, it leads to a risk that the customers prefer the RP and there is a huge migration to the RP from the NP potential customer base. But then, when the demand of the RP customers cannot be satisfied, the loyal customers of the RP of the firm can migrate not only to the NP potential customer base of the firm but also to the RP potential customer base of the other firms in the market. The same risk also exists for case III. However, it is observed that since it increases the customers of the RP and NP efficiently, the increase is much more than the customer loss due to the migration to the market. Therefore, the RP quality can be made as high as the NP to increase the profit of the firm even if it also leads to much more customer loss to the market when the effect of the green image factor is high on the customer behavior.

Case IV: In this case, it is assumed that the firm can determine its product quality level independently of the product quality of the other firms in the market. Therefore, the total profit of the firm is analyzed for different quality levels of the products in the market. Based on the analysis of the quality levels in scenario 1, 0.75 and 0.8 are found as the critical quality ratios to be used for this scenario. The quality ratio is determined by the division of the RP quality of the firm by the NP quality of the firm in the model as in Table 6.10. Therefore, the quality ratio indicates the ratio of the qualities in the related row in Table 6.11.

Table 6.10. Calculation table of the quality ratio.

Quality Ratio (RP/NP)	RP Quality of the Firm	NP Quality of the Firm
0.75	4.5	6
0.8	4.8	6

Table 6.11 The Comparison of the total profit of the firm for different product qualities in the market.

RP Quality of the Firm	NP Quality of the Firm	RP Quality in the Market	NP Quality in the Market	Total Profit of the Firm (Billion $)
4.5	6	4.5	6	36.425
4.5	6	5	6	36.325
4.5	6	4.5	7	35.498
4.8	6	4.8	6	35.979
4.8	6	4	6	36.215
48	6	4.8	5	37.316

The first and the fourth rows in Table 6.9 indicate the profits of the firm for the different product qualities as found in the base case. The second and the third rows indicate the cases when the RP quality of the firm is lower than the RP quality in the market and the NP quality of the firm is lower than the NP quality in the market, respectively. The fifth row indicates the case when the RP quality of the firm is higher than the RP quality in the market. The sixth row shows the case when the NP quality of the firm is higher than the NP quality in the market.

The profits in Table 6.11 show that although the RP or NP quality of the firm is lower than that in the market, the firm can increase its profit by adjusting the quality gap between its NP and RP. Furthermore, although the qualities of the products of the firm are same with the qualities of the products in the market, the gap between the qualities of the RP and the NP of the firm has an incredible effect on the total profit.

7. CONCLUSION

With the increase in the popularity of remanufacturing, there are many studies carried out. On the other hand, although the number of the studies has started to increase also in system dynamics field, there are only limited studies as yet. Differently from most studies in system dynamics field, in this study, remanufacturing is analyzed in macro level to enable the top managers to make a decision about potential investment in remanufacturing through profit comparisons.

In the first step, the system behavior is analyzed in the long term by assigning different values to the qualities of the remanufactured and the new products. The qualities include both the real quality of the product, and the quality perception of the customers about the products. The analyses show that the collectable used product, the quality and the price of the products are the important factors determining the customer behavior. The interesting point is that these factors also have effects on each other indirectly. If the quality of the remanufactured product is assumed high, it increases the migration rate of the customers to the *remanufactured product potential customer base*. However, it also increases the consumption of the used product for remanufacturing and it has a negative effect on the unit acquisition cost per used product and thereby the unit price per remanufactured product. Therefore, the consumption of the used products affects the customer behavior after a delay through the unit price and insufficient sales. As a result, even if the remanufactured product is more advantageous for the customers, the remanufactured product demand can be satisfied for a while since the manufacturing rate decreases due to the decrease in the new product demand. After this point, the behavior of the customers change and the *remanufactured product potential customer base* decreases until the sufficient collection base (which is fed by used products) is provided. When the sufficient collection base is provided, it enables to satisfy the demand of the remanufactured product customers and the remanufactured product becomes more advantageous again since the unit price decreases due to the decrease in the unit acquisition cost per collected product. Therefore, it can be observed that there is a negative feedback loop affected by the potential collection base and it balances the system behavior in the long term. In this step, the system is also analyzed by changing the factors affecting the potential collection base. These scenarios also support the same observation that the used product base, which is called *potential collection base*, has a significant role in the behavior of the customer bases since it enables or restricts the increase in the remanufactured product sales and thereby the quarterly remanufactured product demand since the customers do not wait to buy a remanufactured product forever if their demand cannot be satisfied.

In the second step, the profit analysis is done for different scenarios to determine the cases when the remanufacturing is a profitable strategy for a computer firm. The important point is that if some amount of the new product potential customer base migrates to the remanufactured product potential customer base, they become the potential customers of the remanufactured product of the firm including also the loyal customers. In other words, the customers migrating to the remanufactured product customer base give up being the potential customer base of the new product of the firm. Therefore, there is a high risk that they may also prefer the products of the other firms when the remanufactured product demand cannot be satisfied by the firm. As a result, the right strategy for the firm is to gain as much as customer from its new product potential customer base, as long as the demand can be satisfied. Because the profit increases if the remanufactured product sales increase, but if the demand cannot be satisfied, it leads to a decrease in the total profit of the firm.

Another observation is that the green image factor has an effective role in the increase of the profit of the firm. Even if the quality of the remanufactured product is equal to the new product and there is a high risk to lose the loyal customer of the firm due to the non-availability of remanufactured product, remanufacturing is a profitable strategy. The reason is that it leads to a significant increase in the customer bases due to the consciousness of the people. Therefore, even if the loss of the firm is high due to the non-availability of the remanufactured product, the profit increases since the customers gained due to the green image factor are larger than the customer loss.

Lastly, the firm can increase its profit by adjusting the gap between the qualities of its new and remanufactured product even if the quality of its product is worse than that of the market. The interaction between the manufacturing and remanufacturing rates is important since the collection of used products is a necessity for the remanufacturing, and since only new products accumulate in the used product collection base at the end of their use.

For the future work, the effect of the different levels of government incentives on the total profit can be analyzed. Moreover, the effect of the different profit margins (which are added to the unit cost while determining the unit price) can be analyzed since the unit price has an important role on the customer behavior.

