THE IMPACT OF REMANUFACTURING ON SERVICE LEVELS OF AUTOMOBILE SPARE PARTS SUPPLY CHAIN

by

Hasan Erdoğan

B.S.,Industrial Engineering, Yildiz Technical University, 2004

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

Graduate Program in Industrial Engineering
Bogazici University
2008

ACKNOWLEDGEMENTS

I would like to express my utmost gratitude towards my thesis advisor, Assist.Prof. Aybek Korugan for his support, patience and encouragement during my time at Boğaziçi University. I would not have come this far without his novel ideas and guidance.

My thanks and appreciation goes to my thesis committee members Assoc.Prof.Ali Tamer Ünal and Assoc.Prof.Aslı Erdem for their precious, constructive and valuable comments to finalize my study.

I would also like to extent my special thanks to Mr. Sinan Südütemiz, my manager at Tofaş Türk Otomobil Fab.A.Ş., for supporting my thesis, sharing his cooperative comments, information and worthwhile industry experience which has great value for this study.

Finally, and most importantly, I thank my family. To my parents, Hatice and Ibrahim Erdoğan, I thank their support, patience and love. They deserve to have their names on the diploma more than I do. To the rest of my family – my brothers Mesut and Hakan, my uncles Uğur and Hüseyin, my aunt Semra and my grandmother Aysel, thank you for always being there.

ABSTRACT

THE IMPACT OF REMANUFACTURING ON SERVICE LEVELS OF AUTOMOBILE SPARE PARTS SUPPLY CHAIN

Remanufacturing is described as removing a product or component from a retired system and installing it in another system. In today's world one can already discover an impressive range of application examples representing remanufacturing as the ultimate form of recycling. Remanufacturing has its roots and displays a long tradition already since the very first moves and outcomes of the industrial age like steam engines, railways, power generation and electrical equipment, machine tools etc. Furthermore remanufacturing always has been a strong partner throughout the uprise of the automotive sector, which undoubtedly is the main industrial driving force so far.

In this study, the spare parts supply and distribution system of a major distributor of automotive spare parts in Turkey is analyzed for a representative spare part viz. a brake pad. Control variables of the distributor and dealers together with the main performance indicators of the system are figured out. In order to observe the effect of change in control variables on performance indicators, a simulation model is constructed by using C++. Afterwards, the simulation model is extended with remanufactured parts. The objective of the study is to capture the impact of remanufactured parts on system performance, especially on service levels. Remanufactured parts, in focus of this thesis, is not considered as an alternative but as a safety stock to the original part. In the conclusion of the study it is denoted that service level is subject to change under different disposal and remanufacturing control policies.

ÖZET

YENİLENMİŞ PARÇALARIN OTOMOTİV YEDEK PARÇA TEDARİK ZİNCİRİNDEKİ HİZMET SEVİYELERİNE ETKİSİ

Yeniden üretim, bir parçanın yada onun komponentinin eskimiş bir sistemden çıkartılıp başka bir sisteme entegre edilmesi olarak tanımlanır. Bugünün dünyasında, yeniden üretimi geri dönüşümün son formu olarak sunan oldukça fazla uygulama örnekleri bulunabilir.Yeniden üretimin kökleri endüstri çağının ilk zamanlarına kadar uzanmaktadır, örnek olarak buhar motorları, demiryolları, güç üretimi, elektrik ekipmanları ve makina aletleri verilebilir. Bununla birlikte yeniden üretim, endüstrinin tartışmasız en büyük itici güçlerinden birisi olan otomotiv sektörünün yükselişinde her zaman güçlü bir partner olmuştur.

Bu çalışmada, Türkiye'nin en büyük yedek parça distribütörlerinden birisinin yedek parça temin ve dağıtım sistemi temsili bir yedek parça için, fren balatası, analiz edilmiştir. Distribütör ve bayilerin kontrol ettiği değişkenler ve sistemin performansını belirleyen başlıca indikatörler belirlenmiştir. Kontrol değişkenlerindeki değişimin belirlenmiş olan indikatörlere etkilerini gözlemleyebilmek amacıyla C++ ile bir simulasyon modeli kurulmuştur. Ardından, bu model yenilenmiş parçalarla genişletilmiştir. Yenilenmiş parçalar bu tezin kapsamında orjinal parçalara alternatif olarak değil, bir güvenlik stoğu olarak düşünülmüştür. Çalışmanın sonucunda, hizmet seviyelerinin yenilenmiş üretim ve hurdaya atma ile ilgili kontrol parametrelerindeki değişimden etkilendiği ifade edilmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS / ABBREVIATIONS

SCM	Supply chain management
OEM	Original equipment manufacturer
DOE	Design of experiments
OAD	Orthogonal array design
ANOVA	Analysis of variance
PC	Percentage contribution
min_s_i	Minimum stock level of dealer *i* at order time
max_s_i	Maximum stock level of dealer *i* at order time
min_q_i	Minimum amount to have been ordered by dealer *i*
max_q_i	Maximum amount to have been ordered by dealer *i*
k_i	Shape parameter of customer interarrival times at dealer *i*
σ_i	Scale parameter of customer interarrival times at dealer *i*
μ_i	Location parameter of customer interarrival times at dealer *i*
λ_i	Mean order quantities of customers at dealer *i*
d_ser	Dealer’s servicel level to its customers
D_ser	The distributor’s service level to its dealers
w_back	Average waiting time of backordered demand
c_time	Average cycle time of orders
Σbc	Number of total lost sales of dealers due to unavailability
D_inv	Average inventory at the distributor
d_inv	Average inventory at dealers
D_r_inv	Average remanufactured part inventory at the distributor
d_r_inv	Average remanufactured part inventory at dealers
SL	Total sales of the distributor
Σsl	Total sales of dealers
S	Stock level (Quantity on hand) of the distributor
ES	Stock level of the distributor at the end of simulation
SA	Quantity on order
U	Quantity allocated
SH	Quantity under preparation

I	Quantity invoiced
B	Quantity backordered
D	Quantity not shipped
A	Actual stock
NS	Net stock
F	Forecasted demand
Q	Quantity of order placed to the supplier
s_i	Stock level at dealer *i*
is_i	Initial stock level at dealer *i*
es_i	Stock level at dealer *i* at the end of simulation
ns_i	Net stock level at dealer *i*
sa_i	Quantity on order at dealer *i*
u_i	Quantity allocated for dealer *i*
sh_i	Quantity under preparation for dealer *i*
i_i	Quantity invoiced for dealer *i*
b_i	Backordered quantity of dealer *i*
sl_i	Total sales at dealer *i*
bc_i	Total lost sales at dealer *i*
IS	Initial stock of the distributor
SS	Safety stock of the distributor
LT	Lead time of the distributor's order to the supplier
s_dur	Duration between two successive shipment orders.
s_f_dur	Shipment to invoicing duration
f_r_dur	Invoicing to reception duration
R	Ordering period of the distributor
w	Window value being used in Welch's procedure
C*S*	Core stock level of the distributor (amount of core on hand)
S^R	Remanufactured part stock level of the distributor
SA^R	Quantity on order (Remanufactured parts)
IS^R	Initial remanufactured part stock level of the distributor
ES^R	Remanufactured part stock of the distributor at the end of simulation
U^R	Quantity allocated (Remanufactured Part)
SH^R	Quantity under preparation (Remanufactured Part)

I^R	Quantity invoiced (Remanufactured Part)
B^R	Quantity backordered (Remanufactured Part)
D^R	Quantity not shipped (Remanufactured Part)
A^R	Actual stock (Remanufactured Part)
NS^R	Net stock (Remanufactured Part)
SL^R	Sales (Remanufactured Part)
${s^r}_i$	Remanufactured part stock level at dealer *i*
${is^r}_i$	Initial remanufactured part stock level at dealer *i*
${es^r}_i$	Remanufactured part stock level at dealer *i* at the end of simulation
${ns^r}_i$	Net remanufactured part stock level at dealer *i*
cs_i	Core stock level at dealer *i*
${sa^r}_i$	Quantity on order at dealer *i* (Remanufactured Part)
${u^r}_i$	Quantity allocated for dealer *i* (Remanufactured Part)
${sh^r}_i$	Quantity under preparation for dealer *i* (Remanufactured Part)
${i^r}_i$	Quantity invoiced for dealer *i* (Remanufactured Part)
${b^r}_i$	Backordered quantity of dealer *i* (Remanufactured Part)
${sl^r}_i$	Remanufactured part sales at dealer *i*
cs_{rf}	Core stock at remanufacturing facility
${s^r}_{rf}$	Remanufactured part stock at remanufacturing facility
c	Daily production capacity of remanufacturing facility
p	Quantity produced at remanufacturing facility during the simulation
dis	Quantity disposed at remanufacturing facility during the simulation
$rate$	Remanufacturability rate of returned cores
$will$	Customer's willingness-to-select remanufactured parts
IP	Inventory position
N	Number of cores that can be stored at remanufacturing facility
s_d	Inventory position control parameter for disposal.

1. INTRODUCTION

These days, consumers expect more out of their aftermarket experience than they ever did in the past. As such, consumers expect more time and mileage before their vehicles need service and when it is needed, they expect sameday service or better. This means that dealers must have the parts available on the shelf, which in turn drives higher fill rate requirements throughout all echelons in supply chains. On the other hand, because of the stochastic nature of aftermarket demand, it is almost impossible for the distributor and dealers to balance the system with zero backorders or lost sales. Therefore, it is clear that a solution should be found to increase first-time fill rate of customer orders, without increasing inventory costs too much, and prevent vehicles being off road at workshops because of unavailability of a part. At this point, a business strategist might discover that remanufacturing could reward dealers with new business opportunities in the after sales service market enabling them to offer their customers perfectly interchangable remanufactured parts in case of unavailability of original parts.

Reuse of products and materials is not a new phenomenon. Metal scrap brokers, waste paper recycling, and deposit systems for softdrink bottles are all examples that have been around for a long time. In all these cases, reuse opportunities give rise to a new material flow from the user back to the sphere of producers [1]. There are many reuse alternatives: Recycling, direct reuse and remanufacturing are some of the major alternatives. In remanufacturing a used product is refurbished and reproduced in order to restore it to the original useful state.

The benefits of remanufacturing have wide ranging implications to all stakeholders ranging from customers to shareholders. While customers benefit from reduced costs as the savings from remanufacturing are passed on to the customer, shareholders benefit from increased profits [2]. From an environmentally conscious customer’s viewpoint, the main reason for being interested in remanufacturing is not just their perception of remanufacturing as the most economic way of having access to state-of-art technology products at affordable prices but also their appreciation for remanufacturing as a key principle of securing a sustainable future.

European Commissions rules on cars block exemption, which provides the regulatory framework for the distribution of new motor vehicles and automotive spare parts, became law on 1 October 2002 in Europe, and it came fully into effect on January 1, 2007 in Turkey. The Regulation grants independent service outlets access to vehicle manufacturers' technical information, which they need to be able to compete with the vehicle manufacturers' authorised networks. This gave car owners more freedom in their decision as to who should repair and service their vehicles. Now, subject to certain conditions, any garage can be used without invalidating the manufacturer's warranty. The new exemption has increased competition in the domestic and continental car market which gave consumers more choice and better value for money. This causes for some companies to begin using remanufacturing as a means of gaining competitive advantage.

In this study, service level of a two echelon automotive spare part inventory system with one distributor and 72 dealers is considered as a competitive advantage. Here the effect of remanufactured parts on the service level is investigated. Remanufactured parts are used as extra units of inventory carried to protect dealers from possible stockouts which has a direct effect on service level and customer satisfaction. They are used to cover uncertainties in supply and demand of original parts since the demand and/or lead time for the original parts cannot accurately be predicted. Using remanufactured parts as safety stock instead of original parts is due to the fact that the money spent to maintain a safety stock is less for remanufactured parts than that of original parts, as the value of a remanufactured part is always lower than a new part. Furthermore, since the outsourcing offers the advantage of no longer having to provide large infrastructures with the requisite machinery and considered more practical and cost-efficient for a company to opt for its route while concentrating on its core activity, remanufacturing activities are outsourced to a remanufacturing facility which overhauls returned cores and brings them back to "as new" conditions.

The rest of the thesis is organized as follows. In the next chapter, the relevant literature is reviewed. In Chapter 3, the analyzed problem is defined and research objective is introduced. Two models, namely the base model and the model with remanufacturing are described in Chapter 4. Numerical anaylsis of both models are represented in Chapter 5 and detailed analysis of the models through sensivity anaylsis is provided in Chapter 6. Finally in Chapter 7 the study is concluded by discussing the results of the simulation of the analyzed system.

2. LITERATURE REVIEW

In this chapter, a brief review of the literature related to the topics in our thesis is given. Before focusing on the concept of reverse logistics and remanufacturing, definitions and information on traditional inventory control strategies is introduced. Then, extension of these strategies with remanufacturing and marketing aspect of remanufactured parts are provided and information on related studies is summarized.

2.1. Review of traditional inventory control models

In today's business world, the interest of business enterprises in principles and solution methodologies of supply chain management (SCM) literature is increasing. Simchi-Levi, *et* al. [4] explain the reasons for this curiosity as continuous improvements in communications and transportation technologies, fierce competition in today's global markets, the introduction of new products with shorter life cycles, and the increased importance of customer satisfaction. Silver, *et* al. [5] consider two reasons of increasing the popularity of SCM as the realization of the fact by business enterprises that the actions of one member of the supply chain may dramatically influence the profitability of all others in the chain, and the motivation of enterprises to improve their coordination with their suppliers and customers. In addition to these, success stories of firms such as Wal Mart, Procter & Gambler and Barilla have attracted the attention of professionals of business world as well as academicians.

There are various analytical models of inventory management in the literature. They change in terms of assumptions made for models and the criterion to be optimized. First of all, assumptions related to distribution of demand could be different. Deterministic or probabilistic demand could be assumed. If demand is deterministic, it could be continuous or discrete. If it is probabilistic, then it could be stationary or nonstationary. For the nonstationary case, demand distributions could be dependent to each other or independent from each other. Assumptions of lead times are classified under three headings. There are models where lead time is constant and zero, constant and nonzero, or probabilistic. The review time of inventory in models could be a decision variable as well as a parameter. There are continuous review and periodic review inventory models that have been studied. The number of echelons in the models is another assumption. Some models only recommend policies for one stage systems; others recommend policies for multi-stage systems. There are some models that consider capacity or budget constraints while others assume unlimited capacity. Discounts are taken into consideration in some models. On the other hand, some models assume constant prices. In some models, perishability should be considered if products are perishable. Some models permit backlogging of excess demand while others consider excess demand as lost sales. The planning horizon assumptions of inventory models could also be different. Single period, finite period, and infinite period models exist in the literature. Finally, models differ with respect to number of products in the model. There are many academic publications on single item models due to the simplicity of the problem; on the other hand, there are less academic publications on multi item models in the literature. There are three main approaches for selecting the optimization criterion: 1) common safety factors approach, 2) cost minimization approach, 3) customer service approach. The common safety factors approach applies a common metric to aggregated items. For instance, one could select as a criterion holding two weeks supply of stock for all items in inventory. In the cost minimization approach, the trade off between holding and shortage costs is modeled. This approach requires the calculation of shortage costs which is not a straightforward task in practice. The customer service approach tries to minimize inventory costs with respect to determined service levels. Some common criteria considered in these models are:

1. Probability of no stockouts per replenishment cycle.
2. Fraction of demand satisfied from the shelf.
3. Fraction of time that net stock is positive.
4. Average time between stockouts.
5. Fraction of orders completely satisfied from shelf.

Traditional inventory control problem is theoretically modeled in the literature as a two-stage supply chain that consists of one distributor and N retailers. Interested readers can refer to [6], [7], [8], [9], [10] and [11] to obtain more theoretical information.

2.2. Review of reverse logistics literature

2.2.1. Analytical inventory control models

When returns of goods and remanufacturing options are taken into consideration in inventory control situations, two additional sources of complexity appear in the traditional approaches of optimizing stochastic inventory control. Firstly, due to uncertainty of returns, an additional stochastic impact has to be regarded. Secondly, with remanufacturing a second mode of supply of serviceable goods is given, so that coordination with the regular mode of procurement becomes necessary. The management of this material flow opposite to the conventional supply chain flow is addressed in the rapidly expanding field of “reverse logistics”. Fleischmann *et* al. [1], offers a systematical overview of the issues arising in this context. They subdivide the field into three main areas, namely distribution planning, inventory control and production planning. For each of these fields, they discuss the implications of emerging reuse efforts and review the mathematical models proposed in the literature. Van der Laan *et* al. [12] analyse an (s,Q) inventory model, in which remanufactured products can be remanufactured to new ones, and present a heuristic optimisation procedure. Ouyang and Zhu [13] extend the traditional (s,Q) inventory model to a continious review (s_p, Q, s_d) reorder and disposal policy for product remanufacture with disposal. In this model, an order for Q>1 is placed when the inventory position drops below s_p+1 and procured items arrive after the leadtime. On the other hand, while the inventory position reachs to s_d, the extra returned items are disposed immediately. Comparison of (s_p, Q_p, s_d, N), (s_p, Q_p, s_d) and (s_p, Q_p, N) inventory control strategies is introduced in van der Laan *et* al. [14]. Mahadevan *et* al. [15] study the inventory problem from the point of view of remanufacturing facility and develop several heuristics to find the near optimal solutions of when to release returned products to the remanufacturing line and how many new products to manufacture. They employ experimental design to test these heuristics. Inderfurth and van der Laan [16] made a study to identify and discuss the optimal inventory policy if the leadtimes for remanufacturing and regular procurement differ. The coordination of manufacturing and remanufacturing decisions in order to maximize the expected profit for a single period problem with stochastic returns of used products and stochastic demands of servicable ones can be found in Inderfurth [17]. The problem of determining safety stocks in multi-stage inventory systems with normally distributed demand is treated in Inderfurth and Minner [18].

2.2.2. Simulation models investigating the impact of remanufacturing

There are also many existing simulation studies in the literatur investigating the impact of remanufacturing under different conditions. Souza and Ketzenberg [19] consider a firm that meets demand for an order with remanufactured products, new products or a mix of both. They use a stylized two-stage GI/I/1 queuing network to study the problem and aim to find the optimal, long run production mix that maximizes profit subject to a service-level constraint that restricts the average order lead-time. A simulation model of a reverse logistics networks for collecting end-of-life products is presented in Kara *et* al., [20]. They test different collection strategies and carry out “what if” assessments. Teunter and Vlachos [21] analyse the impact of disposal option ($s_d \neq \infty$) and conclude that, on the base of their model, it is in general not necessary to include a disposal option for returned items. Georgiadis and Vlachos [22] examine the effect of environmental issues, e.g. the firm’s green image effect on customer demand, the take back obligation imposed by legislation and the state campaigns for proper disposal of used products, on long-term behaviour of a single product supply chain with product recovery. Fleischmann *et* al. [23] investigate IBM’s overall reverse logistics activities and develop a proposal for a systematic integration of dismantling as a regular source into spare parts planning.

2.3. Review of marketing literature of remanufactured parts

Another facet of the managerial issues surrounding remanufacturing literature is the marketing of remanufactured parts. One of the most important subjects in this context is consumers' willingness-to-pay for a remanufactured product which is usually a fraction of their willingness-to-pay for new product. Some researchers extend the perspectives with competition from local remanufacturers. Even though the examples of the analysis of competition problems on multiperiod and infinite planning horizons exist, this literature focuses mainly on two-period models where a monopolist OEM makes new products in the first period and has the opportunity to make new and remanufactured products in future periods under the competition from local remanufacturers. Without the competiton, firms generally choose not to remanufacture, as they are concerned that the remanufactured product will cannibalize the sales of the higher-margin new product. Majumder and Groenevelt [24] present a two-period model of remanufacturing in the face of competition and establish the nash equilibrium in the second period sub-game. Similarly, Ferguson and Toktay [25] analyze the competition between new and remanufactured products produced by a monopolist manufacturer and identify conditions under which the firm would choose not to remanufacture its products. Then, they characterize the potential profit loss due to external remanufacturing competiton and analyze two entry-deterrent strategies, e.g. remanufacturing and preemptive collection. Ferrer and Swaminathan [26] extend Majumder and Groenevelt [24] in that they also consider a multiperiod setting where the independent operator competes in the second and subsequent periods. Debo *et* al. [3] introduce the level of remanufacturability as a key variable that is controlled by OEM through the choice of production technology. Guide *et* al. [27] investigate the problem of how to design and manage the reverse supply chain to maximize net asset value recovered from the flow of returned products. From a marketing perspective, they examine how return policies affect consumer purchase probability and return rates. Their model is validated using data collection through in-dept studies of the return processes at Hewlett-Packard Company and Robert Bosch Tool Corporation. Atasu *et* al. [28] provide an alternative approach that considers not only competiton but also existence of green segment and product life cycle effects.

In this thesis, consumers' willingness-to-select remanufactured parts and remanufacturability rate of returned items examined in marketing literature are used in our model with remanufacturing.

3. PROBLEM DESCRIPTION AND RESEARCH OBJECTIVES

In this chapter, the main problem of interest and the objectives of this study are stated. The problems and objectives described in this chapter construct the base for the model development phase of the study.

3.1. Problem Description

The system considered in this thesis has one distributor and 72 dealers. The distributor sells spare parts to dealers and dealers provide services directly to the consumer. Each dealer faces different consumer demand since they serve to different markets. Figure 3.1 gives the schematic representation of this supply chain.

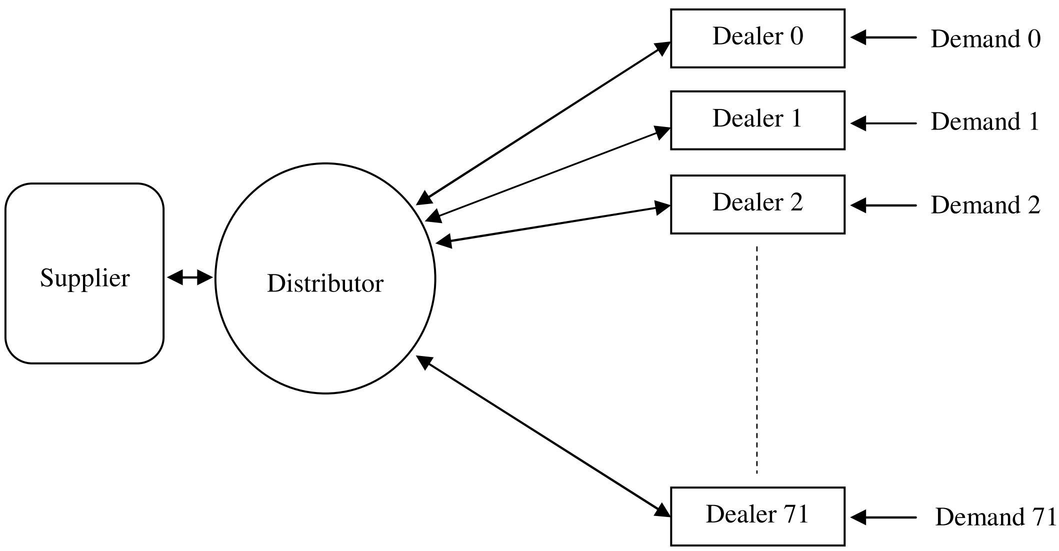

Figure 3.1. Schematic representation of the supply chain

85.000 different spare parts are served by the distributor. Any of these parts can be ordered by dealers at any time. On the other hand, dealers do not have an ordering policy. They send random orders to the distributor. As soon as an order is sent to the distributor, the allocation program is run. This program assigns available quantity to the owner of the order. Available quantity is called as the actual stock of the distributor which does not count previously allocated quantities as stock. If the actual stock of the distributor is more than or equal to the quantity ordered by dealer, the order is completely allocated. In case of shortages, available quantity is allocated while the rest is backordered. The distributor sends shipment orders to its warehouse for allocated pieces once a week. These pieces are picked and packed for the shipment. Once the goods are ready in the warehouse for the shipment, the distributor invoices them to the relevant dealer. It takes about two days to make the goods ready for the shipment. The distributor ships the goods through a third party logistics provider and dealers get their parts after about two days from the invoice date.

In contrast with dealers, the distributor sends regular orders to its supplier once every 30 days. These orders are processed by the supplier and delivered to the distributor after 40 days. Amount to be ordered by the distributor depends on both current safety stock levels and the output of winters exponential smoothing forecasting method. When the distributor receives the order, it first checks if there is any dealer backorders waiting to be met. Backorders are met following their order processing times. The distributor processes backorders in a first in first out fashion. This process is depicted in Figure 3.2.

3.2. Objectives

The aim of the study is to find the effect of remanufacturing on the service level of the distributor and dealers. To gain insights about the impact of remanufacturing under different conditions, a simulation model is created. First, a base model without remanufacturing option is developed. With this model, it is possible to analyze the current system with different parameters. Safety stock of the distributor and lead time of the distributor's orders to its supplier are the main paramaters to be analyzed. In the second model the remanufacturing option is added as an alternative for the customer. In this model, it is possible to see how the key performance indicators are affected by the presence of remanufactured parts in the supply chain. The impact of customer's willingness-to-select remanufactured parts and remanufacturability rate of used products are investigated.

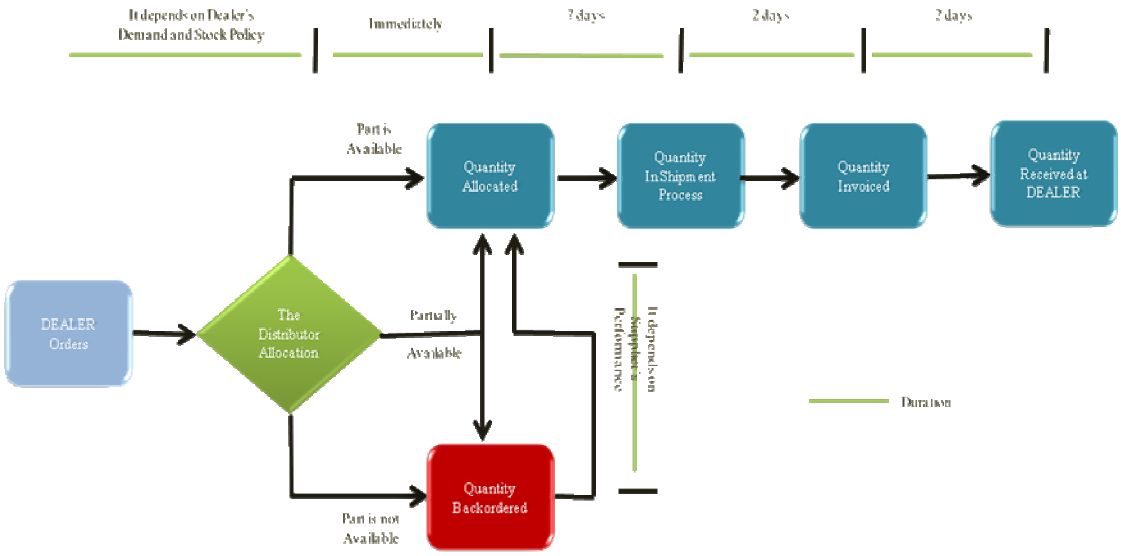

Figure 3.2. Base model without remanufacturing option

4. MODEL DEVELOPMENT

In this chapter, two different models are presented. Firstly, current system without remanufactured parts option is modeled as the base model. Later, remanufactured parts are included in the base model and the model with remanufacturing is constructed. Before the simulation is carried out, the verification and validation necessary to check whether the simulation program runs as intended or not are made. These discussions are also presented in this chapter.

