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Optimal Inventory Policy for Two-echelon Remanufacturing

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Abstract

We present a two-echelon remanufacturing facility subject to constant demand, in which the disassembly process and the repair process observe stochastic yield. We develop an intuitive scheduling policy and perform a robustness test.

Keyword: inventory management, multi-echelon, remanufacturing, product recovery, stochastic process yield, financial holding cost, physical holding cost

Introduction

Yano and Lee (1995) revised several lot-sizing models in which production yield is random. A large number of those models were inspired by the difficulties faced in the production of electronic components, where the production yield in some stages may be very low. A similar situation occurs in remanufacturing sites. Cores entering the remanufacturing shop enter a pre-selection stage in which some disassembly takes place. The disassembly modules are stocked close to the renovation area, where they are repaired and made ready to reuse. One particularity of the remanufacturing shop is the different ways that the inventory held in stock affects the operating cost, whether it is before or after the final production stage. Most of the holding cost in the upstream operation refers to the physical handling of a large number of assemblies that occupy a significant amount of space, but might not survive the remanufacturing process. Meanwhile, most of the holding cost in the downstream operation refers to the opportunity cost of the resources committed to adding value to the sub-assembly renovation.

The remanufacturing shop that we described has not been modeled yet. The paper we propose contributes in this literature by providing a simple policy with two control variables: the lot size in the upstream operation, and the echelon multiple used to identify the lot size in the renovation station. Moreover, it identifies the conditions under which the remanufacturing shop will not hold inventory between the two processes, thus renovating all cores immediately after disassembly.

We assume that demand is constant, and the lead time of both processes is zero. We develop the optimal nested policy and perform numerical tests.

Stochastic Process Yield, Deterministic Demand

Consider a remanufacturing shop where the stock of cores is unlimited and freely available for recovery. The recovery process generates remanufactured units of the widget corresponding to these cores. This demand for the remanufactured widget is fairly stable: initially, we consider a constant demand of *D* remanufactured goods per unit time. The recovery procedure includes two stages: a disassembly process and a renovation process. Both operations are costly, require some setup and are subject to a stochastic output yield. The manager has to decide the operating policy that determines the frequency of the two operations (disassembly and renovation) and the size of the respective lots, such that demand is always satisfied at the lowest operating cost. Figure 1 illustrates this scenario in a tire retreading facility.

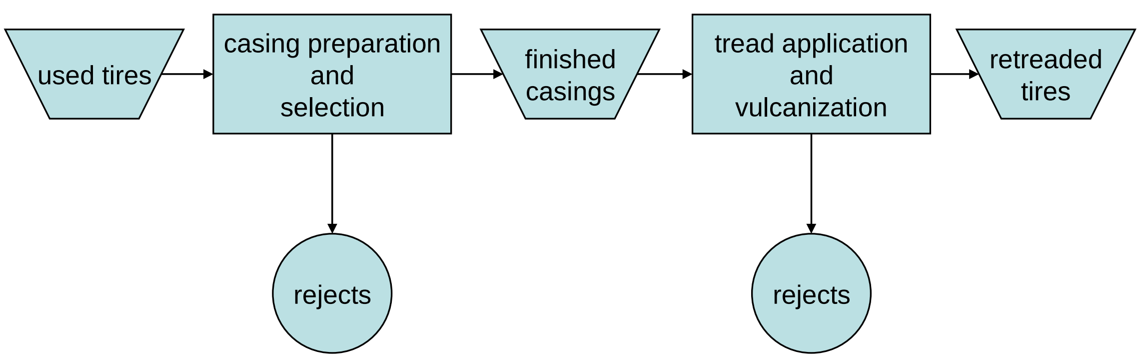

Figure 1. Material Flow in a Tire Retreading Facility

One of the practical problems faced by remanufacturing shops is the constraint in storage space. A large number of used cores arrive at the facility to be processed, but only some of them become re-usable goods. Hence, physical handling may represent a significant fraction of the holding cost, especially in the earlier stages of the operation. The typical representation of echelon stocking, with nested saw-tooth patterns, represents the value added in each stage. However, this does not completely reflect the importance of physical handling in remanufacturing. Hence, it is useful to identify separately which stage is burdened by the financial and the physical inventory. Figure 2 reflects the two-process environment, where both physical and financial stocks are present in a situation in which there are 3 renovation cycles per disassembly event.