APPENDIX A: THE EQUATIONS OF THE MODEL

```
Delayed_Eff_of_coll__base_on_acquisition_cost(t) =
Delayed_Eff_of_coll__base_on_acquisition_cost(t - dt) +
(Eff_rate__of_coll_base) * dt
INIT Delayed_Eff_of_coll__base_on_acquisition_cost =
Eff_of_coll_base_on_acquisition_cost
INFLOWS:
Eff_rate__of_coll_base =
(Eff_of_coll_base_on_acquisition_cost-
Delayed_Eff_of_coll__base_on_acquisition_cost)/Delay_of_effe
ct_of_coll_base
Eff_of_mnf_cap_depreciation_cost(t) =
Eff_of_mnf_cap_depreciation_cost(t - dt) +
(Eff_of_mnf_depr_cost_change) * dt
INIT Eff_of_mnf_cap_depreciation_cost =
Unit_depreciation_cost__per_new_product
INFLOWS:
Eff_of_mnf_depr_cost_change =
(Unit_depreciation_cost__per_new_product-
Eff_of_mnf_cap_depreciation_cost)/Depreciation_effect__delay
Eff_of_RM_cap__depreciation_cost(t) =
Eff_of_RM_cap__depreciation_cost(t - dt) +
(Eff_of_RM_cap_depr_cost_change) * dt
INIT Eff_of_RM_cap__depreciation_cost =
Unit_depreciation_cost_per_RM_cap
INFLOWS:
Eff_of_RM_cap_depr_cost_change =
(Unit_depreciation_cost_per_RM_cap-
Eff_of_RM_cap__depreciation_cost)/Depreciation_effect__delay
Estimated_RM__rate(t) = Estimated_RM__rate(t - dt) +
(Estimated_RM_rate__change) * dt
INIT Estimated_RM__rate = 100
```

```
INFLOWS:
Estimated_RM_rate__change = (RM_rate-
Estimated_RM__rate)/Estimation_delay
Expected_sales_of_new_product(t) =
Expected_sales_of_new_product(t - dt) +
(Expected_sales_of_new_product_change) * dt
INIT Expected_sales_of_new_product = 6425
INFLOWS:
Expected_sales_of_new_product_change =
(Quaterly_demand_of__new_product-
Expected_sales_of_new_product)/Expectation_delay_for_new_pro
duct_sales
Expected_sales_of_RM_Product(t) =
Expected_sales_of_RM_Product(t - dt) +
(Expected_sales_of_RM_product_change) * dt
INIT Expected_sales_of_RM_Product = 100
INFLOWS:
Expected_sales_of_RM_product_change =
(MIN(Potential_amount_of__collectable_product,Quarterly_dema
nd_of__RM_product)-
Expected_sales_of_RM_Product)/Expectation_delay_for_RM_produ
ct_sales
Inuse_new_products(t) = Inuse_new_products(t - dt) +
(Purchasing_rate_of_new_product - Discarding_rate -
Discarding_rate_of_used_goods1) * dt
INIT Inuse_new_products = 6425*12
INFLOWS:
Purchasing_rate_of_new_product = Sales_of_new_product
OUTFLOWS:
Discarding_rate =
Inuse_new_products*Used_product_arrival_frc/Using_Time
Discarding_rate_of_used_goods1 =
Inuse_new_products*Discarding_frc
```

```
Inuse_RM_Products(t) = Inuse_RM_Products(t - dt) +
(Purchasing_rate_of_RM_product -
Discarding_rate_of_used_RM_goods) * dt
INIT Inuse_RM_Products = 0
INFLOWS:
Purchasing_rate_of_RM_product = Sales_of_RM_product
OUTFLOWS:
Discarding_rate_of_used_RM_goods =
Inuse_RM_Products/Using_Time
Manufacturing_capacity(t) = Manufacturing_capacity(t - dt) +
(Mnf__cap_investment_rate - Mnf_cap_disposal_rate -
Mnf_cap_depreciation) * dt
INIT Manufacturing_capacity = 6425
INFLOWS:
Mnf__cap_investment_rate = Perceived_mnf_cap_investment
OUTFLOWS:
Mnf_cap_disposal_rate = Perceived_mnf_cap_disposal
Mnf_cap_depreciation =
Manufacturing_capacity/Mnf_cap_depreciation_time
Net_profit__of_manufacturing(t) =
Net_profit__of_manufacturing(t - dt) +
(Profit_rate_of_manufacturing_per_quarter) * dt
INIT Net_profit__of_manufacturing = 0
INFLOWS:
Profit_rate_of_manufacturing_per_quarter =
Manufacturing_income-Total_expenditure__for_manufacturing
Net_profit_of_RM(t) = Net_profit_of_RM(t - dt) +
(Profit_rate_of_RM_per_quarter) * dt
INIT Net_profit_of_RM = 0
INFLOWS:
Profit_rate_of_RM_per_quarter = Remanufacturing__income-
Total_expenditure__for_remanufacturing
```

```
New_product_potential_cust_base(t) =
New_product_potential_cust_base(t - dt) +
(Growth_rate_of_new_prod_pot_cust_base -
Customer_migration__rate -
Decay_rate_of_new__prod_pot_cust_base) * dt
INIT New_product_potential_cust_base = 77100
INFLOWS:
Growth_rate_of_new_prod_pot_cust_base =
Average__growth_constant_of_new_prod_cust_base*Growth_frc_of
__new_prod_cust_base+Additional_growth_of_new_prod__cust_bas
e_due_to_GIF
OUTFLOWS:
Customer_migration__rate =
New_product_potential_cust_base*MAX(Customer_migration__frac
tion,0)+RM_product_potential_cust_base*MIN(Customer_migratio
n__fraction,0)
Decay_rate_of_new__prod_pot_cust_base =
New_product_potential_cust_base*Decay_frc_of_potential_cust_
base
Perceived_Eff_of_green_image__factor_on_cust_base_growth(t)
= Perceived_Eff_of_green_image__factor_on_cust_base_growth(t
- dt) + (Perceived_eff_of_green_image__factor_change) * dt
INIT
Perceived_Eff_of_green_image__factor_on_cust_base_growth = 0
INFLOWS:
Perceived_eff_of_green_image__factor_change =
(RM_product_potential_cust_base-
Perceived_Eff_of_green_image__factor_on_cust_base_growth)/Ef
f_Del_of_Green__Image_Factor
Perceived_eff_of_new_product_quality_comparing_to_market(t)
= Perceived_eff_of_new_product_quality_comparing_to_market(t
- dt) + (Perceived_eff_of__new_product_quality_change) * dt
```

```
INIT
Perceived_eff_of_new_product_quality_comparing_to_market =
Eff_of_new_product_quality_comparing_to_market
INFLOWS:
Perceived_eff_of__new_product_quality_change =
(Eff_of_new_product_quality_comparing_to_market-
Perceived_eff_of_new_product_quality_comparing_to_market)/Ef
fect_delay2
Perceived_eff_of_new_product_unit_price_comparing_to_market(
t) =
Perceived_eff_of_new_product_unit_price_comparing_to_market(
t - dt) + (Perceived_eff_of__new_product_price_change) * dt
INIT
Perceived_eff_of_new_product_unit_price_comparing_to_market
= Eff_of_new_product_price_in_the_market
INFLOWS:
Perceived_eff_of__new_product_price_change =
(Eff_of_new_product_price_in_the_market-
Perceived_eff_of_new_product_unit_price_comparing_to_market)
/Effect_delay2
Perceived_eff_of_nonavailability_on_mig_frc(t) =
Perceived_eff_of_nonavailability_on_mig_frc(t - dt) +
(Perc_eff_of_nonavailability_change) * dt
INIT Perceived_eff_of_nonavailability_on_mig_frc =
Eff_of_nonavailability__of_RM_product__on_migration_frc
INFLOWS:
Perc_eff_of_nonavailability_change =
(Eff_of_nonavailability__of_RM_product__on_migration_frc-
Perceived_eff_of_nonavailability_on_mig_frc)/Effect_delay1
Perceived_eff_of_qualities'__ratio_on_mig_frc(t) =
Perceived_eff_of_qualities'__ratio_on_mig_frc(t - dt) +
(Perc_eff_of_qualities'_ratio_change) * dt
```

```
INIT Perceived_eff_of_qualities'__ratio_on_mig_frc =
Eff_of_qualities'_ratio_on_migration_frc
INFLOWS:
Perc_eff_of_qualities'_ratio_change =
(Eff_of_qualities'_ratio_on_migration_frc-
Perceived_eff_of_qualities'__ratio_on_mig_frc)/Effect_delay1
Perceived_eff_of_RM_product_unit_price_comparing_to_market(t
) =
Perceived_eff_of_RM_product_unit_price_comparing_to_market(t
- dt) + (Perceived_eff_of_RM_product_price_change) * dt
INIT
Perceived_eff_of_RM_product_unit_price_comparing_to_market =
Eff_of_RM_product_price_in_the_market
INFLOWS:
Perceived_eff_of_RM_product_price_change =
(Eff_of_RM_product_price_in_the_market-
Perceived_eff_of_RM_product_unit_price_comparing_to_market)/
Effect_delay2
Perceived_eff_of_RM_product_quality_comparing_to_market(t) =
Perceived_eff_of_RM_product_quality_comparing_to_market(t -
dt) + (Perceived_eff_of_RM_product_quality_change) * dt
INIT Perceived_eff_of_RM_product_quality_comparing_to_market
= Eff_of_RM_product_quality_comparing_to_market
INFLOWS:
Perceived_eff_of_RM_product_quality_change =