To simplify the problem and facilitate gaining insights, only one item out of 85.000 spare parts, a brake pad, is analyzed. Below are the reasons to select this part;

- It has been sold for more than three years so historical sales data of the distributor and dealers to fit distributions for simulation purposes is available.
- It is a remanufacturable part.
- It is a fast-moving part.

4.1. The base model without remanufacturing option

This model reflects the current system of a major distributor of automotive spare parts in Turkey consisting of one distributor and 72 dealers. These dealers face stochastic demand from customers arriving with generalized pareto distribution and ordering with poisson distribution. Easyfit software is used to determine the best fitting distributions. This software compares 28 different continious distributions. Of the 28 distributions, performances of the best fitting 11 distributions for customer interarrival times are shown in Table 4.1. Numbers indicate that generalized pareto distibution is the best fitting distribution for 28 of 72 dealers while it is the second best one for 10 dealers and the third best one for 12 dealers. In general, generalized pareto distribution is one of the best fitting five distributions for 64 of 72 dealers (See Appendix A for goodness of fit test results).

Table 4.1. Performances of distributions for customer interarrival times.

Distribution Name	Best Fitting	2. Best Fitting	3. Best Fitting	4. Best Fitting	5. Best Fitting
Gen. Pareto	28	10	12	7	7
Lognormal	14	14	9	12	7
Gen. Extreme Value	12	13	12	12	2
Johnson SB	8	2	2	4	5
Weibull	4	5	12	8	16
Gamma	3	4	2	2	1
Lognormal (3P)	3	1	2	3	5
Exponential	2	5	4	2	7
Fatigue Life	2	6	6	18	12
Chi-Squared	1		1	1	5
Fatigue Life (3P)	1	2	1	2	2

A comparison of real data and fitted distribution for a representative dealer is given in Figure 4.1. Please note that p-value of Kolmogorov-Smirnov test for this dealer is 0.000000000000449.

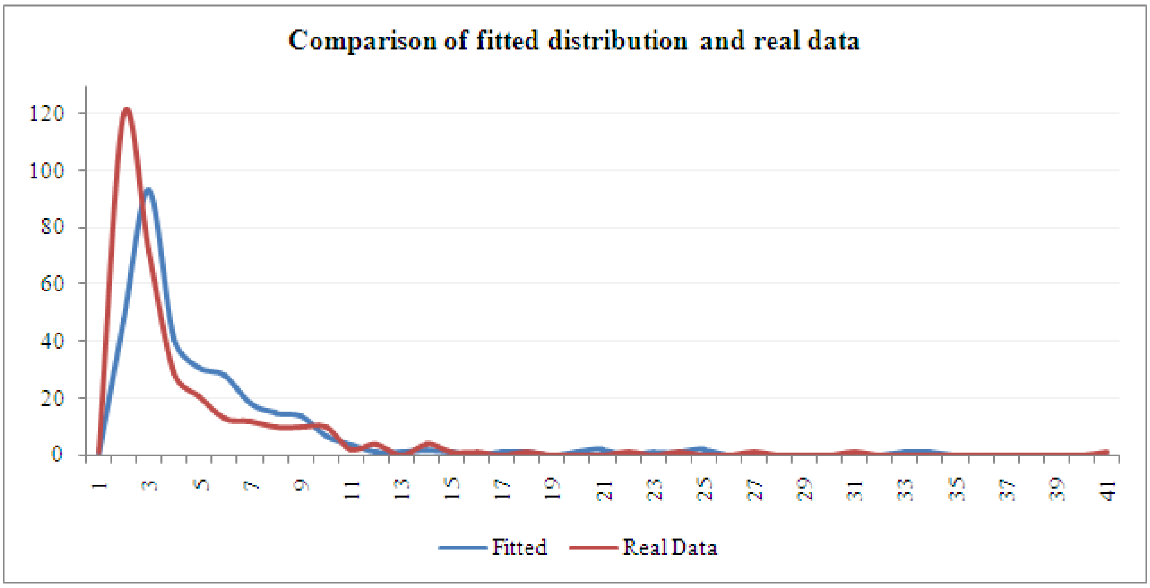

Figure 4.1. Comparison of fitted distribution and real data for the Dealer 5.

When it comes to quantities to be ordered, frequencies of historical order quantities of customers are found and discrete distributions are investigated to find the best fitting one for this data. Poisson distribution is assumed to be the best fitting distribution among other alternatives. Parameters of generalized pareto distribution and poisson distribution can be viewed on Appendix B.

A pattern of stock management policies could not be observed in dealers. Instead, it is seen that they order randomly. Figure 4.2. and Figure 4.3. shows stock movements of two dealers. These figures disclose the fact that dealers do not use any stock management policy.

In order to reflect this randomness to the model, values for maximum stock level at order time (*max_s*), minumum stock level at order time (*min_s*), maximum amount ordered (*max_q*) and minimum amount ordered (*min_q*) for the last three years are found for each dealer (See Appendix C).

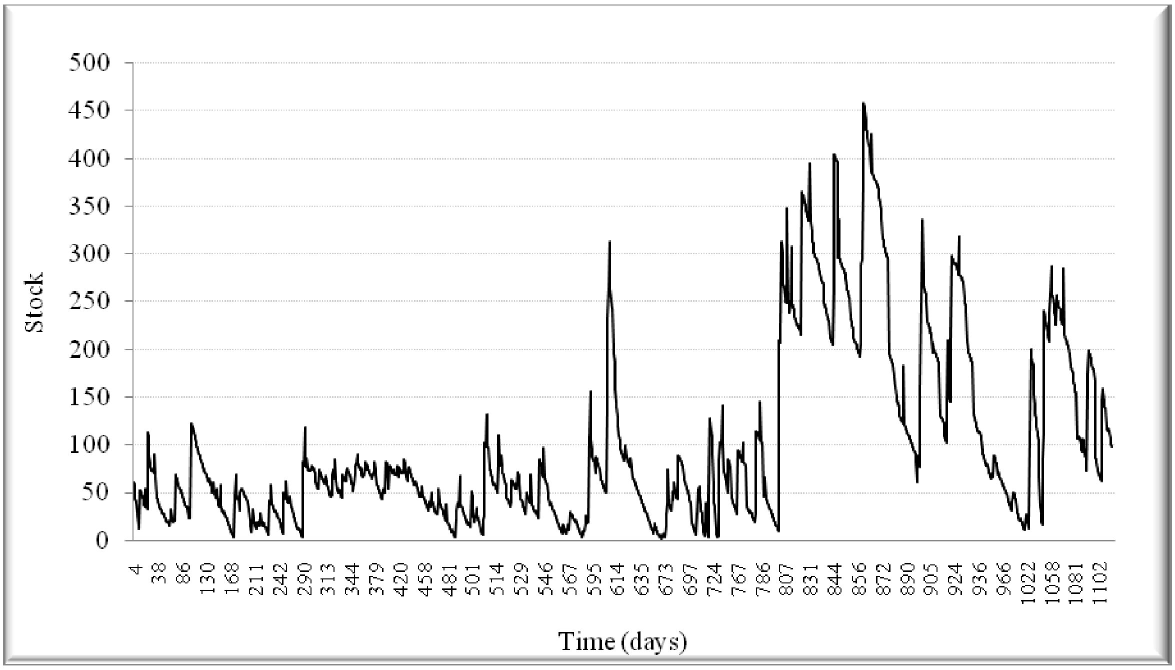

Figure 4.2. Stock movements of the Dealer 6

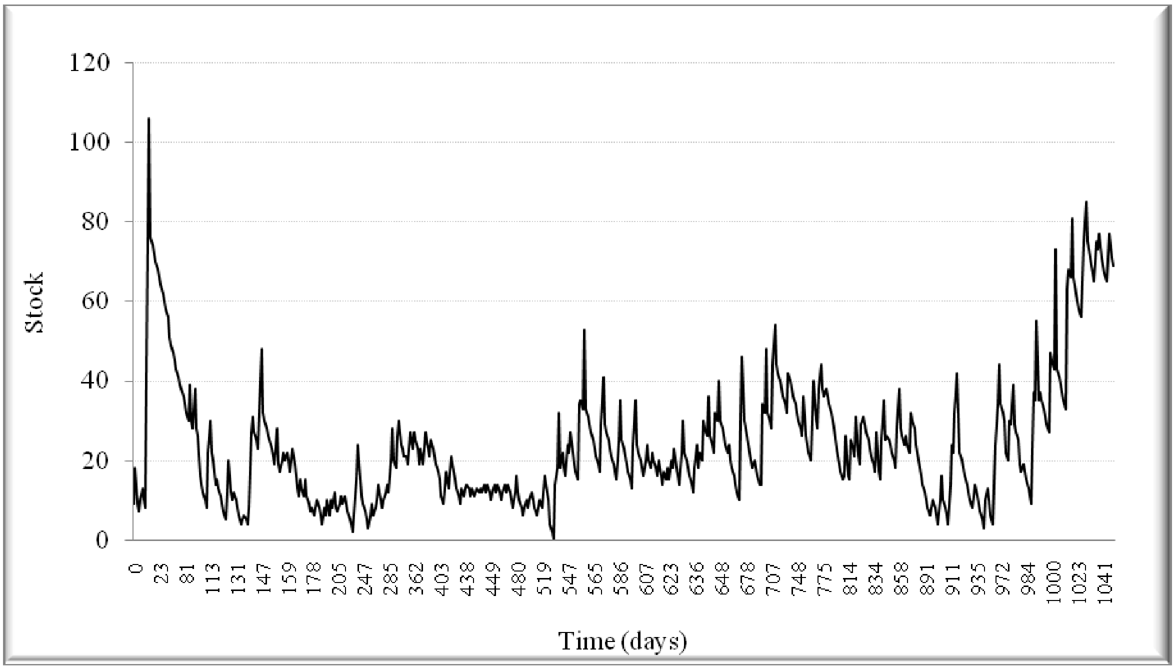

Figure 4.3. Stock movements of the Dealer 48

Uniformly distributed random numbers are created between zero and *max_s*. If the net stock of dealer is less then or equal to this random number, dealer processes a new order. Quantity to be ordered is uniformly distributed between *min_q* and *max_q*. Initial stocks of dealers are set to *max_s*.

The distributor regularly sends orders to its supplier once in 30 days (*R*). Amount to be ordered by the distributor depends on both the safety stock and the output of winters exponential smoothing forecasting method. A detailed explanation and illustration of this method is presented in Appendix D.

The supplier of the distributor processes orders sent and delivers them back to the distributor after 40 days (*LT*). Notice now that at time *t*, all the outstanding orders from moment (*t-LT)* have arrived. When parts are delivered to the distributor's warehouse, first backorders waiting to be met are allocated starting from the oldest one to the newest one. This model is depicted in Figure 4.4

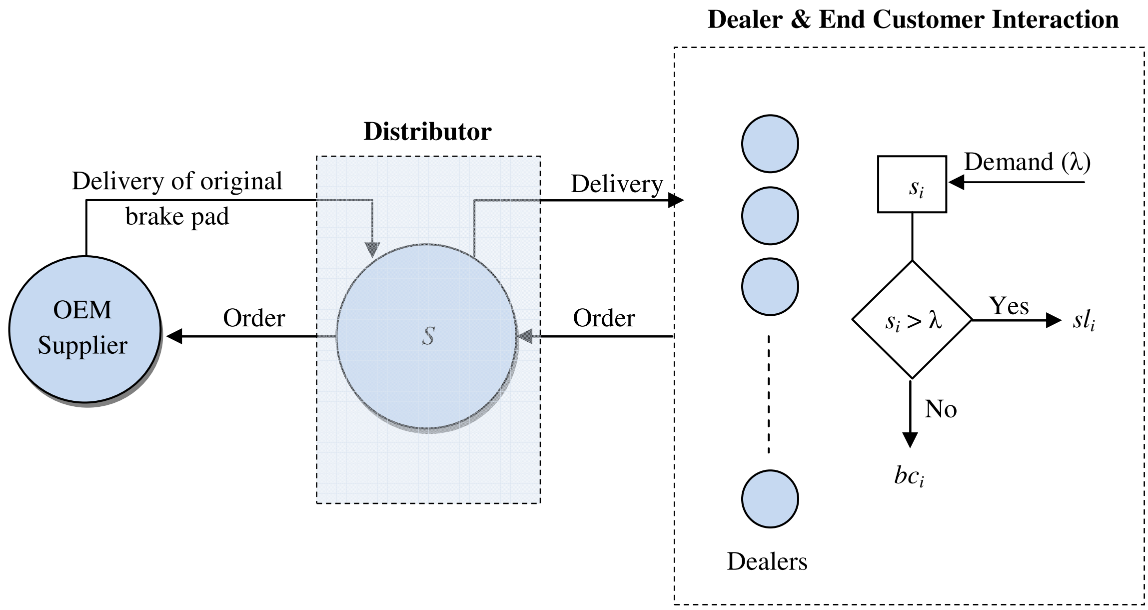

Figure 4.4.The base model

The model described above is simulated in C++ using the next-event time-advanced approach [29]. The simulation clock is initialized to zero and the times of occurence of future events are determined. The simulation clock is then advanced to the time of occurence of the most imminent of these future events, at which point the state of the system is updated to account for the fact that an event has occured, our knowledge of the times of occurence of future events is also updated and an iteration is completed.

4.1.1. Performance measurement

Performance measurement has always exerted considerable influence on the actions of companies. Consequently, the ways of accurately measuring right key performance indicators (KPI) is percieved as being an increasingly important field and has been seen to occupy the minds of managers since it allows pinpointing of those areas where the system can be improved. The major performance measures pertinent to the objectives of our study are listed below;

- Dealer's servicel level to its customers (*d_ser*)

- The distributor's service level to its dealers (*D_ser*)
- Average waiting time of backordered demand (*w_back*)
- Average cycle time of orders (*c_time*)
- Number of total lost sales of dealers due to unavailability (*bc*)
- Average inventory at the distributor and dealers (*D_inv* and *d_inv*)
- Total sales of the distributor and dealers (*SL* and Σsl)

To a world class organisation, a happy and satisfied customer is of utmost importance. In a modern supply chain customers can reside next door or across the globe, and in either case they must be well served. Without a contented customer, the supply chain strategy cannot be deemed effective [30]. Therefore, service level given to the customers is considered as the most important KPI in this study which is the ratio of order lines fulfilled on time to order lines received. This KPI is measured for both the distributor and dealers. In addition to service level, total sales and average inventory levels are also measured for both parties.

Among the KPIs of the distibutor, average cycle time of dealer orders and average waiting time of backordered demand can be listed. The cycle time of an order refers to the time elapsed in between the receipt of dealer order until the delivery of spare parts to the dealer's warehouse. Period from the time when a dealer order is backordered to the time when the order is allocated determines the average waiting time of backordered demands. It is defined to capture the expected delay in satisfying the backorders. If the part is available at the distributor, the dealer order will be allocated just in time hence there will be no backorders and the waiting time will be zero.

As far as dealers are concerned, total lost sales due to unavailability of the part is monitored. Customers arriving to dealers purchase the brake pad if it is available at that time. If the dealer does not have the part on the shelf at the time of customer arrival, the customer does not wait and leaves the dealer immediately and satisfies its demand from the competitors. With this KPI, we are tracking total lost sales of dealers because of this situation. It is an indication of the potential demand which dealers let their outside compatitiors fulfill.

4.1.2.Notation for the base model

The following notation and definitions for the base model are given for the distributor and dealers.

Attributes of the distributor:

S	: Stock level (Quantity on hand)
ES	: Stock level at the end of simulation
SA	: Quantity on order
U	: Quantity allocated
SH	: Quantity under preparation
I	: Quantity invoiced
B	: Quantity backordered
D	: Quantity not shipped
A	: Actual stock
NS	: Net stock
SL	: Sales
F	: Forecasted demand
Q	: Quantity of order placed to the supplier

Attributes of dealers :

The index set i represents the dealer number where,

$i = \{0,...,71\}$

s_i	: Stock level at dealer *i*
is_i	: Initial stock level at dealer *i*
es_i	: Stock level at dealer *i* at the end of simulation
ns_i	: Net stock level at dealer *i*
sa_i	: Quantity on order at dealer *i*
u_i	: Quantity allocated for dealer *i*
sh_i	: Quantity under preparation for dealer *i*
i_i	: Quantity invoiced for dealer *i*
b_i	: Backordered quantity of dealer *i*
sl_i	: Total sales at dealer *i*
bc_i	: Total lost sales at dealer *i*
k_i	: Shape parameter of customer interarrival times at dealer *i*
σ_i	: Scale parameter of customer interarrival times at dealer *i*
μ_i	: Location parameter of customer interarrival times at dealer *i*
λ_i	: Mean order quantities of customers at dealer *i*

The following equations are defined for the base model: First, the following relations hold by definition:

$$U = \Sigma\, u_i \tag{4.1}$$

$$SH = \Sigma\, sh_i \tag{4.2}$$

$$I = \Sigma\, i_i \tag{4.3}$$

$$B = \Sigma\, b_i \tag{4.4}$$

$$sa_i = u_i + sh_i + i_i + b_i \tag{4.5}$$

$$SL = \Sigma\, sl_i - \Sigma\, is_i + \Sigma\, es_i + \Sigma\, i_i \tag{4.6}$$

Furthermore, since the orders of dealers are deemed as met when they are invoiced, total number of orders waiting to be met (*D*) equals the sum of quantity on order for each dealer (Σsa_i) minus sum of quantity invoiced for each dealer (Σi_i). Moreover, a dealer order could either be allocated, or under preparation, or backordered.

$$D = \Sigma\, sa_i - \Sigma\, i_i \tag{4.7}$$

$$D = U + SH + B \tag{4.8}$$

Actual stock refers to the status of inventory as it relates to its ability to be sold or consumed. Hence, quantities already allocated are not taken into consideration while calculating the actual stock.

$$A = S - U \tag{4.9}$$

The distributor calculates net stock just before processing a new order to its supplier. This amount, together with the forecast (*F*) and safety stock (*SS*), determines the size of order. Obviously, the distributor does not place an order if *Q* is less than zero.

$$NS = S + SA - D \tag{4.10}$$

$$Q = F + SS - NS \tag{4.11}$$

Similar to the distributor, dealers also calculate the net stock by summing quantity on order and quantity on hand. On the other hand, unlike the orders of dealers to the distributor, there is no backlogging of end customer orders to dealers.

$$ns_i = s_i + sa_i \tag{4.12}$$

Below are the decision parameters to be varied in the simulation of the base model:

IS	: Initial stock of the distributor
SS	: Safety stock of the distributor
LT	: Lead time of the distributor’s order to the supplier
s_dur	: Duration between two successive shipment orders.
s_f_dur	: Shipment to invoicing duration
R	: Ordering period of the distributor

4.1.3. Warm-up Period

In a simulation study, it is important to ensure that the bias of initial conditions is removed to achieve stationary results. An obvious remedy is to run the simulation for a period large enough to remove the effect of the initial bias. During this warm-up period, no attempt is made to record the output of the simulation. The results are thrown away. At the end of this warm-up period, statistics are collected for analysis. The practical question is "How long should the warm-up period be?". In order to determine the warm-up period, the Welch's graphical procedure [29] is applied in this study. Dealer's service level is analyzed by this procedure and the time at which these service levels reach steady state is found. Several values of window *w* are tried and it is seen that 200 is the smallest value of *w* for which the corresponding plot is reasonably smooth (See Figure 4.5 and Figure 4.6.). It is observed that 500 days is more than adequate for the service levels to reach steady state. Therefore, the first 500 days of each replication are set as the warm-up period within this study and the statistics are collected after 500th day in each replication.

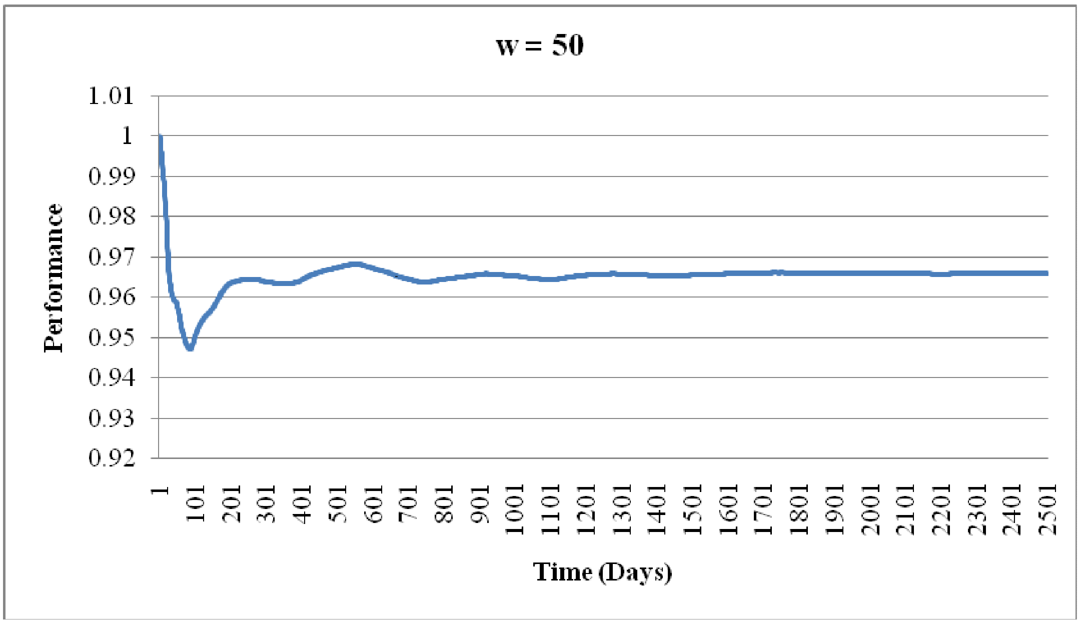

Figure 4.5. Dealers's service level throughout the simulation (SS = 500)

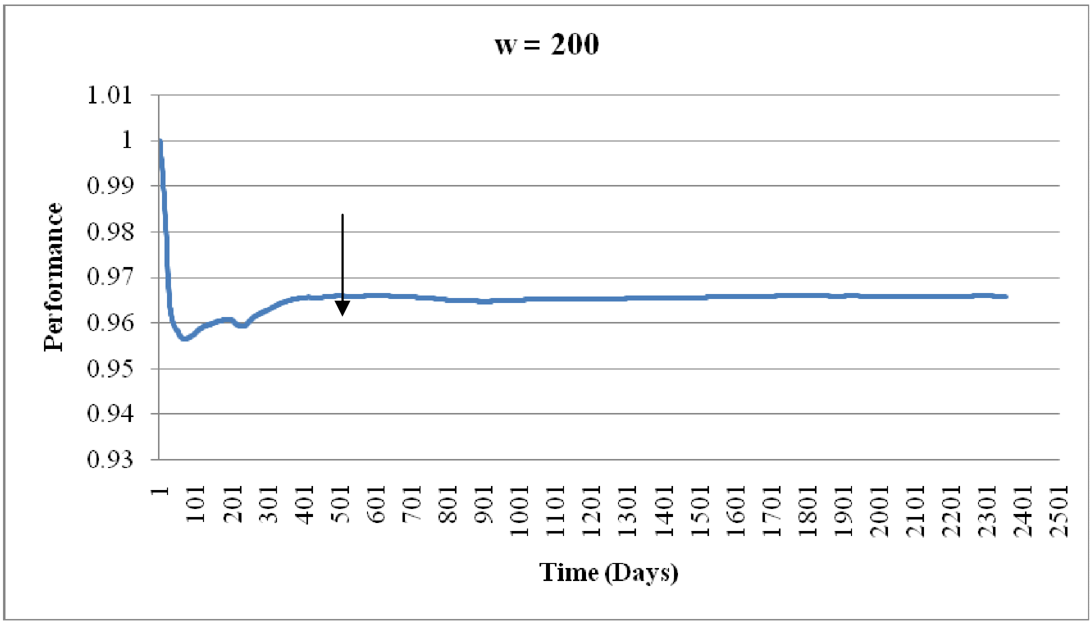

Figure 4.6. Dealer's service level throughout the simulation (*SS* = 500)

4.1.4. Verification and Validation

After the implementation of the simulation model of spare parts ordering and supply process under the above described assumptions and distributions , the verification and validation of the model are conducted.

Verification is concerned with building the model correctly while validation is concerned with building the right model. In other words, verification is the process of determining that a model implementation accurately represents the developer's conceptual description and specifications while validation is the process of determining the degree to which a model is an accurate representation of the real world in relation to the intended use of the model.

In order to verify the simulation model, the model is decomposed and debugged class by class, function by function. Since different parameter sets and experiments are analyzed, the simulation was run under a variety of these settings and the output values were observed. One of the most powerful techniques, that can be used to debug a discrete-event simulation program is a trace. In a trace, the state of the simulated system, i.e., the contents of the event list, the state variables, certain statistical counters, etc., are displayed just after each event occurs and are compared with hand calculations to see if the program is operationg as intended [29]. As suggested, the trace of the simulation model just after each event occurs is analyzed and the outputs are compared with Microsoft Excel calculations. An example of the trace of the system is given in Table 4.2. It is observed that the program is operating as intended.

After the verification of the model is completed and the model is run with the input data, the outputs are collected and the validation step is initiated. The validation is done by comparing the model to what has been observed in the real system. Therefore, realized sales of the distributor for the last three years, 44.145 pcs, are compared to that of the simulation model. Simulation model is run approximately 1095 days (three years) and replicated 10 times. The outputs are presented in Table 4.3.

Table 4.3. Total Sales of distributor in three years
(L=40, *s_dur*=7, *s_f_dur*=2, *f_r_dur* = 2)

Replication	Simulation Length (Days)	Sales of Distributor
1	1087,95	44.122
2	1101,83	44.294
3	1092,24	42.647
4	1095,75	44.512
5	1098,28	44.070
6	1080,17	43.974
7	1090,2	43.755
8	1082,27	43.382
9	1089,53	43.375
10	1101,13	44.764

From these data we get

$$\bar{X}(10) = 43.890 \text{ pcs} \quad \text{and} \quad S^2(10) = 388.201$$

Table 4.2. Trace of the system after 6 sequential events.

