Analysis of Downward Product Substitution in a Recoverable System

Fethullah Gocer[1], S. Sebnem Ahiska[1] and Russell E. King[2]
[1]*Industrial Engineering Department, Galatasaray University, Ortakoy, Istanbul, 34349, Turkey*
[2]*Edward P. Fitts Department of Industrial and Systems Engineering, North Carolina State University, Raleigh, NC, U.S.A.*

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Abstract: We consider the inventory control problem for an infinite-horizon stochastic hybrid manufacturing / remanufacturing system with product substitution under stochastic demand and returns. Remanufactured and manufactured products are considered as two different products, having different costs and selling prices as well as separate demand streams. Remanufactured products have a higher stock out risk because the remanufacturing capacity is mainly dependent on the amount of returns available for remanufacture. One way to cope with the stock-out issue for remanufactured products is to use a downward substitution strategy, which allows a manufactured product (i.e. higher value item) to be substituted for a remanufactured product (i.e. lower value item) in case the latter runs out of stock. We formulate this problem as Markov Decision Process in order to determine the optimal manufacturing and remanufacturing decisions under product substitution, and through numerical experimentation, we investigate the effects of stochastic demand/return distributions on the profitability of the substitution strategy.

1 INTRODUCTION

More and more manufacturers are collecting back their products from customers after usage or at the end of their life due to both environmental regulations and concerns as well as the potential economic benefits of product recovery. Product recovery, especially remanufacturing, can substantially reduce the resource consumption and waste disposal, which consequently results in savings in material, energy and disposal costs.

During the early years of the remanufacturing operations, manufacturers considered only savings in costs. As governments tighten environmental laws and regulations, many manufacturers are required to incorporate product recovery activities where a significant portion of production uses recovered material. As product returns increase, the profitability of hybrid recoverable manufacturing systems increase (Robotis et al., 2005). While manufacturers often consider remanufacturing as an obligation forced by government regulations, in recent years, they have also realized that customers may also prefer remanufactured products for the price advantage as well as environmental awareness.

In this study, we consider inventory control of a hybrid manufacturing/remanufacturing system, which has two modes of supply in order to satisfy customer demand: manufacturing of new items and remanufacturing of returned items. Here production planning and control focuses on the effective utilization of resources in order to satisfy customer demand in a cost-efficient manner. In a hybrid system where the new and remanufactured items are viewed as not having the same value, there are mainly three types of inventories: manufactured items, returned items and remanufactured items. Here, we consider product substitution among manufactured and remanufactured items to mitigate lost sales (backorders) in a cost effective way.

In most hybrid systems studies, the manufactured and remanufactured items are assumed to be alike; therefore they are stored in the same serviceable inventory and have a common demand stream. In some cases though, customers may perceive lower quality in a remanufactured item and expects to pay less for it than for a new item resulting in a segmented market among the items. When manufactured and remanufactured items are non-identical, product substitution may be used in case of a stock-out. The substitution style varies depending on whether it is customer- or manufacturer-driven. Under 'upward substitution' a customer demanding a newly manufactured product agrees to accept a

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remanufactured product. This customer driven process is known as two-way substitution such that when a customer's first-choice product is out-of-stock, he/she buys a similar product within same category (Huang et al., 2011). Alternatively, 'downward substitution' (or one-way substitution) is manufacturer-driven such that a higher-value item is substituted for a stocked-out lower-value item. This strategy is commonly used by automotive spare part manufacturers, e.g. for parts such as injectors and engine starters (Ahiska et al., 2013).

We analyse a periodically reviewed stochastic hybrid manufacturing/remanufacturing system under downward substitution. Using a Markov decision process (MDP), we find optimal inventory control (i.e. optimal manufacturing and remanufacturing decisions). Our research extends earlier research by numerically investigating how the profitability of a product substitution strategy is affected by the characteristics of the demand/return distributions.