(Eff_of_RM_product_quality_comparing_to_market-
Perceived_eff_of_RM_product_quality_comparing_to_market)/Eff
ect_delay2
Perceived_eff_of_RM_prod_nonavailability_on_growth_frc(t) =
Perceived_eff_of_RM_prod_nonavailability_on_growth_frc(t -
dt) + (Perceived_eff_of_RM_prod__nonavailability_change) *
dt
```

```
INIT Perceived_eff_of_RM_prod_nonavailability_on_growth_frc
= Eff_of_nonavailability__of_RM_product_on_growth_frc
INFLOWS:
Perceived_eff_of_RM_prod__nonavailability_change =
(Eff_of_nonavailability__of_RM_product_on_growth_frc-
Perceived_eff_of_RM_prod_nonavailability_on_growth_frc)/Effe
ct_delay2
Perceived_eff_of_unit_prices'_ratio_on_mig_frc(t) =
Perceived_eff_of_unit_prices'_ratio_on_mig_frc(t - dt) +
(Perc_eff_of_unit_prices'_ratio_change) * dt
INIT Perceived_eff_of_unit_prices'_ratio_on_mig_frc =
Eff_of_unit_prices'_ratio_on_migration_frc
INFLOWS:
Perc_eff_of_unit_prices'_ratio_change =
(Eff_of_unit_prices'_ratio_on_migration_frc-
Perceived_eff_of_unit_prices'_ratio_on_mig_frc)/Effect_delay
1
Perceived_mnf_cap_disposal(t) = Perceived_mnf_cap_disposal(t
- dt) + (Mnf_cap_disposal_smooth_rate3) * dt
INIT Perceived_mnf_cap_disposal = 0
INFLOWS:
Mnf_cap_disposal_smooth_rate3 = (Smoothed_mnf_cap_disposal2-
Perceived_mnf_cap_disposal)/(Mnf_cap_disposal_smoothing_dela
y/3)
Perceived_mnf_cap_investment(t) =
Perceived_mnf_cap_investment(t - dt) +
(Perceived_mnf_cap_investment_change) * dt
INIT Perceived_mnf_cap_investment = 0
INFLOWS:
Perceived_mnf_cap_investment_change =
(MAX(Manufacturing_cap_adjustment,0)-
Perceived_mnf_cap_investment)/Mnf_cap_investment__smoothing_
delay
```

```
Perceived_new_product_unit_cost(t) =
Perceived_new_product_unit_cost(t - dt) +
(Perceived_new_product_unit_cost_change) * dt
INIT Perceived_new_product_unit_cost =
Unit_cost_of_new_product
INFLOWS:
Perceived_new_product_unit_cost_change =
(Unit_cost_of_new_product-
Perceived_new_product_unit_cost)/Smoothing_delay_for_perceiv
ed_unit_cost
Perceived_remanufacturing_cap_investment(t) =
Perceived_remanufacturing_cap_investment(t - dt) +
(Perceived_RM__cap_investment_change) * dt
INIT Perceived_remanufacturing_cap_investment = 0
INFLOWS:
Perceived_RM__cap_investment_change =
(MAX(Remanufacturing__cap_adjustment,0)-
Perceived_remanufacturing_cap_investment)/RM_cap_inv_smoothi
ng_delay
Perceived_RM_cap_disposal(t) = Perceived_RM_cap_disposal(t -
dt) + (RM_cap_disposal_smooth_rate3) * dt
INIT Perceived_RM_cap_disposal = 0
INFLOWS:
RM_cap_disposal_smooth_rate3 = (Smoothed_RM_cap_disposal2-
Perceived_RM_cap_disposal)/(RM_cap_disposal_smoothing_delay/
3)
Perceived_RM_product_unit_cost(t) =
Perceived_RM_product_unit_cost(t - dt) +
(Perceived_RM_product_unit_cost_change) * dt
INIT Perceived_RM_product_unit_cost =
Unit_cost_of__RM_product
INFLOWS:
```

```
Perceived_RM_product_unit_cost_change =
(Unit_cost_of__RM_product-
Perceived_RM_product_unit_cost)/Smoothing_delay_for_perceive
d_unit_cost
Potential_collection_base(t) = Potential_collection_base(t -
dt) + (Discarding_rate - Collection_rate -
Discarding_rate_of_used_goods2) * dt
INIT Potential_collection_base = 1928
INFLOWS:
Discarding_rate =
Inuse_new_products*Used_product_arrival_frc/Using_Time
OUTFLOWS:
Collection_rate =
MIN(Potential_collection_base*Collection_ability_level/Coll_
time, Estimated_RM__rate)
Discarding_rate_of_used_goods2 =
Potential_collection_base/Discarding_delay
RM_cap(t) = RM_cap(t - dt) +
(Remanufacturing_cap_investment_rate -
Remanufacturing_cap_disposal_rate - RM_cap__depreciation) *
dt
INIT RM_cap = 100
INFLOWS:
Remanufacturing_cap_investment_rate =
Perceived_remanufacturing_cap_investment
OUTFLOWS:
Remanufacturing_cap_disposal_rate =
Perceived_RM_cap_disposal
RM_cap__depreciation = RM_cap/RM_cap_depreciation_time
RM_product_potential_cust_base(t) =
RM_product_potential_cust_base(t - dt) +
(Growth_rate_of_RM_prod_pot_cust_base +
```

```
Customer_migration__rate -
Decay_rate_of_RM_prod_pot_cust_base) * dt
INIT RM_product_potential_cust_base = 1200
INFLOWS:
Growth_rate_of_RM_prod_pot_cust_base =
Average_growth__constant_of_RM__prod_cust_base*Growth_frc_of
_RM_prod_cust_base+Additional_growth_of_RM_prod_cust_base_du
e_to_GIF
Customer_migration__rate =
New_product_potential_cust_base*MAX(Customer_migration__frac
tion,0)+RM_product_potential_cust_base*MIN(Customer_migratio
n__fraction,0)
OUTFLOWS:
Decay_rate_of_RM_prod_pot_cust_base =
RM_product_potential_cust_base*Decay_frc_of_potential_cust_b
ase
Smoothed_mnf_cap_disposal1(t) = Smoothed_mnf_cap_disposal1(t
- dt) + (Mnf_cap_disposal_smooth_rate1) * dt
INIT Smoothed_mnf_cap_disposal1 = 0
INFLOWS:
Mnf_cap_disposal_smooth_rate1 =
(Planned_amount_of__mnf_cap_disposal-
Smoothed_mnf_cap_disposal1)/(Mnf_cap_disposal_smoothing_dela
y/3)
Smoothed_mnf_cap_disposal2(t) = Smoothed_mnf_cap_disposal2(t
- dt) + (Mnf_cap_disposal_smooth_rate2) * dt
INIT Smoothed_mnf_cap_disposal2 = 0
INFLOWS:
Mnf_cap_disposal_smooth_rate2 = (Smoothed_mnf_cap_disposal1-
Smoothed_mnf_cap_disposal2)/(Mnf_cap_disposal_smoothing_dela
y/3)
Smoothed_RM_cap_disposal1(t) = Smoothed_RM_cap_disposal1(t -
dt) + (RM_cap_disposal_smooth_rate1) * dt
```

```
INIT Smoothed_RM_cap_disposal1 = 0
INFLOWS:
RM_cap_disposal_smooth_rate1 =
(Planned_amount_of_RM_cap_disposal-
Smoothed_RM_cap_disposal1)/(RM_cap_disposal_smoothing_delay/
3)
Smoothed_RM_cap_disposal2(t) = Smoothed_RM_cap_disposal2(t -
dt) + (RM_cap_disposal_smooth_rate2) * dt
INIT Smoothed_RM_cap_disposal2 = 0
INFLOWS:
RM_cap_disposal_smooth_rate2 = (Smoothed_RM_cap_disposal1-
Smoothed_RM_cap_disposal2)/(RM_cap_disposal_smoothing_delay/
3)
Total_profit(t) = Total_profit(t - dt) +
(Total_profit_rate_per_quarter) * dt
INIT Total_profit = 0
INFLOWS:
Total_profit_rate_per_quarter =
(Profit_rate_of_RM_per_quarter+Profit_rate_of_manufacturing_
per_quarter)-
(((Profit_rate_of_RM_per_quarter+Profit_rate_of_manufacturin
g_per_quarter)*Tax_percent)-Tax_credit_for_investment)
Total_quarterly_demand_of_new_product(t) =
Total_quarterly_demand_of_new_product(t - dt) +
(Total_quarterly_demand_of_new_product_creation_rate) * dt
INIT Total_quarterly_demand_of_new_product = 0
INFLOWS:
Total_quarterly_demand_of_new_product_creation_rate =
Quaterly_demand_of__new_product
Total_quarterly_demand_of_RM_product(t) =
Total_quarterly_demand_of_RM_product(t - dt) +
(Total_quarterly_demand_of_RM_product_creation_rate) * dt
INIT Total_quarterly_demand_of_RM_product = 0
```

```
INFLOWS:
Total_quarterly_demand_of_RM_product_creation_rate =
Quarterly_demand_of__RM_product
Total_sales_of__new_product(t) =
Total_sales_of__new_product(t - dt) +
(Sales_amount_of_new_product) * dt
INIT Total_sales_of__new_product = 0
INFLOWS:
Sales_amount_of_new_product = Sales_of_new_product
Total_sales_of__RM_product(t) = Total_sales_of__RM_product(t
- dt) + (Sales_amount_of_RM_product) * dt
INIT Total_sales_of__RM_product = 0
INFLOWS:
Sales_amount_of_RM_product = Sales_of_RM_product
Acquisition_cost_per_collected_product =
Normal_acquisition_cost_per_coll_product*Delayed_Eff_of_coll
__base_on_acquisition_cost
Additional_growth_of_new_prod__cust_base_due_to_GIF =
Perceived_Eff_of_green_image__factor_on_cust_base_growth*Nor
mal_additional_growth*Frc_of_GIF_eff_on_new_prod_cust_base_g
rowth
Additional_growth_of_RM_prod_cust_base_due_to_GIF =