Atributes	Time 65,4377	Time 65,5493	Time 65,6749	Time 65,6872	Time 65,7221	Time 65,8206	Time 66,0844
Σs_i	3916	3913	3913	3908	3905	3901	3900
Σs_r_i	936	936	936	936	936	936	936
Σcs_i	210	213	213	218	221	225	226
Σsl_i	2714	2717	2717	2722	2725	2729	2730
Σsl_r_i	9	9	9	9	9	9	9
Σsa_i	241	241	241	241	241	241	241
Σu_i	119	119	119	119	119	119	119
Σsh_i	0	0	0	0	0	0	0
Σi_i	122	122	122	122	122	122	122
Σb_i	0	0	0	0	0	0	0
Σsa_r_i	504	504	504	504	504	504	504
Σu_r_i	127	127	127	127	127	127	127
Σsh_r_i	0	0	0	0	0	0	0
Σi_r_i	200	200	200	200	200	200	200
Σb_r_i	177	177	177	177	177	177	177
P	1272	1272	1272	1272	1272	1272	1272
dis	1241	1241	1241	1241	1241	1241	1241
rf_cs	0	0	0	0	0	0	0
rf_s_r	0	0	0	0	0	0	0
S	217	217	217	217	217	217	217
A	98	98	98	98	98	98	98
S_R	127	127	127	127	127	127	127
A_R	0	0	0	0	0	0	0
CS	0	0	0	0	0	0	0
SL	2767	2767	2767	2767	2767	2767	2767
SL_R	1145	1145	1145	1145	1145	1145	1145
D	119	119	119	119	119	119	119
U	119	119	119	119	119	119	119
SH	0	0	0	0	0	0	0
I	122	122	122	122	122	122	122
B	0	0	0	0	0	0	0
D_R	304	304	304	304	304	304	304
U_R	127	127	127	127	127	127	127
SH_R	0	0	0	0	0	0	0
I_R	200	200	200	200	200	200	200
B_R	177	177	177	177	177	177	177
SA	2447	2447	2447	2447	2447	2447	2447
Met Order	722	723	724	725	726	727	728
Arrived Order	729	730	731	732	733	734	735
Met Order (The distr.)	109	109	109	109	109	109	109
Arrived_Order (The distr.)	109	109	109	109	109	109	109
Tofas's Service Level	1	1	1	1	1	1	1
Dealer's Service Level	0.990398	0.990411	0.990424	0.990437	0.99045	0.990463	0.990476
Backorder Customer	9	9	9	9	9	9	9

which results in the following confidence interval for μ:

$$\bar{X}(10) \pm t_{9,\,0.95}\sqrt{\frac{S^2(10)}{10}} = 43.890 \pm 1{,}83\sqrt{\frac{388.201}{10}} = 43.890 \pm 360{,}56$$

Therefore, subject to the interpretation stated above, we claim with 90 percent confidence that μ is in the interval [43.528, 44.250]. This suggests that the output of the simulation and realized sales perfectly match each other.

Furthermore, sensivity analysis is consulted to determine if the simulation output changes significantly when the value of an input parameter is changed. Design Expert 7.1.5 is used to construct the experimental design (5 replications) and the effects of the factors are analyzed, eg. a decrease in dealer's lost sales is expected as the distributor's lead-time decreases and our simulation output gave the expected relation. Results are plotted on Figure 4.7.

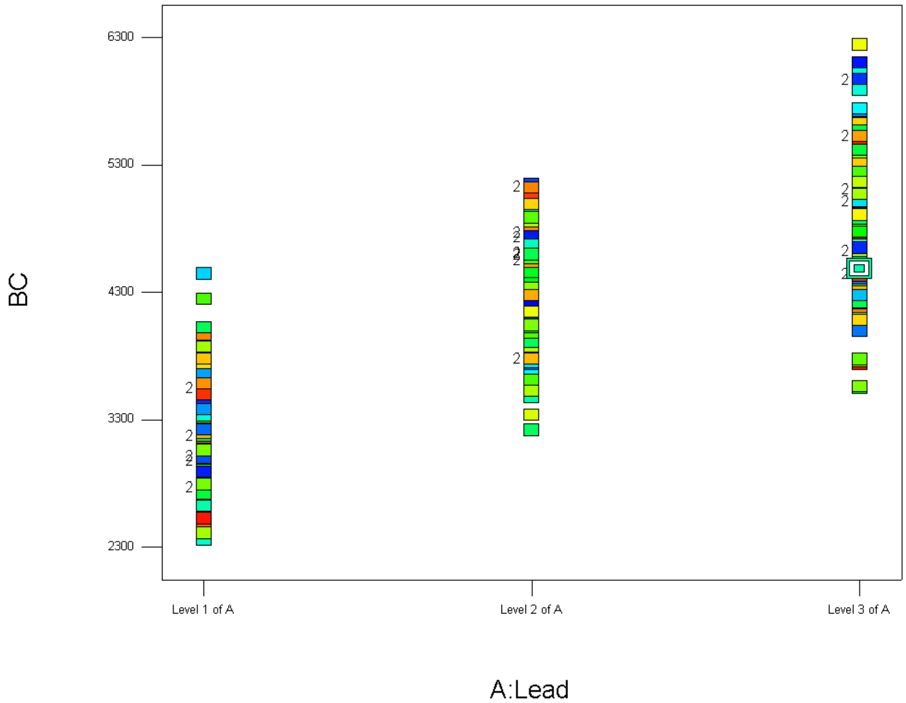

Figure 4.7. Changes in Σ*bc* with the change in *LT* *(Level1:40days, Level2:50days, Level3:60days)*

4.2. Model with remanufacturing

In the base model, only original brake pads are served to end customers through a three-echelon supply chain and it is assumed that when a new brake pad is mounted on a car, dismantled brake pad is disposed. However, in this model remanufacturing of dismantled pieces is considered and its impact on the service levels is investigated. Therefore, besides the distributor, OEM and dealers, a remanufacturing facility is included in the base model. The remanufacturing facility is considered to be a subcontractor of the distributor. These players maintain a stockpile of returned, but not yet remanufactured, cores and remanufactured brake pads in addition to original brake pads.

In addition to the notation of the base model, the following note definitions are given for the distributor, dealers and the remanufacturing facility for this model:

Attributes of the distibutor:

CS	: Core stock (amount of core on hand)
S^R	: Remanufactured part stock
SA^R	: Quantity on order (Remanufactured parts)
IS^R	: Initial remanufactured part stock
ES^R	: Remanufactured part stock at the end of simulation
U^R	: Quantity allocated (Remanufactured Part)
SH^R	: Quantity under preparation (Remanufactured Part)
I^R	: Quantity invoiced (Remanufactured Part)
B^R	: Quantity backordered (Remanufactured Part)
D^R	: Quantity not shipped (Remanufactured Part)
A^R	: Actual stock (Remanufactured Part)
NS^R	: Net stock (Remanufactured Part)
SL^R	: Sales (Remanufactured Part)

Attributes of dealers:

s^r_i : Remanufactured part stock level at dealer i

is^r_i : Initial remanufactured part stock level at dealer i

es^r_i : Remanufactured part stock level at dealer i at the end of simulation

ns^r_i : Net remanufactured part stock level at dealer i

cs_i : Core stock level at dealer i

sa^r_i : Quantity on order at dealer i (Remanufactured Part)

u^r_i : Quantity allocated for dealer i (Remanufactured Part)

sh^r_i : Quantity under preparation for dealer i (Remanufactured Part)

i^r_i : Quantity invoiced for dealer i (Remanufactured Part)

b^r_i : Backordered quantity of dealer i (Remanufactured Part)

sl^r_i : Remanufactured part sales at dealer i

Attributes of the remanufacturing facility:

cs_{rf} : Core stock

s^r_{rf} : Remanufactured part stock

c : Daily production capacity

p : Quantity produced during the simulation

dis : Quantity disposed during the simulation

The following equations given in the base model for the original parts hold for remanufactured parts as well,

$$U^R = \Sigma\, u^r_i \tag{4.13}$$

$$SH^R = \Sigma\, sh^r_i \tag{4.14}$$

$$I^R = \Sigma\, i^r_i \tag{4.15}$$

$$B^R = \Sigma\, b^r_i \tag{4.16}$$

$$sa^r_i = u^r_i + sh^r_i + i^r_i + b^r_i \tag{4.17}$$

$$SL^R = \Sigma\, sl^r_i - \Sigma\, is^r_i + \Sigma\, es^r_i + \Sigma\, i^r_i \tag{4.18}$$

$$D^R = \Sigma\, sa^r_i - \Sigma\, i^r_i \tag{4.19}$$

$$D^R = U^R + SH^R + B^R \tag{4.20}$$

$$A^R = S^R - U^R \tag{4.21}$$

$$ns^r_i = s^r_i + sa^r_i \tag{4.22}$$

$$NS^R = S^R + SA^R - D^R \tag{4.23}$$

The distibutor's inventory control policy for original brake pads is kept as it is in the base model. On the other hand, a remanufactured part inventory control policy is developed for dealers. In our problem, remanufactured parts are not alternative but a safety stock to the original one. In order to calculate a point estimate of safety stock levels for each dealer, lost original part sales of dealers from the instant that the original part stock level of the dealer drops to zero until the original part arrives are observed in the base model for *IS*=1.000, *SS*=0, *L*=40, *s_dur*=7, *s_f_dur*=2, *f_r_dur*=2. The simulation is replicated 30 times. Results are given in Appendix F. It is seen that, for example, the stock level of Dealer 1 drops to zero 526 times and this dealer's average lost sales between [s_1=0,s_1>0] is 8,09 pieces with standart deviation 6,16. It follows that safety stock for 95 per cent confidence interval is 19 pcs.

If the original part inventory of a dealer drops the zero, the dealer offers remanufactured parts to customers in order to prevent lost sales. Customers either accept or reject this offer according to their willingness-to-select remanufactured part ratio (*will*). If the customer accepts to purchase remanufactured parts instead of original, the order is fulfilled with the remanufactured part. When the dealer receives the original part from the distributor, it places an order to replenish its remanufactured part stock level up to the safety stock level. This mechanism is shown in Figure 4.8 for Dealer 1.

Dealers collect cores through sales of either original or remanufactured brake pads. It is assumed that these cores are delivered to the remanufacturing facility in two days. Returned cores are either stored at dealers or at the remanufacturing facility. At this facility the arriving cores are stored for remanufacturing. It is assumed that only a proportion of returned cores (*rate*) are fit for remanufacturing. Therefore, remanufacturing facility first inspects returned cores and dispose those pieces which are not remanufacturable.

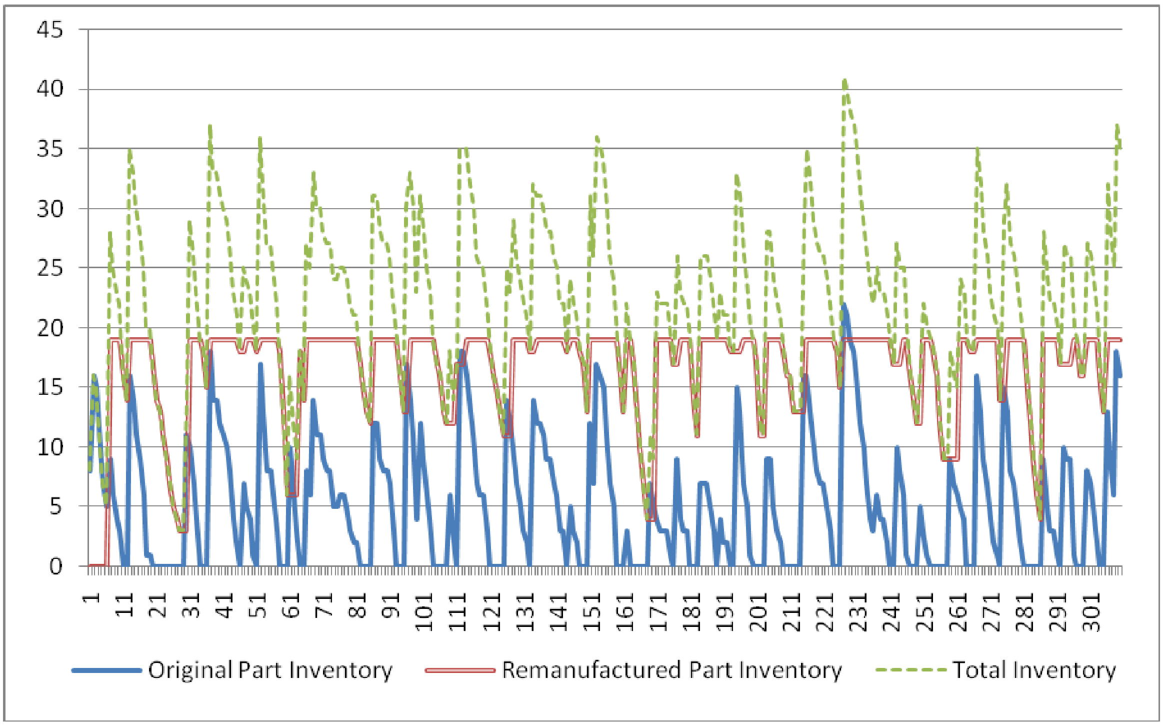

Figure 4.8. Stock movements of Dealer 1.

(s_d, N) inventory control policy is employed in the remanufacturing facility for core remanufacturing and disposal. After the inspection process, remanufacturable returned cores are either remanufactured or disposed of, depending on the inventory position of the system (IP) and number of cores in the remanufacturing facility (N). We have the following equation for the inventory position:

$$IP = \Sigma s^r{}_i + \Sigma sa^r{}_i + s^r{}_{rf} + \Sigma \mathrm{cs}_i + \mathrm{cs}_{rf} \qquad (4.24)$$

The strategy with respect to remanufacturing and disposal is as follows: whenever the inventory position equals s_d, or whenever the number of cores in the remanufacturing facility equals N, returned cores are disposed of upon arrival. Returned cores that are not disposed of enter the remanufacturing facility. The remanufacturing facility has a daily production capacity c.

$$p + dis + \mathrm{cs}_{rf} + \Sigma\, cs_i \;=\; \Sigma\, sl_i + \Sigma\, sl^r{}_i \qquad (4.25)$$

Cores produced in the remanufacturing facility can be in the remanufactured part inventory of either the remanufacturing facility or dealers, or they might have already been invoiced to dealers or sold to end customers. It follows that

$$p = s^r_{rf} + \Sigma\, s^r_i + \Sigma\, i^r_i + \Sigma\, sl^r_i \tag{4.26}$$

Both the schematic representation of the model with remanufacturing and the logic of the C++ code for it are given in Figure 4.9 and Figure 4.10 respectively.

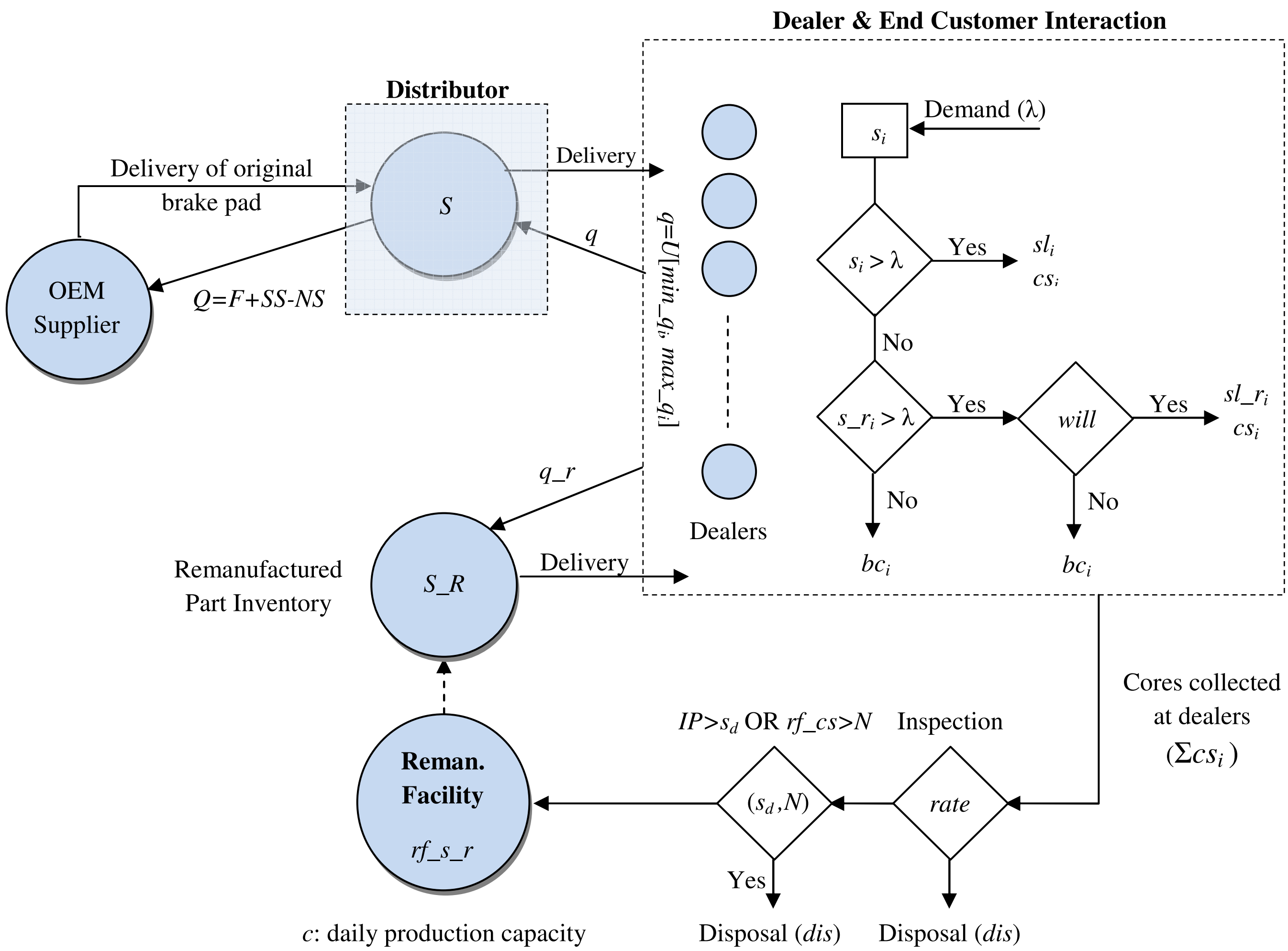

Figure 4.9 Model with remanufacturing

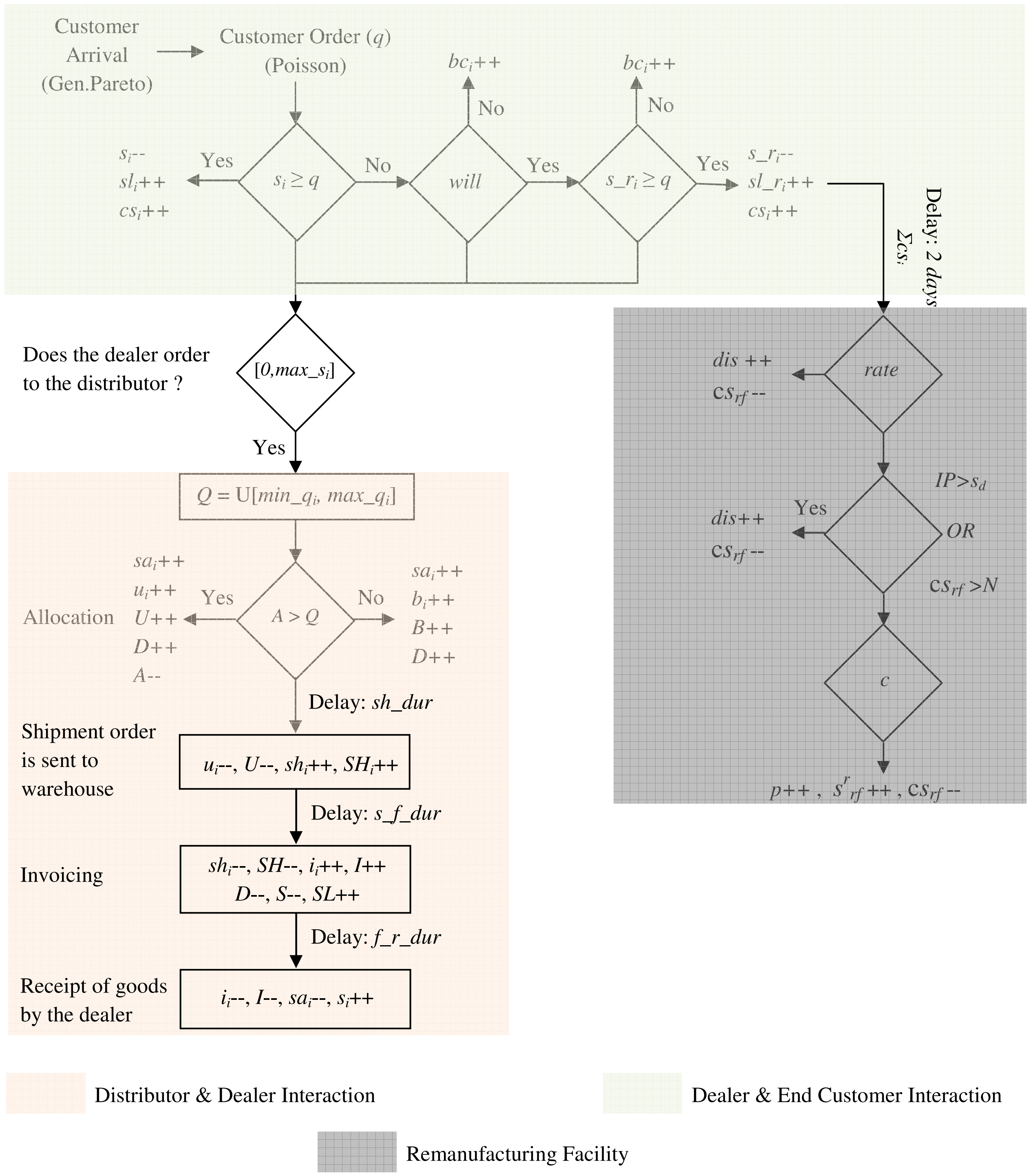

Figure 4.10. Logic of the C++ code of the model with remanufacturing

5. NUMERICAL ANALYSIS

In this study, replication-deletion approach [29] is employed to estimate the steady-state mean of the performance indicators. Only those observations beyond the warmup period in each replication are used to form point estimates and confidence intervals. Number of observations in a replication depend on the lenght of time (in days) between two subsequent observations which is selected as 60 days in this thesis. An example of observations is shown in Table 5.1.

Table 5.1 An example of mean calculation with replication-deletion
(*SS*=0, *L*=40, *s_dur*=2, *s_f_dur*=2, *f_r_dur*=2)

Obs. No	Observation Interval	First-time filled customer orders	Total number of customer orders	*d_ser*	First-time filled dealer orders	Total number of dealer orders	*D_ser*
1	500-560	750	765	***98,04%***	10	119	***8,40%***
2	560-620	626	722	***86,70%***	0	104	***0,00%***
3	620-680	671	697	***96,27%***	36	104	***34,62%***
4	680-740	621	661	***93,95%***	38	95	***40,00%***
5	740-800	664	676	***98,22%***	86	113	***76,11%***
6	800-860	665	691	***96,24%***	19	90	***21,11%***
7	860-920	663	689	***96,23%***	30	110	***27,27%***
8	920-980	574	627	***91,55%***	16	94	***17,02%***
9	980-1040	668	672	***99,40%***	47	103	***45,63%***
10	1040-1100	674	745	***90,47%***	17	102	***16,67%***
11	1100-1160	641	669	***95,81%***	25	98	***25,51%***
12	1160-1220	653	681	***95,89%***	22	79	***27,85%***
13	1220-1280	669	691	***96,82%***	10	109	***9,17%***
14	1280-1340	680	730	***93,15%***	13	98	***13,27%***
15	1340-1400	670	682	***98,24%***	47	96	***48,96%***
16	1400-1460	680	722	***94,18%***	15	105	***14,29%***
17	1460-1520	707	715	***98,88%***	54	90	***60,00%***
18	1520-1580	606	646	***93,81%***	9	104	***8,65%***
19	1580-1640	666	688	***96,80%***	25	87	***28,74%***
20	1640-1700	692	729	***94,92%***	0	111	***0,00%***

In this example, steady-state mean of dealer's service level is calculated as %95,28 while the distributor's service level is calculated as %26,16. On the other hand, standart deviations for these indicators are %3,11 and %20 respectively. This high variance is due to the safety stock of the distributor being zero. With zero safety stock, the distributor runs out of stock frequently. Therefore, the simulation is run again for *SS*=1800 and the results are given in Table 5.2.

Table 5.2 An example of mean calculation with replication-deletion
(*SS*=1500, *L*=40, *s_dur*=2, *s_f_dur*=2, *f_r_dur*=2)

Obs. No	Observation Interval	First-time filled customer orders	Total number of customer orders	*d_ser*	First-time filled dealer orders	Total number of dealer orders	*D_ser*
1	500-560	685	692	***98,99%***	92	100	***92,00%***
2	560-620	702	717	***97,91%***	84	107	***78,50%***
3	620-680	705	709	***99,44%***	106	106	***100,00%***
4	680-740	684	688	***99,42%***	90	110	***81,82%***
5	740-800	646	652	***99,08%***	100	100	***100,00%***
6	800-860	729	745	***97,85%***	110	110	***100,00%***
7	860-920	657	670	***98,06%***	94	94	***100,00%***
8	920-980	644	655	***98,32%***	99	99	***100,00%***
9	980-1040	707	714	***99,02%***	111	116	***95,69%***
10	1040-1100	640	657	***97,41%***	59	92	***64,13%***
11	1100-1160	615	620	***99,19%***	101	101	***100,00%***
12	1160-1220	610	620	***98,39%***	105	105	***100,00%***
13	1220-1280	681	690	***98,70%***	108	110	***98,18%***
14	1280-1340	662	670	***98,81%***	100	110	***90,91%***
15	1340-1400	725	737	***98,37%***	112	112	***100,00%***
16	1400-1460	679	689	***98,55%***	67	108	***62,04%***
17	1460-1520	709	723	***98,06%***	81	100	***81,00%***
18	1520-1580	706	716	***98,60%***	101	115	***87,83%***
19	1580-1640	709	720	***98,47%***	101	109	***92,66%***
20	1640-1700	716	728	***98,35%***	90	96	***93,75%***

From Table 5.2. we get %98,55 for dealer's service level and %90,93 for the distibutor's service level. Standart deviations are %0,54 and %11,79 respectively. This suggest that variance of the system decreases as the safety stock of the distributor increases. From now on, mean values of the indicators will be used for numerical anaylsis.

5.1. Numerical Anaysis of the base model

Five factors, which is considered to significantly influence the performance of the base model are initial stock of the distributor, safety stock of the distributor, lead-time of the distributor's orders, time between two successive shipment orders given to warehouse and shipment to invoicing duration. The correct approach to dealing with several factors is to conduct a factorial experiments. This is an experimental strategy in which factors are varied together, instead of one at a time [31]. In order to analyze the effects of these factors (parameters) on performance indicators, especially on service levels, 2x4x4x3x2 full factorial design with five replications is constructed. The design involved five factors are shown in Table 5.3.

Table 5.3. Experimental factors and their levels

Factor	Name	Levels			
A	Initial stock of the distributor	1000	2000		
B	Safety stock of the distributor,	0	500	1000	1500
C	Lead-time of the distributor's orders	30	40	50	60
D	Time between two successive shipment orders	4	7	10	
E	Shipment to invoicing duration	2	6		

The model results are analysed through analysis of variance table. The name "analysis of variance" is derived from a partitioning of total variability into its components. The total corrected sum of squares is used as a measure of overall variability in the data [31]. The analysis of variance table of our experiments is shown in Table 5.4.

The model F-value of 359,83 implies the model is significant. Similarly, "Lack of fit F-value" of 4,37 implies the lack of fit is also significant. *R-Squared* value of 0,9499 means that factors and their interactions explain about 94,99 per cent of the variability. Values of "Prob>F" less than 0,050 indicate model terms are significant. In this case, it is seen that initial stock of the distributor is not significant as it is supposed to be. The rest of the parameters have an impact on dealer's service level. In additian to main effects, it is observed that there are also interaction effects. Interaction of lead time with other parameters, especially with safety stock, is significant.