2 LITERATURE REVIEW

Hybrid manufacturing and remanufacturing systems are more difficult to control than the traditional pure manufacturing systems due to many factors. First, the flow of product returns in terms of quantity and timing is uncertain. Second, the manufacturing and remanufacturing processes are usually interrelated because they either share common production resources (such as common storage area, production line or workforce) or produce products that are substitutable. Hence, for an efficient control of manufacturing and remanufacturing systems, the coordination between them is essential. The inventory management of hybrid production systems has received significant attention in the literature over the last couple of decades. However, the studies that specifically analyse the use of product substitution strategies in these systems are scarce. Most of these studies consider a single-period setting. Inderfurth (2004) investigates analytically the structure of optimal inventory policy for a hybrid system under one-way product substitution in a single-period setting. Kaya (2010) considers partial substitution of manufactured and remanufactured products in a single-period newsvendor setting. Jin et al. (2007) use a threshold level to control when to offer new products as substitutes for remanufactured products in a single-period monopoly setting. Robotis et al. (2005) consider a single-period multi-product stochastic system with downward substitution where there is only remanufacturing of the used products. Considering the quality of the used items, some portion of them is resold to secondary markets while the remaining part is remanufactured. Bayindir et al. (2005) use a continuous-review inventory policy to control the hybrid system, and they determine whether the remanufacturing option is profitable under one-way substitution policy. Bayindir et al. (2007) extend their study by adding a capacity constraint for the single-period version of the problem, and they investigate the effect of substitution on the optimal utilization of remanufacturing.

Some work on hybrid systems with product substitution assumes a deterministic environment for demand and returns. Pineyro and Viera (2010) formulate an NP-hard deterministic economic lot-sizing problem where new items can substitute for remanufactured items. They find an optimal or near optimal solution using a Tabu-search procedure. Li et al. (2006) propose a dynamic program in order to minimize manufacturing, remanufacturing, holding and substitution costs for an uncapacitated multi-product production planning problem with time-varying demands in a finite time horizon with no disposal or backlog. In another study by Li et al. (2007), the finite-horizon multi-period two-product capacitated dynamic lot sizing problem is analysed for deterministic time-varying demands. They apply a genetic algorithm and then develop a dynamic programming approach to provide the optimal solution to capacitated production planning model with remanufacturing and substitution problem.

Inventory models with two-way substitution is another stream of research that enable consumers to substitute products within the same category. Korugan and Gupta (2001) is among the earliest work on product substitution in a stochastic hybrid system. They study a system where the demand for a certain type of product is satisfied with either new items or remanufactured items. In a later work, Korugan (2004) considers alternative substitution policies for hybrid manufacturing/remanufacturing system using an MDP.

Recently, Ahiska et al., (2013) discuss multi-period periodic-review inventory control problem for a hybrid manufacturing/remanufacturing system with product substitution to find the optimal inventory policies for both with and without one-way product substitution using discrete-time MDPs. They assume stochastic demands and returns and one period lead time for manufacturing and remanufacturing operations.

In this paper, we analyse the profitability of the downward substitution strategy under different stochastic demand and return settings for a periodically-reviewed hybrid system.

3 PROBLEM DESCRIPTION

We consider a recoverable manufacturing system with two production processes: manufacturing and remanufacturing. Manufacturing produces new items using externally supplied virgin materials while remanufacturing uses a returned item to produce a remanufactured item. Remanufactured products are viewed as having an inferior value by customers, therefore they are sold for a lower price than new items and have a different customer profile. Hence, there is a segmented market for manufactured (i.e. new) and remanufactured items. In real-world situations, demand is stochastic, which may cause excessive inventory to build up or lost sales to occur if poor production decisions are made. The classic tradeoff exists between lost sales or excess inventory to avoid loss of customer goodwill. In this paper, downward substitution is considered to reduce the lost sales risk for remanufactured products such that when the remanufactured item inventory runs out of stock, a new item is sold to the customer at the remanufactured item price (i.e. the discounted price). No explicit cost associated with substitution is considered other than the opportunity cost of selling the manufactured item at the discounted price.

Fig. 1 illustrates the hybrid manufacturing/ remanufacturing system under downward product substitution. There are three stocking points in this system: the recoverable inventory that includes the used or returned items, the remanufactured items inventory and the manufactured items inventory. The incoming returned items are disposed only if recovered item inventory is full, otherwise they are stored for later remanufacture. After manufacturing and remanufacturing operations, the resulting items are stored in their respective inventories. During each period, demand for the manufactured and remanufactured items diminish the corresponding inventory levels. At the beginning of every period, the quantities to manufacture and remanufacture must be determined.

This problem was formulated by Ahiska et al., (2013) as a discrete-time MDP to find the optimal manufacturing and remanufacturing decisions. The MDP model formulation is briefly described below.

