THE REPUCLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

THE IMPACT OF RETURN DISPOSAL ON ORDER VARIANCE IN A HYBRID MANUFACTURING AND REMANUFACTURING SYSTEM

Ph.D. Thesis

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ABSTRACT

THE IMPACT OF RETURN DISPOSAL ON ORDER VARIANCE IN A HYBRID MANUFACTURING AND REMANUFACTURING SYSTEM

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This thesis studies the impact of return disposal on production order variance in a hybrid production system with both manufacturing and remanufacturing options. Using discrete event simulation, Push- and Pull-Disposal inventory control strategies are compared in terms of production order variance, which causes bullwhip effect. Variety of scenarios for each system, based on different disposal rates, manufacturing/remanufacturing lead time ratios, and various cost parameters, are considered. Our findings point out that depending on the system parameters combination higher disposal rates may lead to higher or lower production order variance values. As a result, companies that plan to remanufacture with disposal option should take all the costs into account properly by their feasibility calculations. Because while hybrid production systems with a disposal option can increase the profitability through storage place savings, inventory cost reduction and value recovery, high levels of production order variances in such systems may reduce the profitability by inducing additional costs.

Keywords: Remanufacturing, Production and Inventory Control, Simulation, Disposal, Bullwhip Effect

ÖZET

GERİ GÖNDERİLEN ÜRÜN BERTARAFININ İMALAT VE YENİDEN İMALAT İÇEREN BİRLEŞİK BİR ÜRETİM SİSTEMİNDE SİPARİŞ VARYANSINA ETKİSİ

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Bu çalışmada, geri gönderilen ürün bertarafinin bertaraflı itme veya çekme stratejisi ile yönetilen ve imalat/yeniden imalat içeren birleşik bir üretim sisteminde sipariş varyansina etkisi incelendi. Ayrık olaylı benzetim kullanılarak, bertaraflı itme ve çekme stok yönetim stratejileri kamçı etkisine sebep olan üretim sipariş varyansı bakımından karşılaştırıldı. Her sistem için talep, geri dönüş ve bertaraf oranları ile imalat/yeniden imalat değişkenlerine ve çeşitli maliyet parametrelerine bağlı olarak birçok farklı senaryo ele alındı. Elde edilen bulgular yüksek bertaraf oranlarının sistem değişkenlerinin aldıkları değerlere göre sipariş varyansının artmasına ya da azalmasına yol açabildiğini göstermektedir. Bertaraflı birleşik imalat sistemleri stok alanından tasarruf, stok maliyetlerinin azaltılması, ve geri dönüşüm kazanımları ile kârı artırabilirken, yüksek sipariş varyansları ek maliyetler oluşturarak bu kârın azalmasına sebebiyet verebilir. Bu nedenle bertaraflı yeniden imalat yapmayı düşünen firmalar ortaya çıkabilecek tüm maliyet çeşitlerini fizibilite çalışmalarında uygun bir şekilde göz önüne almalıdırlar.

Anahtar Kelimeler: Yeniden İmalat, Üretim ve Stok Yönetimi, Benzetim, Bertaraf, Kamçı Etkisi

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ABBREVIATIONS

EOQ	:	Economic Order Quantity

SYMBOLS

Demand Rate	:	λ_D
Disposal Level	:	s_d
Disposal Rate	:	λ_P
Inventory Holding Rate	:	i
Manufacturing Lead Time	:	L_m
Manufacturing Lead Time Variance	:	σ_m^2
Manufacturing Lot Size	:	Q_m
Manufacturing Reorder Point	:	s_m
Manufacturing Setup Cost	:	K_m
Manufacturing Variable Cost	:	c_m
Recoverable Inventory Cost	:	c_n
Remanufacturing Lead Time	:	L_r
Remanufacturing Lead Time Variance	:	σ_r^2
Remanufacturing Lot Size	:	Q_r
Remanufacturing Reorder Point	:	s_r
Remanufacturing Setup Cost	:	K_r
Remanufacturing Variable Cost	:	c_r
Return Rate	:	λ_R
Standard Normal Random Variable	:	z

1. INTRODUCTION

1.1 IMPORTANCE OF PRODUCT RECOVERY

For several factors, product recovery has gained increased attention over the past decade. Increasing technological innovation rate, shorter product life cycles and increased product variety together with increasing environmental awareness are motivating companies to find alternative ways to recover used products that have completed their economic life. Furthermore, firms are realizing that product recovery could result in not only a corporate green image but also additional profits. In addition, there are legislations like Directive 2002/525/EC regarding End of Life Vehicles and Directive 2002/96/EC regarding Waste Electrical and Electronic Equipment, which force the producers to take responsibility for their used products. By means of such regulations, firms are assigned to recover their products after use or discard them properly. Consequently, in accomplishing the objective of sustainable development, product recovery has become a significant industrial field.

As explained by Kerr and Ryan (2001), closed loop supply chain, in which products are recovered at the end of their economic life, is the unique way to achieve sustainable production.

1.2 PRODUCT RECOVERY ALTERNATIVES

There are five product recovery alternatives: Recycling, repairing, refurbishing, remanufacturing, and cannibalization (Thierry et al., 1995). By means of remanufacturing, repairing or refurbishing, used products can be enhanced in terms of technology as well as quality. While remanufacturing provides the largest improvement, repairing involves the least. Despite a possible quality loss, repairing involves replacing or correcting only the non-working parts so that the product is in a good working order. Via refurbishing a used product can be improved up to a less quality level comparing new products. By recycling option materials are recovered without conserving any product structure. In cannibalization, just a small group of parts or components of used products is recovered, which can be used in remanufacturing, refurbishing or repairing processes later.

Through remanufacturing, used products are enhanced at least to the quality and technology level of new products by replacing worn out parts by new ones. Among these alternative recovery processes, remanufacturing is the unique one by which recovered products meet the quality standards of new products. Remanufactured products can be resold at the market of new products. Since remanufacturing (added value recovery) conserves the product identity, it is more profitable and environmentally friendly than recycling, which recovers only material.

1.3 CHARACTERISTICS OF PRODUCT RECOVERY SYSTEMS

A recoverable manufacturing system that is also called as hybrid manufacturing and remanufacturing production system can meet the demand not only by manufacturing but also by remanufacturing. It is a significant component of a recoverable product environment (Laan et al., 1999). Although remanufacturing can be a profitable business, managing it is a quite challenging task because applying traditional operations management techniques may induce many difficulties in such hybrid production systems due to the highly uncertain nature of remanufacturing processes (Ilgin and Gupta, 2010).

According to Guide (2000), remanufacturing is a quite complex process because of the seven complicated characteristics: (1) Uncertainty in the timing and the quantity of returns, (2) balancing returns with demands, (3) disassembly, (4) uncertainty in materials recovered, (5) reverse logistics, (6) materials matching requirements, (7) routing uncertainty and processing time uncertainty. Based on these characteristics controlling a hybrid production system is more difficult than a traditional one that inspires researchers to find out solutions for inventory and production control problems of such systems.

According to Laan et al. (1995) managers, who plan to remanufacture, should study the hybrid production systems thoroughly to reveal hidden costs. These costs may be incurred by additional uncertainties specific to hybrid systems and cause production and inventory costs of such systems to be higher than that of traditional manufacturing systems. In this regard, during the whole product lifecycle, remanufacturing firms should assess whether all returned products that are qualified for remanufacturing in terms of quality should be remanufactured or not. Because pursuing other return handling options, like disposal could be more cost-effective under some conditions.

When a disposal option is included into a hybrid production system, it is a more challenging task to manage such systems. However, by means of disposal total inventory and production costs can be reduced especially by high return rates in hybrid production systems (Heyman, 1977; Laan et al., 1997; Teunter and Vlachos, 2002). Furthermore, from a physical perspective disposal may also be needed because of some storage capacity limitations. Therefore, a trade-off between cost and complicacy always exists for such cases.

Another important source of cost in production systems is high production order variance values which cause bullwhip effect. Bullwhip problem causes missed production schedules, poorly conceived capacity plans, lost sales, excessive inventory investment, inefficient transportation and consequently unsatisfied customers (Lee et al., 1997).

1.4 MOTIVATION AND CONTRIBUTIONS

Employing Markov Chain approach, Laan and Salomon (1997) developed two continuous stock management strategies called as Push-Disposal and Pull-Disposal in order to control a single product stochastic hybrid manufacturing and remanufacturing system. While by Pull-Disposal control strategy, incoming returns are remanufactured considering not only serviceable inventory position but also remanufacturable inventory on-hand; Push-Disposal control strategy activates remanufacturing process as soon as the on-hand quantity of incoming remanufacturable returns reaches a predetermined position. Furthermore, Push-Disposal policy disposes the incoming returns considering the serviceable inventory position whereas Pull-Disposal policy disposes them considering the remanufacturable inventory on-hand. In their study, they defined a method in order to compute the total production and inventory costs for Push- and Pull-

Disposal policies. While the authors explained the conditions, by which planned disposals are economically profitable and compared the Push- and Pull-Disposal policies with Push and Pull policies in terms of total production and inventory costs, they didn't investigate the effect of disposal on system dynamic performance, i.e. production order variance that might reduce environmental performance of closed loop supply chains by increasing depletion of natural resources, emissions and waste. According to their study, especially by high return rates hybrid production and inventory control policies with return disposal option induce lower costs due to the reduction in the stock variability of the system.