Perceived_Eff_of_green_image__factor_on_cust_base_growth*Nor
mal_additional_growth*Frc_of_GIF_eff_on_RM_prod_cust_base_gr
owth
Average__growth_constant_of_new_prod_cust_base = 100
Average_growth__constant_of_RM__prod_cust_base = 20
Average_quality_of_new_product_in_market = 6
Average_quality_of_RM_product_in_market = 4
Avg_unit_price_of_new_prod_for_market =
Unit_price_per__new_product
Avg_unit_price_of_RM_product_for_market =
Unit_price_per__RM_product
```

```
Collection_ability_level = 0.95
Coll_time = 1/3
Cost_per_increasing_unit_cap_of_remanufacturing = 250
Credit_amount_for_remanufacturing_cap__investment = 0.2
Customer_migration__fraction =
Perceived_eff_of_qualities'__ratio_on_mig_frc+Perceived_eff_
of_unit_prices'_ratio_on_mig_frc+Perceived_eff_of_nonavailab
ility_on_mig_frc+Normal_mig_frc
Decay_frc_of_potential_cust_base = 0.001
Delay_of_effect_of_coll_base = 1.5
Demand_per_quarter_per_person = 1/12
Depreciation_cost_per_RM_cap = 250
Depreciation_cost_per__manufacturing_cap = 250
Depreciation_effect__delay = 1
Discarding_delay = 1
Discarding_frc = 0.70/12
Effect_delay1 = 4
Effect_delay2 = 4
Eff_Del_of_Green__Image_Factor = 4
Eff_of_coll_base_on_acquisition_cost =
GRAPH(Potential_collection_base/Nominal_coll_base)
(0.25, 2.50), (0.375, 2.46), (0.5, 2.32), (0.625, 2.11),
(0.75, 1.81), (0.875, 1.51), (1.00, 1.03), (1.13, 0.82),
(1.25, 0.68), (1.38, 0.62), (1.50, 0.57), (1.63, 0.53),
(1.75, 0.5), (1.88, 0.512), (2.00, 0.5)
Eff_of_new_product_quality_comparing_to_market =
GRAPH(Average_quality_of_new_product_in_market/Quality_of_ne
w_product)
(0.5, 2.00), (0.667, 1.96), (0.833, 1.74), (1, 1.00), (1.17,
0.49), (1.33, 0.29), (1.50, 0.11), (1.67, 0.04), (1.83,
0.02), (2.00, 0.00)
```

```
Eff_of_new_product_price_in_the_market =
GRAPH(Unit_price_per__new_product/Avg_unit_price_of_new_prod
_for_market)
(0.5, 2.00), (0.667, 1.96), (0.833, 1.74), (1, 1.00), (1.17,
0.49), (1.33, 0.29), (1.50, 0.11), (1.67, 0.04), (1.83,
0.02), (2.00, 0.00)
Eff_of_nonavailability__of_RM_product_on_growth_frc =
GRAPH(Ratio_of_demand_and_sales_of_RM_product/Normal_demand_
and_sales_ratio)
(1.00, 3.00), (1.17, 2.98), (1.33, 2.88), (1.50, 2.73),
(1.67, 2.52), (1.83, 2.25), (2.00, 1.81), (2.17, 1.24),
(2.33, 0.66), (2.50, 0.00)
Eff_of_nonavailability__of_RM_product__on_migration_frc =
GRAPH(Ratio_of_demand_and_sales_of_RM_product/Normal_demand_
and_sales_ratio)
(1.00, 0.00), (1.15, -0.002), (1.30, -0.003), (1.45, -
0.009), (1.60, -0.018), (1.75, -0.036), (1.90, -0.063),
(2.05, -0.104), (2.20, -0.156), (2.35, -0.213), (2.50, -
0.296)
Eff_of_qualities'_ratio_on_migration_frc =
GRAPH(Quality_of_RM_product/Quality_of_new_product)
(0.2, -0.1), (0.289, -0.097), (0.378, -0.092), (0.467, -
0.082), (0.556, -0.068), (0.644, -0.045), (0.733, -0.025),
(0.822, -0.012), (0.911, -0.004), (1.00, 0.00)
Eff_of_RM_product_price_in_the_market =
GRAPH(Unit_price_per__RM_product/Avg_unit_price_of_RM_produc
t_for_market)
(0.5, 2.00), (0.667, 1.96), (0.833, 1.74), (1, 1.00), (1.17,
0.49), (1.33, 0.29), (1.50, 0.11), (1.67, 0.04), (1.83,
0.02), (2.00, 0.00)
Eff_of_RM_product_quality_comparing_to_market =
GRAPH(Average_quality_of_RM_product_in_market/Quality_of_RM_
product)
```

```
(0.5, 2.00), (0.667, 1.96), (0.833, 1.74), (1, 1.00), (1.17,
0.49), (1.33, 0.29), (1.50, 0.11), (1.67, 0.04), (1.83,
0.02), (2.00, 0.00)
Eff_of_unit_prices'_ratio_on_migration_frc =
GRAPH(Unit_price_per__RM_product/Unit_price_per__new_product
)
(0.2, 0.1), (0.289, 0.097), (0.378, 0.092), (0.467, 0.082),
(0.556, 0.068), (0.644, 0.045), (0.733, 0.025), (0.822,
0.012), (0.911, 0.004), (1.00, 0.00)
Estimation_delay = 1
Expectation_delay_for_RM_product_sales = 1
Expectation_delay_for_new_product_sales = 1
Frc_of_GIF_eff_on_new_prod_cust_base_growth = 0.0025
Frc_of_GIF_eff_on_RM_prod_cust_base_growth = 0.005
Growth_frc_of_RM_prod_cust_base =
Perceived_eff_of_RM_product_unit_price_comparing_to_market+P
erceived_eff_of_RM_product_quality_comparing_to_market+Perce
ived_eff_of_RM_prod_nonavailability_on_growth_frc+Normal_gro
wth_frc
Growth_frc_of__new_prod_cust_base =
Perceived_eff_of_new_product_unit_price_comparing_to_market+
Perceived_eff_of_new_product_quality_comparing_to_market+Nor
mal_growth_frc
Investment_cost_for_remanufacturing_equipment =
RM_cap__depreciation*Cost_per_increasing_unit_cap_of_remanuf
acturing
Manufacturing_cap_adjustment =
(Expected_sales_of_new_product-
Manufacturing_capacity)/Mnf_capacity_adjustment_time+Mnf_cap
_depreciation
Manufacturing_income =
Sales_of_new_product*Unit_price_per__new_product
```

```
Manufacturing_rate =
MIN(Manufacturing_capacity,Quaterly_demand_of__new_product)
Mnf_cap_depreciation_time = 40
Mnf_capacity_adjustment_time = 6
Mnf_cap_disposal_smoothing_delay = 6
Mnf_cap_investment__smoothing_delay = 1
Nominal_coll_base = 1000
Normal_acquisition_cost_per_coll_product = 50
Normal_additional_growth = 1
Normal_demand_and_sales_ratio = 1
Normal_growth_frc = 0
Normal_mig_frc = -0.01
Planned_amount_of_RM_cap_disposal = MAX(-
Remanufacturing__cap_adjustment,0)
Planned_amount_of__mnf_cap_disposal = MAX(-
Manufacturing_cap_adjustment,0)
Potential_amount_of__collectable_product =
Potential_collection_base*Collection_ability_level/Coll_time
Quality_of_new_product = 6
Quality_of_RM_product = 4
Quarterly_demand_of__RM_product =
RM_product_potential_cust_base*Demand_per_quarter_per_person
Quaterly_demand_of__new_product =
New_product_potential_cust_base*Demand_per_quarter_per_perso
n
Ratio_of_demand_and_sales_of_RM_product =
Quarterly_demand_of__RM_product/MAX(Sales_of_RM_product,1)
Remanufacturing__income =
Sales_of_RM_product*Unit_price_per__RM_product
Remanufacturing__cap_adjustment =
(Expected_sales_of_RM_Product-
RM_cap)/RM_cap_adjustment_time+RM_cap__depreciation
RM_cap_depreciation_time = 40
```

```
RM_cap_adjustment_time = 6
RM_cap_disposal_smoothing_delay = 6
RM_cap_inv_smoothing_delay = 1
RM_rate = MIN(RM_cap,
Potential_amount_of__collectable_product,
Quarterly_demand_of__RM_product)
Sales_of_RM_product = RM_rate
Sales_of_new_product = Manufacturing_rate
Smoothing_delay_for_perceived_unit_cost = 1.5
Tax_credit_for_investment =
Investment_cost_for_remanufacturing_equipment*Credit_amount_
for_remanufacturing_cap__investment
Tax_percent = 0.2
Total_expenditure__for_remanufacturing =
RM_rate*Unit_cost_of__RM_product
Total_expenditure__for_manufacturing =
Manufacturing_rate*Unit_cost_of_new_product
Unit_cost_of_new_product =
Unit_mnf_cost_per__new_product+Eff_of_mnf_cap_depreciation_c
ost
Unit_cost_of__RM_product =
Unit_mnf_cost_per__RM_Product+Eff_of_RM_cap__depreciation_co
st
Unit_depreciation_cost_per_RM_cap =
MIN(30,RM_cap__depreciation*Depreciation_cost_per_RM_cap/MAX
(Sales_of_RM_product,1))
Unit_depreciation_cost__per_new_product =
MIN(30,Mnf_cap_depreciation*Depreciation_cost_per__manufactu
ring_cap/Sales_of_new_product)
Unit_mnf_cost_per__RM_Product =
Unit_mnf_cost_per_RM_prod_except_acquisition_cost+Acquisitio
n_cost_per_collected_product
Unit_mnf_cost_per__new_product = 550
```

```
Unit_mnf_cost_per_RM_prod_except_acquisition_cost = 225
Unit_price_per__new_product =
Perceived_new_product_unit_cost*1.1
Unit_price_per__RM_product =
Perceived_RM_product_unit_cost*1.3
Used_product_arrival_frc = 0.30
Using_Time = 12
```

