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## NEAR OPTIMAL BUFFER ALLOCATION PLAN FOR REMANUFACTURING SYSTEMS

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### ABSTRACT

A remanufacturing system is prone to inefficiencies because of built-in uncertainties and complexities of the nature of the operations. One way to improve the performance of the system is to distribute a given number of available buffer slots among the stations in a strategic manner. In this paper we present a near optimal buffer allocation plan (NOBAP) specifically developed for remanufacturing systems. To this end, we introduce an algorithm that analyzes the system using an open queueing network with finite buffers and unreliable machines. In order to analyze the queueing network, we use the decomposition principle and expansion methodology. The results obtained by using the algorithm are compared with the ones found using the exhaustive search. The results show that the NOBAP is very rigorous and remarkably accurate.

### INTRODUCTION

As environmentally conscious manufacturing is gaining popularity, many manufacturers are changing their attitudes and emphasis towards remanufacturing and recycling of post consumed products. Remanufacturing is not only a direct and preferable way to reduce the amount of waste generated, it also reduces the consumption of virgin resources. 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. On the other hand, recycling is a process performed to retrieve the material content of used, outdated or non-functioning products.

This paper addresses one of the important problems in the remanufacturing area, viz., the allocation of a given number of buffer slots among the remanufacturing stations with the objective of minimizing the expected cost. For modeling purposes, it would be convenient to assume that such systems have unlimited buffer capacities. However, real life situations impose certain conditions that place an upper limit on the number of buffers that can be accommodated in the system. Allocating the buffers among the different stations in a strategic manner can improve the performance of the system. The buffer allocation problem has to be solved in the presence of many conflicting objectives such as minimizing remanufacturing costs, minimizing processing times and maximizing throughput rate. Although the buffer allocation problem has not been reported in the remanufacturing literature, attempts have been made to address this problem in traditional

production lines where, because of computational difficulties, researchers often use simulation techniques to solve the problem (Conway *et al.*, 1988; Vouros and Papadopoulos, 1998).

In this paper, we present a near optimal buffer allocation plan (NOBAP) specifically developed for remanufacturing systems. We model this analytically using an open queueing network with finite buffers and unreliable machines. In order to analyze the queueing network, we use the decomposition principle and expansion methodology (Kerbache and Smith, 1988; Gupta and Kavusturucu, 1998; Kavusturucu and Gupta, 1999).

### LITERATURE REVIEW

There are many steps involved in product recovery and remanufacturing. 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 can be sold to raw-material suppliers and the residuals are disposed of. The problems associated with disassembly and scheduling have been investigated by Brennan *et al.* (1994), Gupta and Taleb (1994).

Muckstadt and Isaac (1981) presented the first production planning and inventory control model for remanufacturing systems. 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 (1977) analyzed the continuous-review inventory control case where incoming returnables are disposed of whenever the inventory position reaches a predetermined level. van der Laan *et al.* (1996) extended Muckstadt and Isaac's (1981) 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. For a comprehensive review of environmentally conscious manufacturing and product recovery, see Gungor and Gupta (1999).

### MODEL DESCRIPTION

A queueing network representation of a simple remanufacturing system is shown in Figure 1. The

remufacturing system considered here consists of three stations, viz., a disassembly and testing station for returned products, a disposition station for non-reusable returns and a remanufacturing station. After the remanufacturing operation, items are directed to the serviceable inventory from where the demand is satisfied (Aksoy and Gupta, 1999).

It is assumed that both return and demand processes are independent and their interarrival times are exponentially distributed with rates  $\lambda_{ar}$  and  $\lambda$  respectively ( $\lambda > \lambda_{ar}$ ). Re-usable rate of the returned products is represented by  $r$ . There is one machine at each node and the buffer capacity at each node is represented by  $B_i$ . The service rate,  $m_i$ , of each station is exponentially distributed and the service discipline is First Come First Serve (FCFS). The machines are prone to breakdowns. The breakdown rate of a machine,  $a_i$ , and the repair rate for a broken machine,  $b_i$ , are also exponentially distributed. At the time of an arrival of an item at node  $i$ , either its buffer is not full and the item joins the queue or buffer is full and the item cannot join the queue and stays where it is originated from and blocks that node. The only exception is when the product first arrives to the disassembly station from outside. In that case, if the product finds the buffer full, it cannot enter the system and is considered lost to the system. The blocking mechanism in the system is 'block after service' (BAS). Note that outside procurement is needed to supplement any demand that cannot be satisfied by the remanufacturing system. 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.