The state of the system in a period, denoted by S, is represented by three variables I_u , I_r , and I_m which are the inventory levels of used (i.e. recoverable), remanufactured and manufactured items respectively. These inventory levels are bounded as $I_m^{min} \leq I_m \leq I_m^{max}$, $I_r^{min} \leq I_r \leq I_r^{max}$ and $0 \leq I_u \leq I_u^{max}$. I_j^{min} means that backordering of the demand is allowed up to $-I_j^{min}$ for $j=r,m$ if $I_j^{min} < 0$.

In this system we have to make the decisions of how many units to manufacture (d_m), and to remanufacture (d_r). For each system state, we find the feasible values for (d_m, d_r) decisions considering the production and storage capacities.

Given that the current state is S=(I_u, I_r, I_m), the manufacturing and remanufacturing decisions are d_r and d_m, and manufactured item demand (X_m), remanufactured item demand (X_r) and returns (Y) take the values x_m ,x_r and y, respectively, the next state will be $S' = (I'_u, I'_r, I'_m)$ where I'_u, I'_r and I'_m are calculated as follows.

The inventory level for used items decreases for each unit sent into the remanufacturing process and increases by the amount of used items that are returned, but cannot exceed the used item storage capacity, as shown below.

$$I'_u = min\{I_u - d_r + y, I_u^{max}\} \quad (1)$$

The inventory levels for both items at the end of the current period depend on current inventories, demand for corresponding items and manufacturing and remanufacturing decisions, and also on the product substitution strategy such that unfulfilled remanufactured item demand is met from the manufactured item stock if stock is available after first satisfying the demand for manufactured items.

The amount of remanufactured item demand satisfied from new item stock, i.e. the amount of substitution, f, is computed as follows.

Clearly, if $I_r \geq x_r$ (no shortage for remanufactured items) or if $I_m \leq x_m$ (no manufactured items left in stock after satisfying demand for manufactured items), no product substitution will occur (f=0). In this case, the amount of remanufactured item demand that remains unsatisfied, denoted by l, is $l=\max\{x_r-I_r, 0\}$. If $I_r<x_r$ (i.e. there is a shortage of x_r-I_r remanufactured items) and if $I_m>x_m$, then there are I_m-x_m items left in manufactured item stock that can be used to deal with the remanufactured item shortage. In this case, the amount of substitution is $f=\min\{I_m-x_m, x_r-I_r\}$ and the amount of remanufactured item demand that remains unsatisfied after product substitution occurs is $l=\max\{x_r-I_r-f, 0\}$. General formulations for f and l that cover all the 'if' conditions defined in this paragraph can be formed as: $f=[\min\{I_m-x_m, x_r-I_r\}]^+$ and $l=[x_r-I_r-f]^+$ where$[x]^+=\max\{x,0\}$.

The substitution amount f and unsatisfied remanufactured item demand l being defined as above, the inventory levels for manufacturing and remanufacturing items at the beginning of next period are formulated as:

$$I'_m = max\{I_m - x_m - f, I_m^{min}\} + d_m \tag{2}$$

$$I'_r = max\{I_r - x_r, -l, I_r^{min}\} + d_r \tag{3}$$

The state transitions under a *no substitution* strategy can be simply obtained by setting f=0 in the formulations above.

The transition probability from S to S' under decision (d_m, d_r), represented by $P(S, S', (d_m, d_r)$ equals the sum of the probabilities of occurrence for demands and returns, $(x_m,\ x_r,\ y)$, that lead to transition from S to S' under the decision (d_m, d_r). The objective of this problem is to maximize the expected profit per period. The profit is simply defined by the total revenue obtained from selling the products minus the total cost including manufacturing and remanufacturing cost, holding costs for different stocking points, backordering cost, lost sales cost and disposal cost.

The following notation is used.

p_m: unit price for manufactured product
p_r: unit price for remanufactured product
s_m: setup cost for manufacturing
s_r: setup cost for remanufacturing
c_m: unit manufacturing cost
c_r: unit remanufacturing cost
h_m: manufactured product period unit holding cost
h_r: remanufactured product period unit holding cost
h_u: used (returned) product period unit holding cost
b_m: manufactured product period unit backorder cost
b_r: remanufactured product period unit backorder cost
l_m: unit lost sales cost for manufactured products
l_r: unit lost sales cost for remanufactured products
k: unit disposal cost for used products
DSP: disposal amount for the current period
LS_m: current period manufactured items lost sales
LS_r: current period remanufactured items lost sales
BO_m: current period backordered manufactured item demand
BO_r: current period backordered remanufactured item demand