In contrast to Laan and Salomon (1997), Zanoni et al. (2006) analyzed not only cost performance but also production order variance performance of a hybrid manufacturing and remanufacturing system without any disposal option. They employed Pull, Shifted Pull, Separate Pull, and Dual policies to control the production and inventory. Afterwards, Corum et al. (2014) compared a hybrid production system, which is controlled by Push or Pull policy, with a traditional manufacturing system in terms of inventory operating costs and production order variance. The system they studied doesn't include any disposal option, which can be needed due to several reasons such as stock area limitation, remanufacturing capacity restriction or high inventory holding costs. As an extension study of Corum et al. (2014), Dev et al. (2017) researched the impact of further control policies on cost and production order variance in a hybrid production system without any disposal option. Dev et al. (2017) suggested studying impact of return disposal on production order variance. Hence, the present study is an extension of their efforts and investigates the impact of return disposal on production order variance in a stochastic hybrid production system through discrete event simulation methodology.

Based on the fact that Push- and Pull-Disposal policies are easy to implement and so widely preferred in practice, I also prefer to utilize them in my thesis. To the best of my knowledge, there is no study in the literature that investigates the impact of return disposal on dynamic behavior of a continuously reviewed stochastic hybrid manufacturing and remanufacturing production system, which is regulated by Push- or Pull-Disposal production and inventory control strategy.

The rest of the thesis is organized as follows: In section 2, the relevant literature is surveyed. In section 3, the hybrid manufacturing and remanufacturing system is explained, and the inventory control strategies utilized to manage this system are described. In section 4, the simulation model is explained in detail. In section 5, the results of the study are discussed. In section 6, the thesis is concluded with final remarks.

2. LITERATURE REVIEW

2.1 RESEARCH TOPICS IN CLOSED LOOP SUPPLY CHAIN MANAGEMENT

There are lots of studies in the literature regarding closed-loop supply chain management. Ilgin and Gupta (2010) categorized the relevant literature in four groups: (1) Reverse and closed-loop supply chains, (2) environmentally conscious product design, (3) disassembly, (4) remanufacturing.

Production and capacity planning, forecasting, inventory control and production scheduling are the common topics studied under remanufacturing category. An excellent review was also provided by Ozcan and Corum (2019), who adopted scientometric and tech-mining approaches to examine remanufacturing research. In the literature review below, we mainly focus on the inventory management in hybrid manufacturing and remanufacturing production systems with disposal option.

2.2 INVENTORY MODELS FOR HYBRID PRODUCTION SYSTEMS

Thus far, several economic order quantity (EOQ)-based inventory management models for hybrid manufacturing and remanufacturing production systems have been suggested. It is widely accepted that Schrady (1967) made the first contribution to this field. In his deterministic model, while recovery and external order lead times are fixed, demand and return have constant rates. In order to calculate optimal repair and external order lot sizes, he modified the basic EOQ formula by considering the repairable and serviceable stocks as two independent parts taking a disposal rate into account.

Richter (1994) extended Schrady's (1967) model by using variable return and disposal rate and investigated the dependency between cost function and return rate. In his study, optimal waste disposal rate is defined through a closed form expression. He showed that as far as serviceable inventory carrying costs are greater than recoverable inventory carrying costs the cost function is convex in the return rate. He concluded that adjusting the return rate by virtue of disposal can lead to economically beneficial results. Teunter (2001) extended Richter's (1994) work in such a way that remanufactured and manufactured products have distinct inventory carrying cost rates. Teunter (2001) and Teunter and Vlachos (2002) showed that return disposal can reduce costs significantly only by slow moving-items with high return rates.

Laan and Teunter (2006) developed EOQ-based closed form heuristic expressions to compute near optimal inventory control policy parameters for a hybrid production system, which is managed by Push or Pull strategy, under a cost minimization objective. By means of a numerical study, they showed that near-optimal strategy parameters can be found through the suggested formulas.

Heyman (1977) studied a class of policies for hybrid systems, in which lead times and fixed costs are assumed to be zero, and in order to calculate the optimal disposal level he developed a closed form expression. According to his findings, when the rate of demand is larger than the return rate and remanufacturing is profitable, stock level of returns never reaches the optimal dispose-down-to level. Therefore, return disposal makes a very limited contribution to reducing costs. Laan et al. (1996a) extended his work addressing disposal issues in a repair shop setting and proposed a (s, Q) policy, in which fixed costs and lead times have non-zero values. Nonetheless, remanufacturables had zero holding cost and total expected cost was calculated approximately. With the objective of minimizing the total long-term average inventory costs they determined parameters of optimal reorder point, optimal order quantity, and storage capacity for repairables and concluded that models must consider disposal of items to avoid excessive costs. Still, in a subsequent study, Laan et al. (1996b) assumed non-zero inventory carrying costs for remanufacturables and studied a variety of disposal policies. They proved that in order to increase the economical profitability of remanufacturing, both of remanufacturable and serviceable inventories should be considered by disposal decisions. Afterwards, Laan and Salomon (1997) studied a stochastic hybrid inventory system with manufacturing, remanufacturing and disposal. They defined and compared Push- and Pull-Disposal strategies and concluded that economically Pull-Disposal policy is more beneficial than Push-Disposal policy if serviceable inventory carrying costs are larger than recoverable inventory carrying costs.

The first periodic review hybrid production system model with disposal option was proposed by Simpson (1978). While inventory holding, variable remanufacturing and outside purchasing, backordering, and disposal costs are the components of his cost function to be minimized, zero lead times and zero fixed costs are the main assumptions of his model. He showed that using three parameters, i.e., repair quantity, purchase quantity, and disposal level, structure of optimal solution for n-period repairable inventory problem can be wholly defined. Inderfurth (1997) extended this model by using nonzero lead times and derived the structure of optimal control strategies which is quite complex to be implemented in practice.

Kiesmuller and Laan (2001) studied an inventory system, which is reviewed periodically and has only one sort of single reusable product with return flow that depends explicitly on the demand flow. In their system, only unplanned disposal was applied, and so a returned product was only disposed if it didn't meet the quality requirements for remanufacturing. The study shows that if the dependency between demand and return flows isn't considered, then the total system costs may increase. The authors also explained how both the minimal total cost and the optimal policy depend on the recovery probability.

While most of the inventory control models for hybrid production systems consider only stationary demand and return flows and do not study product life cycles and seasonal effects, Kleber et al. (2002) provided a continuous time deterministic inventory model with dynamic demands and returns. They tried to answer the question if the surplus returns ought to be retained for potential future recovery or discarded. Utilizing Pontryagins Maximum Principle, they derived optimal manufacturing, remanufacturing, and disposal strategies for a linear cost model. In their model, there are different demand types defined according to product quality and a decision must be made as to which demand category, returns will be used.

Dobos (2003) compared the performance of two reverse logistics model in terms of cost. While the first model applies a continuous disposal strategy, by which disposal may take place at any time during the planning horizon, in the second model disposal may occur only at the end of the planning horizon. The study shows that the second model gives better results in terms of total system cost that is composed of holding, manufacturing, remanufacturing as well as disposal costs.

Deriving an exact expression for total cost, Ouyang and Zhu (2006) extended the classical (s, Q) stock management strategy to an (s, Q, s_d) strategy in order to coordinate production and disposal activities simultaneously, and studied the influence of inventory carrying cost, marginal cost, lead time, disposal cost and disposal level to the system performance in terms of cost. Unlike most other studies, their strategy could be applied during the whole product life cycle, especially in the final phase of the cycle, where return rate exceeds demand rate. According to their simulation results, especially by relatively large return flows their inventory and production control strategy reduces the total cost.

Takahashi et al. (2007) described a hybrid production system, where returned products are classified as waste to be discarded, raw material to be used in production, and parts to be remanufactured. They proposed two push control policies to control the system. In the first policy, manufacturing and remanufacturing are independent processes, which may cause an excessive disposal of parts. The second policy utilizes a second control limit for part production to be able to control the total amount of part in the system. Changing several cost factors, it was proven that managing the system with the second push policy always results in lower total cost.

While most of product recovery models in the literature deal with fixed disposal policies, Kim (2007) determined the structure of the optimal disposal strategy for a hybrid production system, which utilizes the information of inventory of both serviceable and recoverable goods. They showed that the optimal disposal strategy can be characterized through a monotonic threshold type of curve and has monotonic properties with respect to system parameters. Assuming Poisson demand and return processes and exponentially distributed lead times, they described a control policy which is used to define when the returned products should be disposed or accepted for remanufacturing to maximize the profit.

Pinçe et al. (2008) studied a hybrid production system that is reviewed continuously. In their system, lead times have non-zero values, demands and returns have independent flows and fixed disposal costs are incurred. They introduced closed form expressions with the objective of minimizing procuring, holding, ordering and disposal costs considering a customer service level constraint and concluded that considerable cost reductions can be achieved via disposal even if the disposal costs have non-zero values. Employing discrete event simulation approach, Gallo et al. (2009) tried to determine an optimal multistage inventory management policy with respect to total system cost for a hybrid production system. They generated various scenarios corresponding to various product life cycle stages by changing several cost parameters including holding, shortage, disposal, production, and purchase costs. They showed that since cost parameters and recovery rate have different values at each product life cycle stage, it is impossible to identify a unique optimal control policy that is valid for all stages and thus different control policies must be adopted at different product life cycle stages to improve cost performance of the system.