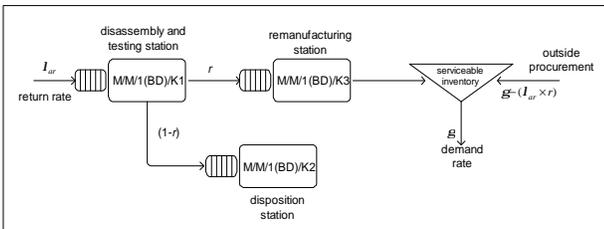


Figure 1. Remanufacturing network with unreliable stations and finite buffers.

The decomposition principle and the expansion methodology are used to analyze the queuing network. The decomposition principle is widely used in the analysis of a queuing 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.

Once the network is decomposed, we use the expansion methodology to analyze each node

individually (Gupta and Kavusturucu, 1998; Kavusturucu and Gupta, 1999; Gupta and Kavusturucu, 2000). 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 that 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 determined (Kerbache and Smith, 1988). Although the throughput rate is by far the performance measure of choice in the traditional production lines, for the remanufacturing systems, the performance measure representing the total cost is equally crucial because there is a mythical perception that the remanufacturing system is more difficult to justify economically.

The total cost function for the remanufacturing system of the type depicted in Figure 1 is as follows:

$$E(TC_j) = c_p E(RP) + c_d E(D) + c_t E(T) + c_{dis} E(Dis) + c_r E(R) + c_m E(OP) + c_{hs}(I) + c_l E(Ls)$$

where

- $c_d$  : disposition cost/item.
- $c_{dis}$  : disassembly cost/item.
- $c_{hs}$  : on-hand serviceable inventory cost/item.
- $c_l$  : lost sales cost/item.
- $c_m$  : outside procurement/manufacturing cost.
- $c_p$  : purchase cost of cores/item.
- $c_r$  : remanufacturing cost/item.
- $c_t$  : testing cost/item.
- $E(D)$  : expected number of disposed products.
- $E(Dis)$  : expected number of disassembled products.
- $E(I)$  : expected number of on hand inventory.
- $E(Ls)$  : expected number of lost sales.
- $E(OP)$  : expected number of products procured from outside suppliers.
- $E(R)$  : expected number of remanufactured products.
- $E(RP)$  : expected number of returned products.
- $E(T)$  : expected number of tested products.
- $E(TC_j)$  : total cost of the remanufacturing system at iteration  $j$ .

The above technique to calculate the throughput and the total cost for the remanufacturing system facilitates the development of the near optimal buffer allocation plan. The optimal buffer allocation problem considered here seeks to minimize the total cost ( $TC$ ) and can be expressed mathematically as follows.

Find  $B_i$  so as to

Min.  $TC$

$$\text{Subject to } \sum_{i=1}^3 K_i = N$$

where  $K_i$  is the job holding capacity at station  $i$  and  $N$  is the total number of buffer slots available in the system. Figure 2 provides a schematic diagram of the NOBAP.

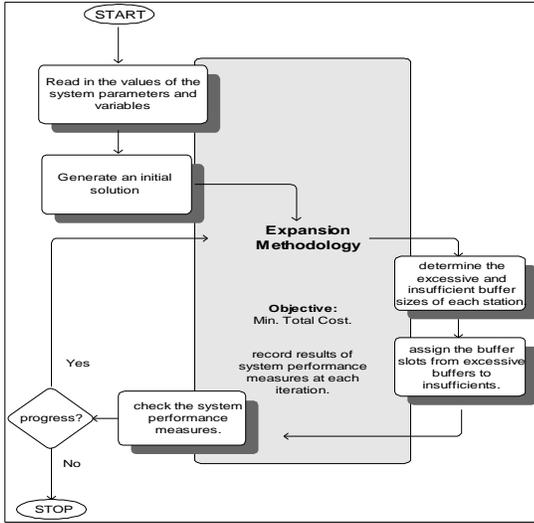


Figure 2. Schematic diagram of the NOBAP.

