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## AN ANALYTICAL MODEL FOR REMANUFACTURING SYSTEMS

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### ABSTRACT

In this paper, we introduce an open queueing network with finite buffers to model a remanufacturing system. The system consists of three modules, viz., a testing module for returned products, a disposition module for non-reusable returns and a remanufacturing module. We analyze the network using the decomposition principle and the expansion methodology. The model has been shown to be very rigorous and remarkably accurate. An example is presented to illustrate the use of the model.

### INTRODUCTION

In recent years, due to the environmental awareness, a growing number of manufacturers have begun to emphasize recycling and remanufacturing of post consumed products. Recycling is a process performed to retrieve the material content of used and non-functioning products. Remanufacturing is an industrial process in which worn-out products are restored to "like-new" conditions. Thus, remanufacturing provides quality standards of new products with used parts. Remanufacturing is not only a direct and preferable way to reduce the amount of waste generated, it also reduces the consumption of virgin resources. The objective of product recovery management is to recover as much of the economic (and ecological) value as reasonably possible, thereby reducing the ultimate quantities of waste.

Implementation of a remanufacturing system is fraught with two types of uncertainties, viz., internal uncertainty and external uncertainty. Internal uncertainty comprises of the variations within the remanufacturing process such as, the processing time, the throughput rate of the process, and the possibility of system failure. External uncertainty comprises of the variations originating from factors outside the remanufacturing process which include the timing, quantity and quality of the returned products, and the timing and level of demand for parts and remanufactured products. The consequences of these uncertainties include under supply of inventory (which could lead to the procurement of the all too expensive new parts/products in order to meet the impending demand) or over supply of inventory (which could lead to obsolescence), improper remanufacturing plan and loss of competitiveness in the market.

Due of the aforementioned uncertainties and complexities, developing a robust model to study a remanufacturing system is necessary. Typically, most researchers would resort to simulation, which of course, has its own deficiencies. For example, simulation cannot provide closed form solution; each change of input variables requires a separate set of runs; complex simulation models are costly and require too much time to build and run. On the other hand, if it were possible to develop an analytical model, it would be inexpensive, very easy to implement and any change in input variables might be simply a matter of plugging in different values in a formula and solving it. In this paper, we model a remanufacturing system analytically considering stochastic process times, finite buffers and unreliable servers.

### LITERATURE REVIEW

The first crucial step of product recovery is disassembly. Disassembly is a methodical extraction of valuable parts/subassemblies and materials from post-used products through a series of operations. After disassembly, re-usable parts/subassemblies are cleaned, refurbished, tested and directed to the part/subassembly inventory for remanufacturing operations. The recyclable materials are sold to raw-material suppliers and the residuals are disposed of. Several researchers have discussed the various aspects of product recovery. The problems associated with disassembly and scheduling have been investigated by Brennan et al. [1], Gupta and Taleb [4], Taleb and Gupta [9], and Taleb et. al. [10]. Moyer and Gupta [7] provide a comprehensive review of recycling and disassembly efforts in the electronics industry. Gungor and Gupta [3] review the literature in the area of environmentally conscious manufacturing and product recovery. The problems associated with remanufacturing have been addressed by Guide and Srivastava [2].

A production planning and inventory control model for remanufacturing systems was first presented by Muckstadt and Isaac [8]. The authors developed an approximate control strategy with respect to the re-order points and order quantities for a single item product case where returned products are remanufactured. They considered fixed lead times and no disposal of returned products. In an earlier paper, Heyman [6] analyzed the continuous-review

inventory control case where incoming returnable are disposed of whenever the inventory position reaches a predetermined level. The author assumed zero repair times and did not consider procurement lead times. van der Laan et al. [11] extended Muckstadt and Isaac's [8] strategy by proposing two alternative approximation methods for cost evaluation and optimization. The authors showed that disposition is necessary, otherwise inventory may reach very high levels due to the variability in product returns. In yet another paper, van der Laan et al. [12] considered a single-product, single-echelon production and inventory system with product returns, remanufacturing and disposal.

### MODEL DESCRIPTION

A remanufacturing system can be thought of as a collection of various service areas where jobs arrive at different rates and demand services with unequal processing times. We introduce an open queuing network (OQN) with finite buffers to model the remanufacturing system. A queueing network representation of a typical remanufacturing system is shown in Figure 1.