Table 5.4. Analysis of variance table for *d_ser* (The base model)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	
Model	0,4865	48	0,0101	359,83	< 0.0001	significant
A-*IS*	0,0000	1	0,0000	0,55	0.4598	
B-*SS*	0,2699	3	0,0900	3.193,99	< 0.0001	
C-*LT*	0,1432	3	0,0477	1.695,12	< 0.0001	
D-*s_dur*	0,0093	2	0,0047	165,85	< 0.0001	
E-*s_f_dur*	0,0163	1	0,0163	580,12	< 0.0001	
AB	0,0000	3	0,0000	0,16	0.9235	
AC	0,0001	3	0,0000	0,68	0.5650	
AD	0,0001	2	0,0000	0,99	0.3708	
AE	0,0000	1	0,0000	0,04	0.8402	
BC	0,0291	9	0,0032	114,87	< 0.0001	
BD	0,0005	6	0,0001	2,81	0.0103	
BE	0,0003	3	0,0001	3,43	0.0166	
CD	0,0149	6	0,0025	88,29	< 0.0001	
CE	0,0012	3	0,0004	14,03	< 0.0001	
DE	0,0015	2	0,0008	27,37	< 0.0001	
Residual	0,0257	911	0,0000			
Lack of Fit	0,0115	143	0,0001	4,37	< 0.0001	significant
Pure Error	0,0141	768	0,0000			
Cor Total	0,5122	959				

The decompostion of the variability in the observations through an analysis of variance identity is a purely algebraic relationship. However, the use of the partitioning to test formally for no differences in treatment means requires that certain assumptions be satisfied. The most important assumption is the normality assumption on the errors. Therefore, a check of this assumption should be made. The normal probability plot of the observations shown in Figure 5.1. discloses that there are a few outliers but it is not a severe indication of nonnormality. This lends support to our conclusion about the significance of factors and their interactions.

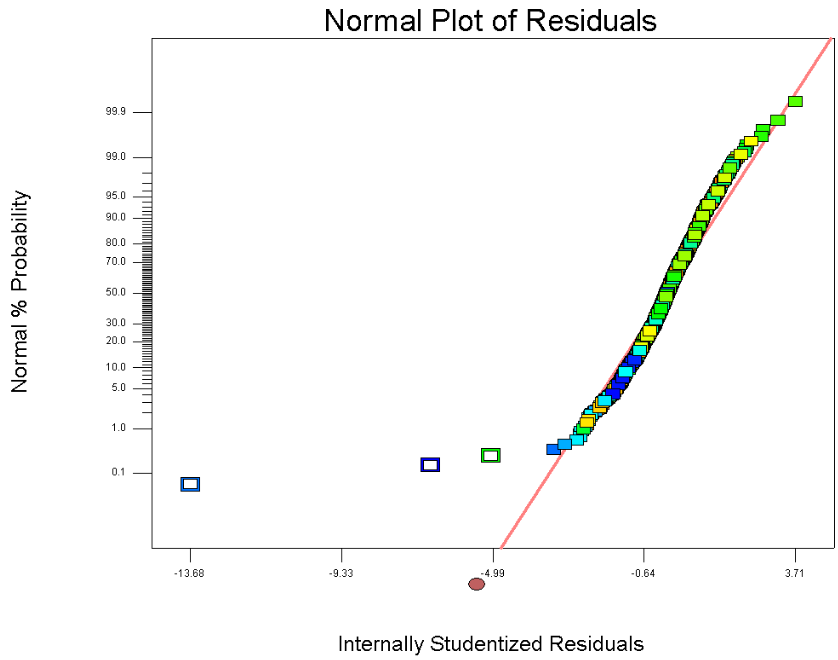

Figure 5.1. Normal probability plot of residuals (The base model)

5.2. Numerical analysis of the model with remanufacturing

As previously explained, the technique of defining and investigating all the possible conditions in an experiment involving multiple factors is known as the design of experiments (DOE). Basically, classical parameter design, developed by Fisher, is complicated and not easy to use. Especially, a large number of experiments must be conducted when the number of the process parameters increases. To solve this problem, Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only [32]. Therefore, DOE methodology adopting Taguchi approach is employed in the analysis of this model. Taguchi method involves establishment of large number of experimental situations described as orthogonal arrays to reduce errors and to enhance the efficiency and reproducibility of the experiments and it is believed to incorporate the advantages of simplex method and factorial design.

The reason to use orthogonal arrays is to ensure that the design of experiment is balanced, the factor levels are equally weighted.

The results of the orthogonal array design (OAD) experiments can be statistically treated by two ways: analysis of variance (ANOVA) and direct observation analysis. In ANOVA, the effects of different factors on response functions can be evaluated by both significance (*F* value) and PC% (percentage contribution) value. In other words, the importance of a factor or the interaction among different factors can be estimated from the significance and PC% value. Direct observation analysis is also called range analysis. The fluctuation range and tendency of response functions versus the levels of different factors can be directly observed from a broken line plot. From ANOVA and direct observation analysis of experimental results, factors that significantly affect the output responses can be found and optimal parameters for an analytical procedure can be obtained [33]. In this study, ANOVA is employed for the analysis of results.

The first step of experimental methodology is to identify the important factors to be optimized; whose variation has a critical effect on the overall performance of the system. In the numerical analysis of the model with remanufacturing, L_{25} (5^6) , which denotes six factors each with five levels, is chosen. Six factors, which significantly influence the performance are customers' willingness-to-select remanufactured parts, remanufacturability rate of returned cores, *SS*, *L*, s_d and *N*. The design involved six factors at five levels are shown in Table 5.5.

Table 5.5. Experimental factors and thier levels in L_{25} (5^6) OAD

Factors	Levels				
	1	2	3	4	5
will	0,2	0,4	0,6	0,8	1
rate	0,2	0,4	0,6	0,8	1
c	2	8	14	20	2
s_d	250	500	750	1000	1250
N	20	40	60	80	100
L	10	20	30	40	50

To test a variety of customers' willingness-to-select remanufactured parts (*will*) and remanufacturability of returned cores (*rate*), these parameters are varied from 0,2 to 1. Likewise, to test a wide range of *c* settings, this parameter is varied from 2 pcs to 26 pcs. A range of 250-1250 pcs for s_d, 20-100 pcs for *N* and 10-50 days for *L* are selected.

The experimental data obtained was processed by using Design Expert 7.1.5 software to evaluate the influence of individual factors and multiple interaction of the selected factors on the service levels. The software is equipped to use L_{25} arrays along with a selection of six factors with five levels to each. The automatic design option allows the software to select the array used and assign factors to the appropriate columns. Table 5.6 represents the selected orthogonal array for this study.

In order for all model terms, including two level interactions, be given a chance of inclusion in the model, the backward method is selected instead of stepwise. These methods are properties of Design Expert Software. For the level settings of our experiments, *rate*, *c*, s_d and *N* are removed from analysis of variance calculations after implementing backward method. It is due to the fact that only a small fraction of returned cores are needed to satisfy remanufactured part demand of the customers. Therefore, disposal control variables, namely *rate*, s_d and *N*, together with remanufacturing capacity *c* have not an influnce on dealer's service level. *F* and *R-Squared* values for these parameters are given in Table 5.7. Further analysis will be given in sensivity analysis chapter for different values of these parameters. The analysis of variance table of the model is given in Table 5.8.

R-Squared value of 0,9089 means that factors and their interactions explain about 90,89 per cent of the variability. The model *F*-value of 19,45 implies that the model is significant. Values of Prob>F less than 0,05 indicates that model terms are significant. Therefore, it can be said that *will* and *LT* has an influence on dealer's service level.

Table 5.6. L_{25} (5^6) randomized experimental plan table

Std	Run	Parameters and their levels					
		will	*rate*	*c*	s_d	*N*	*L*
7	1	0.4	0.4	14	1000	100	10
5	2	0.2	1	26	1250	100	50
8	3	0.4	0.6	20	1250	20	20
23	4	1	0.6	8	250	100	40
6	5	0.4	0.2	8	750	80	50
12	6	0.6	0.4	20	250	60	50
18	7	0.8	0.6	2	1000	40	50
10	8	0.4	1	2	500	60	40
19	9	0.8	0.8	8	1250	60	10
22	10	1	0.4	2	1250	80	30
11	11	0.6	0.2	14	1250	40	40
24	12	1	0.8	14	500	20	50
9	13	0.4	0.8	26	250	40	30
15	14	0.6	1	8	1000	20	30
1	15	0.2	0.2	2	250	20	10
4	16	0.2	0.8	20	1000	80	40
2	17	0.2	0.4	8	500	40	20
20	18	0.8	1	14	250	80	20
16	19	0.8	0.2	20	500	100	30
3	20	0.2	0.6	14	750	60	30
14	21	0.6	0.8	2	750	100	20
17	22	0.8	0.4	26	750	20	40
21	23	1	0.2	26	1000	60	20
25	24	1	1	20	750	40	10
13	25	0.6	0.6	26	500	80	10

Table 5.7. Removed parameters after implementing backward method.

Removed Factors	Value	Prob > F	R-Squared	MSE
s_d		1	98.02%	0.0000347
c	1.03788762	0.4861	95.97%	0.0000353
rate	1.075844024	0.4289	93.80%	0.0000362
N	1.513571129	0.2597	90.68%	0.0000409

Table 5.8. Analysis of variance table for *d_ser* (The model with remanufacturing)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F
Model	0.0063632	8	0.0007954	19.4492620	< 0.0001
will	0.0009304	4	0.0002326	5.6873789	0.0048
LT	0.0054328	4	0.0013582	33.2111452	< 0.0001
Residual	0.0006543	16	0.0000409		
Cor Total	0.0070175	24			

Dealers sell not only remanufactured parts but also original parts. Service level calculation is effected by the availability of both parts. *LT* is related to original parts and it is plausible that as *LT* gets longer, dealers get poor service from the distributor as the distributor gets poor service from its supplier. As a result of this, dealers are likely to run out of stock for original parts for high values of *LT*. On the other hand, as *will* increases, remanufactured parts compansate original parts and service level gets higher. More detailed analysis will be presented in next chapter.

Before the conclusions from the analysis of variance are adapted, the adequacy of the underlying model should be checked. As before, primary diagnostic tool is residual analysis. The normal probability plot of these residuals (Figure 5.2.) does not reveal anything particularly troublesome. In this chapter, significant factors are determined. Sensivity analysis of these factors is given in next chapter.

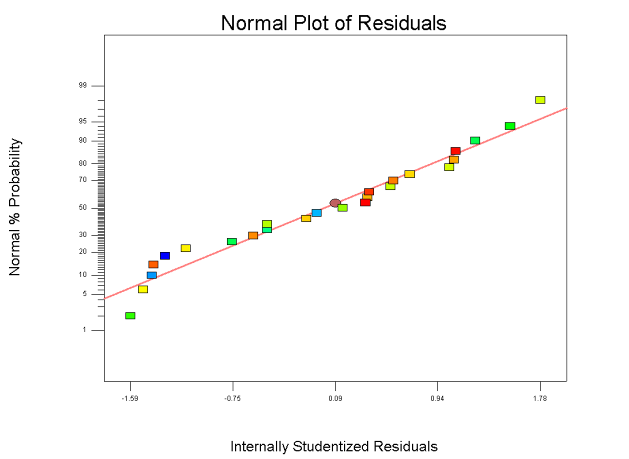

Figure 5.2. Normal probability plot of residuals(The model with reman.)

6. SENSIVITY ANALYSIS

In this section, some sensitivity analysis is presented to extract inferences about the behavior of the models. The analysis is performed by observing the change in the performance indicators by changing the parameters. 30 replications of the simulation each of 20.000 iterations (approximately 1.700 days) are made for each value of a parameter. As described in Chapter 5., only those observations beyond the warm-up period is used to form point estimates

6.1. Sensivity analysis of the base model

Paremeters of interest in the base model are *IS*, *SS*, *LT*, *s_f_dur* and *R*. Design of experiments constructed in numerical analysis chapter suggest that initial stock of the distributor (*IS*) is not a significant parameter in this model so sensivity analysis is not performed for this parameter. First, the impact of the supplier's delivery lead times on the system performance is studied. Lead time (*LT*) is a core parameter that varies and affects all supply chain partners. *LT* uncertainty is known as a kind of supply uncertainty in the supply chain literature which attracts attention of many researchers.

The effect of changing *LT* on service levels of the distributor and dealers (*D_ser* and *d_ser*) is represented in Figure 6.1. The simulation results indicate that service levels of both the distributor and dealers decrease as *LT* increases. On the other hand, it is observed that there is a significant interaction effect between *LT* and *R*. Service levels increase as *LT* gets closer to multipliers of *R* and then they decrease again. In order to verify this interaction, the effect of *LT* is investigated for different values of *R*. The results given in Figure 6.2. and Figure 6.3. reveal this interaction. Please note that *d_ser* is less sensitive to *LT* than *D_ser* as dealers are in a downstream echelon in the supply chain and inventory level of the distributor makes the effect of *LT* moderate for dealers. Furthermore, the variance of the effect of *LT* on *d_ser* is more than *D_ser* due to dealers random ordering policy.

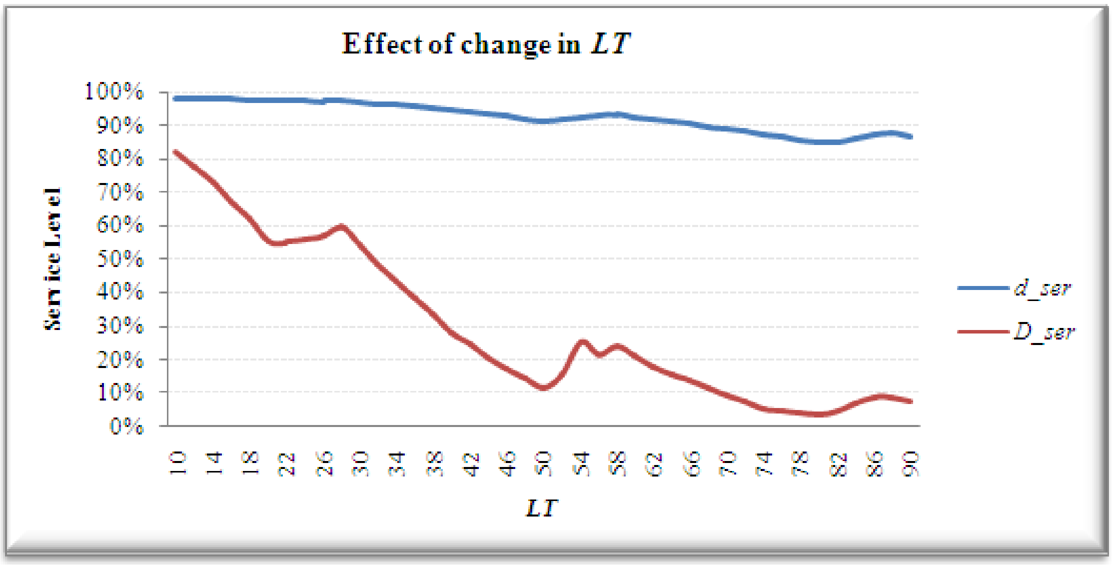

Figure 6.1. Effect of change in *LT* on service levels

IS=1000, SS=0, s_dur=7, s_f_dur=2, R=30

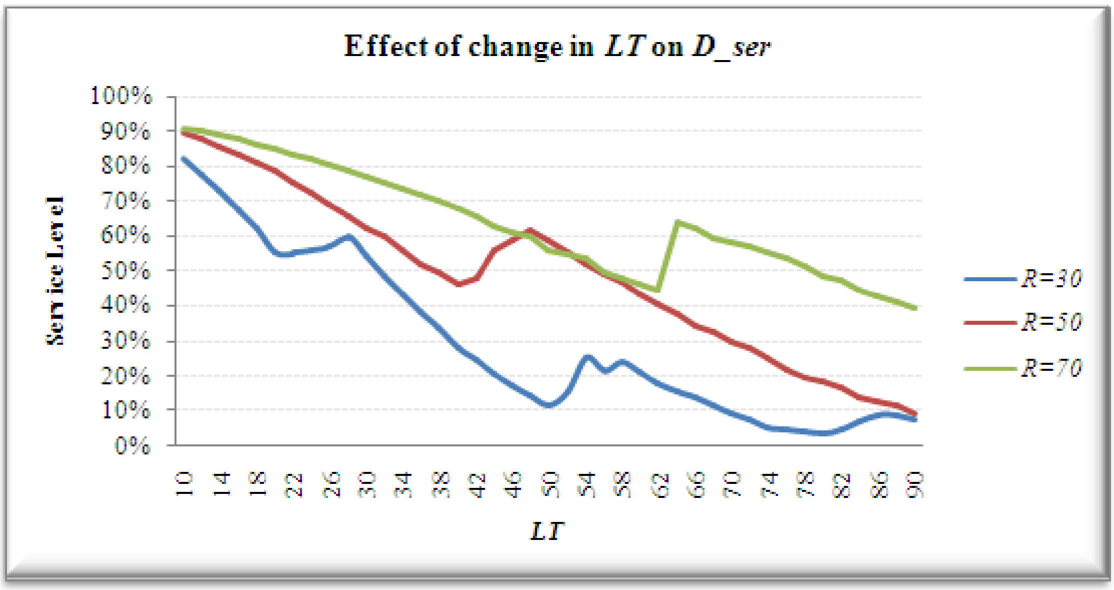

Figure 6.2. Effect of change in *LT* on *D_ser*

IS=1000, SS=0, s_dur=7, s_f_dur=2

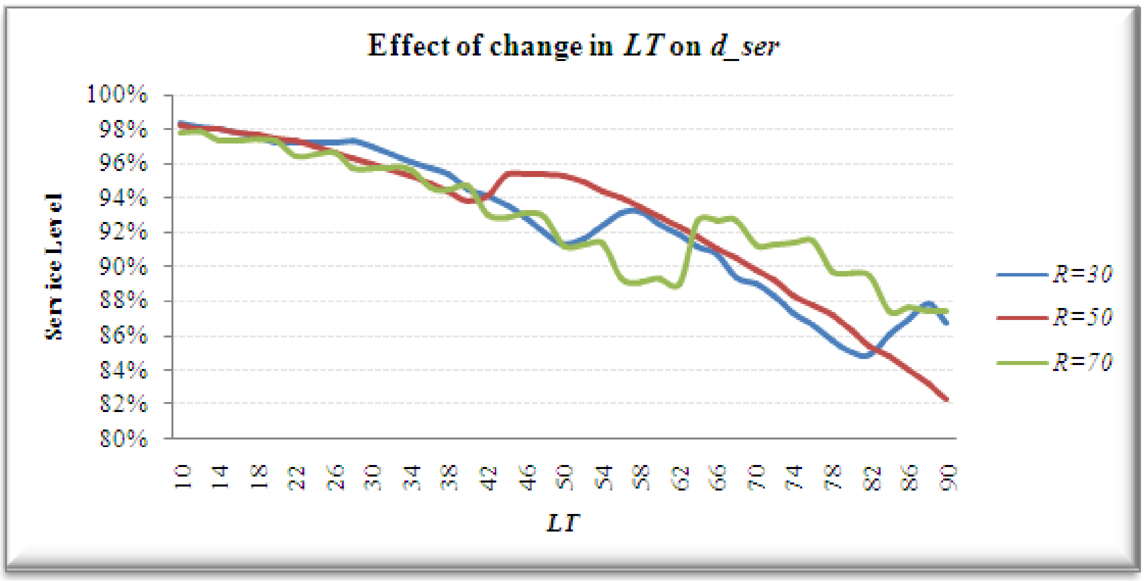

Figure 6.3. Effect of change in *LT* on *d_ser*

IS=1000, SS=0, s_dur=7, s_f_dur=2

Average inventory levels of the distributor and dealers for different values of *LT* and *R* are shown in Figure 6.4 and Figure 6.5. The interaction effect between *LT* and *R* is literally observed in these figures as well.

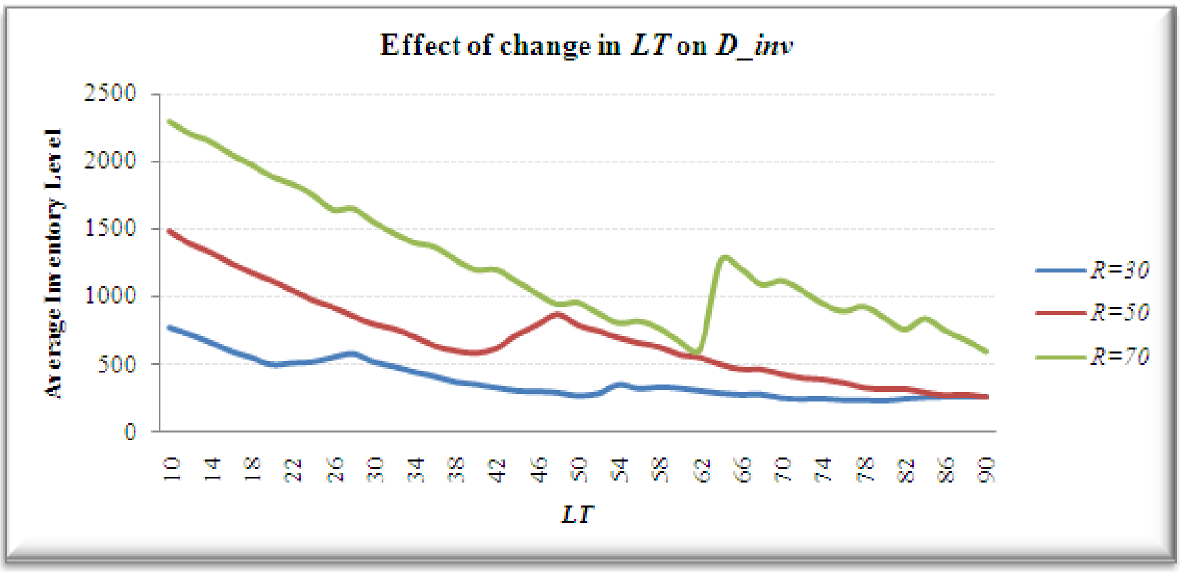

Figure 6.4. Effect of change in *LT* on *D_inv*

IS=1000, SS=0, s_dur=7, s_f_dur=2

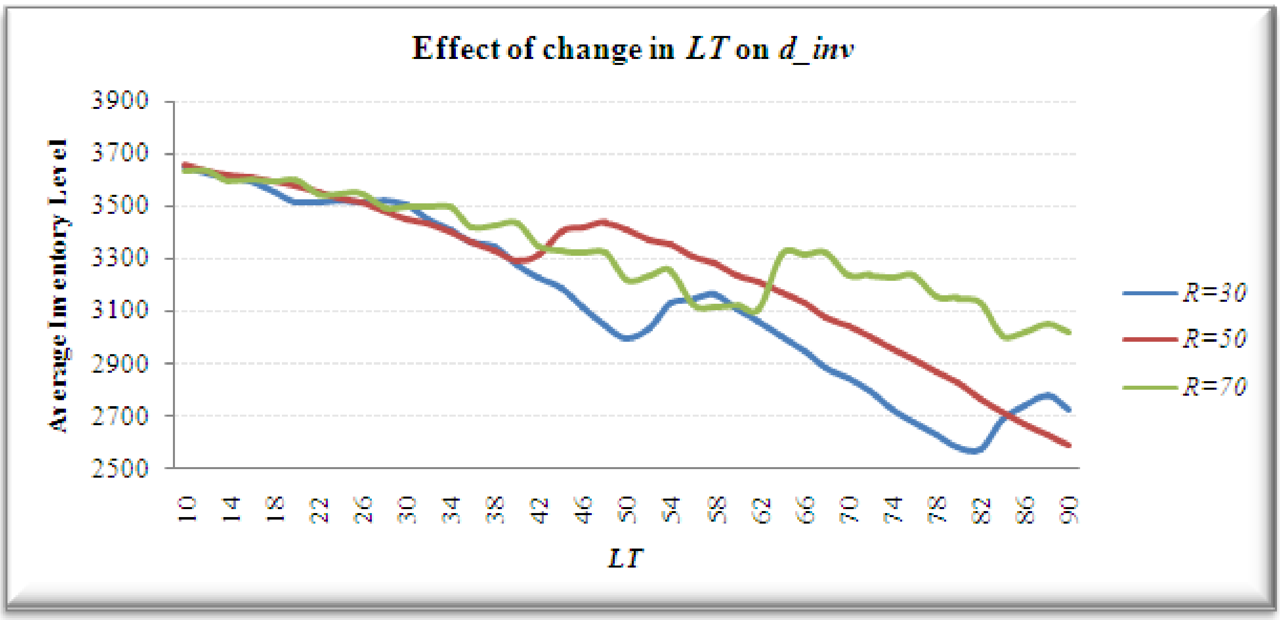

Figure 6.5. Effect of change in *LT* on *d_inv*

IS=1000, SS=0, s_dur=7, s_f_dur=2

LT and *R* interaction is also evidenced by Figure 6.6. which demonstrates the effect of *LT* on average cycle time of orders (*c_time*) and average waiting time of backordered demand (*w_back*). It should be noted from this figure that increasing *LT* results in longer cycle times and waiting times for dealer orders due to decreasing inventory level of the distributor.

Figure 6.7. shows the change in sales of the distributor (*SL*) and dealers (Σsl_i) together with the total lost sales of dealers (Σbc_i) as *LT* lengthens. This figure suggests that total lost sales of dealers goes up as *LT* increases. This is due to the poor service level given by the distributor to dealers causing them run out of stock. It can also be seen that *SL* is truly coherent with Σsl_i .

Effect of changing safety stock of the distributor (*SS*) on service levels of the distributor and dealers for *L*=40 and *L*=70 cases are represented in Figure 6.8. and Figure 6.9. It is observed that *D_ser* converges to 100 per cent while *d_ser* converges less than 100 per cent as *SS* approaches 3.000 pieces implying that service level of the distributor is not the only factor effecting the service level of dealers.