If the remanufacturing operation pays for the cores received at the time of delivery, the financial holding cost lasts until the recovered good is finally delivered to the customer. That is reflected in the downward slope of the financial inventory level in both processes. However, the physical inventory follows a staircase shape in the first process, and a saw-tooth shape in the lower process. That behavior is the same as most other multi-echelon systems. However, the remanufacturing operation is better represented if the two holding costs are treated separately.

In Figure 2, the first station disassembles Q machines, subject to a certain yield, p_d. We propose a nested policy such that the output of the upstream station is split into n equal lots to be processed in the downstream operation. Table 1 shows the notation used in the optimization of this policy.

DISASSEMBLY ECHELON		RENOVATION (REPAIR) ECHELON	
k_d	setup cost of disassembly	k_r	setup cost of renovation
$h_{f,d}$	financial holding cost of disassembled items	$h_{f,r}$	financial holding cost of renovated items
$h_{ph,d}$	physical holding cost of disassembled items	$h_{ph,r}$	physical holding cost of renovated items
p_d	yield of the disassembly operation	p_r	yield of the renovation operation
Q	core disassembly lot-size	n	number of renovation cycles per disassembly event

Table 1. Notation

Costs incurred in the renovation (downstream) process

Considering the yield in the disassembly operation, $p_d\, Q$ ready-to-recover items are available for renovation in the second step. We choose equal lot sizes of $p_d\, Q / n$ cores in each of the next n cycles in the renovation process. If the yield realization in the first renovation cycle is p_r, we have that $p_r\, p_d\, Q / n$ items are produced in the first cycle, which are gradually consumed. Moreover, the renovation cycle lasts $p_r\, p_d\, Q / n\, D$ time units. Hence, the holding costs incurred in the renovation cycle are given by the expressions:

Equation 1. Financial holding cost during renovation cycle: $h_{f,r} \frac{p_d Q}{2n} \frac{p_d p_r Q}{nD}$

Equation 2. Physical holding cost during renovation cycle: $h_{ph,r} \frac{p_d p_r Q}{2n} \frac{p_d p_r Q}{nD}$

There are different reasons driving the yield in each process. Generally, the yield in the renovation process is due to process failures, while the yield in the disassembly process depends on the quality of the incoming material, the used cores. Hence, we may assume that the two yield distributions are not correlated. The setup cost per renovation cycle equals k_r. Therefore, the expected value of the renovation cost per time unit can be expressed as:

Equation 3. $$E\left[\text{renovation cost/time}\right] = \frac{k_r nD}{Q} E\left[\frac{1}{p_d}\right] E\left[\frac{1}{p_r}\right] + \frac{Q}{2n}\left(h_{f,r} E\left[p_d\right] + h_{ph,r} E\left[p_d\right] E\left[p_r\right]\right)$$