Nikoofal and Moattar Husseini (2010) investigated the relationship between reorder point and structure of optimal control policy of a hybrid production system where the disposed items are a constant percentage of returned items. In their model, stochastic return and demand flows are dependent. Considering the influence of disposal cost on the total inventory cost, they made important observations on effective coordination of manufacturing, remanufacturing and return disposal. Utilizing Markov decision process, Kim et al. (2013) modeled a hybrid production system with disposal option to maximize the average profit. According to their study, the optimal inventory and production control strategy can be defined via three state-dependent thresholds regarding (re)manufacturing base stocks and return acceptance. In their study, since the optimal control strategy has a quite complicated structure, an implementable heuristic strategy was introduced and it was shown that the heuristic strategy reduces costs considerably by improving coordination of manufacturing, remanufacturing, and disposal activities.

Vadde et al. (2014) studied an analytical model to find the optimal disposal level and price of recoverable goods. Their model also allows to calculate the quantity of discarded products to be acquired proactively whenever the recoverable good demand can’t be met through the passively accepted returns sufficiently. While remanufactured good demand is classified as like new, good, and acceptable, it is regulated by price, obsoleteness and remaining life of goods, and customer willingness to pay. Considering the profit maximization objective, remaining recoverable goods are discarded or held at the end of a selling horizon. Using the model, product recovery facilities can regulate the recovered goods prices dynamically and adjust the discarding level to manage their stock quantities effectively in an environment of uncertain demand and return trends.

Gayon et al. (2017) investigated a hybrid production system, in which whereas random returns are either be put in serviceable stock or disposed of upon arrival, serviceable goods may be discarded anytime. They suggested a new control policy combining these two different types of disposal options to avoid excessively high levels of inventory. Modeling the system as a M/M/1 make-to-stock queuing environment, they derived an optimal inventory management strategy with three threshold parameters determined by considering production and discarding costs. Furthermore, the authors presented explicit expressions to calculate the costs and optimal thresholds.

Employing a simulation-based optimization approach and multivariate optimization methods, Fang et al. (2017) suggested a production and inventory control policy, which enables to compute the optimal portion of old products to be recycled as well as allocates the capacity to the new and remanufactured goods production appropriately. Furthermore, maximizing the manufacturer’s profit is considered as an objective by their model in order to mitigate the competition between new and remanufactured goods. They studied five scenarios, generated by varying demand and capacity of production, to determine the optimal manufacturing, remanufacturing and recycling lot sizes as well as the corresponding optimized total profit. The authors argued that through the proposed model, which considers manufacturing, remanufacturing, recycling, disassembly, inventory, shortage and disposal costs, a manufacturer can manage various market demands properly and maximize its profit.

Ahiska et al. (2017) suggested a heuristic for inventory control strategies to manage systems with one-way product substitution. By their strategies, if a company is short of a remanufactured product with lower quality then the corresponding manufactured one with higher quality can be used instead of the remanufactured one. Considering the desired profit structure, their heuristic search algorithm optimizes the strategy parameters. In their hybrid production environment, each group of recoverable, manufactured and remanufactured items has a separate stocking area. And as far as there is enough storage capacity, incoming remanufacturable items are stocked; otherwise they are disposed of.

Dhaiban et al. (2018) introduced an optimal stock management model to control a hybrid production system, in which disposal of returns and deterioration of goods may occur. Adopting Pontryagin Maximum Principle, the authors derived the explicit solution of the model, through which rates of manufacturing and remanufacturing can be balanced effectively. To obtain the optimum production run length, Polotski et al. (2019) studied an imperfect hybrid production system with two failure-prone machines. While one of these machines uses raw materials to manufacture, the other one utilizes end-of-life products for remanufacturing. They evaluated the system performance in terms of long-term discounted costs, which consist of manufacturing, remanufacturing, disposal and inventory holding costs. By optimizing the hybrid system behavior, they determined the combined manufacturing, remanufacturing and disposal strategy that gives considerably good results in an environment with dynamic market conditions and machine failures.

Assid et al. (2019a) structured a new control policy in order to coordinate manufacturing, remanufacturing, disposal and setup operations effectively. Whereas minimizing the total cost, their policy can determine the optimal size of storage space for both finished products and returns. Assid et al. (2019b) proposed a set of joint control strategies, which can make decisions simultaneously regarding manufacturing, remanufacturing and discarding and also return and raw material purchasing processes. They applied a simulation-based optimization technique to calculate the optimal order quantities for returns and raw materials as well as the optimal size of storage space for finished products, while minimizing the total incurred costs.

2.3 IMPACT OF REMANUFACTURING ON BULLWHIP EFFECT

Each member of a supply chain orders from its immediate upstream member and each upstream member takes its inventory and production decisions according to the information coming from its immediate downstream member in form of “orders”. Since this information is liable to be distorted, it may mislead upstream members and cause them to make wrong decisions regarding production and inventory control. Therefore, orders to the supplier can have larger variances than sales to the buyer and this distortion becomes larger whereas one moves upstream, what is called bullwhip effect. Within the supply chain, bullwhip effect can cause different types of inefficiencies in hybrid production systems just as in traditional manufacturing systems (Lee et al., 1997). Remanufacturing in a production system influences not only the variance of production lot sizes but also frequency of production orders and so has a certain impact on the bullwhip effect.

Employing a control engineering methodology, Tang and Naim (2004) designed a production system with product recovery managed by a push policy without any disposal option and studied its dynamic behavior. They concluded that the robustness of a hybrid production system increases with increasing information transparency. Using control theory and simulation methods, Zhou et al. (2006) investigated a hybrid production system in order to get insight into its dynamic performance, low levels of which can increase inventory holding costs, unutilized capacity and thus customer service failures. While the authors utilize an automatic pipeline, inventory and order-based production management system to regulate the manufacturing process, a Kanban policy is adopted to control the remanufacturing process in their study. They analyzed the hybrid production system’s robustness to variations in (re)manufacturing lead times and return yield and concluded that remanufacturing helps to enhance system dynamics performance.

According to Zhou and Disney (2006), larger product return rates help to alleviate bullwhip effect in their hybrid production system. Furthermore, they concluded that it is very hard to find a unique inventory control strategy which both reduces the total inventory cost and alleviate bullwhip effect. By defining the serviceable inventory position in a different way, they suggested Shifted-Pull inventory management strategy and made comparisons between it and some other inventory control strategies in the literature. Huang and Wang (2007) investigated the impact of remanufacturing on the traditional supply chains as regards bullwhip effect and inventory variance. Contrary to the previous results in the literature, bullwhip effect in the closed loop supply chain was greater than in the traditional system in their specific case.

Utilizing statistical modeling approach, Pati et al. (2010) suggested a closed form expression that can determine the impact of variance amplification on a multi-echelon closed-loop supply chain. They investigated the variation of bullwhip effect with return segregation and lead times. As per their study, bullwhip effect is decreased with increasing segregation level at the source. Adopting simulation modeling, Corum et al. (2014) investigated the effect of remanufacturing on total inventory cost and production order variance in traditional and hybrid production systems. They showed that hybrid systems that are managed by push or pull strategy have lower serviceable inventory costs and production order variance than traditional manufacturing systems. Using discrete event simulation, Dev et al. (2017) employed five kinds of inventory control policies without disposal option to manage a hybrid production system which is reviewed periodically or continuously in different scenarios. They concluded that continuous review policies perform better than periodic review policies in terms of order variance in all cases. Furthermore, in terms of total inventory cost they showed that especially by large review periods and return to demand rate ratios continuous review gives worse results than periodic review does.

Dominguez et al. (2019a) studied a multi-echelon closed loop supply chain with variable remanufacturing lead time to find out the effect of information transparency and return rate on system dynamic performance. They concluded that while increased information transparency alleviates bullwhip effect and inventory variability, it may cause larger average inventory positions in case of highly uncertain remanufacturing operations. Utilizing difference equation modeling approach, Dominguez et al. (2019b) studied the dynamic behavior of a hybrid production system with limited production capacity. They showed that the capacity restriction can be utilized to mitigate bullwhip effect even though manufacturing and remanufacturing capacities need to be so adjusted that customer demand is met in a cost-effective manner. Considering a hybrid production system with imperfect correlation between demand and return streams, Ponte et al. (2019) showed that highly variable return rates affect the performance of the system in terms of bullwhip effect. A control structure for controlling the return stream was suggested, which outperforms push control policy and improves the system in terms of profitability and production stabilization. Their study showed that just pushing the returns into the supply chain rather than managing them decreases the system dynamic performance of such closed loop supply chains.