## NUMERICAL RESULTS

In this section, we present some numerical results that were obtained by applying the NOBAP and exhaustive search. The cost variables were assumed to be as follows:  $c_m = 25$ ,  $c_p = 4$ ,  $c_{dis} = 5$ ,  $c_d = 5$ ,  $c_r = 10$ ,  $c_{hs} = 1$ ,  $c_l = 10$ ,  $c_t = 1$ .

In Tables 1-3, columns 1 and 2 give the total available buffer slots and the buffer allocation results of NOBAP respectively with the associated total costs in column 3. Optimal buffer allocation obtained using exhaustive search and total cost,  $TC^*$ , are depicted in columns 4 and 5 respectively. Finally, column 6 of the tables gives  $D$ , the absolute percentage difference between the  $TC$  obtained from NOBAP and the minimum  $TC^*$ , determined from exhaustive search, i.e.

$$D = (|TC^* - TC|) / TC^* \times 100.$$

From the results given in Tables 1-3, we can conclude that the performance of the algorithm, when applied to the example network, is consistent, robust and produces good results in a variety of experimental conditions.

Table 1.  $I_{ar} = 1$ ,  $r = 0.8$ ,  $m_1 = m_2 = m_3 = 1.5$ ,  $a_1 = a_2 = a_3 = 1$ ,  $b_1 = b_2 = b_3 = 2$ .

$N$	NOBAP	NOBAP $TC$	Op. Buf. Alloc	$TC^*$	$D(\%)$
3	(1-1-1)	24.053	(1-1-1)	24.053	0.00
4	(2-1-1)	25.304	(1-2-1)	24.474	3.28
5	(3-1-1)	25.625	(1-3-1)	24.599	4.00
6	(4-1-1)	25.718	(1-4-1)	24.650	4.15
7	(5-1-1)	25.737	(5-1-1)	25.737	0.00
8	(4-2-2)	27.898	(6-1-1)	25.727	9.41
9	(5-2-2)	27.941	(7-1-1)	25.708	7.99
10	(5-2-3)	28.641	(1-1-8)	25.678	10.30

Table 2.  $I_{ar} = 1$ ,  $r = 0.6$ ,  $m_1 = 3$ ,  $m_2 = 2$ ,  $m_3 = 1.5$ ,  $a_1 = a_2 = a_3 = 1$ ,  $b_1 = b_2 = b_3 = 2$ .

$N$	NOBAP	NOBAP $TC$	Op. Buf. Alloc	$TC^*$	$D(\%)$
3	(1-1-1)	31.047	(1-1-1)	31.047	0.00
4	(2-1-1)	34.641	(1-2-1)	31.415	9.31
5	(1-1-3)	32.476	(3-1-1)	31.278	3.69
6	(4-1-1)	31.101	(4-1-1)	31.101	0.00
7	(5-1-1)	30.983	(5-1-1)	30.983	0.00
8	(6-1-1)	30.909	(6-1-1)	30.909	0.00
9	(7-1-1)	30.864	(7-1-1)	30.864	0.00
10	(4-2-4)	33.201	(8-1-1)	30.838	7.12

Table 3.  $I_{ar} = 1$ ,  $r = 0.6$ ,  $m_1 = 1.5$ ,  $m_2 = 2$ ,  $m_3 = 1.3$ ,  $a_1 = a_2 = a_3 = 1$ ,  $b_1 = b_2 = b_3 = 2$ .

$N$	NOBAP	NOBAP $TC$	Op. Buf. Alloc	$TC^*$	$D(\%)$
3	(1-1-1)	29.371	(1-1-1)	29.371	0.00
4	(1-2-1)	29.875	(1-2-1)	29.875	0.00
5	(3-1-1)	30.943	(1-3-1)	30.006	3.03
6	(1-1-4)	30.979	(1-4-1)	30.053	2.99
7	(1-1-5)	31.010	(1-5-1)	30.073	3.02
8	(1-1-6)	31.025	(1-6-1)	30.083	3.04
9	(7-1-1)	30.789	(1-7-1)	30.089	2.27
10	(8-1-1)	30.742	(1-8-1)	30.092	2.11

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