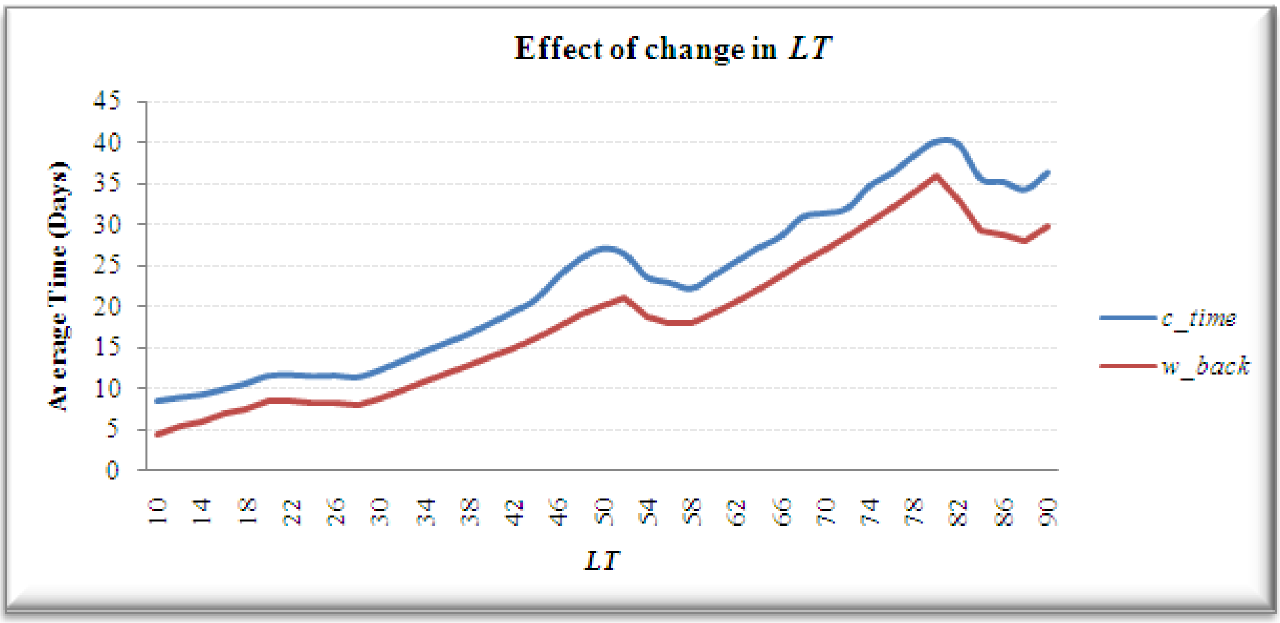

Figure 6.6. Effect of change in *LT* on *c_time* and *w_back*

IS=1000, SS=0, s_dur=7, s_f_dur=2, R=30

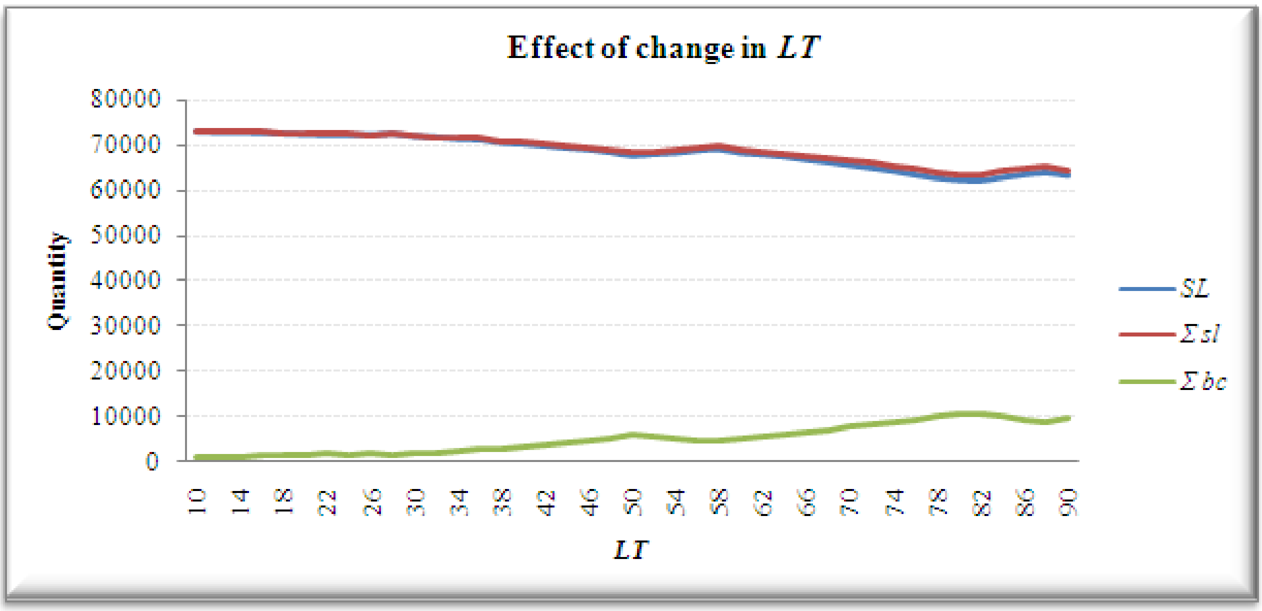

Figure 6.7. Effect of change in *LT* on total sales and lost sales

IS=1000, SS=0, s_dur=7, s_f_dur=2, R=30

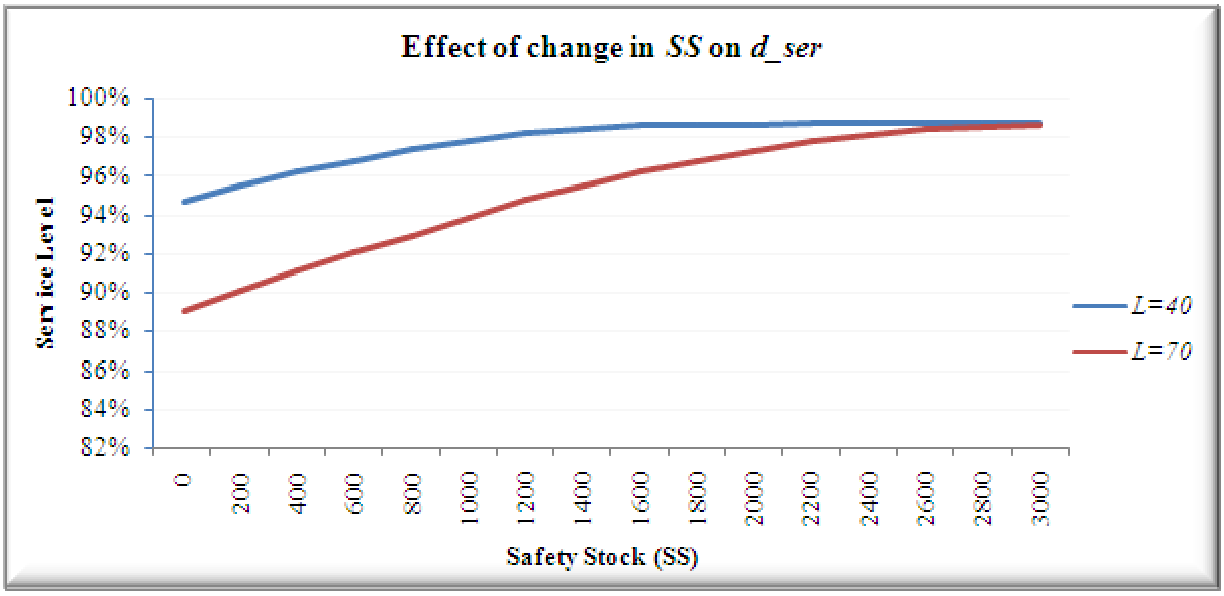

Figure 6.8. Effect of change in *SS* on *d_ser*

IS=1000, s_dur=7, s_f_dur=2, R=30

It can also be noted from Figure 6.8 and Figure 6.9 that the higher the *LT* is, the more safety stock is required for convergence.

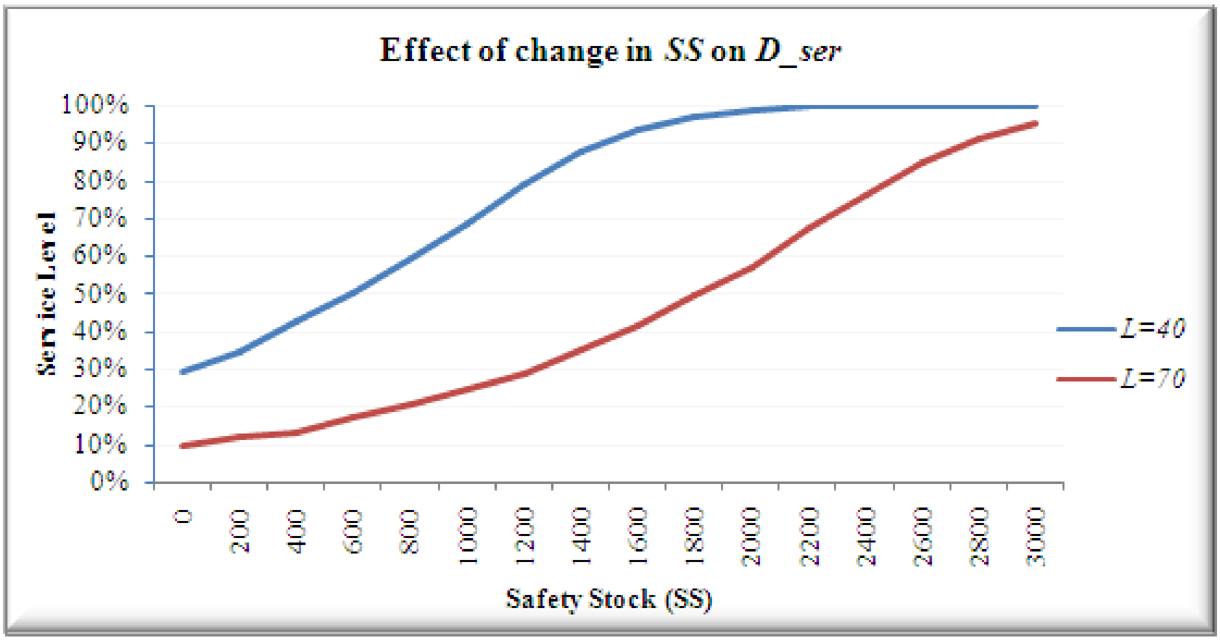

Figure 6.9 Effect of change in *SS* on *D_ser*

IS=1000, s_dur=7, s_f_dur=2, R=30

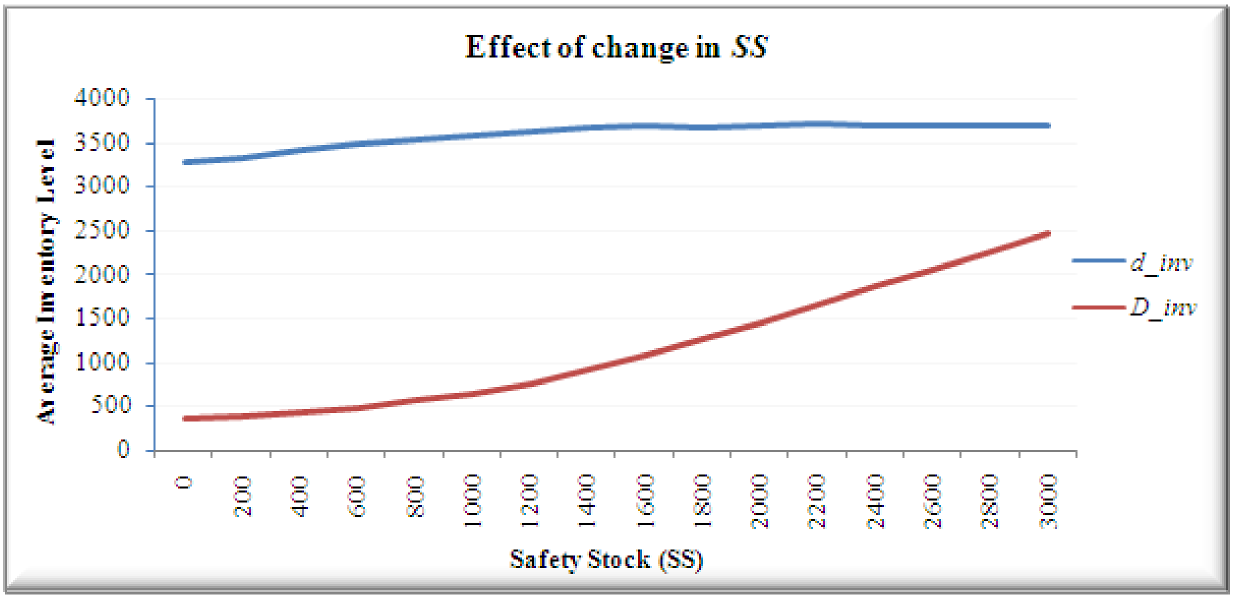

Figure 6.10 Effect of change in *SS* on *d_inv* and *D_inv*

IS=1000, s_dur=7, s_f_dur=2, R=30, L=40

Figure 6.10 shows that average inventory level of dealers is less sensitive to *SS* than average inventory level of the distributor. Please note that service level of dealers is increased three per cent by increasing the average inventory 500 pcs. Figure 6.11. indicates that, for *L*=40, average waiting time of backordered orders converges to zero as there are no backorders for *SS* being more than 2.200.

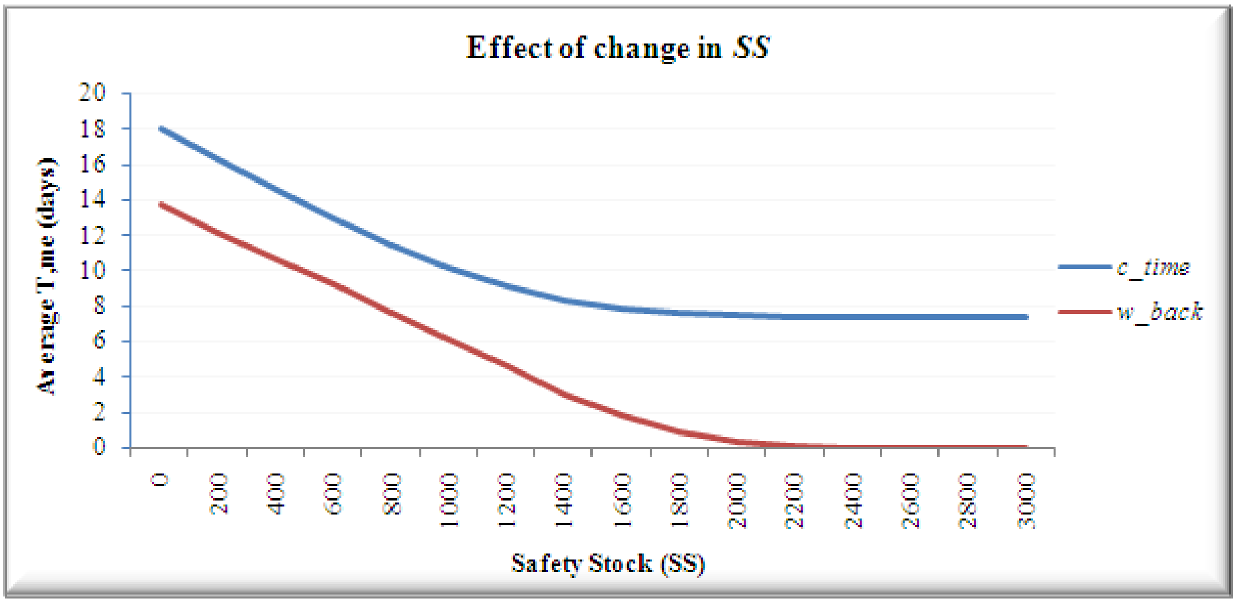

Figure 6.11 Effect of change in *SS* on *c_time* and *w_back*

IS=1000, s_dur=7, s_f_dur=2, R=30, L=40

Similarly, total lost sales of dealers converges to approximately 650 pieces as shown in Figure 6.12. Total lost sales superior to zero for even high *SS* values can be explained by dealer's random ordering policy.

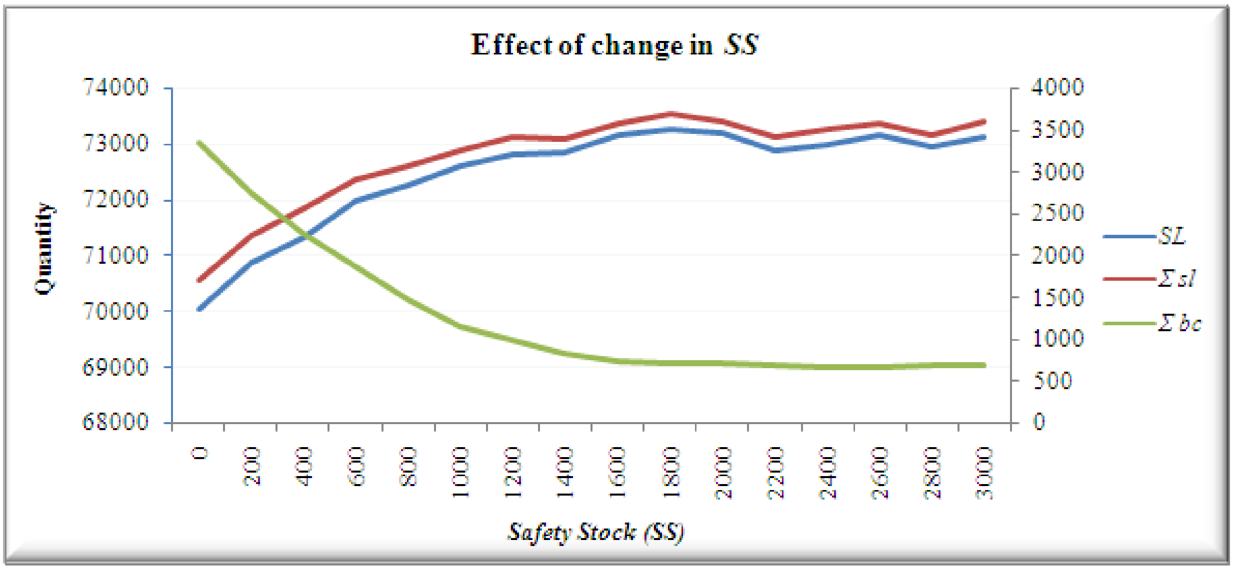

Figure 6.12 Effect of change in *SS* on total sales and lost sales

IS=1000, s_dur=7, s_f_dur=2, R=30, L=40

Shipment to invoicing duration (*s_f_dur*) is considered as the operational performance of the warehouse of the distributor since it is the time elapsed during the preparation of goods in the warehouse. The effect of *s_f_dur* on *d_ser* and *D_ser* is presented in Figure 6.13 and 6.14. It is recognized that *d_ser* decreases while *D_ser* increases as *s_f_dur* increases. This is, similar to the effect of *s_dur*, due to the fact that dealers do not place order to the distributor since they already have quantity on order waiting to be invoiced.

The impact of *s_f_dur* on average inventory levels of the distributor and dealers shown in Figure 6.15. exhibits a similar pattern. Average inventory level of dealers decreases while average inventory level of the distributor increases as *s_f_dur* increases. Furthermore, as shown in Figure 6.16., average waiting time of backordered demand converges to zero as *s_f_dur* increases. It also reveals that dealers do not process a new order considering that there is already quantity on order. It can also be noted from Figure

6.20. that average cycle time of orders steadily increases as *s_f_dur* increases. This is reasonable since cycle time consists of *s_f_dur* as well.

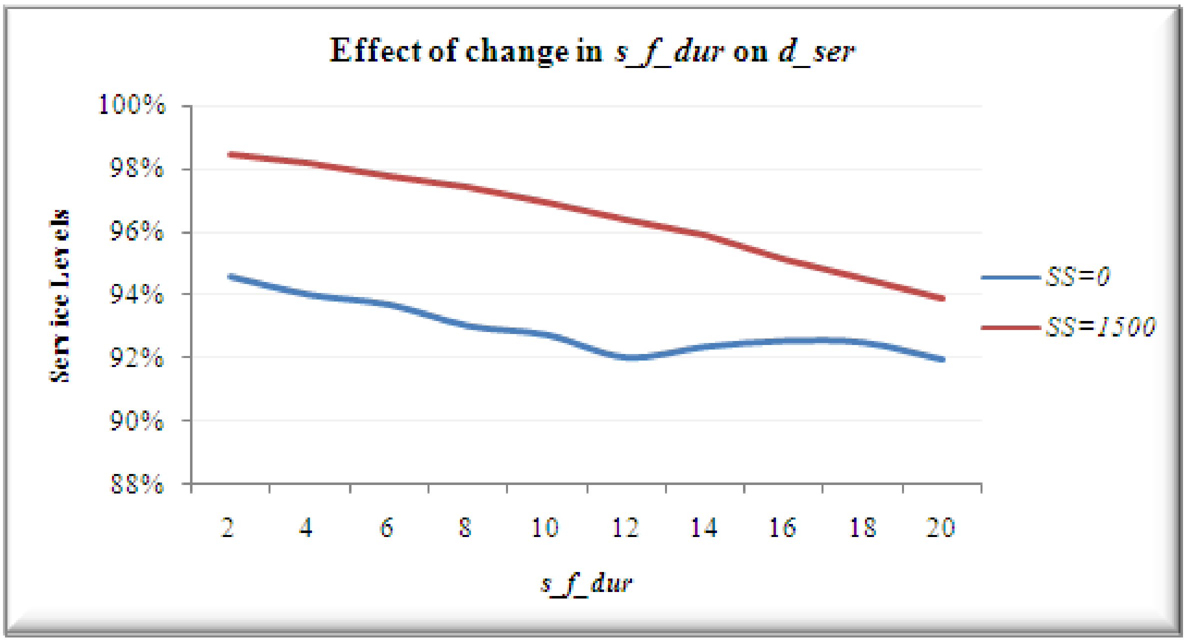

Figure 6.13. Effect of change in *s_f_dur* on *d_ser*

IS=1000, s_dur=7, R=30, L=40

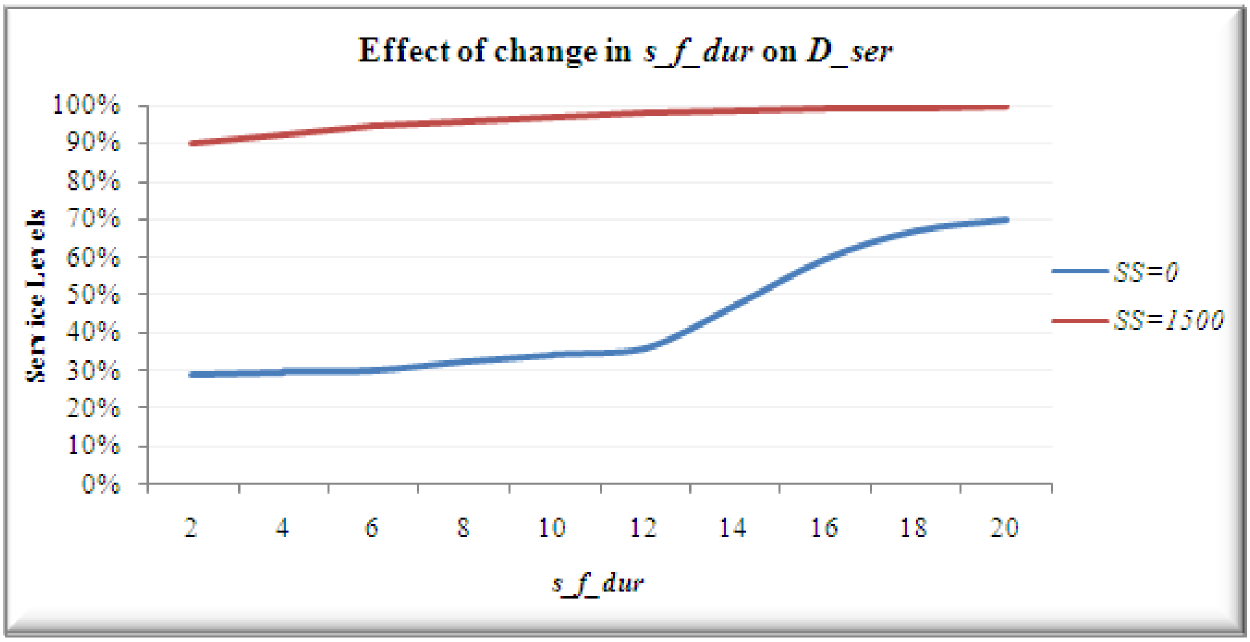

Figure 6.14. Effect of change in *s_f_dur* on *D_ser*

IS=1000, s_dur=7, R=30, L=40

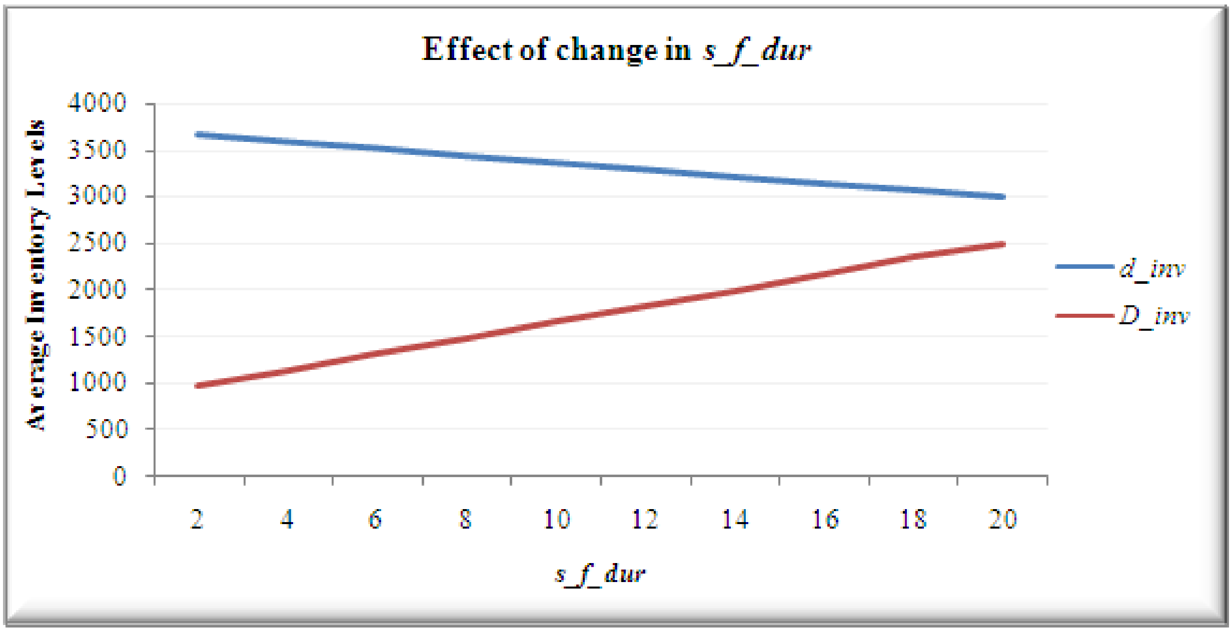

Figure 6.15. Effect of change in *s_f_dur* on *d_inv* and *D_inv*

IS=1000, SS=1500, s_dur=7, R=30, L=40

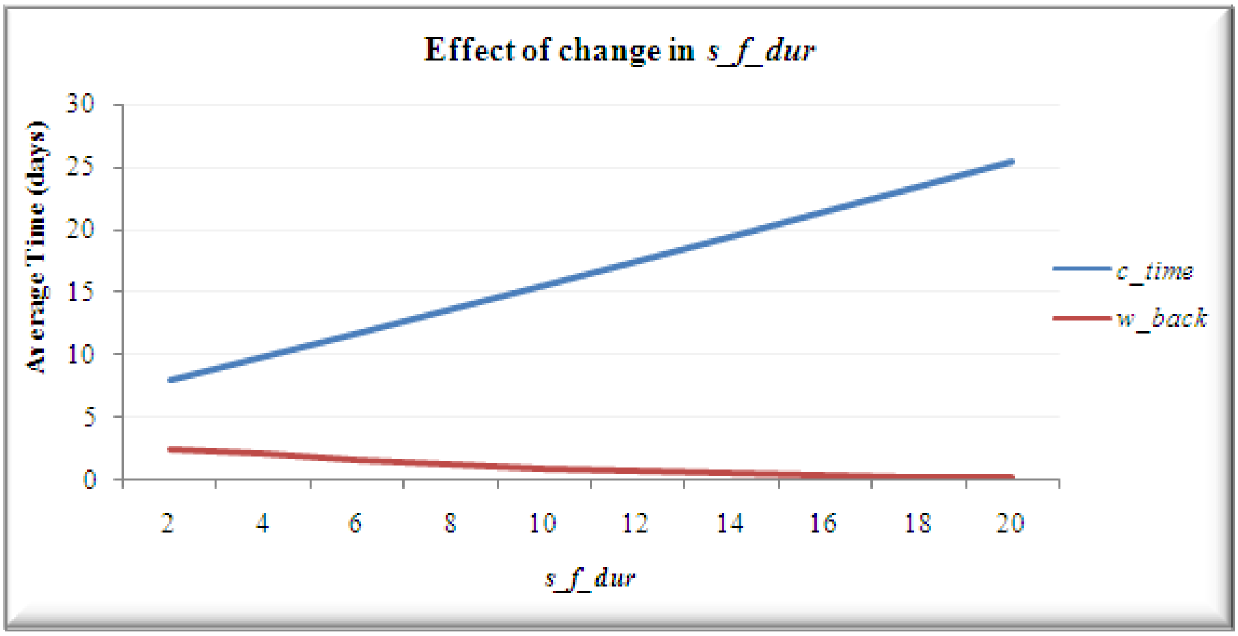

Figure 6.16. Effect of change in *s_f_dur* on *c_time* and *w_back*

IS=1000, SS=1500, s_dur=7, R=30, L=40

Similarly, Figure 6.17. shows that total lost sales of dealers increases as *s_f_dur* increases. This is plausible since the service level of dealers decreases.