Given that the system state is S, demand is x_m and x_r units for manufactured and remanufactured items respectively, y units of return occur, and decisions d_r and d_m are made, the profit is calculated as:

$$\begin{aligned} &Profit\big(S, (d_r, d_m), (x_m, x_r, y)\big) \\ &= p_r(Q_r + f) + p_m Q_m \\ &- \begin{bmatrix} \delta(d_r) + \gamma(d_m) + h_r[I'_r]^+ + h_m[I'_m]^+ + h_u\, I'_u \\ +b_m BO_m + b_r BO_r + l_m LS_m + l_r LS_r + kDSP \end{bmatrix} \end{aligned} \tag{4}$$

where Q_r and Q_m represent the amounts of remanufactured and manufactured items sold for their corresponding prices, respectively.

$$Q_r = \begin{cases} x_r & if\ x_r < I_r \\ max\{I_r, 0\} & otherwise \end{cases} \tag{5}$$

$$Q_m = \begin{cases} x_m & if\ x_m < I_m \\ max\{I_m, 0\} & otherwise \end{cases} \tag{6}$$

$$\delta(d_r) = \begin{cases} s_r + c_r d_r & for\ d_r > 0 \\ 0 & for\ d_r = 0 \end{cases} \tag{7}$$

$$\gamma(d_m) = \begin{cases} s_m + c_m d_m & for\ d_m > 0 \\ 0 & for\ d_m = 0 \end{cases} \tag{8}$$

$$\begin{aligned} &BO_m \\ &= \begin{cases} -max\{I_m - x_m, I_m^{min}\} & if\ I_m < x_m \\ 0 & otherwise \end{cases} \end{aligned} \tag{9}$$

$$BO_r = \begin{cases} l & if\ \ l \leq -I_r^{min} \\ -I_r^{min} & otherwise \end{cases} \tag{10}$$

$$\begin{aligned} &LS_m \\ &= \begin{cases} I_m^{min} - (I_m - x_m) & if\ I_m - x_m < I_m^{min} \\ 0 & otherwise \end{cases} \end{aligned} \tag{11}$$

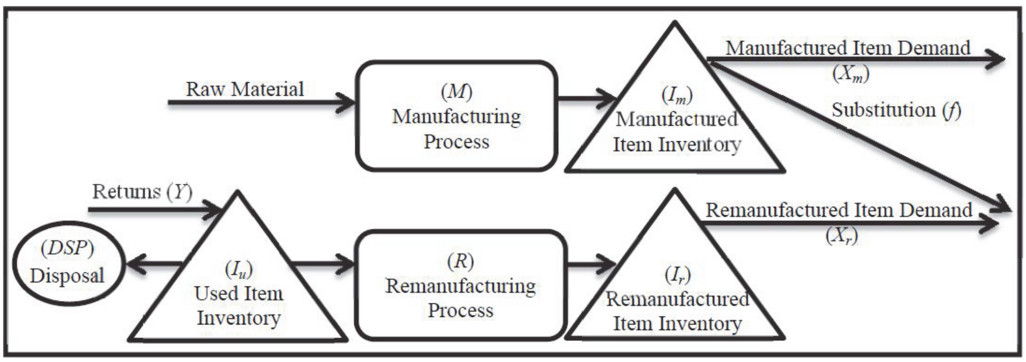

Figure 1: Hybrid manufacturing/remanufacturing system under downward substitution.

$$LS_r = \begin{cases} 0 & if\ \ l \leq -I_r^{min} \\ l + I_r^{min} & otherwise \end{cases} \tag{12}$$

$$DSP = \begin{cases} I_u - d_r + y - I_u^{max} & if\ I_u - d_r + y > \\ 0 & otherwise \end{cases} \tag{13}$$

Then the expected profit in a given period is calculated as:

$$E\big[Profit\big(S,(d_r,d_m)\big)\big] = \sum_{x_m,x_r,y} P(x_m,x_r,y)\,Profit\big(S,(d_r,d_m),(x_m,x_r,y)\big)$$

where $P(x_m, x_r, y)$ represents the joint probability mass function for the random variables X_m, X_r and Y.

The formulation is solved with a variant of the Howard (1960) policy iteration method using the fixed policy successive approximation method by Morton (1971) for computational efficiency.

4 NUMERICAL EXPERIMENTS AND RESULTS

In this section, we analyse numerically the profitability of using the downward substitution strategy under different demand/return distributions.