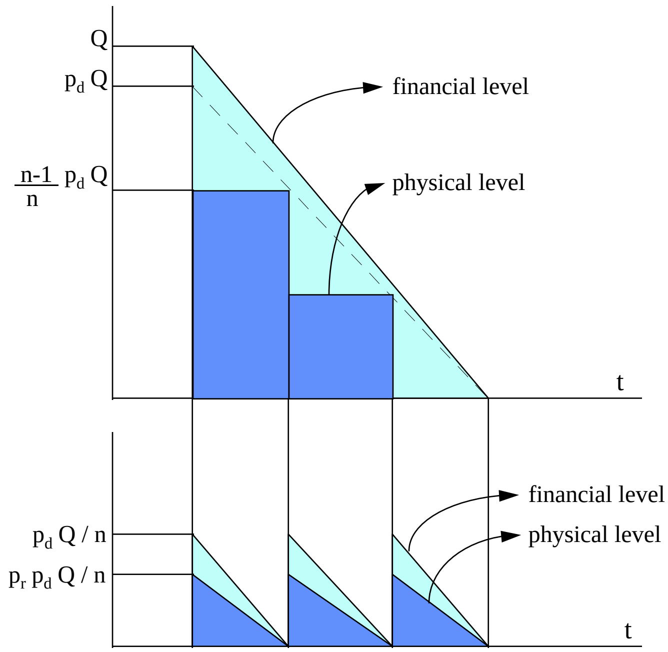

Figure 2. Financial and Physical Level in a Two-process System

Costs incurred in the disassembly (upstream) process

Prior to the renovation process, the used goods inventory is processed and pre-selected during the disassembly process. The duration of the disassembly process depends both on the yield of this operation, as well as on the yield of each subordinate renovation cycle, $p_{r,i}$ (i = 1, … n). Hence,

Equation 4. Disassembly cycle length: $$\frac{p_d Q}{D} \sum_{i=1}^{n} \frac{p_{r,i}}{n}$$

Separating the financial and the physical holding cost, we obtain the expressions:

Equation 5. Financial holding cost during disassembly cycle: $$h_{f,d} \frac{Q}{2} \frac{p_d Q}{D} \sum_{i=1}^{n} \frac{p_{r,i}}{n}$$

Equation 6. Physical holding cost during disassembly cycle: $$h_{ph,d} \frac{n-1}{2n} p_d Q \frac{p_d Q}{D} \sum_{i=1}^{n} \frac{p_{r,i}}{n}$$

The setup cost per disassembly cycle equals k_d. Considering that the yield distributions are not correlated, and that the expected duration of the disassembly cycle is *n* times longer than the expected duration of the renovation cycle, the expected disassembly cost per time units equals:

Equation 7. $$E\left[\text{disassembly cost/time unit}\right]=\frac{k_d D}{Q}E\left[\frac{1}{p_d}\right]E\left[\frac{1}{p_r}\right]+\frac{Q}{2}\left(h_{f,d}+h_{ph,d}E\left[p_d\right]\frac{n-1}{n}\right)$$

Choice of optimal lot-size at the disassembly process

Equations 3 and 7 provide the closed-form expressions for the relevant inventory costs at each process as a function of the lot-size of the disassembly process (Q) and the number of renovation cycles per disassembly cycle (n). Hence, we can define $K(n)$ and $H(n)$ as follows:

Equation 8. $$K(n)=(k_d+nk_r)E\left[1/p_d\right]E\left[1/p_r\right]$$

Equation 9. $$H(n)=h_{f,d}+\frac{E\left[p_d\right]}{n}\left(h_{ph,d}(n-1)+h_{f,r}+h_{ph,r}E\left[p_r\right]\right)$$

In addition, we may write in compact form the expected operating cost per unit time as:

Equation 10. $$E\left[C(Q,n)\right]=\frac{DK(n)}{Q}+\frac{QH(n)}{2}$$

Obviously, the expression is convex in Q. For a given value of $n > 0$, the optimal lot-size is:

Equation 11. $$Q^*(n)=\sqrt{\frac{2DK(n)}{H(n)}}$$

and the respective minimum cost is:

Equation 12. $$C^*(n)=\sqrt{2DK(n)H(n)}$$

Now, we have to identify the integer value of n that minimizes this cost expression. It is simple to show that such minimization is equivalent to minimizing $X(n)$ given by the expression:

Equation 13. $$X(n)=\frac{E\left[p_d\right]}{n}\left(h_{f,r}-h_{ph,d}+h_{ph,r}E\left[p_r\right]\right)k_d+\left(h_{f,d}+h_{ph,d}E\left[p_d\right]\right)nk_r$$

The value $n_{real}\in R$ that satisfies the first-order condition in the minimization of the $X(n)$ expression is:

Equation 14. $$n_{real}=\sqrt{\frac{E\left[p_d\right]\left(h_{f,r}-h_{ph,d}+h_{ph,r}E\left[p_r\right]\right)}{h_{f,d}+h_{ph,d}E\left[p_d\right]}\frac{k_d}{k_r}}$$

The value above is generally not integer. If $n_{real}\le 1$, the minimizing value is $n^* = 1$. Otherwise, we examine two approximations of n_{real}. Define n_{lo} and n_{hi}, integer numbers such that $n_{lo}=\max\left\{n\in \text{Integer Numbers}\,\middle|\,n\le n_{real}\right\}$ and $n_{hi}=n_{lo}+1$.