APPENDIX B: PC MARKET GROWTH

Table B.1. U.S and worldwide PC market Growth.

	1975	1980	1985	1990	1995	2000	2005	2010	2015
U.S. PC Sales (#M)	0.04	0.76	6.6	9.5	21.4	46	62	77.1	88-90
U.S. PC Revenues ($B)	0.05	1.5	17.2	24.5	56.8	86.9	90.5	75.4	70-75
U.S. PC Installed Base (#M)	0.04	1.4	19	51	86	177	234	295	360-370
Worldwide PC Sales (#M)	0.05	1.1	11	24	58	132	207	301	400-410
Worldwide PC Revenues ($B)	0.06	3.6	29.5	71	155	251	301	300	310-320
Worldwide Installed Base (#M)	0.05	2.1	33	100	225	529	910	1,415	1,980-2,030

APPENDIX C: STOCK-FLOW DIAGRAM FOR PRM MODEL

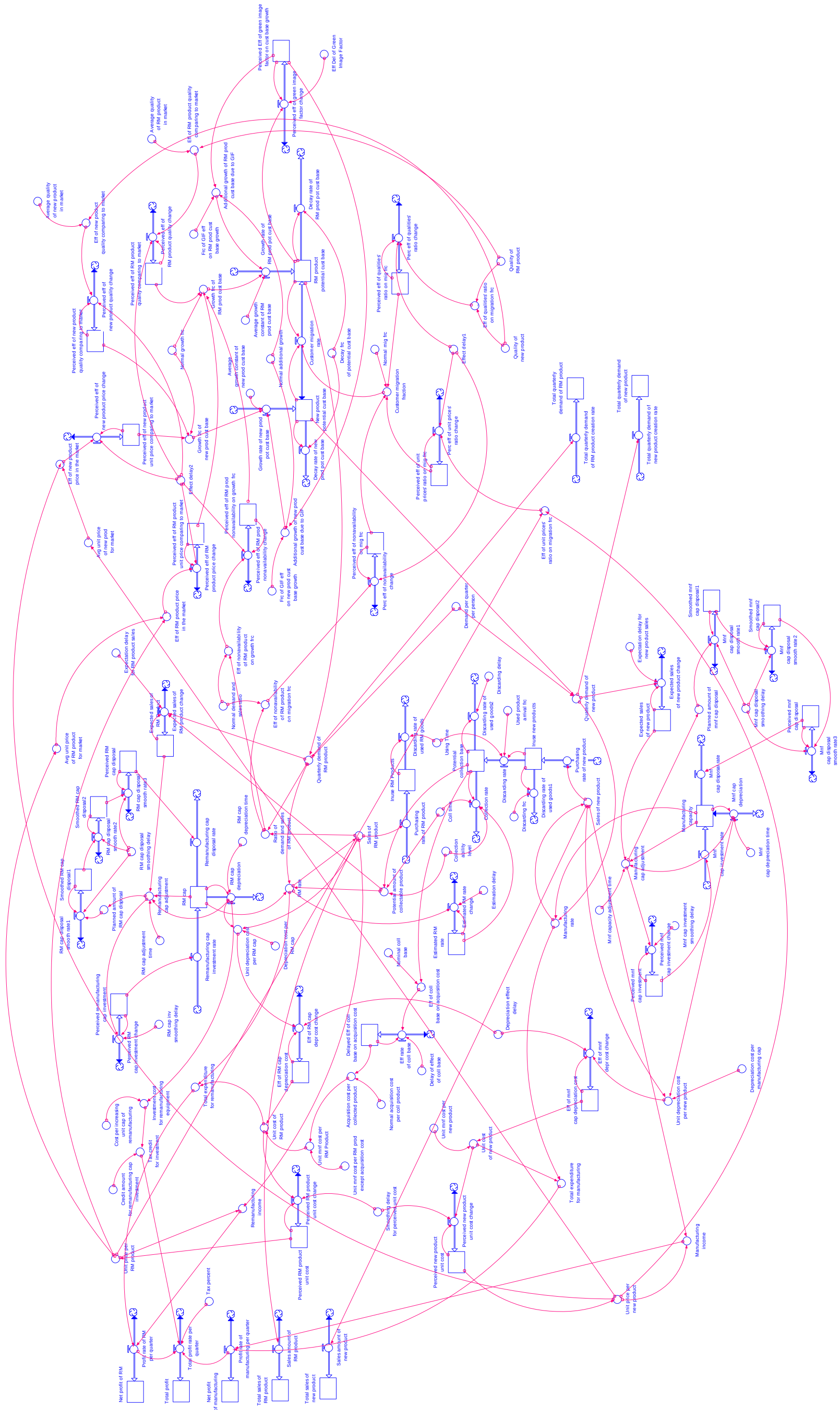

Figure C.1. Stock-Flow diagram of the PRM model of the firm.