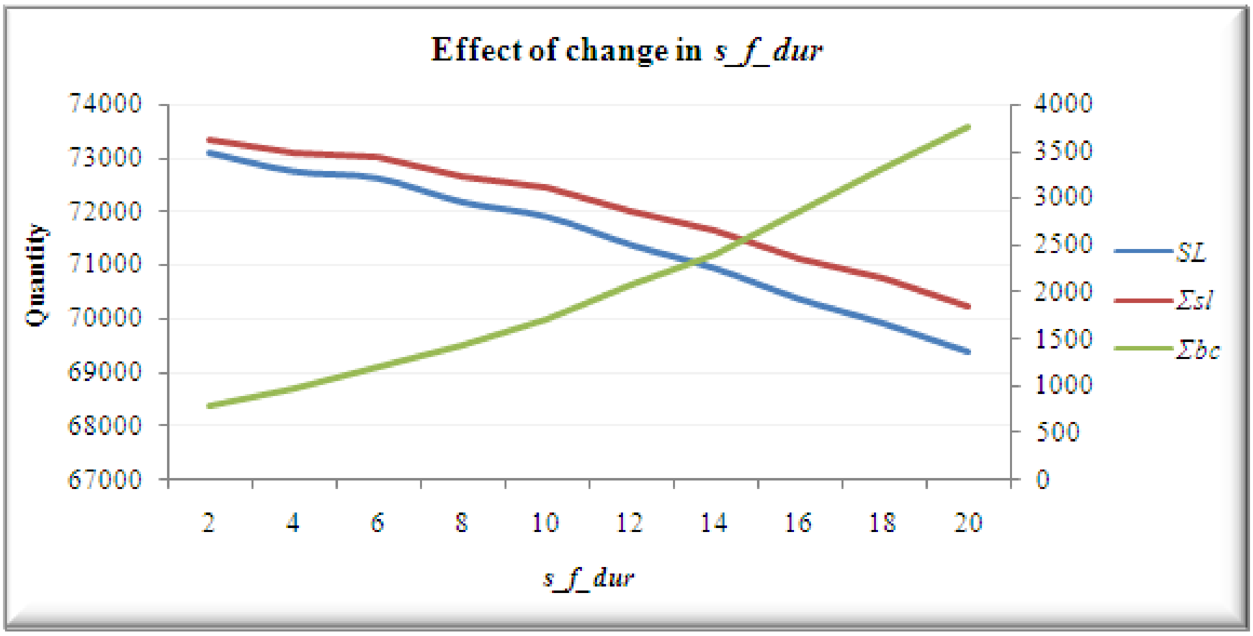

Figure 6.17. Effect of change in *s_f_dur* on total sales and lost sales

IS=1000, SS=1500, s_dur=7, R=30, L=40

The effect of changing the parameters on the base model is analyzed in this section. Almost all parameters have some impact on performance indicators. The observations indicate that the base model is highly sensitive to the changes in lead time and safety stock. It is also observed that there is an interaction effect between lead time (*L*) and ordering period (*R*). One practical recommendation of these observations is to set *R* close, but a little more, to *LT* in order to have better service levels. The outcomes of the base model provide a basis for assessing the different options for the model with remanufacturing.

6.2. Sensivity analysis of the model with remanufacturing

In this section, five more parameters, namely *rate*, *will*, s_d, *N* and *c,* are included and their impact on service levels are investigated. Please note that *rate*, s_d and *N* influence disposed quantity whilst *c* determines daily production capacity of remanufacturing. Figure

6.18. demonstrates the effect of remanufacturability rate (*rate*) of returned cores on dealers' service level (*d_ser*) for different values of customer's willingness-to-select remanufactured parts (*will*) if the dealer is out of stock for the original part.

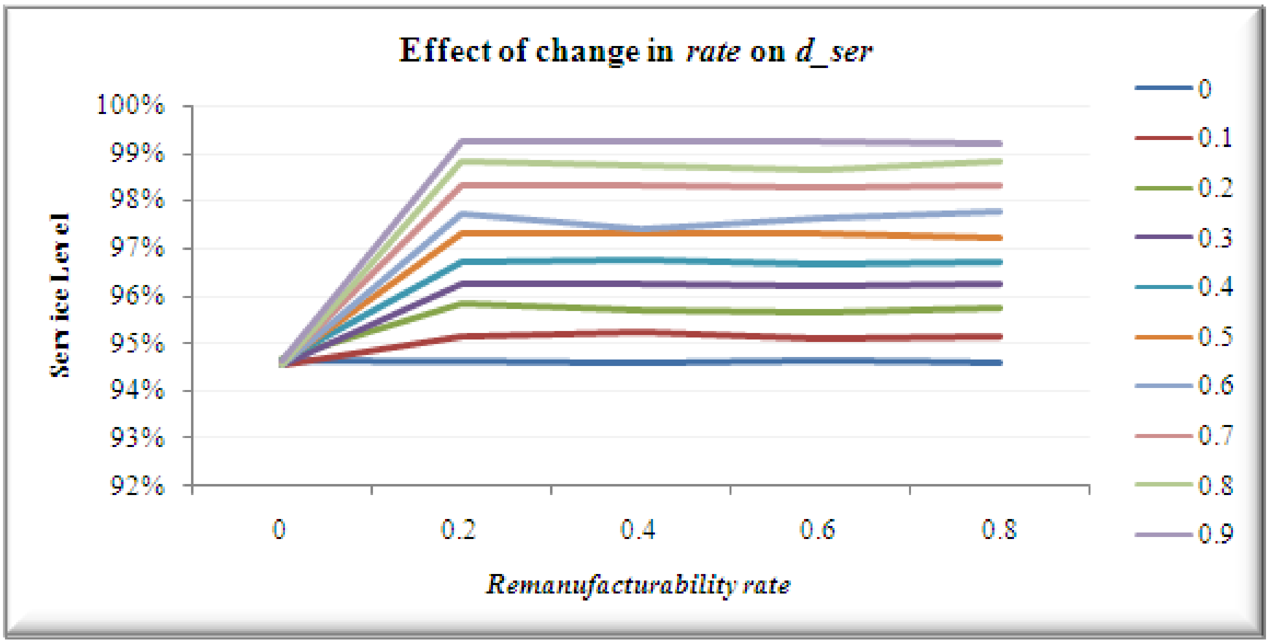

Figure 6.18. Effect of change in *rate* on *d_ser*

IS=1000, SS=0, L=40, s_dur=7, s_f_dur=2, R=30, c=100, s_d*=2000, N=500*

Observing the service levels plotted in Figure 6.18, it is clear that the model with remanufacturing produces same results with the base model if *rate* or *will* equals to zero. This is because all returned cores are disposed of in these cases. It is also observed that, for *c*=100, s_d=2000 and *N*=500, *d_ser* tends to stabilize at *rate* being higher than 0,2 indicating that remanufacturing only 20 per cent of returned cores is more than enough under these settings. In other words, *rate* is not a binding constraint after 0,2. Whereas, *d_ser* gradually increases with the increase in *will*.

As shown in Figure 6.19., total lost sales of dealers decreases as *will* increases. Please note that when *rate* equals to zero, all returned cores are disposed of upon arrival. Therefore, remanufacturing facility can not yield any remanufactured parts as there is not necessary cores.

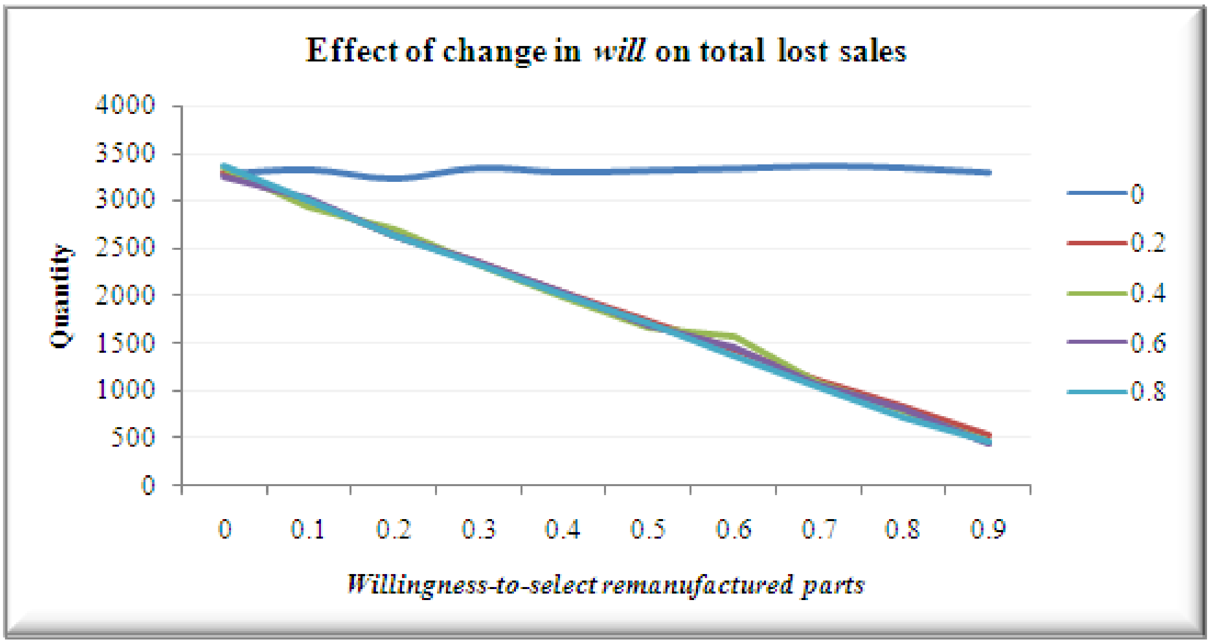

Figure 6.19. Effect of change in *will* on total lost sales

IS=1000, SS=0, L=40, s_dur=7, s_f_dur=2, R=30, c=100, s_d*=2000, N=500*

Figure 6.20. demonstrates the effect of change in *will* on remanufactured part sales. Both the sales of the distributor and dealers steadily increase as *will* increases. Please note that the difference of sales of the distributor and dealers, marked with high-low lines, is constant for all values of *will*. This suggests that there are enough remanufactured parts and cores to produce these remanufactured parts for each value of *will*. An increase in *N* or s_d can increase disposed quantity and that would distort steadily increasing sales.

As shown in Figure 6.21., remanufactured part inventory levels of the distributor and dealers also stay constant for different values of *will*. As stated before, dealers hold remanufactured parts inventory as a safety stock for the original part. Each time inventory level of remanufactured part drops below this safety stock, a new remanufactured part order is placed to the distributor. Since there are enough remanufactured parts at the remanufacturing facility, this constant stock level is reasonable.

Original part inventory levels of the distributor and dealers for different values of *will* are given in Figure 6.22. The results show that original part inventories are not affected by remanufacturing. This is expected since the ordering policies of the distributor and dealers for original parts are completely independent from that of the remanufactured parts.

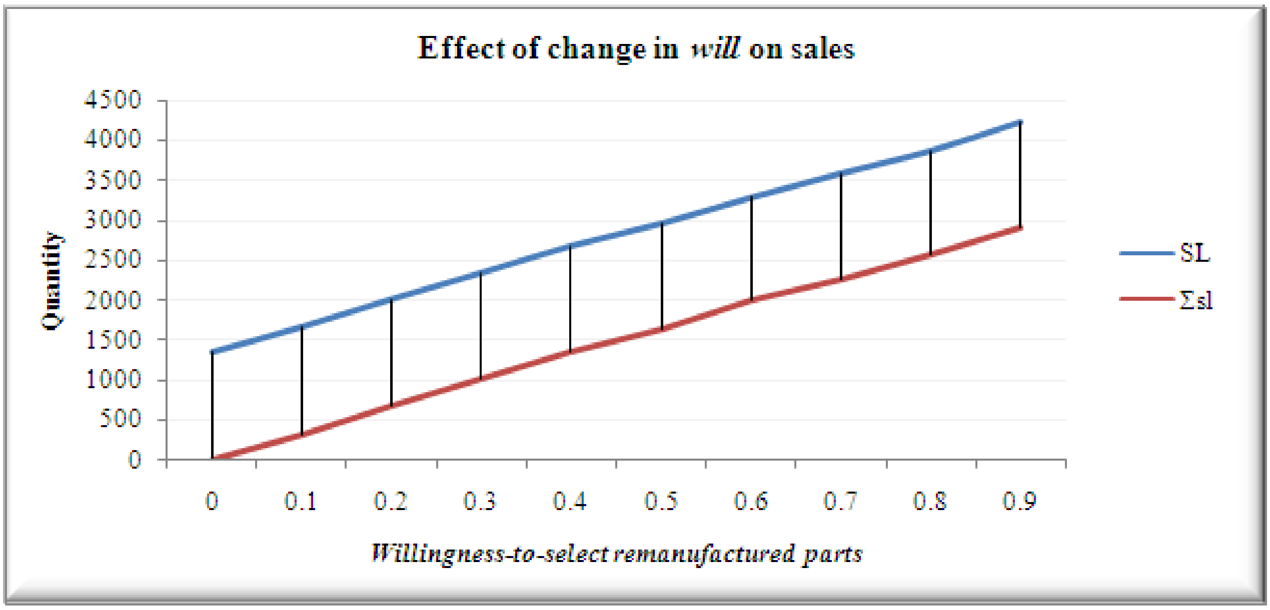

Figure 6.20. Effect of change in *will* on sales

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30,c=100,s_d*=2000,N=500,rate=0,2*

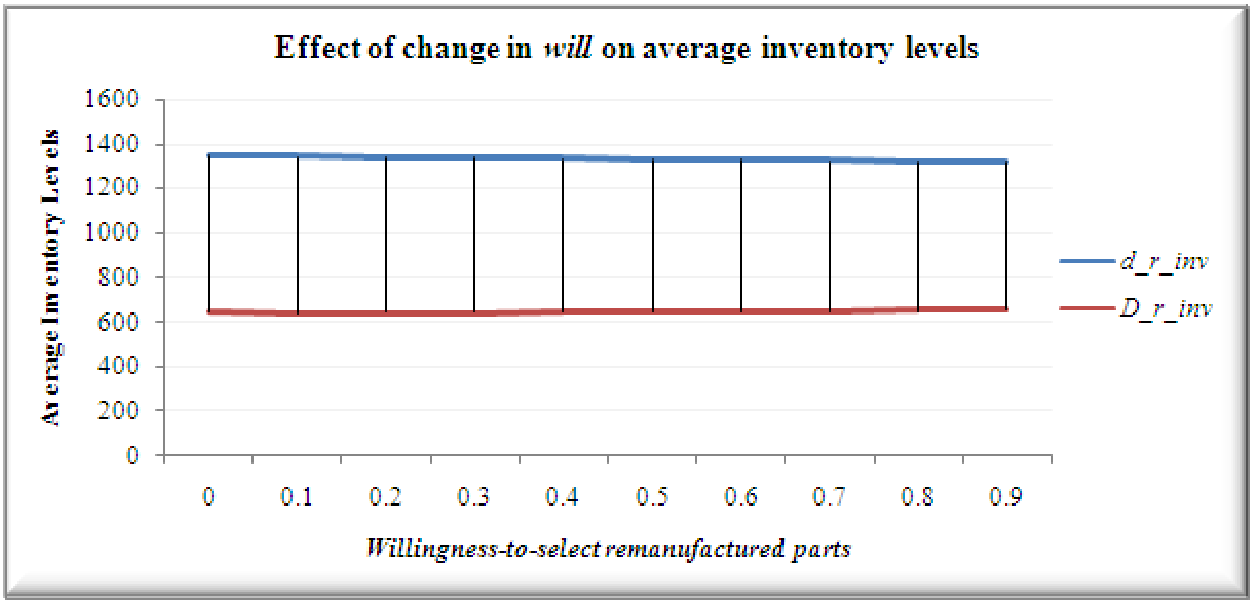

Figure 6.21. Effect of change in *will* on *d_r_inv* and *D_r_inv*

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30,c=100,s_d*=2000,N=500,rate=0,2*

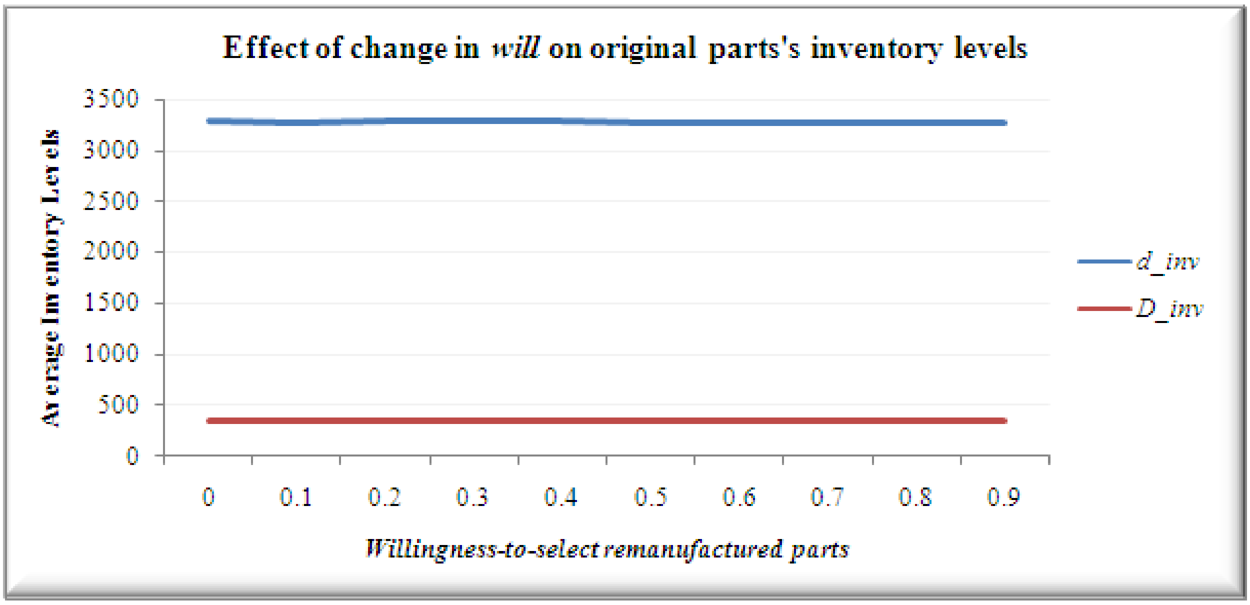

Figure 6.22. Effect of change in *will* on *d_inv* and *D_inv*

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30,c=100,s_d*=2000,N=500,rate=0,2*

The triple effect of the changes in *c*, *N* and s_d on service level is illustrated in Figure 6.23. Please note that *c* is varied from 20 to 100, *N* is varied from 0 to 400 and finally s_d is varied from 0 to 2000. It is observed that *c* has no influence on service level. A remanufacturing facility capable of remanufacturing even less than 20 pieces per day could be sufficient to get higher service levels under these settings. As far as *N* is concerned, 100 pieces seems to be more than enough which indicates that disposing returned cores when inventory level of cores at remanufacturing facility reaches 100 pieces or 400 pices does not differ. Unlike *c* and *N*, each value of s_d has a significant effect on service level. However, the impact of s_d gradually declines as s_d gets bigger than 1600 pcs. Similar results are obtained in Figure 6.24. for total lost sales of dealers. In the above analysis, *rate* set as 0,8 meaning that 80 per cent of returned cores are subject to *N* and s_d settings since 20 per cent is being disposed of upon arrival due to quality problems. Lower values of *rate* can increase the influence of *N*, s_d and *c* on service levels since it restricts available cores for remanufacturing.

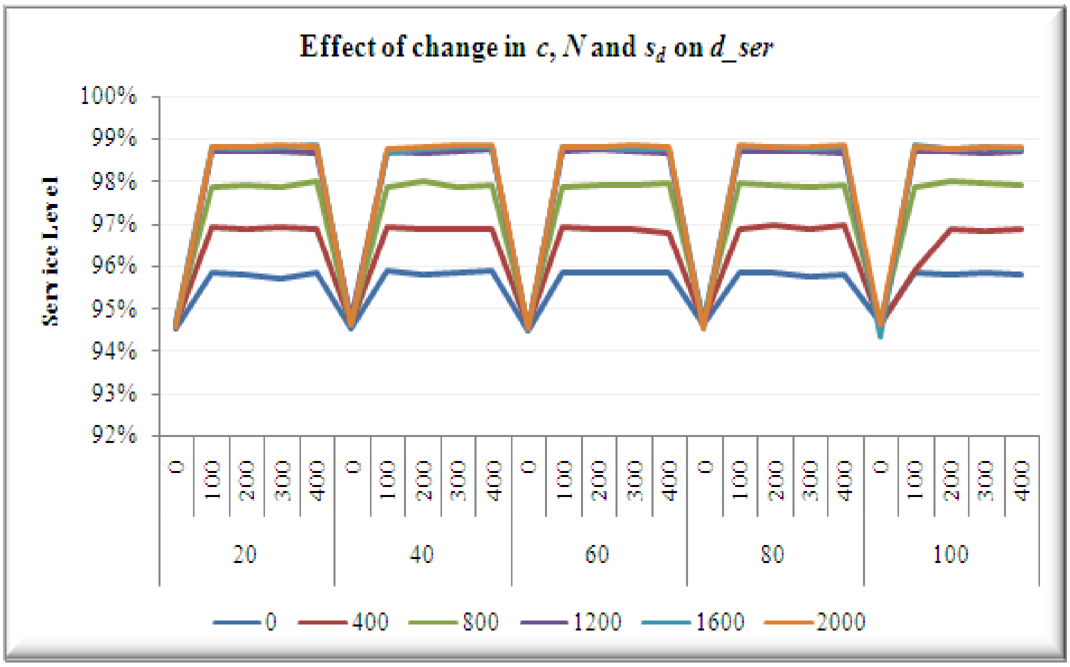

Figure 6.23. Effect of change in *c, N* and s_d on service level

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, rate=will=0,8

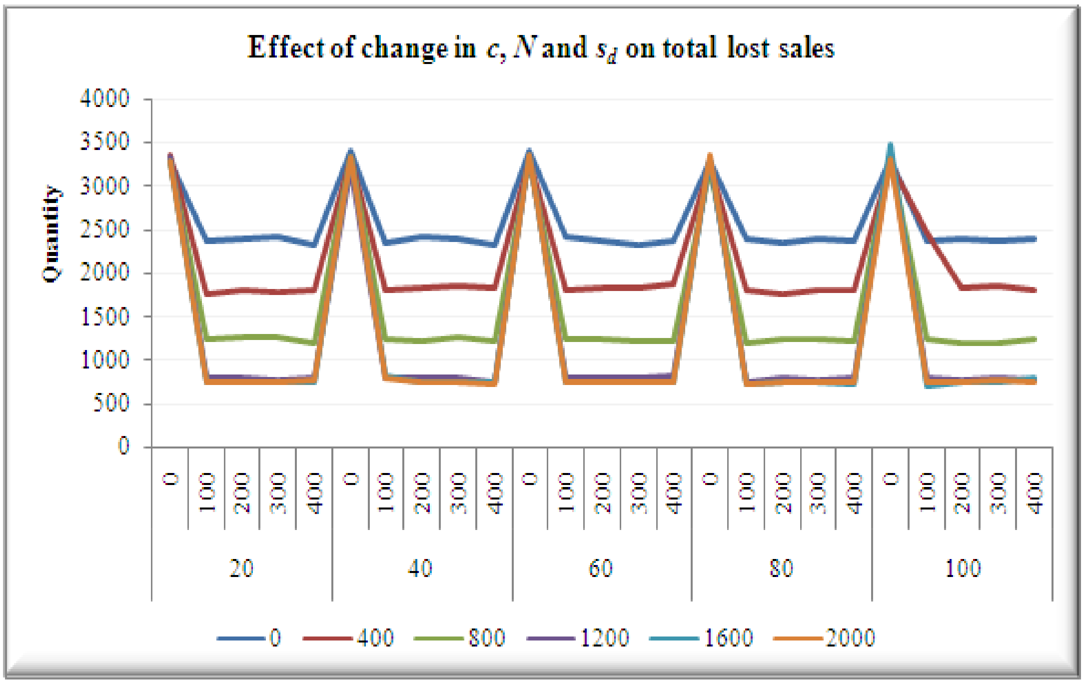

Figure 6.24. Effect of change in *c, N* and s_d on total lost sales

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, rate=will=0,8

Average remanufactured part inventory level of dealers for the same settings of *c*, *N* and s_d is represented in Figure 6.25. This figure also reveals the impact of s_d.

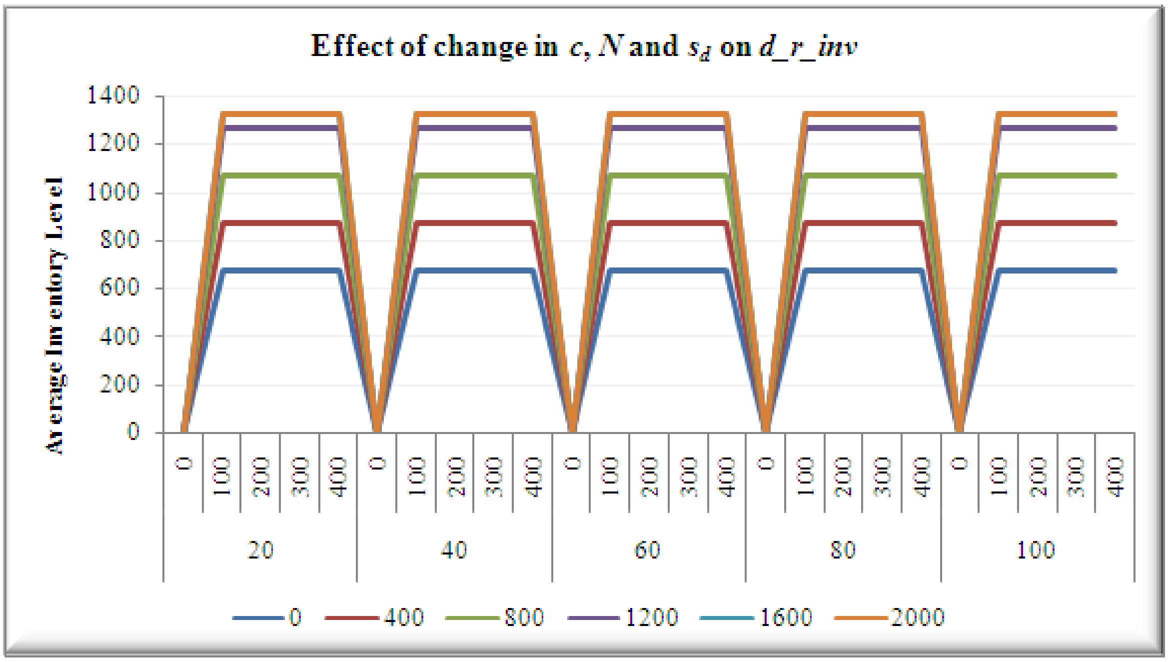

Figure 6.25. Effect of change in *c, N* and s_d on *d_r_inv*

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, rate=will=0,8

The effect of change in s_d and *N* on service level is given in Figure 6.26 where s_d is varied from 0 to 2400 pcs whilst *N* is varied from 0 to 800 pcs. Please note that when *N* equals to zero, the impact of remanufactured parts is not seen as all returned cores are disposed of. It can be inferred that dealer's service level in this case is maintained through only use of original parts. However, it is observed that higher s_d values can result in a rise of up to five per cent on service level by including remanufactured parts. Service level never gets 100 per cent as the safety stock level of remanufactured parts are determined for 95 per cent service level for remanufactured parts. Lower values of *will* obviously reduces the required safety stock level of remanufactured parts as some customers leaves the dealer without asking for a remanufactured part in case of unavailability of the original part.