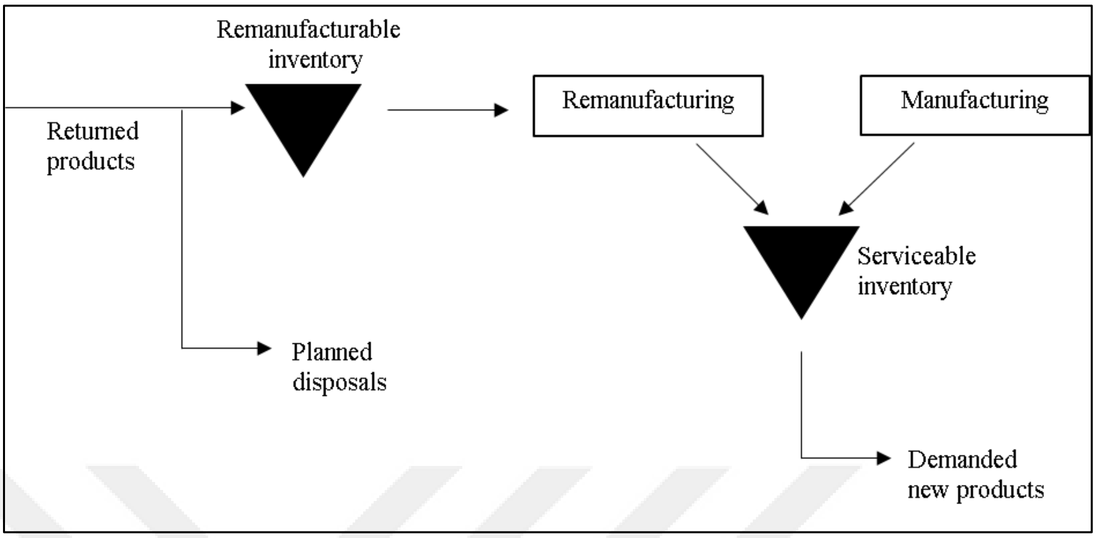
3. DATA AND METHOD

3.1 SYSTEM CHARACTERISTICS

In this thesis, we define two hybrid production systems and compare them in terms of production order variance. These are stochastic hybrid manufacturing and remanufacturing product recovery systems, which are regulated by Push- or Pull-Disposal inventory control policies. We assume continuous review policy to manage inventories that consist of only one single recoverable product. An inventory system obeys (r, Q) policy by classical continuous review policy, which observes the inventory position perpetually and orders a batch of Q items once the inventory position is less than or equal to reorder point r. On the other hand, unlike traditional manufacturing systems, hybrid manufacturing and remanufacturing product recovery systems with disposal option include a remanufacturing process and mostly an additional stock space for returned items (Kiesmuller, 2003; Teunter et al., 2004).

In our system, used products are collected from customers and stored in the remanufacturable inventory area. If the predetermined serviceable inventory position is reached, then upon arrival they are discarded. If not, the producer remanufactures them in accordance with the schedule as determined by the chosen inventory control policy (Push- or Pull-Disposal). Afterwards, the producer stores the remanufactured products in its serviceable stock, where they are treated as good as newly manufactured products and used to meet customer demand. Therefore, in our system customer demand can be met either by manufactured or remanufactured goods. A schematic representation of the hybrid production system under consideration is outlined in Figure 3.1.

Figure 3.1: A hybrid production system with manufacturing, remanufacturing and disposal option

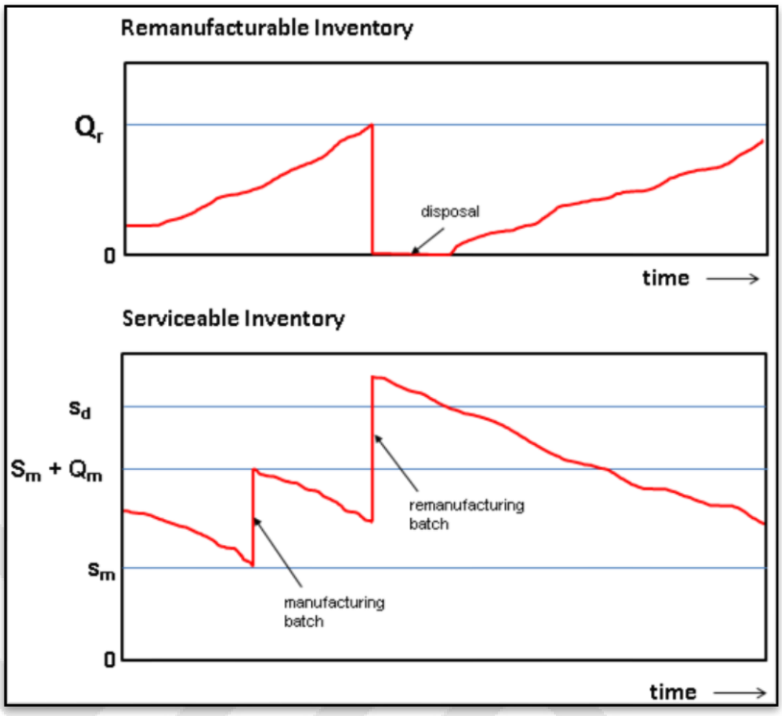


Source: Laan and Salomon (1997)

3.2 STRATEGY DEFINITIONS

Under Push-Disposal inventory control policy (s_m, Q_m, Q_r, s_d) defined by Laan and Salomon (1997), remanufacturing process with lead time L_r is activated whenever the remanufacturable inventory on-hand reaches Q_r (remanufacturing lot size). At that point, remanufacturable products of quantity Q_r are started to be remanufactured, remanufacturable inventory on-hand amounts to zero and the serviceable inventory position increases by the amount Q_r. By this policy, the remanufacturing process is driven totally by the returned products since once the remanufacturable inventory on-hand has enough amount of remanufacturable products, remanufacturing is started immediately. Manufacturing occurs in batches of size Q_m in a lead time of L_m and starts whenever the serviceable inventory position amounts to manufacturing reorder point s_m. An incoming return is discarded upon arrival if the serviceable inventory position is at least as much as the disposal level s_d. Push-Disposal inventory control policy is illustrated in Figure 3.2.

Figure 3.2: Push-Disposal policy

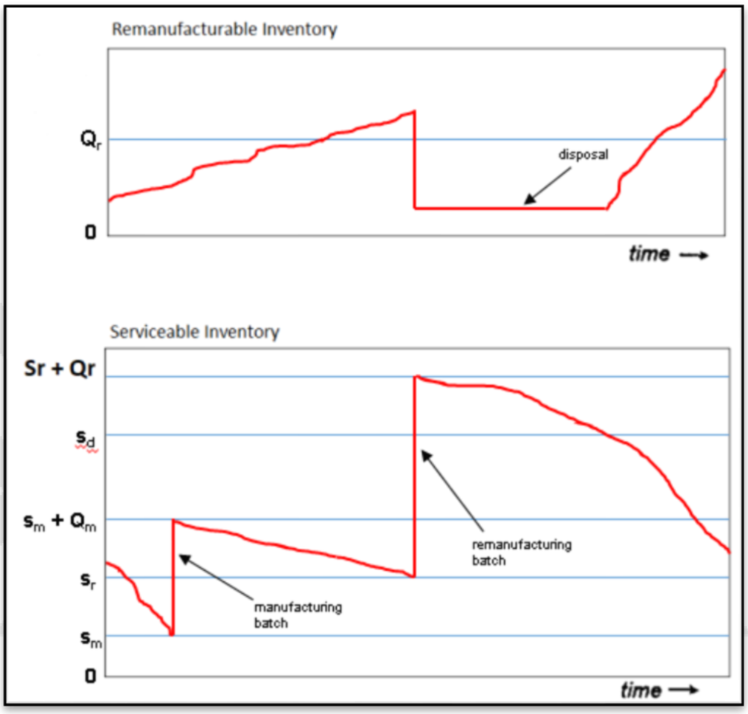


Source: Laan and Salomon (1997)

Under Pull-Disposal inventory control policy (s_m, Q_m, s_r, Q_r, s_d) defined by Laan and Salomon (1997), once the serviceable inventory position drops below the remanufacturing reorder point s_r, it is perpetually verified whether there are enough remanufacturable products in order to increase the serviceable inventory position by the amount of remanufacturing batch size of Q_r. If the sufficient amount of remanufacturable products is available, then the remanufacturing process having a lead time of L_r is activated, remanufacturable inventory on-hand decreases by the amount of Q_r, and the serviceable inventory position increases by Q_r. Nonetheless, once the serviceable inventory position is less than or equal to the manufacturing reorder point s_m and still the remanufacturable inventory on-hand does not have enough remanufacturable products to increase the serviceable inventory position by the amount Q_r, then the manufacturing process with lead time of L_m is activated to increase the serviceable inventory position in an amount of Q_m. An incoming return is discarded upon arrival if the serviceable inventory position is at least as much as the disposal level s_d. By Pull-Disposal policy, illustrated in Figure 3.3, one remanufactures items when deemed necessary and hence the remanufacturing process is started as late as possible.

While by Pull-Disposal strategy, remanufacturing is started considering both serviceable and remanufacturable inventory and thus the remanufacturing process is activated as late as possible, Push-Disposal strategy starts remanufacturing once the remanufacturable stock on-hand reaches the predetermined level.

Figure 3.3: Pull-Disposal policy



Source: Laan and Salomon (1997)

3.3 SIMULATION MODEL

One of the widely employed methods for investigating the closed-loop chain performance is simulation (Ilgin and Gupta, 2010). In this regard, discrete event simulation modeling is adopted to imitate the hybrid production system studied in this thesis. 128 distinct scenarios for each inventory control policy (Push-Disposal and Pull-Disposal) regulating the hybrid production system are generated and simulated during 1500 time periods using Arena software (by Rockwell Software Inc.). After spotting that the average serviceable inventory position needs 500 periods to reach steady state at the beginning, the first 500 periods are counted as the warm-up period and not taken into account to exclude the initial setup effect. Furthermore, in order to estimate the key performance metric of the simulated system within 95 percent confidence interval, 10 replications for each scenario are conducted.