In order to analyze the queueing network, we use the decomposition principle and the expansion methodology. The decomposition principle is widely used in the analysis of a queueing network when a closed form solution for the network does not exist. The idea is to partition the network into individual nodes so that one is able to analyze and estimate the necessary parameters of each node independent of the rest of the network. When the analysis of each node is complete, the interaction of each node with the rest of the network can be reviewed. After decomposing the network, we use the expansion methodology to analyze each node individually [5]. The expansion methodology is an efficient tool for the analysis of nodes with finite buffers. In this methodology, we expand the network by adding an extra node in front of each finite buffer. These extra nodes are modeled as infinite buffer nodes with zero processing times. They act as "holding nodes" for jobs which cannot enter the destination node because the buffer is full. The blocked jobs stay there until a space becomes available at the full buffer. Next, the parameters that define the expanded network, such as the actual arrival rate to the system, the probability of a job being blocked by the full buffer, etc. are calculated. Finally, using the newly calculated parameters, the throughput of the entire network can be calculated [5].

The remanufacturing system considered here (Figure 1) consists of three modules, viz., a testing module for returned products, a disposition module for non-reusable returns and a remanufacturing module. The

remanufacturing module consists of four different stations to accomplish the distinct operations required by the variations in the returned products. After the remanufacturing operations, items are directed to the serviceable inventory from where the demand is satisfied. We assume that the demand rate is greater than the product return rate. Thus, outside procurement is needed to supplement any additional demand. It is assumed that when the demand is not satisfied, a lost sales cost is incurred. Similarly, when the demand is less than the inventory level, an inventory holding cost is incurred. Note that, in the queueing network, all the stations have finite buffer capacities and are prone to breakdowns.

We analyze a single item, single location serviceable inventory system where returned products are remanufactured. We assume that the product return rate, demand rate and the outside procurement rate are independent and exponentially distributed. There is one server at each station whose service rate is exponentially distributed and the service discipline is First Come First Serve. The breakdown rate of each station and the repair time for a broken station are also exponentially distributed. When an item is ready to join a station, either the buffer at that station is not full, in which case the item joins the queue, or the buffer is full and the item cannot join the queue, in which case it stays where it originated from and hence blocks that original server. The only exception is when the returned product first arrives at the disassembly station from outside. In that case, if the returned product finds the buffer of that station full, it cannot enter the remanufacturing system and is considered lost to the system. See the paper by Gupta and Kavusturucu [5], for the derivation and development of a methodology to address such a problem.

### EXAMPLE

Consider the remanufacturing system given in Figure 1. The total cost function of the system can be written as follows:

$$TC = c_p E(RP) + c_d E(D) + c_t E(T) + c_{dis} E(Dis) + \sum_{i=1}^4 c_{ri} E(R_i) + c_m E(OP) + c_{hs} E(I) + c_l E(LS)$$

where

- $c_p$  : purchase cost of returned product/item.
- $c_d$  : disposition cost/item.
- $c_t$  : cost of testing /item.
- $c_{dis}$  : disassembly cost/item.
- $c_{ri}$  : remanufacturing cost/item ( $i=1, 2, 3$ ).

$c_{rd}$ : final inspection cost/item.  
 $c_m$ : outside procurement cost/item.  
 $c_{hs}$ : on-hand serviceable inventory cost/item.  
 $c_l$ : lost sales cost/item.  
 $E(RP)$ : expected number of returned products.  
 $E(D)$ : expected number of disposed products.  
 $E(T)$ : expected number of tested products.  
 $E(Dis)$ : expected number of disassembled products.  
 $E(R_i)$ : expected number of products processed by remanufacturing node  $i$  ( $i=1,2,3$ ).  
 $E(R_4)$ : expected number of final inspections.  
 $E(OP)$ : expected number of products procured from outside suppliers.  
 $E(I)$ : expected number of on hand inventory.  
 $E(LS)$ : expected number of lost sales.

Assume that the following data is given:

$I_{ar}$  (return rate) = 1,  $r$  (reusable rate) = 0.8 and  
 $B_i$  (buffer size) = 3, 9, 9, 6, 9, 3, 6;  $\mu_i$  (service rate) = 2, 1, 1.5, 2, 2, 1, 1;  $\alpha_i$  (breakdown rate) = 1, 1, 0.8, 0.8, 1, 1.2, 1.2; for nodes  $i = 1, 2, 3, 4, 5, 6$ , and 7 respectively.  
 Also,  $c_p = 4$ ,  $c_d = 2$ ,  $c_t = 0.5$ ,  $c_{dis} = 5$ ,  $c_{ri} = 1, 1.5, 2, 0.5$  ( $i=1, 2, 3, 4$ ),  $c_m = 25$ ,  $c_{hs} = 0.5$ ,  $c_l = 2.5$ .  
 Furthermore, the routing probabilities are;  $p_{12} = 0.5$ ,  $p_{13} = 0.4$ ,  $p_{14} = 0.1$ ,  $p_{23} = 0.8$ ,  $p_{24} = 0.2$ ,  $p_{34} = 1.0$ .

We can use the model described in the previous section to obtain the various expected values needed in the total cost function. Then, by substituting those expected values together with the cost values given above, we obtain the throughput rate for the remanufacturing system as 0.601 and the average total cost as \$17.71.

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