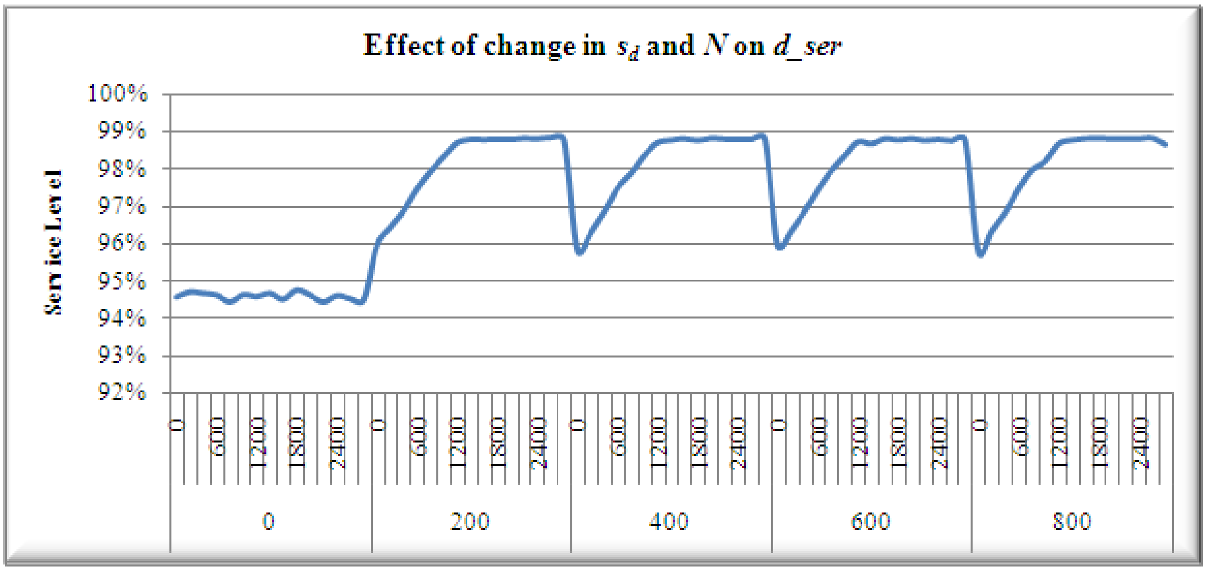

Figure 6.26. Effect of change in s_d and N on service level

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, c=100, rate=will=0,8

Figure 6.27. shows the effect of s_d and N on average remanufactured part inventory level of dealers. Maximum amount of inventory level to be reached, e.g. sum of safety stock levels of remanufactured parts of each dealer, is 1345 pcs in our model. This amount is reached when s_d is between 1200 pcs and 1800 pcs.

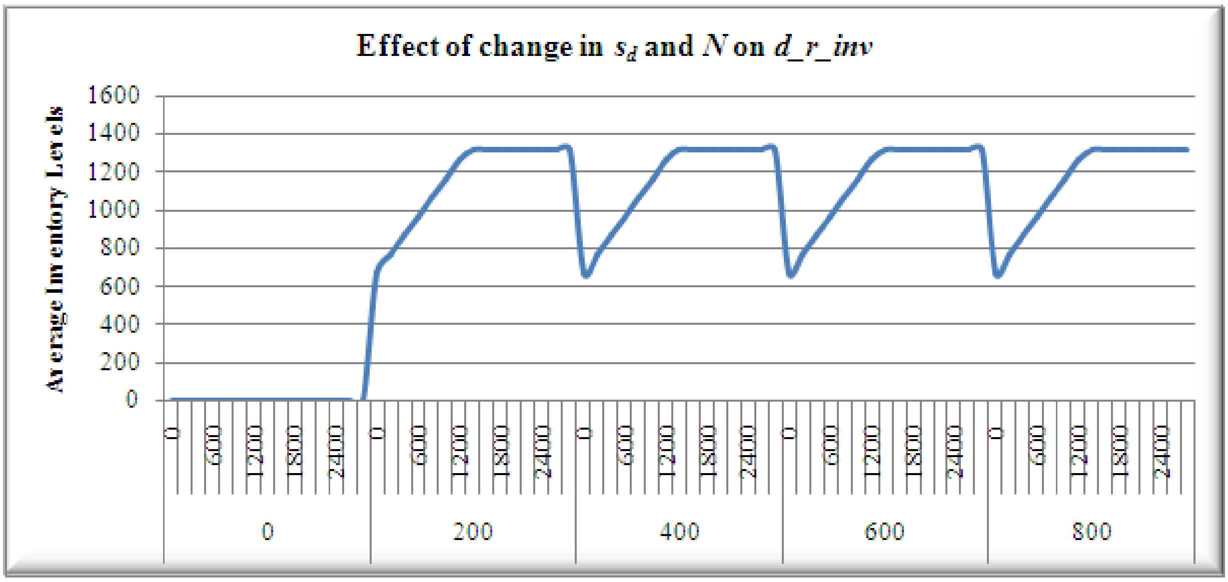

Figure 6.27. Effect of change in s_d and N on *d_r_inv*

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, c=100, rate=will=0,8

Figure 6.28. gives the effect of s_d and N on total lost sales of dealers. This figure exhibits a similar, but adverse, pattern with Figure 6.26. as service level and total lost sales are negatively correlated to each other.

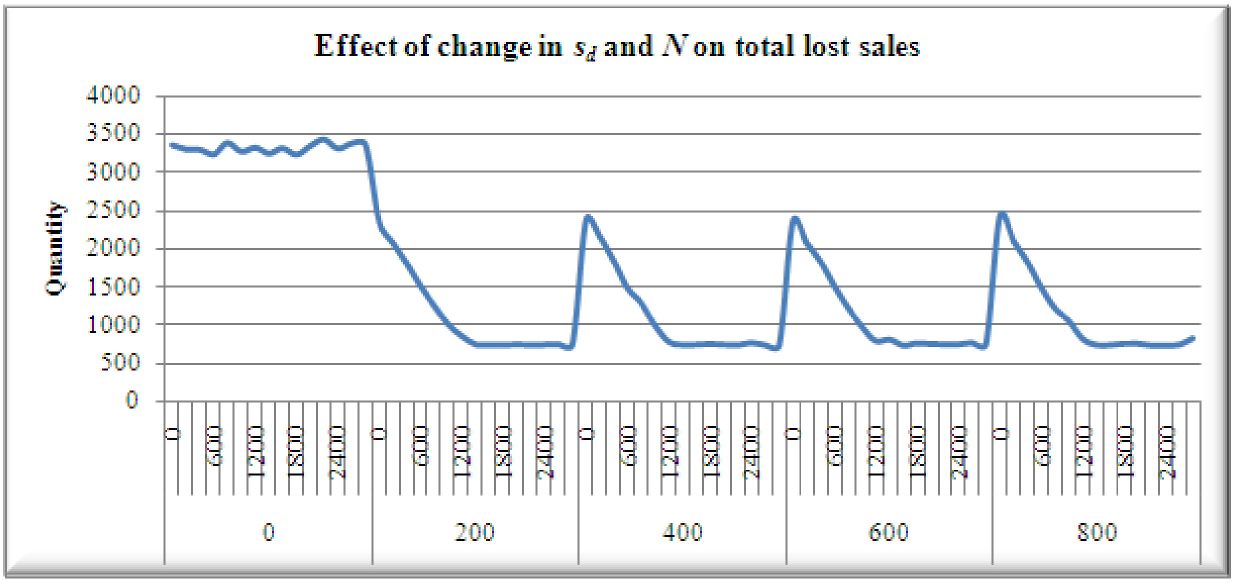

Figure 6.28. Effect of change in s_d and N on total lost sales

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, c=100, rate=wi

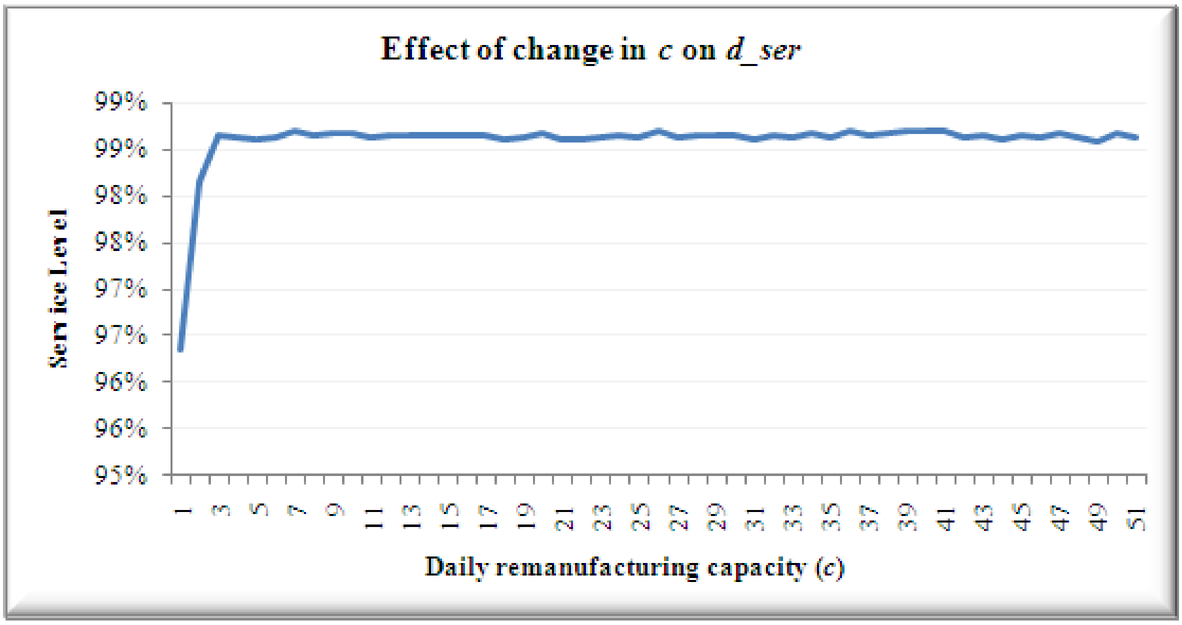

Figure 6.29. Effect of change in c on service level

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, s_d*=1200 ,N=500,rate=will=0,8*

Furthermore, the effect of daily remanufacturing capacity of remanufacturing facility on service level is investigated. Results given in Figure 6.29. suggest that capacity of 3 pcs is more than enough under these settings of the simulation.

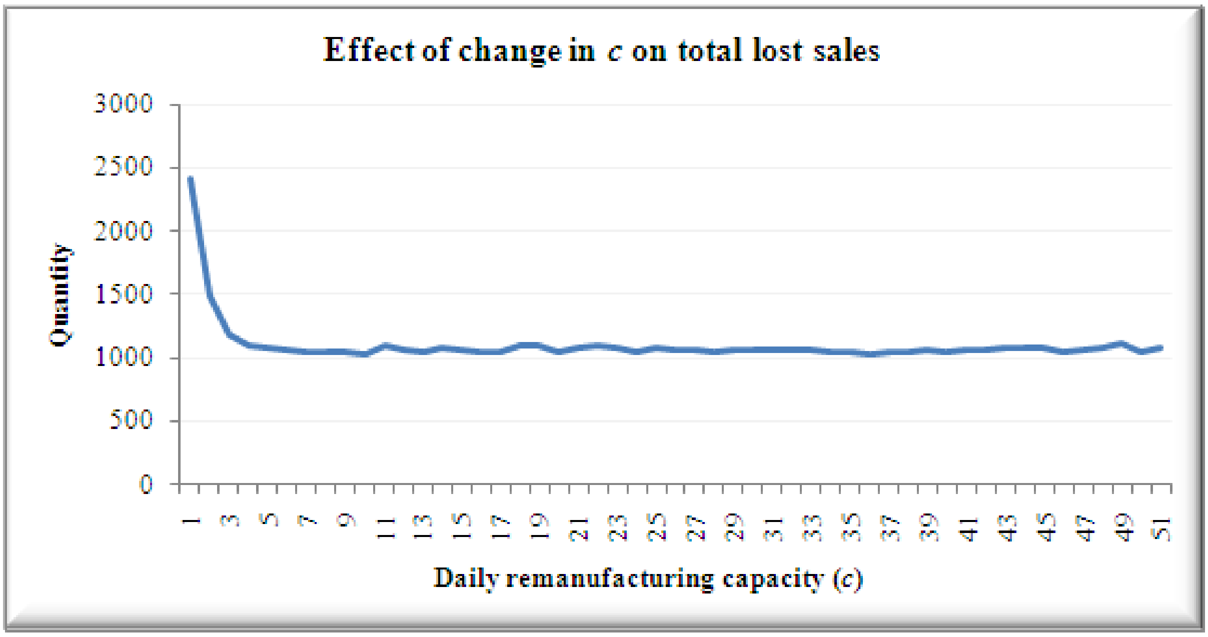

Figure 6.30. Effect of change in *c* on total lost sales

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, s_d*=1200 ,N=500*

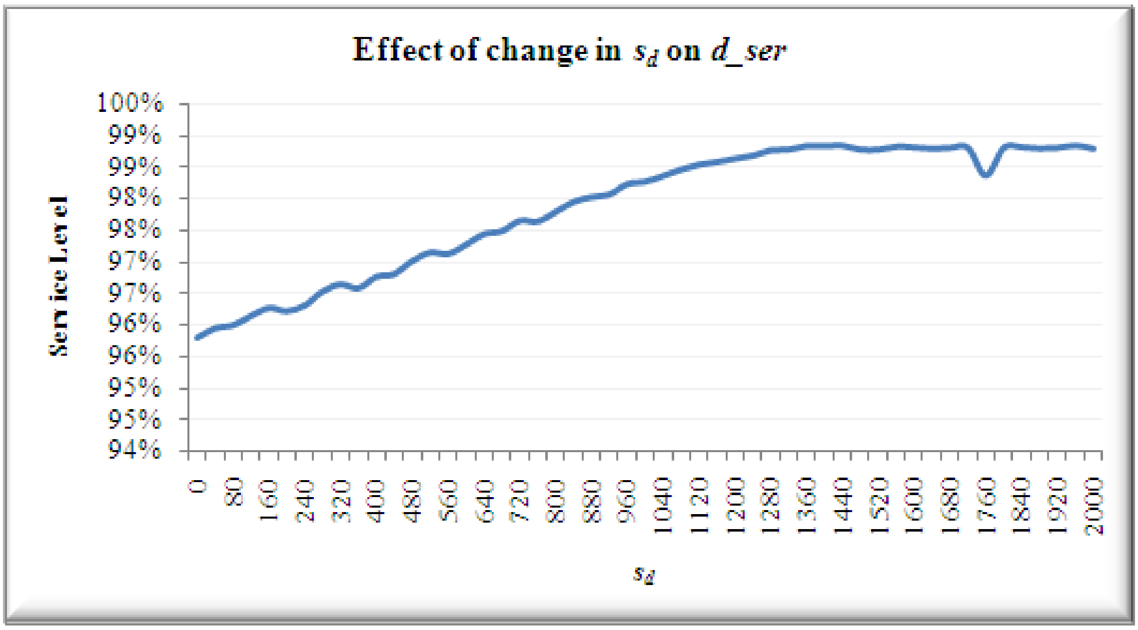

Figure 6.31. Effect of change in s_d on service level

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, c=20 ,N=500,rate=will=0,8

Figure 6.31. and Figure 6.32. shows the effect of s_d on service level and total lost sales of dealers respectively. It is found that the highest service level and lowest lost sales are obtained for values of s_d being more than 1400 pcs.

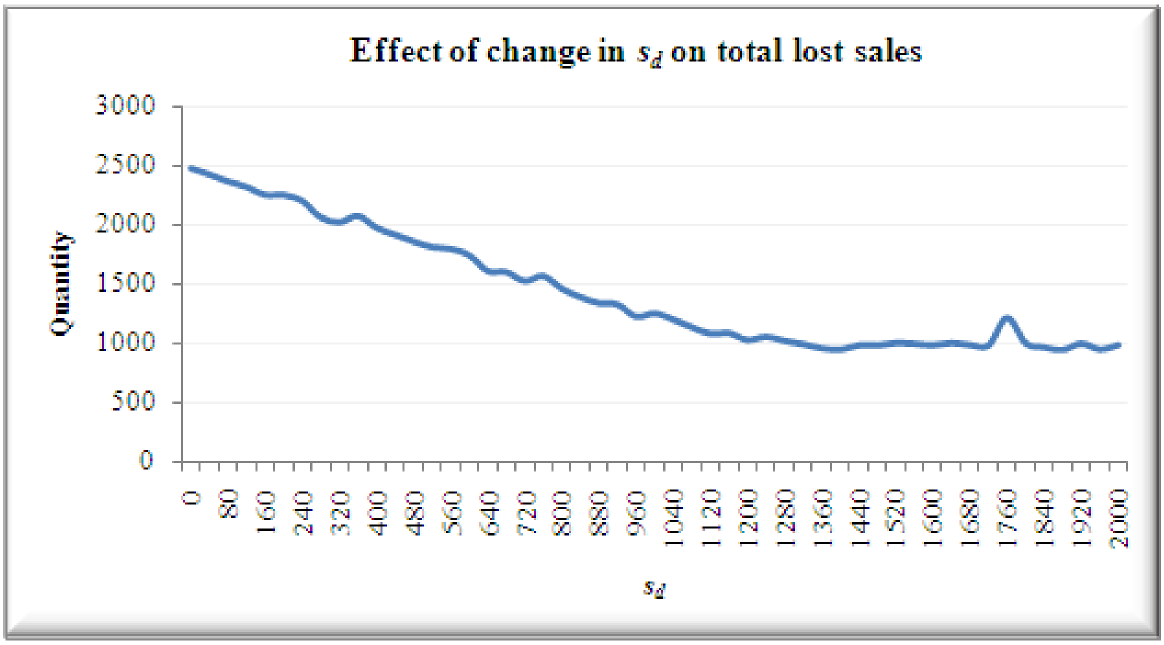

Figure 6.32. Effect of change in s_d on total lost sales

IS=1000,SS=0,L=40,s_dur=7,s_f_dur=2,R=30, c=20 ,N=500,rate=will=0,8

Further simulation runs with varying *c*, *N*, s_d, *rate* and *will* can also be undertaken using the above model. The results of the study show that an increase in *N*, s_d and *rate* decreases the service level by limiting available cores for remanufacturing. It is also found that s_d has more influence in our model than *c* and *N*.

7. CONCLUSION AND FURTHER RESEARCH

Over the past decades a combination of economic, technologic and market forces have made it imperative for companies to examine their after sales service and in particular service parts supply. The supply of spare parts has become increasingly important for companies wishing to stay ahead of competition. Companies are moving from competing with products to competing with service supply chains. Increasing importance of the after sales and service dimensions differentiates the truly successful companies, and the set up of supply chains determines customer retention rates. The number one priority is to improve customer satisfaction, across all sectors. In such an environment, ensuring the availability of the parts at the right time in the right location is inevitably necessary.

In this study, above described availability problem of a major automotive spare parts distributor in Turkey is modeled at the first stage and then the impact of remanufactured parts, as a safety stock of the original parts, on performance indicators is investigated. Each model is developed using C++ and run with appropriate warm-up period, run length and number of replications. Besides the service level of the distributor and dealers, some other performance measures such as average cycle time of orders, average waiting time of backordered demand, average inventory levels and average lost sales are also considered Our base model without remanufacturing option captures the effect of supplier lead times, safety stocks and distributor's order processing decisions on these performance measures. Lead time effects are monitored under different order review period settings of the distributor and some interesting behaviour of the effect of lead time e.g. the performance of the system gets better as *LT* gets closer to multipliers of *R*, is observed. One practical recommendation of this observation is to set *R* close, but a little more, to *LT* in order to have better service levels. Better service levels can also be expected as safety stock of the distributor increases. However, it is inferred that dealers' service level is not only affected by the service that they are getting from the distributor. This is due to the fact that dealer's service level never reaches 100 per cent even if the service level of the distributor is assured to be 100 per cent through the selection of high safety stocks. Another instructive insight is that as the safety stock decreases, the variance of the system amplifies which implies that at least moderate levels of safety stocks should be selected in order to have a robust system.

After the inclusion of remanufacturing option, an inventory control policy should be applied in order to prevent inventory levels to explode. Therefore, disposal option is employed and two disposal control variables, namely s_d and N are defined. In addition to disposal, a daily production capacity (c) is also set for the remanufacturing facility. These parameters can be controlled by the distributor or dealers. On the other hand, customer's willingness-to-select remanufactured parts (*will*) and remanufacturability rate of returned cores (*rate*) depend on customers and the quality of the returned cores respectively. Each of these parameters are varied in order to obtain some insights about their effect on system performances. The behaviour of the model with remanufacturing is equivalent to that of the base model when *rate* or *will* equals to zero since all returned cores are disposed of upon arrival in these cases. The results of the simulation indicates that system performance is not binding on c and N, e.g. even small values of these parameters are enough to get maximum service level. However, performance indicators are found to be more sensitive to the change in s_d. Our observations suggest that holding less than 1.400 pieces of remanufactured parts inventory for all dealers can result in a rise of five per cent on dealer's service levels.

This research could be extended in some areas that are not considered in this study. The most significant areas are outlined below.

- Dealers' random ordering policy is employed in this study as is. Instead of this random policy, an optimum inventory control policy and its impact on service levels could be investigated for dealers.
- It seems valuable for future research to try and extend the analysis presented in this thesis to other remanufacturable inventory models. Additional research should also focus on formulating optimum disposal and remanufacturing control parameters.

- Other possible extension with respect to marketing perspective is to consider remanufactured parts as an alternative to the original one. Competition from outside remanufacturers can also be considered.

APPENDIX A: GOODNESS OF FIT TEST RESULTS

Appendix A represents the goodness of fit test results of generalized pareto distribution produced by Easyfit distribution fitting software. Kolmogorov-Smirnov and Chi-Square tests are applied.

Table A.1. Goodness of fit test results for generalized pareto distribution

Dealer No	Kolmogorov-Smirnov			Chi-Squared		
	Sample Size	Statistics	p-value	Degrees of Freedom	Statistics	p-value
0	173	0.1264	0.0072	7	5.6766	0.5780
1	48	0.1636	0.1370	3	5.8367	0.1198
2	125	0.1187	0.0544	6	7.1774	0.3048
3	140	0.1339	0.0119	6	8.1250	0.2291
4	315	0.2138	0.0000	5	87.0550	0.0000
5	136	0.2660	0.0000	4	48.6350	0.0000
6	524	0.3466	0.0000	3	298.7200	0.0000
7	236	0.1758	0.0000	5	31.5010	0.0000
8	103	0.1202	0.0938	4	20.3350	0.0004
9	157	0.1306	0.0086	6	34.1580	0.0000
10	205	0.1820	0.0000	5	24.5850	0.0002
11	214	0.1663	0.0000	6	10.1400	0.1189
12	134	0.1432	0.0074	6	11.1090	0.0851
13	219	0.1494	0.0001	6	41.9040	0.0000
14	150	0.1675	0.0004	6	9.2774	0.1586
15	33	0.1488	0.4177	3	3.0820	0.3792
16	265	0.1635	0.0000	6	61.7080	0.0000
17	71	0.0785	0.7444	6	3.4485	0.7508
18	93	0.0834	0.5110	6	9.2159	0.1618
19	121	0.0834	0.3499	6	15.4020	0.0174
20	196	0.1560	0.0001	5	23.7010	0.0002
21	161	0.0996	0.0766	7	6.4389	0.4895
22	94	0.0843	0.4902	6	13.9520	0.0302
23	48	0.0893	0.8066	N/A	-	N/A
24	148	0.1213	0.0062	6	10.1730	0.1772
25	34	0.1170	0.6974	3	1.0669	0.7851
26	103	0.1253	0.0722	6	21.1580	0.0017
27	300	0.1806	0.0000	6	48.7710	0.0000
28	638	0.3775	0.0000	3	425.1900	0.0000
29	415	0.2764	0.0000	4	122.4700	0.0000

Table A.1. (Cont'd) Goodness of fit test results for generalized pareto distribution

Dealer No	Kolmogorov-Smirnov			Chi-Squared		
	Sample Size	Statistics	p-value	Degrees of Freedom	Statistics	p-value
30	107	0.0825	0.4363	5	7.1394	0.2105
31	72	0.0682	0.8685	6	2.2935	0.8908
32	54	0.0961	0.6648	N/A	-	N/A
33	118	0.0959	0.2138	6	11.1850	0.0828
34	106	0.0841	0.4182	6	6.7847	0.3412
35	19	0.1292	0.8693	2	1.0995	0.5771
36	172	0.1480	0.0009	6	17.5800	0.0074
37	307	0.2624	0.0000	5	62.6660	0.0000
38	224	0.1398	0.0003	6	19.4190	0.0035
39	122	0.0792	0.4071	6	22.9500	0.0008
40	217	0.1403	0.0003	6	12.3240	0.0551
41	175	0.1470	0.0009	6	23.9940	0.0005
42	127	0.0855	0.2943	6	3.4326	0.7529
43	74	0.0752	0.7685	6	2.1596	0.9045
44	215	0.1915	0.0000	5	30.9910	0.0000
45	131	0.1311	0.0201	6	16.4050	0.0117
46	11	0.1417	0.9581	1	0.0001	0.9921
47	29	0.0844	0.9750	4	0.9647	0.9151
48	256	0.1703	0.0000	6	29.5200	0.0000
49	43	0.0811	0.9178	4	1.0821	0.8971
50	26	0.1398	0.6398	N/A	-	N/A
51	233	0.1840	0.0000	5	43.2380	0.0000
52	82	0.0812	0.6218	6	0.7599	0.9931
53	173	0.1102	0.0276	7	3.1521	0.8706
54	362	0.2223	0.0000	5	85.4450	0.0000
55	236	0.1450	0.0001	6	22.7150	0.0009
56	183	0.1394	0.0015	6	27.3350	0.0001
57	290	0.1720	0.0000	5	67.8390	0.0000
58	49	0.0874	0.8168	4	6.0467	0.1957
59	22	0.1277	0.8217	2	2.2580	0.3234
60	237	0.2171	0.0000	5	18.9630	0.0020
61	42	0.0595	0.9963	5	1.2178	0.9432
62	283	0.1751	0.0000	5	79.0410	0.0000
63	57	0.1054	0.5169	5	7.5831	0.1808
64	148	0.1183	0.0291	7	12.2700	0.0920
65	18	0.1395	0.8284	2	2.4638	0.2917
66	24	0.1055	0.9267	2	6.2474	0.0440
67	7	0.2859	0.5246	N/A	-	N/A
68	75	0.0807	0.6828	6	1.8737	0.9309
69	18	0.1561	0.7162	2	1.5789	0.4541
70	88	0.0892	0.4599	6	1.5226	0.9580
71	111	0.0903	0.3067	6	3.3580	0.7628

APPENDIX B: PARAMETERS OF GENERALIZED PARETO AND POISSON DISTRIBUTIONS

Appendix B presents the parameters of generalized pareto distribution and poisson distribution. As previously explained, customers arrives to dealers with generalized pareto disribution and orders with poisson distribution. Please note that generalized pareto distribution equals to exponential distribution for k=0 and m=0 while it equals to pareto distribution for k>0 and σ =0.