Additionally, we verify our simulation models in order to guarantee that they function as expected (Kelton et al., 2010). We apply various methods to verify our models. Firstly, a detailed animation is created to watch system activities. Then, to observe the robustness of the system we use some constants instead of randomly distributed simulation parameters. It turns out that in our simulation models Push- and Pull-Disposal inventory control policies behave as intended and provide satisfactory performance.

3.4 MODEL PARAMETERS

Simulation parameters and their values are given in Table 3.1 in alignment with Dev et al. (2017) and their effect on production order variance is studied. We call the combination of recoverable inventory cost, variable manufacturing cost and variable remanufacturing cost values listed in this table as cost structure. Since the impact of these parameters on inventory costs in such hybrid production systems has already been thoroughly studied by many researchers (Laan et al., 1996a; Laan et al., 1996b; Laan and Salomon, 1997; Inderfurth, 1997; Teunter and Vlachos, 2002; Zanoni et al., 2006; Gallo et al., 2009; Kim et al., 2013; Dev et al., 2017; Gayon et al., 2017), we try to understand their effect on production order variance. Return and demand processes are independent of each other and modeled using Poisson distribution. We base our disposal decisions on the serviceable inventory position and choose such disposal levels that at the end of a simulation run we have average disposal quantities per time period as listed in Table 3.1. Unmet demand is lost and, not only manufacturing but also remanufacturing lead time of one lot is normally distributed with a constant variance. In the literature, similar assumptions are encountered commonly (Laan and Salomon, 1997; Inderfurth, 1997; Zanoni et al., 2006; Corum et al., 2014; Dev et al., 2017). Moreover, in accordance with Dev et al. (2017) unit costs of returned products, remanufactured products, and manufactured products may take one of the values ($20, $70, $200) or ($75, $180, $200) respectively. These value sets enable us to observe the effect of low and high remanufacturing profitability levels clearly. In the calculation of inventory carrying costs, inventory holding rate (i) might take two alternative values that are 5 percent and 30 percent per 1000 periods. While the fixed cost to start remanufacturing process might have one of the alternative values that are \$50 or \$10 per batch, the fixed cost to activate manufacturing process has the unique value of \$50 per batch in each scenario.

Scenarios are generated by varying the parameters depending on lead times ratio (L_m/L_r), disposal rate (λ_P) over recovery rate (λ_R/λ_D), inventory holding cost rate, remanufacturing setup cost over manufacturing setup cost, variable production costs and return value. In our experiments, most of the parameters have only two levels, which are selected very differently so that the influence of the respective parameter on production order variance can be observed apparently. For remanufacturing batch size estimation, carrying cost of recoverable inventory is calculated as a net unit contribution of remanufacturing relative to manufacturing as proposed by Teunter (2001). Disposal costs are assumed to be zero. These cost parameters considered are consistent with the literature (Laan and Salomon, 1997; Lund and Hauser, 2010; Corum et al, 2014; Dev et al., 2017).

Through an EOQ based approach, manufacturing and remanufacturing lot sizes (Q_m and Q_r) for each inventory control policy are calculated, whereas we compute the reordering levels utilizing the formulas below. Note that they are very similar to those used in the traditional perpetually reviewed reorder level inventory models for uncertain demand and lead time case. Consistent with Dev et al. (2017), priority is given to the remanufacturing process in these formulas, where z is standard normal random variable for a stockout probability of 10 percent.

$$S_m = \lambda_D * L_m + z\sqrt{L_m * \lambda_D + \lambda_D^2 * (\sigma_m)^2}$$

$$S_r = \text{Max}\left\{\lambda_D * L_r + z\sqrt{L_r * \lambda_D + \lambda_D^2 * (\sigma_r)^2} \;, S_m\right\}$$

For the simulation models, system performance is evaluated by production order variance which is our key performance metric and causes bullwhip effect. We are interested in the impact of disposal on production order variance in our hybrid production system. Production order variance is computed by considering lot sizes data and both numbers of manufacturing and remanufacturing setups that are collected during each simulation run. Since the variance of demand within the simulation is constant, the bullwhip effect is also accounted for.

Table 3.1: Simulation parameters

Parameter	Distribution	Values
Demand rate (λ_D) (units/period)	Poisson	100
Return rate (λ_R) (units/period)	Poisson	90
Disposal rate (λ_P) (units/period)		0
		5
		10
		15
		25
		40
		60
		90
Remanufacturing lead time (periods/batch)	N (L_r,σ_r^2)	N (4,4)
Manufacturing lead time (periods/batch)	N (L_m,σ_m^2)	N (2,1)
		N (8,1)
Remanufacturing setup cost (K_r) (\$/batch)		10
		50
Manufacturing setup cost (K_m) (\$/batch)		50
Inventory holding rate (i) (%/1000 periods)		5
		30
Recoverable inventory cost (c_n) (\$/unit)		20
		75
Remanufacturing variable cost (c_r) (\$/unit)		70
		180
Manufacturing variable cost (c_m) (\$/unit)		200
Stockout probability during lead time (%)		10

4. RESULTS AND DISCUSSION

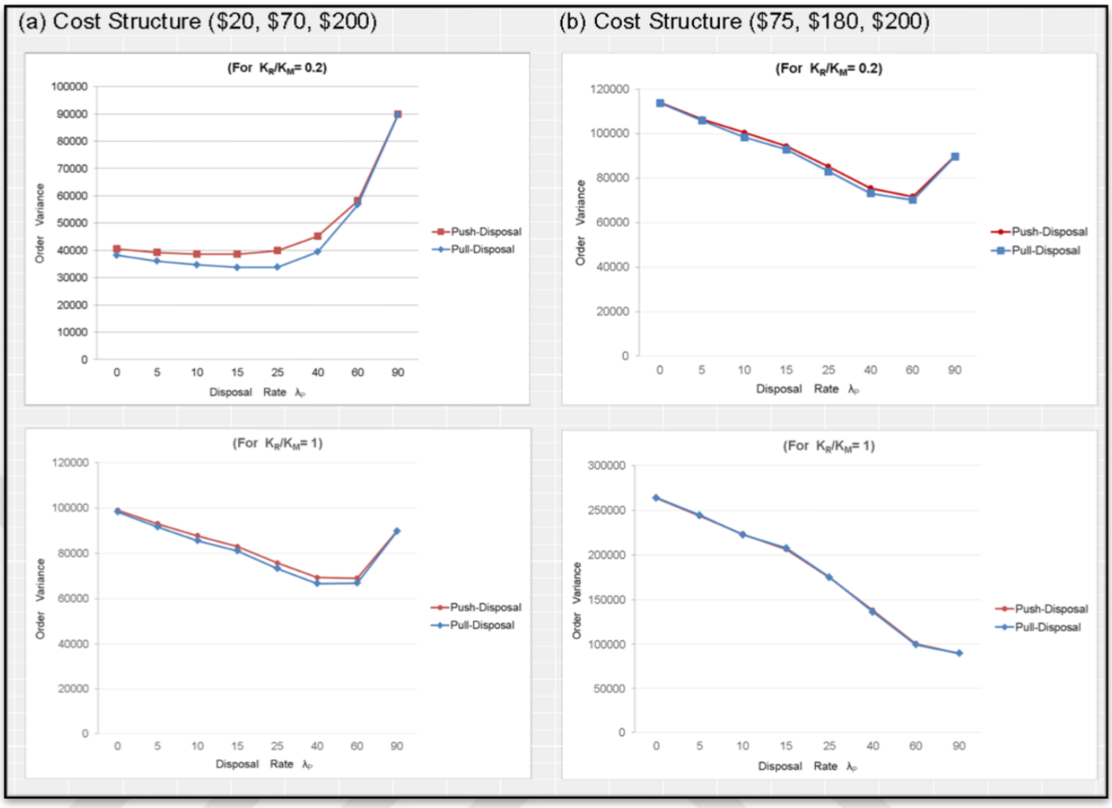
In this section, system performance as regards production order variance is investigated by changing important system parameters. In order to compute production order variance in our hybrid production system with disposal option, we consider not only manufacturing but also remanufacturing order placements. In Figures 4.1-4.4, production order variances for both Push- and Pull-Disposal strategies are depicted as regarding the average disposal rate λP for different cost parameters and lead time ratios. Through these figures, it is clearly observed that production order variance values for Push- and Pull-Disposal policies are very close to each other. It is mainly because these policies have the same manufacturing and remanufacturing batch quantities and very close number of setups for various disposal rates. This is also in agreement with the findings of Corum et al. (2014). Furthermore, since the stocks are reviewed perpetually, (re)manufacturing lot sizes and number of orders don't change with lead times of (re)manufacturing. Consequently, in accordance with Dev et al. (2017) increasing value of manufacturing lead time does not affect production order variance by Push- or Pull-Disposal policy. Nonetheless, production order variance values show different tendencies under different parameter combinations as explained in the sequel.