APPENDIX D: VARIABLES AND PARAMETERS

Table D.1. All model variables and parameters with their definitions.

Variable	**Definition**
Delayed Eff of collbase on acquisiton cost	Delayed effect of potential collection base on acquisition cost
Eff of mnf cap depreciation cost	Effect of manufacturing capacity depreciation cost
Eff of RM cap depreciation cost	Effect of Remanufacturing capacity depreciation cost
Estimated RM rate	Estimated Remanufacturing Rate
Expected sales of new product	Expected sales of new product
Expected sales of RM Product	Expected sales pf remanufactured product
Inuse new products	New products inuse
Inuse RM Products	Remanufactured products inuse
Net profit of RM	Net profit of remanufacturing
Net profit of manufacturing	Net profit of manufacturing
Manufacturing capacity	Manufacturing capacity
New product potential cust base	New product potential customer base
Perceived Eff of green image factor on cust base growth	Perceived effect of green image factor on customer base growth
Perceived eff of new product quality comparing to market	Perceived effect of new product quality comparing to market
Perceived eff of nonavailability on mig frc	Perceived effect of nonavailability on migration fraction
Perceived eff of qualities' ratio on mig frc	Perceived effect of qualities' ratio on migration fraction
Perceived eff of RM product quality comparing to market	Perceived effect of remanufactured product quality comparing to market
Perceived eff of RM product unit price comparing to market	Perceived effect of remanufactured product unit price compairng to market
Perceived eff of RM prod nonavailability on growth frc	Perceived effect of remanufactured product nonavailability on growth farction
Perceived eff of unit prices' ratio on mig frc	Perceived effect of unit prices' ratio on migration fraction
Perceived mnf cap disposal	Perceived manufacturing capacity disposal
Perceived mnf cap investment	Perceived manufacturing capacity investment
Perceived new product unit cost	Perceived new product unit cost
Perceived remanufacturing cap investment	Perceived remanufacturing capacity investment
Perceived RM cap disposal	Perceived remanufacturing capacity disposal
Perceived RM product unit cost	Perceived remanufactured product unit cost
Potential collection base	Potential colleciton base
RM cap	Remanufacturing capacity

Table D.1. All model variables and parameters with their definitions (Continued).

Variable	**Definition**
RM product potential cust base	Remanufactured product potential customer base
Smoothed mnf cap disposal1	Smoothed manufacturing capacity disposal 1
Smoothed mnf cap disposal2	Smoothed manufacturing capacity disposal 2
Smoothed RM cap disposal1	Smoothed remanufacturing capacity disposal 1
Total profit	Total profit
Total quarterly demand of new product	Total quarterly demand of new product
Total quarterly demand of RM product	Total quarterly demand of remanufactured product
Total sales of new product	Total sales of new product
Total sales of RM product	Total sales of remanufactured product
Collection rate	Collection rate
Customer migration rate	Customer migration rate
Decay rate of new prod pot cust base	Decay rate of new product potential customer base
Decay rate of RM prod pot cust base	Decay rate of remanufactured product potential customer base
Discarding rate	Discarding rate
Discarding rate of used goods1	Discarding rate of used goods 1
Discarding rate of used goods2	Discarding rate of used goods 2
Discarding rate of used RM good	Discarding rate of used remanufactured good
Eff of mnf depr cost change	Effect of manufacturing depreciation cost change
Eff of RM cap depr cost change	Effect of remanufacturing capacity depreciation cost change
Eff rate of coll base	Effect rate of collection base
Estimated RM rate change	Estimated remanufacturing rate
Expected sales of new product change	Expected sales of new product change
Expected sales of RM product change	Expected sales of remanufactured product change
Growth rate of new prod pot cust base	Growth rate of new product potential customer base
Growth rate of RM prod pot cust base	Growth rate of remanufactured product potential customer base
Mnf cap depreciation	Manufacturing capacity depreciation
Mnf cap disposal rate	Manufacturing capacity disposal rate
Mnf cap disposal smooth rate1	Manufacturing capacity disposal smooth rate-1st order
Mnf cap disposal smooth rate2	Manufacturing capacity disposal smooth rate-2nd order
Mnf cap disposal smooth rate3	Manufacturing capacity disposal smooth rate-3rd order
Mnf cap investment rate	Manufacturing capacity investment rate

Table D.1. All model variables and parameters with their definitions (Continued).

Variable	**Definition**
Perceived eff of green image factor change	Perceived effect of green image factor change
Perceived eff of RM product price change	Perceived effect of remanufactured product price change
Perceived eff of RM product quality change	Perceived effect of remanufactured product quality change
Perceived eff of RM prod nonavailability change	Perceived effect of remanufactured product nonavailability change
Perceived eff of new product price change	Perceived effect of new product price change
Perceived eff of new product quality change	Perceived effect of new product quality change
Perceived mnf cap investment change	Perceived manufacturing capacity investment change
Perceived new product unit cost change	Perceived new product unit cost change
Perceived RM product unit cost change	Perceived remanufactured product unit cost change
Perceived RM cap investment change	Perceived remanufacturing capacity investment change
Perc eff of nonavailability change	Perceived effect of nonavailability change
Perc eff of qualities' ratio change	Perceived effect of qualities' ratio change
Perc eff of unit prices' ratio change	Perceived effect of unit prices' ratio change
Profit rate of manufacturing per quarter	Profit rate of manufacturing per quarter
Profit rate of RM per quarter	Profit rate of remanufacturing per quarter
Purchasing rate of new product	Purchasing rate of new product
Purchasing rate of RM product	Purchasing rate of remanufactured product
Remanufacturing cap disposal rate	Remanufacturing capacity disposal rate
Remanufacturing cap investment rate	Remanufacturing capacity investment rate
RM cap disposal smooth rate1	Remanufacturing capacity disposal smooth rate1
RM cap disposal smooth rate2	Remanufacturing capacity disposal smooth rate2
RM cap disposal smooth rate3	Remanufacturing capacity disposal smooth rate3
RM cap depreciation	Remanufacturing capacity depreciation
Sales amount of new product	Sales amount of new product
Sales amount of RM product	Sales amount of remanufactured product
Total profit rate per quarter	Total profit rate per quarter
Total quarterly demand of new product creation rate	Total quarterly demand of new product creation rate
Total quarterly demand of RM product creation rate	Total quarterly demand of remanufactured product creation rate
Acquisition cost per collected product	Acquisition cost per collected product

Table D.1. All model variables and parameters with their definitions (Continued).

Variable	**Definition**
Additional growth of new prod cust base due to GIF	Additional growth of new product potential customer base due to green image factor
Additional growth of RM prod cust base due to GIF	Additional growth of remanufactured product potential customer base due to green image factor
Average growth constant of RM prod cust base	Average growth constant of remanufactured product potential customer base
Average quality of new product in market	Average quality of new product in market
Average quality of RM product in market	Average quality of remanufactured product in market
Average growth constant of new prod cust base	Average growth constant of new product potential customer base
Avg unit price of new prod for market	Average unit price of new product for market
Avg unit price of RM product for market	Average unit price of remanufactured product for market
Collection ability level	Used product collection ability level
Coll time	Collection time
Cost per increasing unit cap of remanufacturing	Cost per increasing unit capacity of remanufacturing
Credit amount for remanufacturing cap investment	Credit amount for remanufacturing capacity investment
Customer migration fraction	Customer migration fraction
Decay frc of potential cust base	Decay fraction of potential customer bases
Delay of effect of coll base	Delay of effect of potential collection base
Demand per quarter per person	Demand per quarter per person
Depreciation cost per RM cap	Depreciation cost per remanufacturing capacity
Depreciation cost per manufacturing cap	Depreciation cost per manufacturing capacity
Depreciation effect delay	Depreciation effect delay
Discarding delay	Discarding delay
Discarding frc	Discarding fraction
Effect delay1	Effect delay1
Effect delay2	Effect delay2
Eff Del of Green Image Factor	Effect delay of green image factor
Estimation delay	Estimation delay
Expectation delay for new product sales	Expectation delay for new product sales
Expectation delay for RM product sales	Expectation delay for remanufactured product sales
Frc of GIF eff on new prod cust base growth	Fraction of green image factor effect on new product potential customer base growth

Table D.1. All model variables and parameters with their definitions (Continued).