Table B.1. Parameters of generalized pareto and poisson distributions

Dealer	Generalized Pareto Distribution	Poisson
Dealer 0	k=0,13166 σ=4,7605 μ=0,50032	λ=2,6782
Dealer 1	k=0,10905 σ=4,9758 μ=0,10267	λ=2,2449
Dealer 2	k=0,59943 σ=3,291 μ=0,56819	λ=2,3175
Dealer 3	k=0,53532 σ=3,38 μ=0,65469	λ=2,617
Dealer 4	k=0,37333 σ=1,8035 μ=0,65854	λ=7,1361
Dealer 5	k=0,58991 σ=0,97357 μ=0,8392	λ=7,0584
Dealer 6	k=0,45308 σ=0,70596 μ=0,82943	λ=8,1371
Dealer 7	k=0,4659 σ=2,0938 μ=0,77468	λ=4,4262
Dealer 8	k=0,28612 σ=3,1781 μ=0,68401	λ=4,4231
Dealer 9	k=0,10078 σ=3,5117 μ=0,74438	λ=2,4114
Dealer 10	k=0,54716 σ=2,0643 μ=0,79748	λ=2,4563
Dealer 11	k=0,23227 σ=3,4501 μ=0,59485	λ=4,8372
Dealer 12	k=0,22414 σ=2,9257 μ=0,75145	λ=2,6296
Dealer 13	k=0,23476 σ=3,0678 μ=0,92259	λ=4,9864
Dealer 14	k=0,31924 σ=2,8609 μ=0,53749	λ=2,4106
Dealer 15	k=0,33676 σ=8,263 μ=-0,36765	λ=2,2941
Dealer 16	k=0,30707 σ=2,3703 μ=0,73401	λ=5,9173
Dealer 17	k=-0,20887 σ=11,201 μ=0,28362	λ=6,9444
Dealer 18	k=0,11568 σ=9,2034 μ=0,1948	λ=2,3511
Dealer 19	k=0,40856 σ=4,7646 μ=0,61338	λ=3,0574
Dealer 20	k=0,02138 σ=3,026 μ=0,56099	λ=2,3046
Dealer 21	k=0,25366 σ=4,7884 μ=0,49094	λ=2,3765
Dealer 22	k=0,46015 σ=5,4073 μ=0,70715	λ=2,1895
Dealer 23	k=0,30421 σ=9,4644 μ=1,8976	λ=2,2449
Dealer 24	k=0,32585 σ=3,9336 μ=0,88615	λ=2,5168
Dealer 25	k=0,27677 σ=6,4935 μ=0,19788	λ=2,0571
Dealer 26	k=0,40853 σ=6,0084 μ=0,75421	λ=3,4038
Dealer 27	k=0,19676 σ=2,4323 μ=0,64861	λ=5,6578
Dealer 28	k=0,36532 σ=0,56016 μ=0,86193	λ=4,9671

Table B.1. (Cont'd) Parameters of generalized pareto and poisson distributions

Dealer	Generalized Pareto Distribution	Poisson
Dealer 29	k=0,37148 σ=1,1922 μ=0,76346	λ=3,9327
Dealer 30	k=0,37046 σ=6,4036 μ=0,52914	λ=2,2037
Dealer 31	k=0,27599 σ=9,9813 μ=0,4084	λ=1,9178
Dealer 32	k=0,54557 σ=7,6057 μ=1,2263	λ=2,0182
Dealer 33	k=0,1388 σ=7,2458 μ=0,2644	λ=2,2017
Dealer 34	k=0,25853 σ=7,5184 μ=0,33176	λ=2,0935
Dealer 35	k=0,04206 σ=14,95 μ=-0,07993	λ=2,55
Dealer 36	k=0,49905 σ=2,6452 μ=0,61507	λ=3,2717
Dealer 37	k=0,40273 σ=1,6535 μ=0,63549	λ=7,3442
Dealer 38	k=0,3098 σ=3,0424 μ=0,57413	λ=2,4044
Dealer 39	k=0,21116 σ=6,2478 μ=0,81748	λ=2,1951
Dealer 40	k=0,04856 σ=3,7811 μ=0,6803	λ=2,5046
Dealer 41	k=0,46321 σ=3,0069 μ=0,75832	λ=2,3182
Dealer 42	k=0,30855 σ=5,5354 μ=0,49845	λ=2,3594
Dealer 43	k=0,06685 σ=9,9045 μ=0,22377	λ=2,0533
Dealer 44	k=0,16629 σ=2,1761 μ=0,68294	λ=3,2176
Dealer 45	k=0,46679 σ=3,5837 μ=0,8058	λ=2,3636
Dealer 46	k=0,12174 σ=39,71 μ=-4,124	λ=2,5
Dealer 47	k=0,29339 σ=23,108 μ=1,0211	λ=2,3667
Dealer 48	k=0,22553 σ=2,664 μ=0,64616	λ=2,5681
Dealer 49	k=0,02657 σ=16,74 μ=0,29134	λ=2,0455
Dealer 50	k=0,20813 σ=26,708 μ=2,1562	λ=2,0741
Dealer 51	k=0,4635 σ=1,8797 μ=0,77963	λ=2,6154
Dealer 52	k=0,15831 σ=11,423 μ=0,02558	λ=2,3976
Dealer 53	k=0,0947 σ=5,2045 μ=0,62679	λ=2,6839
Dealer 54	k=0,25258 σ=1,7665 μ=0,70562	λ=4,135
Dealer 55	k=0,25609 σ=2,9047 μ=0,659	λ=2,9198
Dealer 56	k=0,37591 σ=2,6877 μ=0,63874	λ=2,587
Dealer 57	k=0,21064 σ=2,3609 μ=0,68153	λ=3,9244
Dealer 58	k=0,15467 σ=16,865 μ=0,04971	λ=3,7
Dealer 59	k=0,19031 σ=37,53 μ=-0,85073	λ=2,1304
Dealer 60	k=0,41629 σ=1,9635 μ=0,6489	λ=2,8571
Dealer 61	k=0,18847 σ=18,931 μ=0,98165	λ=2,3023
Dealer 62	k=0,24274 σ=2,167 μ=0,71428	λ=3,1268
Dealer 63	k=0,69531 σ=5,459 μ=0,97813	λ=2,2069
Dealer 64	k=0,16927 σ=5,4652 μ=0,79283	λ=2,2752
Dealer 65	k=0,16228 σ=29,643 μ=0,83704	λ=2,5
Dealer 66	k=-0,27447 σ=56,741 μ=-3,2294	λ=1,96
Dealer 67	k=-0,37931 σ=7,6576 μ=1,4483	λ=2,5
Dealer 68	k=0,05984 σ=11,461 μ=0,50285	λ=2,6842
Dealer 69	k=-0,1142 σ=65,157 μ=-7,8123	λ=1,9474

APPENDIX C: MIN_S, MAX_S, MIN_Q, MAX_Q VALUES OF DEALERS

Appendix C represents minimum and maximum values of *s* and *q* observed within the last 3 years.

Table C.1. Minimum and maximum values of *s* and *q* observed.

Dealer	*min_s*	*max_s*	*min_q*	*max_q*
Dealer 0	0	52	1	40
Dealer 1	0	8	2	20
Dealer 2	0	18	1	24
Dealer 3	0	34	1	34
Dealer 4	0	196	1	100
Dealer 5	0	411	2	146
Dealer 6	0	374	1	200
Dealer 7	0	50	1	82
Dealer 8	0	283	2	100
Dealer 9	0	21	1	24
Dealer 10	0	16	1	24
Dealer 11	0	99	1	88
Dealer 12	0	26	1	18
Dealer 13	0	76	1	86
Dealer 14	0	33	1	35
Dealer 15	0	10	1	8
Dealer 16	0	99	1	78
Dealer 17	0	16	1	61
Dealer 18	0	17	1	30
Dealer 19	0	30	1	40
Dealer 20	0	170	1	86
Dealer 21	0	31	1	20
Dealer 22	0	20	1	10
Dealer 23	0	18	1	14
Dealer 24	0	23	1	20
Dealer 25	0	16	1	10
Dealer 26	0	21	1	10
Dealer 27	0	60	1	72
Dealer 28	0	115	1	101
Dealer 29	0	106	1	70
Dealer 30	0	34	1	30

Table C.1. (Cont'd) Minimum and maximum values of *s* and *q* observed.

Dealer	*min_s*	*max_s*	*min_Q*	*max_Q*
Dealer 31	0	21	1	20
Dealer 32	0	28	1	20
Dealer 33	0	37	1	30
Dealer 34	0	36	1	20
Dealer 35	0	4	2	23
Dealer 36	0	95	1	40
Dealer 37	0	126	1	115
Dealer 38	0	38	1	43
Dealer 39	0	16	1	16
Dealer 40	0	55	2	50
Dealer 41	0	36	1	40
Dealer 42	0	33	1	50
Dealer 43	0	10	1	12
Dealer 44	0	118	2	115
Dealer 45	0	14	1	20
Dealer 46	0	6	2	4
Dealer 47	0	7	1	11
Dealer 48	0	73	1	68
Dealer 49	0	10	1	10
Dealer 50	0	8	2	12
Dealer 51	0	37	1	65
Dealer 52	0	30	1	20
Dealer 53	0	34	1	60
Dealer 54	0	68	2	70
Dealer 55	0	42	1	86
Dealer 56	0	37	1	70
Dealer 57	0	60	1	50
Dealer 58	0	37	1	20
Dealer 59	0	10	2	10
Dealer 60	0	46	1	60
Dealer 61	0	24	1	20
Dealer 62	0	62	2	50
Dealer 63	0	24	1	22
Dealer 64	0	39	2	50
Dealer 65	0	13	1	10
Dealer 66	0	7	1	6
Dealer 67	0	46	2	20
Dealer 68	0	40	1	40
Dealer 69	0	10	1	10
Dealer 70	0	28	1	30
Dealer 71	0	37	1	30

APPENDIX D: WINTERS EXPONENTIAL SMOOTHING

D.1. Theoritical Explanation

Winters exponential smoothing method is an extension of Holt's exponential smoothing method for a trend model which is, in turn, an extension of the simple exponential smoothing method. This method is extremely useful if the underlying demand pattern exhibits seasonality. It can be used moreover for modeling trend or average level of demand of an item. In other words, it is the most comprehensive exponential smoothing method. On the other hand, it is the most complex one in terms of calculations. Also, it requires a significant number of past observations, especially for its initialization stage. Silver *et* al. [5] recommend Winters exponential smoothing method if there is data for four complete seasons.

The underlying model for Winters exponential smoothing method is:

$$x_t = (L+T*t)\ S_t + \varepsilon_t \qquad \text{(D.1)}$$

where

t = the period (30 days in our study)

x_t = the demand at period t

L = the level

T = the linear trend

S_t = seasonal index of period t

ε_t = independent random variables with mean 0 and constant variance σ^2 .

There are two implementation stages of Winters exponential smoothing method: 1) initialization, and 2) updating. At the initialization stage, the initial values of average demand level, the trend level, and the seasonality indices are calculated. Ratio to moving average procedure was utilized at the initialization stage since it is the most commonly used method. Initial data is taken from the real sales of the distributor.

At the updating stage, after observing the previous month's actual demand data, new values for demand forecasts of level, trend, and seasonality for upcoming months were generated. The following formulas for updating were utilized at this stage:

$$L_t = \alpha\ (x_t / S_{t-p}) + (1 - \alpha)\ (F_{t-1} + T_{t-1}) \qquad (D.2)$$

$$S_t = \beta\ (X_t / F_t) + (1 - \beta)\ S_{t-p} \qquad (D.3)$$

$$T_t = \gamma\ (F_t - F_{t-1}) + (1 - \gamma)\ Tt_{-1} \qquad (D.4)$$

$$W_{t+m} = (F_t + mT_t)\ St \qquad (D.5)$$

L_t = Smoothed value for period t

x_t = Realized value for period t

α = Smoothing constant ($0 < \alpha < 1$, 0,2 in our study)

L_{t-1} = Average experience of series smoothed for period t - 1

T_{t+1} = Trend estimate

S_t = Seasonality estimate

β = Smoothing constant for seasonality estimate ($0 < \beta < 1$, 0,3 in our study)

γ = Smoothing constant for trend estimate (0,1 in our study)

m = Number of periods ahead to be forecast

p = Number of periods of the seasonal cycle

W_{t+m} = Forecasted value for next m periods

D.2. A Numerical Illustration of Winters Exponential Smoothing Method

Consider we are at the end of September 2007 and want to generate demand forecasts for an item for following months. The following demand data is given.

Table D.1. An illustrative demand data

	1	2	3	4	5	6	7	8	9	10	11	12
2006	326	915	629	1283	840	1518	787	1413	1243	1569	581	583
2007	390	662	1251	1120	1605	797	1012	924	880			

At the first step indices are assigned for each month and moving averages are calculated. Moving average of demand for a month of a particular year is calculated by taking average of five numbers. Two of them are demand values of precedent two months, another two is demand values of antecedent months and the last one is the demand value of the current month. In other words,

$$MA_{t,i} = \frac{(MA_{t-2,i} + MA_{t-1,i} + MA_{t,i} + MA_{t+1,i} + MA_{t+2,i})}{5} \qquad \text{(D.6)}$$

where $MA_{t,i}$ is the moving average of month t of i^{th} year. For instance, moving average of the fourth month of 2006 is equal to (915 + 629 +1283 + 840 + 1518) /5, that is 1037.

Table D.2. Moving average calculation

Year	Month	Period Index	Demand	Moving Average
2006	1	-20	326	
	2	-19	915	
	3	-18	629	799
	4	-17	1283	1037
	5	-16	840	1011
	6	-15	1518	1168
	7	-14	787	1160
	8	-13	1413	1306
	9	-12	1243	1119
	10	-11	1569	1078
	11	-10	581	873
	12	-9	583	757
2007	1	-8	390	693
	2	-7	662	801
	3	-6	1251	1006
	4	-5	1120	1087
	5	-4	1605	1157
	6	-3	797	1092
	7	-2	1012	1044
	8	-1	924	
	9	0	880	

As the second step, seasonality indices are calculated. Seasonality indices are important parameters in the model that shows the seasonality influence of a particular month on the demand pattern of the item. Seasonality index is equal to the ratio of demand to the moving average.

Table D.3. Calculation of seasonality indices

Year	**Month**	**Demand**	**5-Months Moving Average**	**Seasonality Index**
2006	1	326		
	2	915		
	3	629	799	0.8
	4	1283	1037	1.2
	5	840	1011	0.8
	6	1518	1168	1.3
	7	787	1160	0.7
	8	1413	1306	1.1
	9	1243	1119	1.1
	10	1569	1078	1.5
	11	581	873	0.7
	12	583	757	0.8
2007	1	390	693	0.6
	2	662	801	0.8
	3	1251	1006	1.2
	4	1120	1087	1
	5	1605	1157	1.4
	6	797	1092	0.7
	7	1012	1044	1
	8	924		
	9	880		

If seasonality index value of a month is greater than 1, then it means the month and demand is positively correlated. If it is less than 1, there is negative correlation between the month and demand. If it is 1, then it can be said that the month has not any influence on the demand. As it can be seen, there are more than one seasonality index values for some months. At the next step, all months will have one seasonality index value and the sum over all seasonality index values would become 12 after normalization.

Table D.4. Normalization of seasonality factors

Month	Average Seasonality Factor	Final Seasonality Factor
1	0.6	0.6
2	0.8	0.9
3	1	1.1
4	1.1	1.2
5	1.1	1.2
6	1	1.1
7	0.8	0.9
8	1.1	1.1
9	1.1	1.2
10	1.5	1.5
11	0.7	0.7
12	0.8	0.8
Sum	12	12

Now, the initial values of average demand level and trend level will be determined. At this stage, following regression formulas are utilized.

$$a_0 = \frac{6}{n(n+1)} \sum_t t x_t + \frac{2(2n-1)}{n(n+1)} \sum_t x_t \tag{D.7}$$

$$b_0 = \frac{12}{n(n^2-1)} \sum_t t x_t + \frac{6}{n(n+1)} \sum_t x_t \tag{D.8}$$

where

a_0 = initial level estimate

b_0 = initial trend estimate

x_t = realized demand at period t.

t = period index

n = number of periods

Up to this point, in addition to the estimates of seasonality factor parameters, initial level and trend level parameters were estimated. Now, we have all necessary data to generate forecasts for next months.

Table D.5. Initial level and trend calculation

Estimate of Level	**Demand*Period Index**	**Total Demand**	**Initial Level Estimate**	**Initial Trend Estimate**
559	-6520	19862	948	0.2
1068	-17385	**Sum (Demand*Period Index)**		
597	-11322	-198486		
1091	-21811			
730	-13440			
1442	-22770			
921	-11018			
1259	-18369			
1079	-14916			
1039	-17259			
842	-5810			
730	-5247			
669	-3120			
773	-4634			
1187	-7506			
952	-5600			
1396	-6420			
757	-2391			
1184	-2024			
823	-924			
764	0			

The equations for generating forecasts from average level, trend and seasonal parameters are straightforward. They are called as the equations of multiplicative trend-seasonal model. They are in the general form of

$$x_t = \left(a + bt\right) F_t + \varepsilon_t \tag{D.9}$$

where,

a = level

b = linear trend

F_t = seasonality index

t = period index

ε_t = independent random variables with mean 0 and constant variance σ^2

For instance, in our example we calculate forecast values as in the below figure:

Table D.6. Forecast generation

Month	**Calculation**	**Forecast**
10	(948+0.2)*1.5	1422
11	(948+0.4)*0.7	664
12	(948+0.6)*0.8	759
1	(948+0.8)*0.6	569
2	(948+1.0)*0.9	854
3	(948+1.2)*1.1	1044

APPENDIX E: SAFETY STOCK LEVELS OF DEALERS FOR REMANUFACTURED PARTS

Appendix F represents safety stock levels of each dealer for remanufactured parts. These values are calculated by observing lost sales of dealers in the base model.

Table E.1. Safety stock levels of dealers for remanufactured parts.

Dealer	# of obs.	Average Lost Sales	St.dev	Safety Stock (95%)
0	4	7.50	5.00	16
1	526	8.09	6.16	19
2	176	6.56	5.42	16
3	48	6.77	4.49	15
4	15	18.33	14.21	42
6	3	55.00	45.92	131
7	165	14.70	11.71	34
9	336	8.42	6.94	20
10	433	9.89	8.35	24
11	9	8.22	6.50	19
12	354	9.57	8.04	23
13	47	12.98	13.67	36
14	116	7.98	7.59	21
15	385	5.46	4.62	14
16	86	16.52	12.74	38
17	420	13.80	11.04	32
18	98	4.30	3.27	10
19	79	7.10	5.40	16
21	83	5.11	4.20	13
22	161	5.89	5.08	15
23	64	4.28	3.69	11
24	192	7.02	5.40	16
25	226	4.71	3.85	12
26	399	7.84	6.26	19
27	309	22.56	18.77	54
28	280	28.83	23.24	68
29	36	15.22	11.38	34
30	5	5.60	4.51	14
31	15	2.47	1.73	6
32	2	8.50	3.54	15
33	8	3.88	2.75	9
34	5	3.20	1.64	6
35	241	4.63	3.47	11
36	1	2.00	0.00	2
37	115	25.91	20.43	60
38	34	5.50	5.56	15
39	195	5.19	3.97	12
40	11	6.64	4.43	14

Table E.1. (Cont'd) Safety stock levels of dealers for remanufactured parts.

Dealer	# of obs.	Average Lost Sales	St.dev	Safety Stock (95%)
41	33	5.27	3.33	11
42	9	6.22	4.55	14
43	287	4.62	3.71	11
44	1	2.00	0.00	2
45	315	6.63	5.34	16
46	230	3.39	2.75	8
47	113	3.30	2.24	7
48	2	8.00	7.07	20
49	159	3.58	2.69	9
50	58	2.91	1.94	7
51	84	9.45	7.86	23
52	13	3.92	2.66	9
53	40	7.63	4.63	16
54	164	17.04	13.37	40
55	37	8.89	6.52	20
56	50	7.38	7.15	20
57	159	13.33	10.86	32
58	22	3.64	2.61	8
59	31	2.35	1.76	6
60	83	9.63	9.07	25
61	3	2.33	1.53	5
62	50	9.78	7.32	22
63	18	4.28	2.99	10
64	5	3.80	2.68	9
65	81	2.64	1.87	6
66	100	2.33	1.69	6
67	5	3.40	2.70	8
68	1	1.00	1.00	3
69	39	2.56	1.77	6
70	68	5.97	4.88	14
71	4	7.25	7.46	20

REFERENCES

1. Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., van der Laan, E., van Nunen, J.A.E.E., van Wassenhove, L.N., “Quantitative models for reverse logistics: A review.”, *European Journal of Operational Research*, Vol. 103, pp. 1-17, 1997

2. Giuntini, R. and Gaudette, K., “Remanufacturing: The next great opportunity for boosting US productivity”, *Business Horizons*, Vol.46, pp. 41-48, 2003

3. Debo, L.G., Toktay, L.B., van Wassenhove, L.N., “Market segmentation and product technology selection for remanufacturable products.”, *Management Science*, Vol. 51 No.8, pp.1193-1205, 2005

4. Simchi-Levi, D., Kaminsky, P., and Simchi-Levi, E., *Designing and Managing the Supply Chain: Concepts, Strategies, and Case Studies*, Irwin/McGraw-Hill, New York, 2003

5. Silver, E., Pyke, D., Peterson, R., *Inventory Management and Production Planning and Scheduling*, John Wiley & Sons, New York, 1998

6. Chen, F., and Y. Zheng. “Evaluating Echelon Stock (R,nQ) Policies in Serial Production/Inventory Systems with Stochastic Demand.” *Management Science*, 40(10)(1994b), pp.1262-75.

7. Chen, F., and Y. Zheng. “One-Warehouse Multi-retailer Systems with Centralized Stock Information.” *Operations Research*, 45(2) (1997), pp.275-87.

8. Clark, A. J., and H. Scarf. “Optimal Policies for a Multi-Echelon Inventory Problem.” *Management Science*, 6(4) (1960), pp.475-90.

9. Federgruen, A., and P. Zipkin, F. "Allocation Policies and Cost Approximations for Multilocation Inventory Systems." *Naval Research Logistics*, 31 (1984a), pp.97-129.

10. Federgruen, A., and P. Zipkin, F. "Computational Issues in an Infinite Horizon Multiechelon Inventory Model." *Operations Research*, 32(4) (1984b), pp.818-36.

11. Glasserman, P., and S. Tayur. "Sensitivity Analysis for Base-Stock Levels in Multiechelon Production-inventory Systems." *Management Science*, 41(2) (1995), pp.263-81.

12. Van der Laan, E., Dekker, R., Salomon, M., Ridder, A., "An (s,Q) inventory model with remanufacturing and disposal", *International Journal of Production Economics*, Vol. 46-47, pp. 339-350, 1996

13. Ouyang, H., Zhu, X., "An inventory control system for remanufacture with disposal", *IEEE Conference*, pp. 1-5, 2006

14. Van deer Laan, E., Dekker, R., Salomon, M., "Product remanufacturing and disposal: A numerical comparison of alternative control strategies.", *International Journal of Production Economics*, Vol. 45, pp. 489-498, 1996

15. Mahadevan, B., Pyke, D.F., Fleischmann, M., "Periodic review, push inventory policies for remanufacturing", *European Journal of Operational Research*, Vol. 151, pp. 536-551, 2003

16. Inderfurth, K., van der Laan, E., "Leadtime effects and policy improvement for stochastic inventory control with remanufacturing", *International Journal of Production Economics*, Vol. 71, pp. 381-390, 2001

17. Inderfurth, K., "Optimum policies in hybrid manufacturing/remanufacturing systems with product substitution.", *International Journal of Production Economics*, Vol. 90, pp. 325-343, 2004

18. Inderfurth, K., Minner, S., "Safety stocks in multi-stage inventory systems under different service measures.", *European Journal of Operational Research,* Vol. 106, pp. 57-73, 1998

19. Souza, G.C., Ketzenberg, M.E., "Two-stage make-to-order remanufacturing with service level constraints", *International Journal of Production Research*, Vol. 40, No. 2., pp. 477-493, 2002

20. Kara, S., Rugrungruang, F., Kaebernick, H., "Simulation modelling of reverse logistics networks", *International Journal of Production Economics*, Vol. 106, pp. 61-69, 2007

21. Teunter, R.H., Vlachos, D., "On the necessity of a disposal option for returned items that can be remanufactured.", *International Journal of Production Economics*, Vol. 75, pp. 257-266, 2002

22. Georgiadis, P., Vlachos, D., "The effect of environmental parameters on product recovery", *European Journal of Operational Research*, Vol.157, pp. 449-464, 2004

23. Fleischmann, M., Nunen, J.V., Grave, B., Gapp, R., "Reverse Logistics: Capturing value in the extended supply chain.", *ERIM Report Series Research in Management*, 2004

24. Majumder, P., Groenevelt, H., "Competition in remanufacturing.", *Production and Operations Management*, Vol.10 No.2, pp.125, 2001

25. Ferguson, M.E., Toktay, L.B., "The effect of competition on recovery strategies", *Production and Operations Management,* Vol.15, No.3., pp. 351-368, 2006

26. Ferrer, G., Swaminathan, J.M., "Managing new and remanufactured products.", *Management Science*, Vol.52 No.1., pp.15-26, 2006

27. Guide Jr, V.D.R., Souza, G.C., van Wassenhove, L.N., Blackburn, J.D., "Time value of commercial product returns.", *Management Science*, Vol.52 No.8, pp.1200-1214, 2006

28. Atasu, A., Sarvary, M., van Wassenhove, L.N., "Remanufacturing as a marketing", *INSEAD*, 2006

29. Law, A.M. and Kelton W.D., *Simulation Modeling and Analysis*. McGraw-Hill Press, Singapore, 2000

30. Gunasekaran, A., Patel, C., McGaughey, R.E., "A framework for supply chain performance measurement", *International Journal of Production Economics*, Vol.87, pp. 333-346, 2004

31. Montgomery, D.C., *Design and Analysis of Experiments*, 5th ed., John Wiley & Sons, New York, 2001

32. Moghaddam, J., Sarraf-Mamoory, R., Abdollahy, M., Yamini, Y., "Purification of zinc ammoniacal leaching solution by cementation: Determination of optimum process conditions with experimental design by Taguchi's method.", *Separation and Purification Technology*, Vol.51, pp. 157-164, 2006

33. Guanghua, Z., Huangxian, J., "Determination of naproxen with solid substrate room temperature phosphorimetry based on an orthogonal array design.", *Analytica Chimica Acta*, Vol.506, pp.177-181, 2004