For the numerical experimentation, we consider a product produced by an international automotive spare part manufacturer. Due to privacy concerns, the data is scaled and the identity of the firm is kept anonymous. Due to the vigorous competition in the sector, over the last few years the firm noticed that the lost sales due to stock-outs of remanufactured products were resulting in loss of customers and damage to the image of the firm in the market. Hence, customer satisfaction is very important, and in order to guarantee a high level of customer satisfaction, the company is considering a stock-out based substitution strategy. The product for which we evaluate the substitution strategy is an 'engine starter' which is a type of electric motor. This product family was among the firm's first production, and a better service level for this product is considered to be prestigious by the manufacturer (Ahiska et al., 2013).

The unit selling prices for the manufactured (i.e. new) and remanufactured engine starter are 68.39€ and 51.85€, respectively, and the unit manufacturing and remanufacturing costs are 22.74€ and 17.46€. The manufacturer tolerates the backordering of the manufactured item demand up to a certain level (i.e. $I_m^{min} < 0$) while backordering of the remanufactured item demand is not allowed (i.e. $I_r^{min} = 0$) due to the risks associated with receiving returns when needed. If some remanufactured item demand remains unsatisfied after the substitution is done, then this demand is lost. Unit backordering cost for manufactured product per period is calculated as 20% of its unit price while unit lost sales cost (cost of goodwill loss) for both manufactured and remanufactured products are calculated as 25% of the corresponding unit price. The annual holding costs for manufactured and remanufactured items are calculated as 20% of the corresponding unit cost, and the holding cost for a used item is considered to be half of the holding cost for a remanufactured item. The lead times for manufacturing and remanufacturing are both one period. No set up costs exists for either production option.

We design the first set of experiments in order to investigate how the profitability of product substitution strategy is affected as the means of the demand and return distributions change. In this set of experiments, we use bounded discrete stochastic distributions with three different shapes for the manufactured and remanufactured item demands and used item returns, which are uniform, normal, and right skewed. The mean of each different-shape stochastic distribution is assigned three different values: low, medium and high, as shown in Table 1.

Table 1: Mean values for different distributions.

	Mean		
Distribution shape	High	Medium	Low
Uniform (Uni)	2.00	1.50	1.00
Normal (Nrm)	2.51	2.00	1.50
Right skewed (RS)	1.20	1.05	0.54

In all, 27 combinations of the three means are created by assigning the three different levels of the mean of the distribution for manufactured item demand ($E[X_m]$), remanufactured item demand ($E[X_r]$) and used item returns ($E[Y]$). These 27 combinations coupled with the three distribution shapes yield a total of 81 scenarios. For each scenario, the optimal expected profits per period for the hybrid system under substitution and no substitution strategies are determined by solving the MDP as defined in the previous section.

The % improvements in profit gained by substitution vs. no substitution are reported in Table 2. We make the following observations: When the mean of remanufactured item demand is at least as much as the mean of returns ($E[X_r] \geq E[Y]$), the substitution strategy results in additional profit for the manufacturer. Among the 54 scenarios where $E[X_r] \geq E[Y]$, the highest improvement in profit was 85%. When returns are substantially higher than the remanufactured item demand (i.e. $E[X_r]<E[Y]$), the use of substitution is not economically justified. It caused loss of profit but only up to 3% among the 27 scenarios we considered (see Table 2). Further experimentation (not shown here) reveals that if the average returns exceed the demand but at a lower level than the amounts shown in Table 1, substitution is still profitable.

It is worth noting that the mean of manufactured item demand does not affect the amount of change in profit by substitution. However because the profit of manufacturing is lower for lower manufactured item demand, a same amount of change in profit by substitution corresponds to a higher percent change of profit over no substitution case as the mean of manufactured item demand decreases. In short, the profitability of product substitution strategy is mainly dependent on the size of remanufactured item demand relative to that of returns.

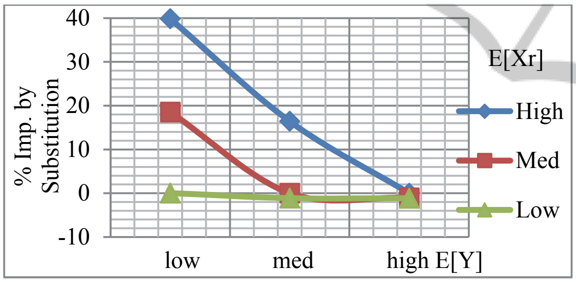

Figure 2: % improvement in profit as $E[X_r]$ and $E[Y]$ change (for Normal-shape distribution and low $E[X_m]$).