In Figure 4.1, production order variance values for Push- and Pull-Disposal strategies are depicted with respect to average disposal rate λ_P for different parameter combinations. Notice that, by the parameter set of Figure 4.1.a1 remanufacturing is more favorable than disposal in terms of cost due to relatively low remanufacturing and inventory holding costs. Since during the simulation we order either in amount of EOQ or zero, in our hybrid production systems magnitude of order variance depends on values of re(manufacturing) lot sizes Q_r and Q_m and total number of re(manufacturing) setups. As smaller and more frequent orders help to mitigate order variance, total number of time periods during which order amount is zero is also an important factor for the magnitude of order variance.

In Figure 4.1.a1, order variance first decreases and then increases due to disposal. At the beginning, as the disposal rate starts to increase from zero, amount of Q_r also decreases simultaneously, and causes order variance also to decrease. Although Q_m value increases because of disposal during these beginning stages, its impact on order variance is very limited due to the relatively low number of manufacturing setup. During these beginning stages, the system rarely needs to manufacture because of relatively high number of returns. However, in final stages amount of manufacturing lot size increases considerably while remanufacturing lot size decreases up to zero because of disposal, what increases order variance. Remanufacturing does not help mitigate order variance until average disposal rate is approximately 15 units per time period. After that point, while we can remanufacture less and less due to disposal, amount of order variance starts to increase.

Disposal causes order variance to decrease in Figure 4.1.b2, in contrast to previous case described by Figure 4.1.a1. Notice that, by the parameter combination of Figure 4.1.b2 disposing a return is more favorable than remanufacturing in terms of cost because of relatively high remanufacturing and inventory holding costs. As disposal rate starts to increase from zero, amount of Q_r also decreases simultaneously, and causes also order variance to decrease. Although Q_m value increases due to disposal, its impact on order variance is very limited due to relatively small magnitude of manufacturing lot size. In addition, the amount of the increase in manufacturing lot size is relatively small as regards the decrease in remanufacturing batch size. Therefore, the decrease in remanufacturing lot size has a dominating effect and causes order variance to decrease as the disposal rate increases. With the parameter set applied, remanufacturing does not help reduce order variance because when we remanufacture less frequently due to disposal then we have smaller order variance values. As can be concluded from these cases, impact of remanufacturing on order variance depends strongly on the parameter setting and it might lead to better or worse production order variance values.

Figure 4.1: Production order variances (L_m= 2, L_r= 4, i= 5%)



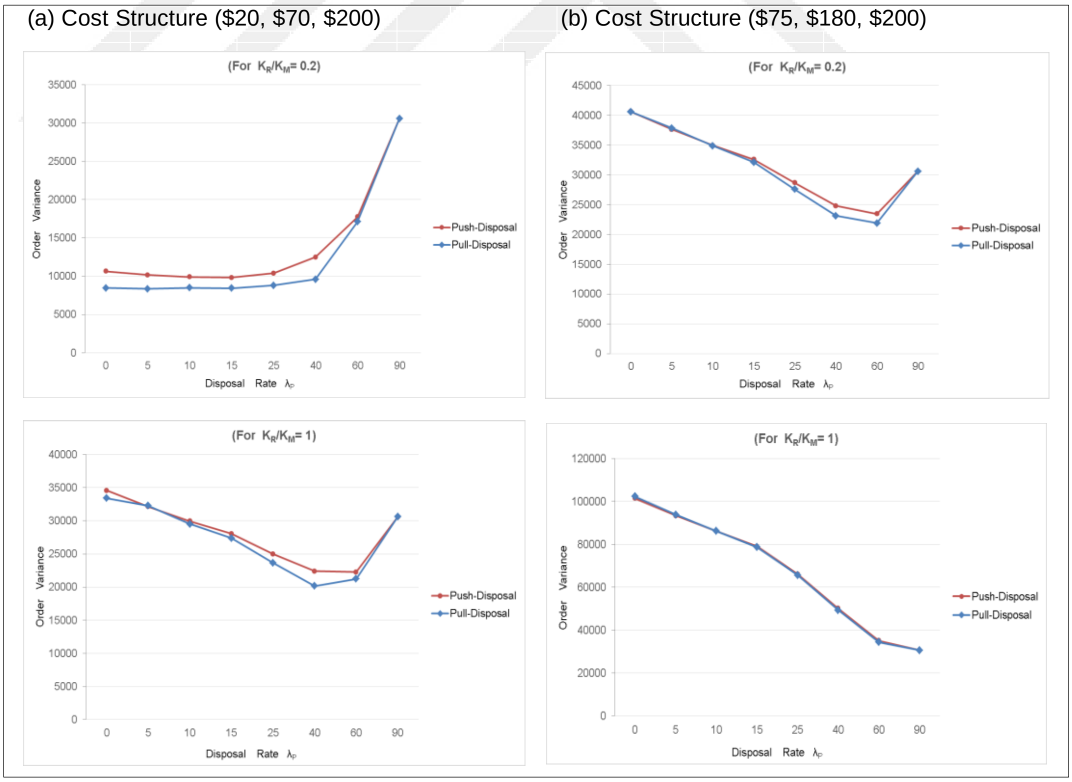
In Figure 4.1.a2, disposal causes order variance to decrease up to the point where average disposal rate is approximately 60 units per time period. Till that point, although the number of remanufacturing setups decreases and the manufacturing lot size increases, the reduction in remanufacturing lot size and the increase in the manufacturing number of setups have a dominating effect and cause order variance to decrease as the disposal rate increases. When all the returns are disposed of (i.e., λ_P= 90), order variance increases to a value, which is higher than the order variance value reached by average disposal rate of approximately 10 units per time period.

In Figure 4.1.b1, order variance decreases with disposal up to the level, at which average amount of disposal per time period amounts to approximately 60 units. Till that level, although number of remanufacturing setups decreases and manufacturing lot size increases, the reduction in remanufacturing lot size and the increase in manufacturing number of setups have a dominating effect and lead to a reduction in order variance values as the disposal rate increases. After the level where average disposal rate is about

60 units per time period, order variance starts to increase and when all of the returns are discarded (i.e., λ_P= 90), it reaches a level, which is higher than the order variance level by average disposal rate of approximately 25 units per time period. Note that, on average, order variance values of Figure 4.1.b1 are smaller than that of Figure 4.1.b2 because of smaller remanufacturing batch sizes resulting from smaller remanufacturing setup cost. Furthermore, it can be seen clearly that the unique parameter difference between Figure 4.1.a1 and Figure 4.1.b1 is the cost structure and it influences the trends considerably.

With a different value of inventory holding rate, it is observed that all the trends shown in Figure 4.2 are very similar to the corresponding ones in Figure 4.1. Nonetheless, order variance values in Figure 4.2 come out to be smaller due to smaller lot sizes computed through EOQ formula.

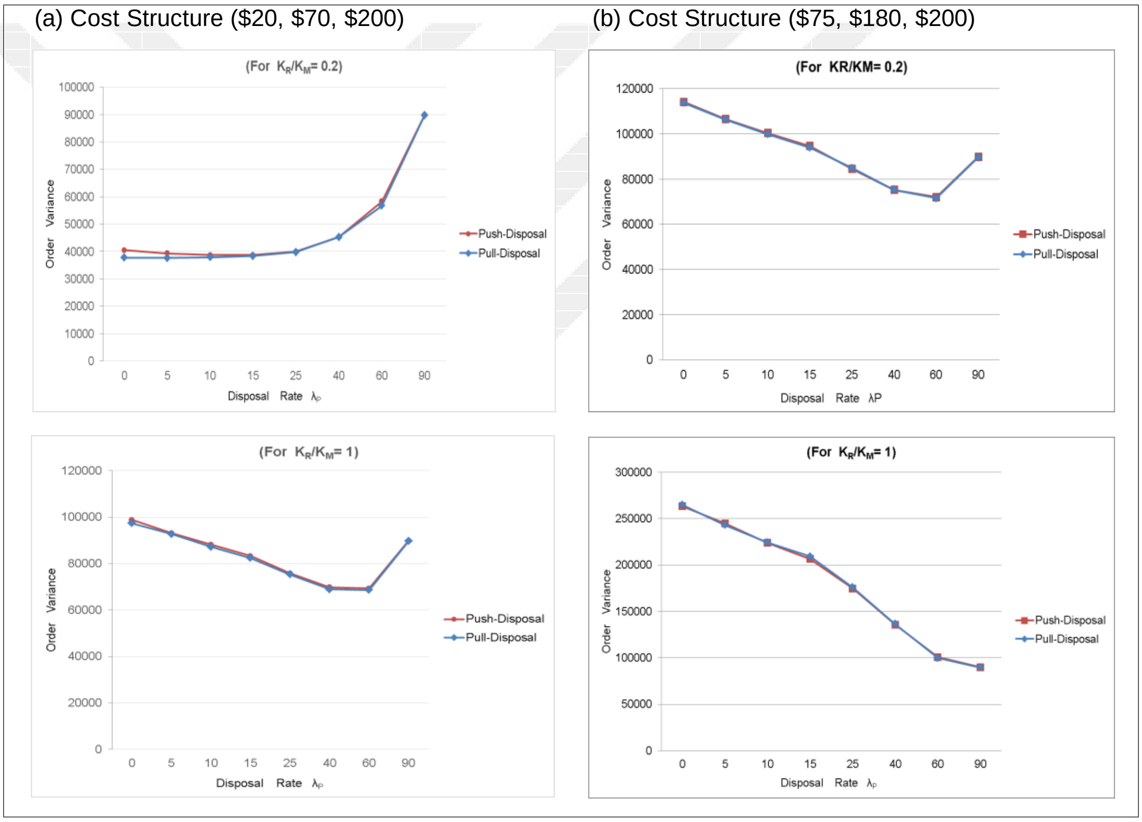
Figure 4.2: Production order variances (L_m=2, L_r=4, i=30 %)


(a) Cost Structure ($20, $70, $200)

(b) Cost Structure ($75, $180, $200)

The unique difference between the values of parameters of Figure 4.1 and Figure 4.3 is the value of manufacturing lead time. However, it is apparent that all the trends presented in Figure 4.3 are very similar to the corresponding ones observed in Figure 4.1. Despite the manufacturing lead time difference between these two groups of diagrams, corresponding order variance values in Figure 4.3 are very close to those in Figure 4.1 due to very small and negligible differences in number of setups and the same lot sizes. This result is consistent with Dev et al. (2017). The same behavior can also be observed between Figures 4.2 and 4.4, where inventory holding rates have a greater value relative to those of Figures 4.1 and 4.3.

