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Analysis of Remanufacturing System with Server Vacation

H. KıvançAksoy

***Abstract*—Product recovery management deals with the collection of used and discarded products and explores the opportunities to remanufacture the products, reuse the components or recycle the materials. Remanufacturing operations involved with highly uncertain recovery rate of used products and parts that complicate the planning and control of the process. Also, recovery operations tend to be labor intensive that lead to significant variability in the processing times at various shop floor operations. To reduce the effect of these uncertainties we need to employ server operation policy. This paper considers the performance of the remanufacturing system with finite buffers and random time-span server vacations. The term *server vacation* may be used to cases where the server leaves the primary queuing system to work on an external workload for a random duration every time the server becomes idle. We model the remanufacturing system as an open queuing network and use the decomposition principle and expansion methodology to analyze it.**

***Index Terms*—Remanufacturing, open queueing network, expansion method, server vacations.**

I. Introduction

Remanufacturing and reusing of durable goods and subassemblies have become important alternatives to assembling new parts and components. This is a direct consequence of the implementation of extended manufacturer responsibility, together with the new more rigid environmental legislation and public awareness. In addition, the economic attractiveness of reusing products, subassemblies or parts instead of disposing them has further fueled this phenomenon. Remanufactured parts/components can be utilized for assembly of new 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 new materials and energy resources. On the other hand, recycling is a process performed to retrieve the material content of used and non-functioning products (cores) without retaining their identities.

Product recovery management deals with the collection of used and discarded products and explores the opportunities to remanufacture the products, reuse the components or recycle the materials. The objective of product recovery management, as stated by Thierry et al. (1995) [1], is "to recover as much of the economic (and ecological) value as reasonably possible, thereby reducing the ultimate quantities of waste". Remanufacturing is one of the most desirable options of product recovery. Remanufacturing operations tend to be labor intensive that lead to significant variability in the processing times at various shop floor operations. The uncertainties surrounding the returned products further complicate the modeling and analysis of product recovery problems. As such, forecasting the quantity and the quality level of used products are difficult. There are two different types of uncertainties that affect the remanufacturing process: internal uncertainty and external uncertainty. Internal uncertainty comprises of the variations within the remanufacturing process such as the quality level of the product, the remanufacturing lead time, the yield 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 (reusable rate) of the returned products, the timing and the level of demand, and the procurement lead times of new parts/products. The results of the stated uncertainties include undersupply or obsolescence of inventory, improper remanufacturing plan and loss of competitive edge in the market. Typical remanufacturing operations and their flows are depicted in Fig. 1.

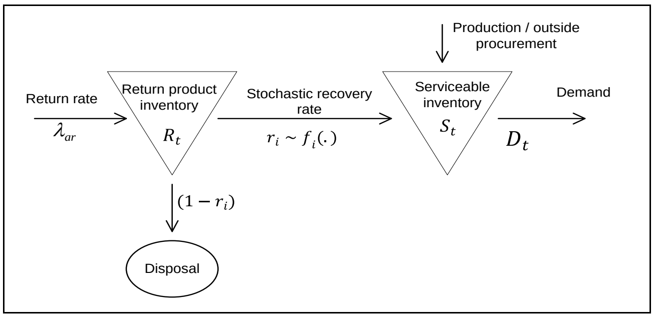

Figure 1.Manufacturing/ remanufacturing system and flow of operation.

In this paper an open queuing network model is constructed to represent the remanufacturing operations with finite buffers and service time is subject to interruption as a result of the server vacation. In other words, the server will stop service for a random amount of time during which arrivals can occur. During the vacation period the server appointed to secondary operations in the remanufacturing system or goes to preventive maintenance before starting to process of new jobs (Figure 2). The service rate μ_i at each station is exponentially distributed and γ_i vacation rate of node (station) i also exponentially distributed. Thus, the motivation for a server vacation model comes forward from the need to use the idle time of the server more efficiently. In

H. KıvançAksoy, Department of Statistics, EskişehirOsmangazi University, Eskişehir, Turkey

order to analyze the queuing network, we use the decomposition principle and expansion methodology [2], [3], [4], [5].