Clearly, substitution results in a higher improvement in profit when the expected remanufactured item demand gets higher and/or the expected return gets lower. For representative results supporting this comment, see figure 2, which plots the % improvements in profit by substitution for nine scenarios with the low level of mean manufactured item demand and the Normal shaped distribution, and the mean of remanufactured item demand and returns as low, medium and high. As the ratio of the mean remanufactured item demand to the mean returns increases from lowest ($E[X_r]$=low, $E[Y]$=high) to highest ($E[X_r]$=high, $E[Y]$=low), the percent change of firm's profit when the product substitution strategy is used increases from -1.1% to 39.9%.

Table 2: The improvement in profit by substitution (%) for different combinations of $E[X_m]$, $E[X_r]$ and $E[Y]$ under different-shape distributions.

Means			Improvement in profit by substitution (%)		
$E[X_m]$	$E[X_r]$	$E[Y]$	Uni	Nrm	RS
high	high	high	1.75	0.00	2.29
high	high	med	15.25	12.00	7.63
high	high	low	37.11	27.61	43.84
high	med	high	-1.06	-0.77	-0.53
high	med	med	1.16	0.00	2.18
high	med	low	17.49	13.02	32.81
high	low	high	-1.24	-0.80	-1.63
high	low	med	-1.23	-0.79	-1.64
high	low	low	0.47	0.02	1.11
med	high	high	2.03	0.00	2.47
med	high	med	18.23	13.86	8.30
med	high	low	46.42	32.63	49.31
med	med	high	-1.27	-0.89	-0.59
med	med	med	1.38	0.01	2.37
med	med	low	21.58	15.28	36.74
med	low	high	-1.53	-0.95	-1.86
med	low	med	-1.51	-0.94	-1.87
med	low	low	0.57	0.02	1.22
low	high	high	2.44	0.00	3.47
low	high	med	22.73	16.43	11.84
low	high	low	62.10	39.87	84.82
low	med	high	-1.58	-1.04	-0.82
low	med	med	1.70	0.02	3.42
low	med	low	28.14	18.54	61.82
low	low	high	-2.00	-1.13	-3.03
low	low	med	-1.97	-1.12	-3.02
low	low	low	0.73	0.03	2.01

We performed a second set of experiments in order to clearly see how the economic attractiveness of the substitution strategy varies as the return distribution changes. For this purpose, nine different return distributions are created with different coefficients of variations (CVs) ranging from 0.2 to 1.0 with an increment of 0.1, which are plotted in figure 3. All the distributions have the standard deviation of 0.5, hence they differ only by their mean, which ranges from 2.5 to 0.5 as CV changes from 0.2 to 1.0. The return distribution with coefficient of variation of 0.6 is also used as the demand distributions for remanufactured and manufactured items in this set of experiments.

Figure 4 shows how the expected profits for the hybrid system with/without product substitution change as the mean of the return distribution decreases from 2.5 to 0.5 (or CV increases from 0.2 to 1). The expected profits from the remanufacturing and manufacturing processes are also plotted separately for the no substitution case.

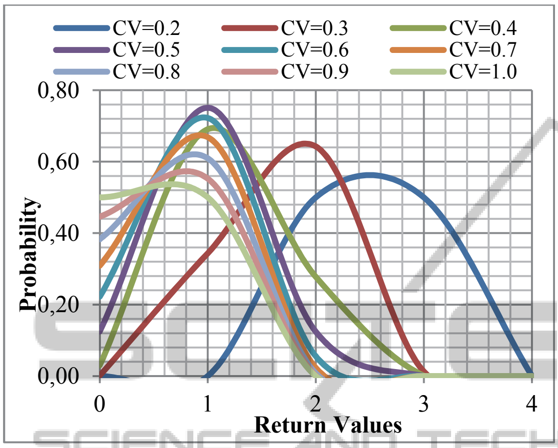

Figure 3: The return distributions with different coefficient of variations (CVs).