Variable	**Definition**
Frc of GIF eff on RM prod cust base growth	Fraction of green image factor effect on remanufactuerd product potential customer base growth
Growth frc of RM prod cust base	Growth fraction of remanufactured product potential customer base
Growth frc of new prod cust base	Growth fraction of new product potential customer base
Investment cost for remanufacturing equipment	Investment cost for remanufacturing equipment
Manufacturing cap adjustment	Manufacturing capacity adjustment
Manufacturing income	Manufacturing income
Manufacturing rate	Manufacturing rate
Mnf capacity adjustment time	Manufacturing capacity adjustment time
Mnf cap depreciation time	Manufacturing capacity depreciation time
Mnf cap disposal smoothing delay	Manufacturing capacity disposal smoothing delay
Mnf cap investment smoothing delay	Manufacturing capacity investment smoothing delay
Nominal coll base	Nominal(Reference) collection base
Normal acquisition cost per coll product	Normal acquisition cost per collected product
Normal additional growth	Normal additional growth
Normal demand and sales ratio	Normal demand and sales ratio
Normal growth frc	Normal growth fraction
Normal mig frc	Normal migration fraction
Planned amount of RM cap disposal	Planned amount of remanufacturing capacity disposal
Planned amount of mnf cap disposal	Planned amount of manufacturing capacity disposal
Potential amount of collected product	Potential amount of collected product
Quality of new product	Quality of new product(of the firm)
Quality of RM product	Quality of remanufactured product(of the firm)
Quarterly demand of RM product	Quarterly demand of remanufactured product
Quaterly demand of new product	Quarterly demand of new product
Ratio of demand and sales of RM product	Ratio of demand and sales of remanufactured product
Remanufacturing cap adjustment	Remanufacturing capacity adjustment
Remanufacturing income	Remanufacturing income
RM cap adjustment time	Remanufacturing capacity adjustment time
RM cap depreciation time	Remanufacturing capacity depreciation time
RM cap disposal smoothing delay	Remanufacturing capacity disposal smoothing delay
RM cap inv smoothing delay	Remanufacturing capacity investment smoothing delay

Table D.1. All model variables and parameters with their definitions (Continued).

Variable	**Definition**
RM rate	Remanufacturing rate
Sales of new product	Sales of new product
Sales of RM product	Sales of remanufactured product
Smoothing delay for perceived unit cost	Smoothing delay for perceived unit cost
Tax credit for investment	Tax credit for investment(on remanufacturing)
Tax percent	Tax percent
Total expenditure for manufacturing	Total expenditure for manufacturing
Total expenditure for remanufacturing	Total expenditure for remanufacturing
Unit cost of new product	Unit cost of new product(of the firm)
Unit cost of RM product	Unit cost of remanufactured product(of the firm)
Unit depreciation cost per RM product	Unit depreciation cost per remanufactured product
Unit depreciation cost per new product	Unit depreciation cost per new product
Unit mnf cost per RM prod except acquisition cost	Unit manufacturing cost per remanufactured product except acquisition cost
Unit mnf cost per new product	Unit manufacturing cost per new product
Unit mnf cost per RM Product	Unit manufacturing cost per remanufactured product
Unit price per new product	Unit price per new product
Unit price per RM product	Unit price per remanufactured product
Used product arrival frc	Used product arrival fraction
Using Time	Using time
Eff of coll base on acquisition cost	Effect of potential collection base on acquisition cost
Eff of new product price in the market	Effect of new product price in the market
Eff of new product quality comparing to market	Effect of new product quality comparing to market
Eff of nonavailability of RM product on growth frc	Effect of nonavailability of remanufactured product on growth fraction
Eff of nonavailability of RM product on migration frc	Effect of nonavailability of remanufactured product on migration fraction
Eff of qualities' ratio on migration frc	Effect of qualities' ratio on migration fraction
Eff of RM product price in the market	Effect of remanufactured product price in the market
Eff of RM product quality comparing to market	Effect of remanufactured product quality comparing to market
Eff of unit prices' ratio on migration frc	Effect of unit prices' ratio on migration fraction

Table D.2. All model variables and parameters with their types and dimensions.

Variable	**Type**	**Dimension**
Delayed Eff of collbase on acquisiton cost	Stock	Unitless
Eff of mnf cap depreciation cost	Stock	Dollar/product/quarter
Eff of RM cap depreciation cost	Stock	Dollar/product/quarter
Estimated RM rate	Stock	Products/quarter
Expected sales of new product	Stock	Products/quarter
Expected sales of RM Product	Stock	Products/quarter
Inuse new products	Stock	Products
Inuse RM Products	Stock	Products
Net profit of RM	Stock	Dollar
Net profit of manufacturing	Stock	Dollar
Manufacturing capacity	Stock	Products/quarter
New product potential cust base	Stock	Customers
Perceived Eff of green image factor on cust base growth	Stock	Customers
Perceived eff of new product quality comparing to market	Stock	Unitless
Perceived eff of nonavailability on mig frc	Stock	Unitless
Perceived eff of qualities' ratio on mig frc	Stock	Unitless
Perceived eff of RM product quality comparing to market	Stock	Unitless
Perceived eff of RM product unit price comparing to market	Stock	Unitless
Perceived eff of RM prod nonavailability on growth frc	Stock	Unitless
Perceived eff of unit prices' ratio on mig frc	Stock	Unitless
Perceived mnf cap disposal	Stock	Products/quarter/quarter
Perceived mnf cap investment	Stock	Products/quarter/quarter
Perceived new product unit cost	Stock	Dollar/product
Perceived remanufacturing cap investment	Stock	Products/quarter/quarter
Perceived RM cap disposal	Stock	Products/quarter/quarter
Perceived RM product unit cost	Stock	Dollar/product
Potential collection base	Stock	Products
RM cap	Stock	Products/quarter
RM product potential cust base	Stock	Customers
Smoothed mnf cap disposal1	Stock	Products/quarter/quarter
Smoothed mnf cap disposal2	Stock	Products/quarter/quarter
Smoothed RM cap disposal1	Stock	Products/quarter/quarter

Table D.2. All model variables and parameters with their types and dimensions (Continued).

Variable	Type	Dimension
Smoothed RM cap disposal2	Stock	Products/quarter/quarter
Total profit	Stock	Dollar
Total quarterly demand of new product	Stock	Products
Total quarterly demand of RM product	Stock	Products
Total sales of new product	Stock	Products
Total sales of RM product	Stock	Products
Collection rate	Flow	Products/quarter
Customer migration rate	Flow	Customers/quarter
Decay rate of new prod pot cust base	Flow	Customers/quarter
Decay rate of RM prod pot cust base	Flow	Customers/quarter
Discarding rate	Flow	Products/quarter
Discarding rate of used goods1	Flow	Products/quarter
Discarding rate of used goods2	Flow	Products/quarter
Discarding rate of used RM good	Flow	Products/quarter
Eff of mnf depr cost change	Flow	Dollar/product/quarter/quarter
Eff of RM cap depr cost change	Flow	Dollar/product/quarter/quarter
Eff rate of coll base	Flow	Unitless
Estimated RM rate change	Flow	Products/quarter/quarter
Expected sales of new product change	Flow	Products/quarter/quarter
Expected sales of RM product change	Flow	Products/quarter/quarter
Growth rate of new prod pot cust base	Flow	Customers/quarter
Growth rate of RM prod pot cust base	Flow	Customers/quarter
Mnf cap depreciation	Flow	Products/quarter/quarter
Mnf cap disposal rate	Flow	Products/quarter/quarter
Mnf cap disposal smooth rate1	Flow	Products/quarter/quarter/quarter
Mnf cap disposal smooth rate2	Flow	Products/quarter/quarter/quarter
Mnf cap disposal smooth rate3	Flow	Products/quarter/quarter/quarter
Mnf cap investment rate	Flow	Products/quarter/quarter
Perceived eff of green image factor change	Flow	Customers/quarter
Perceived eff of RM product price change	Flow	Unitless
Perceived eff of RM product quality change	Flow	Unitless
Perceived eff of RM prod nonavailability change	Flow	Unitless
Perceived eff of new product price change	Flow	Unitless
Perceived eff of new product quality change	Flow	Unitless
Perceived mnf cap investment change	Flow	Products/quarter/quarter/quarter
Perceived new product unit cost change	Flow	Dollar/product/quarter/quarter
Perceived RM product unit cost change	Flow	Dollar/product/quarter/quarter
Perceived RM cap investment change	Flow	Products/quarter/quarter/quarter

Table D.2. All model variables and parameters with their types and dimensions (Continued).