Clearly, $X(n_{lo}) \leq X(n_{hi}) \Rightarrow n^* = n_{lo}$ minimizes the cost function. Otherwise, $n^* = n_{hi}$ is the cost minimizer. Now, we can identify the lot-size at the disassembly process that minimizes the operating cost in the remanufacturing site. It suffices to substitute n^* in the expression for $K(n)$ and $H(n)$ and, subsequently, substitute them in the expression for $Q^*(n)$ to solve the cost minimization problem.

Discussion

Equations 11 and 14, combined with the integrality constraint, identify the decision variables that optimize the nested policy suggested for this problem. It gives proper weight to the financial and physical holding costs faced by the remanufacturing firm. Equation 14 shows that the number of renovation cycles is proportional to the ratio between the setup costs of both processes. The same result is observed with the basic two-echelon problem with deterministic production output. Other results are less intuitive: Let the financial holding cost at the disassembly process be relatively low, and the physical holding cost be the same in both processes. In this case, equation 14 may be approximated by the expression

Equation 15. $$n_{real} \approx \sqrt{\left(\frac{h_f}{h_{ph}} - 1 + E[p_r]\right)\frac{k_d}{k_r}}$$

where h_f is the financial holding cost, incurred at the renovation process only, and h_{ph} is the physical holding cost, of the same magnitude in both processes. Hence,

- The number of renovation cycles increases with the financial cost of the remanufacturing operation. This happens because by increasing the number of cycles, the size of finished goods inventory reduces, which drives the financial holding cost.
- The number of renovation cycles decreases with the physical handling cost. This is an indirect effect. Increasing the number of renovation cycles implicitly reduces the lot-size in the disassembly process, hence, reducing the physical holding cost at this level.
- If the expected renovation yield is low, and the physical holding cost is relatively high, there will be as many renovation cycles as disassembly cycles. This happens if the expression inside the square root is less than 1 (or even negative), implying that $n^* = 1$.

The last effect clarifies why, in some remanufacturing operations, the manager chooses not to hold inventory between the two events. In these environments, once the lot of used goods is disassembled, it proceeds immediately to the renovation area. This behavior is justifiable because handling an excessive stock of disassembled goods may be quite problematic if storage space is at a premium. However, if physical handling is not costly, it is likely that the renovation station will process smaller lots than the disassembly station.

Example

A remanufacturing facility faces an annual demand of 600 units of a certain electric motor series. The facility has access to an ample supply of used motors to repair at a small cost. Holding costs have been estimated as $h_{f,d} = 0.5$, $h_{f,r} = 4$, $h_{ph,d} = h_{ph,r} = 2$. Moreover, ordering and setup costs have been estimated as $k_d = 30$ and $k_r = 6$. Pre-inspection yield for each lot is uniformly distributed between 0.5 and 0.95. Final inspection yield is also uniformly distributed—between 0.75 and 0.95. Under these conditions, we find that $n_{lo} = 2$ and $n_{hi} = 3$. Since $X(3) = 61.9 < 63.6 = X(2)$, we conclude that $n^* = 3$. Hence, $K(3) = 80.9$ and $H(3) = 2.84$, leading to $Q(3) = 185$; and expected inventory management cost is minimized at $C(3) = 525$. The following graph shows the expected inventory costs at different (*Q, n*) combinations.

Figure 3 illustrates that the operating cost does not change significantly close to the optimal value solution (185, 3). The cost increase for erring in just one dimension (either lot size or number of renovation cycles) is quite minor, but simultaneous errors in both dimensions can easily increase operating costs by 50% or more. Consequently, the remanufacturing facility must be careful deciding the inventory policy associated with its production process to ensure that the operating cost is remains close to its theoretical optimum.