The following observations are made: Recall that the CV of remanufacturing item demand distribution was set 0.6. Hence, in all the scenarios with return distribution's CV<0.6, the mean of return is higher than the mean of remanufactured item demand ($E[Y]$>$E[X_r]$). When CV<0.6, the use of substitution does not provide substantial additional profit over no substitution case (only around 0.2%) since the amount of returns available are typically sufficient to meet remanufactured item demand. However when CV exceeds 0.6 (i.e. $E[Y]$ goes below $E[X_r]$), a decrease in returns increases the economic attractiveness of product substitution from 0.6% to nearly 28%.

Another observation is that when CV<0.6, an increase in CV (i.e. decrease in expected return) results in an increase in remanufacturing process profit while the effect is opposite for CV>0.6. This can be explained as follows: For CV<0.6, the expected remanufacturing amount (consequently, the sales revenue for remanufactured items and the remanufacturing cost) remains unchanged as expected returns decrease because the returns are sufficient to meet the remanufactured item demand and the expected remanufacturing amount is just as much as remanufactured item demand. In this case the increase in profit for remanufacturing process is explained by the significant amount of savings obtained in disposal cost since less disposal is needed as returns get lower (see figure 5). For CV>0.6 (i.e. returns are not sufficient to meet all remanufactured item demand), a decrease in expected return decreases the profit for remanufacturing process because in this case sales revenue from remanufactured items decreases and the lost sales cost increases (see figure 5).

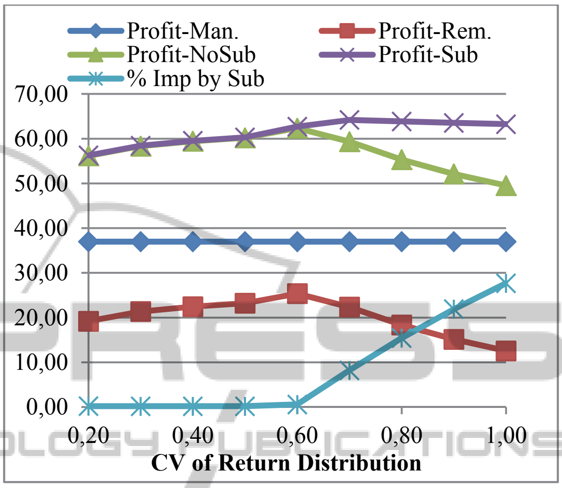

Figure 4: The expected profits under different CVs.

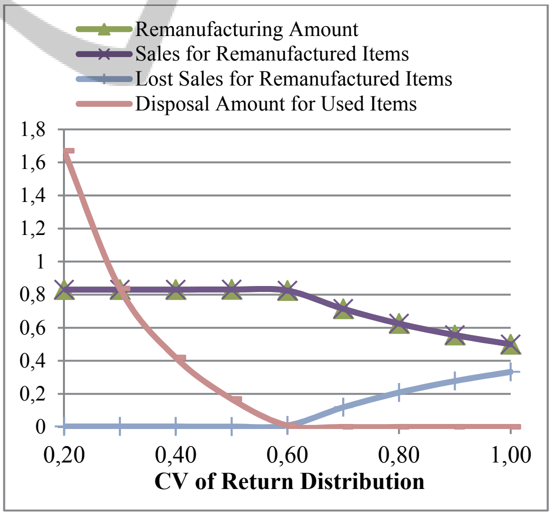

Figure 5: Expected values for remanufacturing amount, sales/lost sales for remanufactured items and disposal amount for used items for the no substitution case under different return CVs.

5 CONCLUSIONS

We analyze a periodically reviewed stochastic manufacturing/remanufacturing system where the remanufacturing items have an inferior value from customers' point of view compared to newly manufactured items. A downward product substitution strategy is employed in case of a stock-out for remanufactured items. The problem is formulated as a discrete-time MDP in order to find the optimal inventory policies for both with and without product substitution. Through a numerical study based on real data for a product produced by an automotive spare part manufacturer, the profitability of substitution is investigated under different demand and return distributions. The results show that the substitution strategy is economically attractive when the expected demand for remanufactured items is at least as much of expected returns, and the improvement in profit by substitution increases significantly as the size of returns decreases relative to the size of remanufactured item demand. These results should encourage the manufacturers operating hybrid systems to use the product substitution strategy since it may increase significantly their profit along with improving the service level by reducing the expected lost sales for remanufactured parts.

Opportunities for future work include performing extensive experimentation using a broad range of input parameters to better understand the scenarios best suited for substitution and those least suited. In addition, characterization of the optimal policies will lead to implementable policies.

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