Variable	Type	Dimension
Perc eff of nonavailability change	Flow	Unitless
Perc eff of qualities' ratio change	Flow	Unitless
Perc eff of unit prices' ratio change	Flow	Unitless
Profit rate of manufacturing per quarter	Flow	Dollar/quarter
Profit rate of RM per quarter	Flow	Dollar/quarter
Purchasing rate of new product	Flow	Products/quarter
Purchasing rate of RM product	Flow	Products/quarter
Remanufacturing cap disposal rate	Flow	Products/quarter/quarter
Remanufacturing cap investment rate	Flow	Products/quarter/quarter
RM cap disposal smooth rate1	Flow	Products/quarter/quarter/quarter
RM cap disposal smooth rate2	Flow	Products/quarter/quarter/quarter
RM cap disposal smooth rate3	Flow	Products/quarter/quarter/quarter
RM cap depreciation	Flow	Products/quarter/quarter
Sales amount of new product	Flow	Products/quarter
Sales amount of RM product	Flow	Products/quarter
Total profit rate per quarter	Flow	Dollar/quarter
Total quarterly demand of new product creation rate	Flow	Products/quarter
Total quarterly demand of RM product creation rate	Flow	Products/quarter
Acquisition cost per collected product	Auxiliary	Dollar/product/quarter
Additional growth of new prod cust base due to GIF	Auxiliary	Customers/quarter
Additional growth of RM prod cust base due to GIF	Auxiliary	Customers/quarter
Average growth constant of RM prod cust base	Auxiliary	Unitless
Average quality of new product in market	Auxiliary	Unitless
Average quality of RM product in market	Auxiliary	Unitless
Average growth constant of new prod cust base	Auxiliary	Unitless
Avg unit price of new prod for market	Auxiliary	Dollar/product/quarter
Avg unit price of RM product for market	Auxiliary	Dollar/product/quarter
Collection ability level	Auxiliary	Unitless
Coll time	Auxiliary	Quarter
Cost per increasing unit cap of remanufacturing	Auxiliary	Dollar/product/quarter
Credit amount for remanufacturing cap investment	Auxiliary	Unitless
Customer migration fraction	Auxiliary	Unitless
Decay frc of potential cust base	Auxiliary	Unitless
Delay of effect of coll base	Auxiliary	Quarter

Table D.2. All model variables and parameters with their types and dimensions (Continued).

Variable	**Type**	**Dimension**
Demand per quarter per person	Auxiliary	Products/quarter/person
Depreciation cost per RM cap	Auxiliary	Dollar/product
Depreciation cost per manufacturing cap	Auxiliary	Dollar/product
Depreciation effect delay	Auxiliary	Quarter
Discarding delay	Auxiliary	Quarter
Discarding frc	Auxiliary	Unitless
Effect delay1	Auxiliary	Quarter
Effect delay2	Auxiliary	Quarter
Eff Del of Green Image Factor	Auxiliary	Quarter
Estimation delay	Auxiliary	Quarter
Expectation delay for new product sales	Auxiliary	Quarter
Expectation delay for RM product sales	Auxiliary	Quarter
Frc of GIF eff on new prod cust base growth	Auxiliary	Unitless
Frc of GIF eff on RM prod cust base growth	Auxiliary	Unitless
Growth frc of RM prod cust base	Auxiliary	Unitless
Growth frc of new prod cust base	Auxiliary	Unitless
Investment cost for remanufacturing equipment	Auxiliary	Dollar/quarter
Manufacturing cap adjustment	Auxiliary	Products/quarter/quarter
Manufacturing income	Auxiliary	Dollar/quarter
Manufacturing rate	Auxiliary	Products/quarter
Mnf capacity adjustment time	Auxiliary	Quarter
Mnf cap depreciation time	Auxiliary	Quarter
Mnf cap disposal smoothing delay	Auxiliary	Quarter
Mnf cap investment smoothing delay	Auxiliary	Quarter
Nominal coll base	Auxiliary	Products
Normal acquisition cost per coll product	Auxiliary	Dollar/product/quarter
Normal additional growth	Auxiliary	Customers/quarter
Normal demand and sales ratio	Auxiliary	Unitless
Normal growth frc	Auxiliary	Unitless
Normal mig frc	Auxiliary	Unitless
Planned amount of RM cap disposal	Auxiliary	Products/quarter/quarter
Planned amount of mnf cap disposal	Auxiliary	Products/quarter/quarter
Potential amount of collected product	Auxiliary	Products/quarter
Quality of new product	Auxiliary	Unitless
Quality of RM product	Auxiliary	Unitless
Quarterly demand of RM product	Auxiliary	Products/quarter
Quaterly demand of new product	Auxiliary	Products/quarter
Ratio of demand and sales of RM product	Auxiliary	Unitless

Table D.2. All model variables and parameters with their types and dimensions (Continued).

Variable	**Type**	**Dimension**
Remanufacturing cap adjustment	Auxiliary	Products/quarter/quarter
Remanufacturing income	Auxiliary	Dollar/quarter
RM cap adjustment time	Auxiliary	Quarter
RM cap depreciation time	Auxiliary	Quarter
RM cap disposal smoothing delay	Auxiliary	Quarter
RM cap inv smoothing delay	Auxiliary	Quarter
RM rate	Auxiliary	Products/quarter
Sales of new product	Auxiliary	Products/quarter
Sales of RM product	Auxiliary	Products/quarter
Smoothing delay for perceived unit cost	Auxiliary	Quarter
Tax credit for investment	Auxiliary	Dollar/quarter
Tax percent	Auxiliary	Unitless
Total expenditure for manufacturing	Auxiliary	Dollar/quarter
Total expenditure for remanufacturing	Auxiliary	Dollar/quarter
Unit cost of new product	Auxiliary	Dollar/product/quarter
Unit cost of RM product	Auxiliary	Dollar/product/quarter
Unit depreciation cost per RM product	Auxiliary	Dollar/product/quarter
Unit depreciation cost per new product	Auxiliary	Dollar/product/quarter
Unit mnf cost per RM prod except acquisition cost	Auxiliary	Dollar/product/quarter
Unit mnf cost per new product	Auxiliary	Dollar/product/quarter
Unit mnf cost per RM Product	Auxiliary	Dollar/product/quarter
Unit price per new product	Auxiliary	Dollar/product/quarter
Unit price per RM product	Auxiliary	Dollar/product/quarter
Used product arrival frc	Auxiliary	Unitless
Using Time	Auxiliary	Quarter
Eff of coll base on acquisition cost	Auxiliary	Unitless
Eff of new product price in the market	Auxiliary	Unitless
Eff of new product quality comparing to market	Auxiliary	Unitless
Eff of nonavailability of RM product on growth frc	Auxiliary	Unitless
Eff of nonavailability of RM product on migration frc	Auxiliary	Unitless
Eff of qualities' ratio on migration frc	Auxiliary	Unitless
Eff of RM product price in the market	Auxiliary	Unitless
Eff of RM product quality comparing to market	Auxiliary	Unitless
Eff of unit prices' ratio on migration frc	Auxiliary	Unitless

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