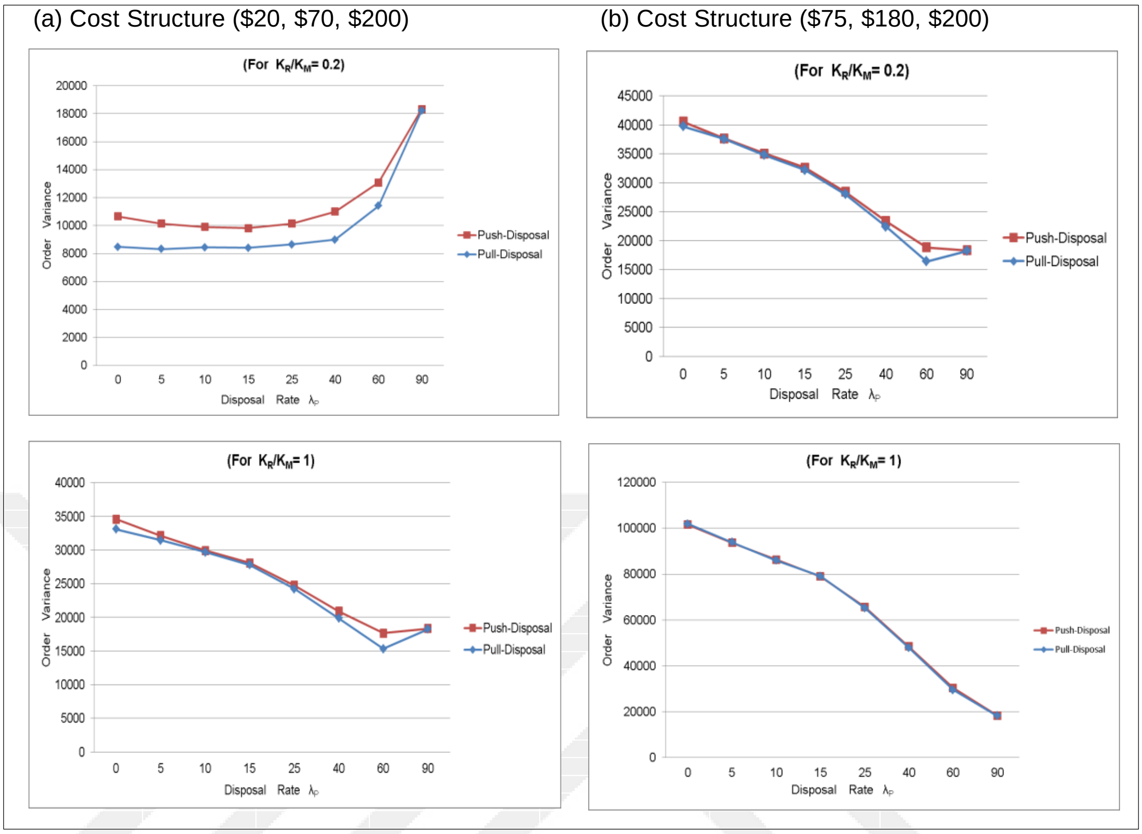
Figure 4.3: Production order variances (L_m= 8, L_r= 4, i= 5%)



(a) Cost Structure ($20, $70, $200) (b) Cost Structure ($75, $180, $200)

With a different inventory holding rate, it is clearly seen that all the trends shown in Figure 4.4 are very similar to the corresponding ones in Figure 4.3. However, order variance values in Figure 4.4 come out to be smaller than those of Figure 4.3 because of the higher value of inventory holding rate used in the calculation of economic order quantities.

Figure 4.4: Production order variances (L_m=8, L_r=4, i=30 %)


(a) Cost Structure ($20, $70, $200)

(b) Cost Structure ($75, $180, $200)

Note further that even if inventory holding rate and lead time ratio are varied simultaneously as in Figures 4.1 and 4.4, the trends remain almost the same. However, production order variance values change due to differing lot sizes, which is a result of different inventory holding rate values used in EOQ calculations. It is also observed that by cost structure of ($75, $180, $200), an increase in remanufacturing setup cost relative to manufacturing setup cost doesn’t affect the trends profoundly. On the other hand, by cost structure of ($20, $70, $200) a remanufacturing setup cost increase considerably changes the trends. Additionally, it is clearly seen that when the setup cost ratio is 0.2, change of cost structure affect the trends noticeably. Nonetheless, if the setup cost ratio is 1, then cost structure change doesn’t cause substantial differences in trends.

To sum up, it is observed that diagrams shown in Figure 4.1 to 4.4 have the same trends and the parameters that affect production order variance trends mostly are setup cost ratio, cost structure, and disposal rate. A variation in the value of inventory holding rate affects only values of production order variance rather than its trends. Any change in policy or lead time ratio doesn’t affect production order variance values or its trends markedly. Furthermore, traditional manufacturing system, which corresponds to the scenarios with average disposal rate of 90 units per time period in our cases, may have lower production order variance values than hybrid production systems depending on the parameter setting used.

5. CONCLUSION

Over the past decade, interest in recovery of used goods in various industries has been growing rapidly due to several motives such as ethical concerns, increased profitability, environmental legislations, secured spare part supply, brand protection and enhanced market share through green image. There are many alternative methods to recover material and/or value such as recycling, repair, cannibalization, refurbishing, and remanufacturing. Since used products are enhanced at least to the quality as well as technology level of new products by replacing worn out parts with new ones, remanufacturing is known to be a value recovery process. As regards production costs, it is considerably more effective to reuse the components in manufacturing of other products than recycling, which recovers only material. In hybrid production systems, (re)manufacturing processes are used cooperatively in order to fulfill the customer demand.

We believe that this study offers important insights into the return disposal's effect on production order variance of hybrid production systems, which causes bullwhip problem. In this study, we compared Push- and Pull-Disposal inventory control policies in terms of production order variance with different scenarios based on various combinations of disposal rates, (re)manufacturing setup costs and lead times, return values, variable manufacturing and remanufacturing costs, and inventory holding rates. The impact of several production system parameters on production order variance was investigated via discrete-event simulation models which were developed using simulation software Arena. Totally 256 simulation experiments have been conducted and analyzed. It turned out that both policies have almost the same performance with respect to production order variance.

While in some scenarios having higher disposal rates leads to lower production order variance values, in others it results in higher production order variance values depending on the parameter set. In this regard, traditional manufacturing system, which corresponds to a disposal rate of 90 units per time period in our relevant scenarios, may impose better production order variance values than hybrid production systems. However, an increase in manufacturing lead time has no significant impact on production order variance by both control policies. In addition, it is invariably complicated to plan and control such hybrid production and inventory systems. Furthermore, depending on the valuation of recoverable and serviceable inventories different results may come out. Therefore, companies that plan to remanufacture with disposal option should take all the costs into account properly by their feasibility calculations. Because while hybrid production systems with a disposal option can increase the profitability through storage place savings, inventory cost reduction, and value recovery, high levels of production order variance may increase the cost and decrease the profitability.

A further development of this study could be investigating the impact of production capacity restriction on production order variance in such hybrid systems. Furthermore, investigating the impact of different uncertainty levels of return flow on bullwhip effect in hybrid production systems managed by various inventory control strategies, could be another possible extension of this research.

REFERENCES

Books

Kelton, W.D., Sadowski, R.P. and Swets, N.B., 2010. *Simulation with Arena*, fifth ed. McGraw-Hill.

Periodicals

Ahiska, S.S., Gocer, F. and King, R.E., 2017. Heuristic inventory policies for a hybrid manufacturing/remanufacturing system with product substitution. *Computers & Industrial Engineering*, 114, pp.206-222.

Assid, M., Gharbi, A. and Hajji, A., 2019. Production and setup control policy for unreliable hybrid manufacturing-remanufacturing systems. *Journal of Manufacturing Systems*, 50, pp.103-118.

Assid, M., Gharbi, A. and Hajji, A., 2019. Production planning of an unreliable hybrid manufacturing– remanufacturing system under uncertainties and supply constraints. *Computers & Industrial Engineering*, 136, pp.31-45.