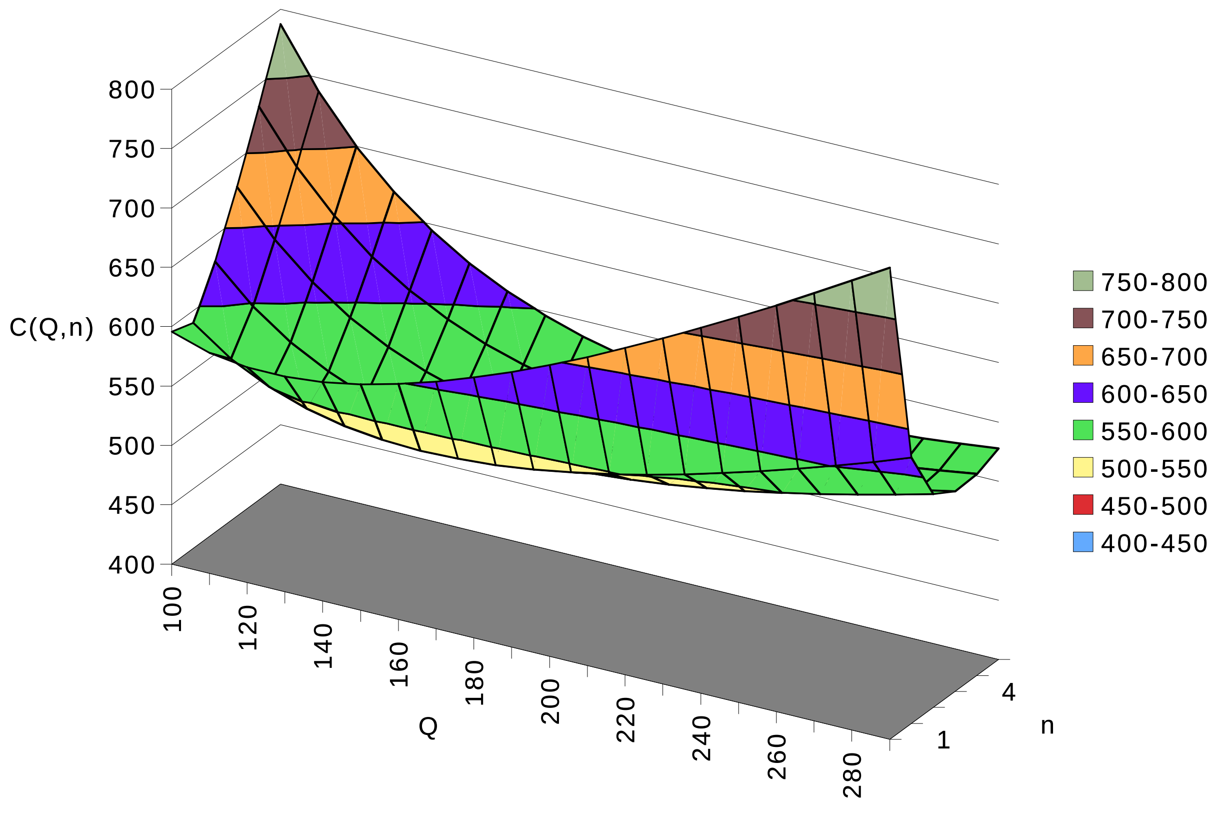

Figure 3. Expected Inventory Costs at Different (*Q, n*) Combinations

Conclusion

We have proposed an inventory policy for multi-echelon remanufacturing operations in which the first echelon corresponds to the product disassembly and sorting operations, and the second echelon corresponds to the repair, renovation and final inspection operations. The separation between these two sets of operations is important because they present sizable yield, affecting the holding cost at each level of the process. We find a simple inventory policy built upon the familiar structure of the economic order quantity, leading to the optimal disassembly lot size and the number of renovation cycles per disassembly event.

This policy is useful in DoD depots, where large remanufacturing programs are engaged periodically for the recovery of valuable durable assets. We intend to extend this study by testing the policy provided herein in actual remanufacturing operations in the DoD.

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