Corum, A., Vayvay, Ö. and Bayraktar, E., 2014. The impact of remanufacturing on total inventory cost and order variance. *Journal of Cleaner Production*, 85, pp.442-452.

Dev, N.K., Shankar, R. and Choudhary, A., 2017. Strategic design for inventory and production planning in closed-loop hybrid systems. *International Journal of Production Economics*, 183, pp.345-353.

Dhaiban, A.K., Baten, M.A. and Aziz, N., 2018. An optimal inventory control in hybrid manufacturing/remanufacturing system with deteriorating and defective items. *International Journal of Mathematics in Operational Research*, 12(1), pp.66-90.

Dobos, I., 2003. Optimal production–inventory strategies for a HMMS-type reverse logistics system. *International Journal of Production Economics*, 81, pp.351-360.

Dominguez, R., Cannella, S., Ponte, B. and Framinan, J.M., 2019a. On the dynamics of closed-loop supply chains under remanufacturing lead time variability. *Omega*, p.102106.

Dominguez, R., Ponte, B., Cannella, S. and Framinan, J.M., 2019b. On the dynamics of closed-loop supply chains with capacity constraints. *Computers & Industrial Engineering*, 128, pp.91-103.

Fang, C.C., Lai, M.H. and Huang, Y.S., 2017. Production planning of new and remanufacturing products in hybrid production systems. *Computers & Industrial Engineering*, 108, pp.88-99.

Gayon, J.P., Vercraene, S. and Flapper, S.D.P., 2017. Optimal control of a production-inventory system with product returns and two disposal options. *European Journal of Operational Research*, 262(2), pp.499-508.

Guide Jr, V.D.R., 2000. Production planning and control for remanufacturing: industry practice and research needs. *Journal of Operations Management*, 18(4), pp.467-483.

Heyman, D.P., 1977. Optimal disposal policies for a single- item inventory system with returns. *Naval Research Logistics Quarterly*, 24(3), pp.385-405.

Ilgin, M.A. and Gupta, S.M., 2010. Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art. *Journal of Environmental Management*, 91(3), pp.563-591.

Inderfurth, K., 1997. Simple optimal replenishment and disposal policies for a product recovery system with leadtimes. *Operations-Research-Spektrum*, 19(2), pp.111-122.

Kerr, W. and Ryan, C., 2001. Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia. *Journal of Cleaner Production*, 9(1), pp.75-81.

Kiesmüller, G.P. and Van der Laan, E., 2001. An inventory model with dependent product demands and returns. *International Journal of Production Economics*, 72(1), pp.73-87.

Kiesmüller, G.P., 2003. A new approach for controlling a hybrid stochastic manufacturing/remanufacturing system with inventories and different leadtimes. *European Journal of Operational Research*, 147(1), pp.62-71.

Kim, E., Saghafian, S. and Van Oyen, M.P., 2013. Joint control of production, remanufacturing, and disposal activities in a hybrid manufacturing–remanufacturing system. *European Journal of Operational Research*, 231(2), pp.337-348.

Kim, E.G., 2007. Optimal disposal policy in a hybrid production system with manufacturing and remanufacturing. *Journal of the Korean Institute of Industrial Engineers*, 33(3), pp.312-321.

Kleber, R., Minner, S. and Kiesmüller, G., 2002. A continuous time inventory model for a product recovery system with multiple options. *International Journal of Production Economics*, 79(2), pp.121-141.

Lee, H.L., Padmanabhan, V. and Whang, S., 1997. Information distortion in a supply chain: The bullwhip effect. *Management Science*, 43(4), pp.546-558.

Nikoofal, M.E. and Moattar Husseini, S.M., 2010. An inventory model with dependent returns and disposal cost. *International Journal of Industrial Engineering Computations*, 1(1), pp.45-54.

Ozcan, S. and Corum, A., 2019. A Scientometric Analysis of Remanufacturing by Mapping Scientific, Organizational, and National Concentration Zones. *IEEE Transactions on Engineering Management*.

Pati, R.K., Vrat, P. and Kumar, P., 2010. Quantifying bullwhip effect in a closed loop supply chain. *Opsearch*, 47(4), pp.231-253.

Pinçe, Ç., Gürler, Ü. and Berk, E., 2008. A continuous review replenishment–disposal policy for an inventory system with autonomous supply and fixed disposal costs. *European Journal of Operational Research*, 190(2), pp.421-442.

Polotski, V., Kenné, J.P. and Gharbi, A., 2019. Production control of hybrid manufacturing–remanufacturing systems under demand and return variations. *International Journal of Production Research*, 57(1), pp.100-123.

Ponte, B., Naim, M.M. and Syntetos, A.A., 2019. The value of regulating returns for enhancing the dynamic behaviour of hybrid manufacturing-remanufacturing systems. *European Journal of Operational Research*, 278(2), pp.629-645.

Schrady, D.A., 1967. A deterministic inventory model for reparable items. *Naval Research Logistics Quarterly*, 14(3), pp.391-398.

Simpson, V.P., 1978. Optimum solution structure for a repairable inventory problem. *Operations Research*, 26(2), pp.270-281.

Takahashi, K., Morikawa, K., Takeda, D. and Mizuno, A., 2007. Inventory control for a Markovian remanufacturing system with stochastic decomposition process. *International Journal of Production Economics*, 108(1-2), pp.416-425.

Tang, O. and Naim*, M.M., 2004. The impact of information transparency on the dynamic behaviour of a hybrid manufacturing/remanufacturing system. *International Journal of Production Research*, 42(19), pp.4135-4152.

Teunter, R., Van der Laan, E. and Vlachos, D., 2004. Inventory strategies for systems with fast remanufacturing. *Journal of the Operational Research Society*, 55(5), pp.475-484.

Teunter, R.H. and Vlachos, D., 2002. On the necessity of a disposal option for returned items that can be remanufactured. *International Journal of Production Economics*, 75(3), pp.257-266.

Teunter, R.H., 2001. Economic ordering quantities for recoverable item inventory systems. *Naval Research Logistics* (NRL), 48(6), pp.484-495.

Thierry, M., Salomon, M., Van Nunen, J. and Van Wassenhove, L., 1995. Strategic issues in product recovery management. *California Management Review*, 37(2), pp.114-136.

Vadde, S., Zeid, A. and Kamarthi, S., 2014. Optimal pricing and disposal decisions for product recovery facilities under a single portfolio. *International Journal of Collaborative Enterprise*, 4(3), pp.160-187.

Van der Laan, E. and Salomon, M., 1997. Production planning and inventory control with remanufacturing and disposal. *European Journal of Operational Research*, 102(2), pp.264-278.

Van der Laan, E. and Teunter, R.H., 2006. Simple heuristics for push and pull remanufacturing policies. *European Journal of Operational Research*, 175(2), pp.1084-1102.

Van der Laan, E., Dekker, R. and Salomon, M., 1996b. Product remanufacturing and disposal: A numerical comparison of alternative control strategies. *International Journal of Production Economics*, 45(1-3), pp.489-498.

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

Van der Laan, E., Salomon, M. and Dekker, R., 1995. Production planning and inventory control for remanufacturable durable products [R]. *ERASM Management Report Series*, 175.

Van Der Laan, E., Salomon, M., Dekker, R. and Van Wassenhove, L., 1999. Inventory control in hybrid systems with remanufacturing. *Management Science*, 45(5), pp.733-747.

Zanoni, S., Ferretti, I. and Tang, O., 2006. Cost performance and bullwhip effect in a hybrid manufacturing and remanufacturing system with different control policies. *International Journal of Production Research*, 44(18-19), pp.3847-3862.

Zhou, L. and Disney, S.M., 2006. Bullwhip and inventory variance in a closed loop supply chain. *Or Spectrum*, 28(1), pp.127-149.

Zhou, L., Naim, M.M., Tang, O. and Towill, D.R., 2006. Dynamic performance of a hybrid inventory system with a Kanban policy in remanufacturing process. *Omega*, 34(6), pp.585-598.

Other Publications

Gallo, M., Grisi, R., Guizzi, G. and Romano, E., 2009, October. A comparison of production policies in remanufacturing systems. *In Proceedings of the 8th WSEAS International Conference on System Science and Simulation in Engineering, ICOSSSE '09 (p. 334).*

Huang, L. and Wang, Q., 2007, July. The bullwhip effect in the closed loop supply chain. *In Conference Proceedings, The 2007 International Conference of the Systems Dynamics Society, Boston, Massachusetts, USA.*

Lund, R. T., & Hauser, W. M., 2010. Remanufacturing-an American perspective. *5th International Conference on Responsive Manufacturing - Green Manufacturing. Ningbo China.*

Ouyang, H. and Zhu, X., 2006, June. An Inventory Control System for Remanufacture with Disposal. *In 2006 IEEE Conference on Robotics, Automation and Mechatronics (pp. 1-5). IEEE.*

Richter, K., 1994, February. An EOQ repair and waste disposal model. *In Proceedings of the Eighth International Working Seminar on Production Economics (Vol. 3, p. 21). Amsterdam, The Netherlands: Elsevier.*

Van der Laan, E., 1997. The effects of remanufacturing on inventory control, *Ph.D. thesis, Erasmus University Rotterdam, The Netherlands.*