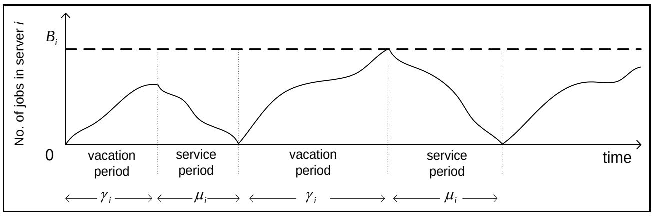

Figure 2. *M/M/*1(*SV*)/$B_i$queue.

II. LITERATURE REVIEW

Single server queue with vacation has been investigated by several researchers; Doshi [6] compiled the literature for the single server queues with vacation period. Lee [7] studied the finite capacity M/G/1 queue with server vacations and obtained the performance measures of the queue in terms of Laplace-Stieltjes transforms. Fuhrman and Cooper [8] studied the aspects of *M/G/*1 type queue with multiple vacation, Choudhury [9] investigated the steady state behavior of the Poisson queue with a random setup time and vacation period with batch arrivals ($M^x/M/1$ queuing system). Ke*et al.* [10] analyzed the finite capacity *G/M/*1 queueing system with *N*-policy and a single vacation. Ke [11] studied machine interference problem with an unreliable server who leaves for a vacation of random length when there are no failed machines queueing up for repair in the system. Cha*et al.* [12] analyzed the *GI/M/*1 queue with multiple and single vacation. Chao and Rahman [13] studied a queueing system with state-dependent services and state-dependent vacations. They presented a recursive algorithm using the supplementary variable technique to numerically compute the stationary queue length distribution of the system. Ke and Wang [14] studied vacation policies for machine repair problem consisting of *M* operating units with two type spare machines and multi repairmen.

Problems associated with remanufacturing have been addressed by Guide and Srivastava [15]. Ferrer and Whybark [16] presented a material requirements planning system to facilitate a remanufacturing system considering the major uncertainty issues in the system, such as, supply of used components, the good parts in those returned items and the demand for remanufactured products. Ferrer [17] provided a framework for designing an efficient remanufacturing procedure of a generic durable good at the end of its useful life considering design measures for instance recyclability, disassemblability and reusability of the used product recovery. Flapper *et al.* [18] indicated that in different process industries input materials may have partly unknown composition which leads to uncertainty about the distribution of defective items. Hees*et al.* [19] analyzed benefits of taking back of used products and pricing policies. The authors found that a firm can increase its profit margins by taking back and reselling refurbished products. Webster ant Mitra [20] examined the impact of take-back laws within a manufacturer/remanufacturer competitive framework.

III. THE REMANUFACTURING MODEL

In this paper we analyze a single item, single location serviceable inventory system where returned products are remanufactured. A returned item gets into the system from outside through the first station (disassembly station) and is processed by all stations sequentially, and finally departs from the system after joining the serviceable inventory. We assume that both return of products and demand arrive to the system according to a renewal process, viz., the inter-arrival times of products and demand are independently and identically distributed exponential random variables with rates (λ_{ar}) and (d) respectively.There is one server and a finite buffer capacity represented by B_i at each station *i*. The service rate μ_i at each station is exponentially distributed and the service discipline is First Come First Serve (FCFS). The blocking mechanism in the remanufacturing system is 'block after service' (BAS). When an item is ready to leave the *i*th station (after processing), the item goes directly to the downstream (*i*+1th) station, where it enters into service immediately if the server is free; otherwise, it joins the queue if there is a place in the buffer. If a buffer slot is not available in the downstream station the part stays at station *i* and blocks that station. For the period of blocking, station *i* remains idle and cannot process any parts that might be waiting in its queue. A blocked job is released to the downstream station as a space becomes available there. The only exception is when the used products first arrive at the disassembly station from outside. In that case, if a returned product finds the buffer of the station full, it cannot enter the remanufacturing system and is considered lost to the system. (However in this situation, because of potential recovery opportunity of the returned product a penalty cost is applied). A remanufactured unit is instantly directed to the serviceable inventory from where the demand is satisfied. Any deficiency is fulfilled with outside procurement of new products. The transfer times of items between buffers and stations are assumed to be negligible. When a failure of a station occurs during the processing of a part, the part stays there while the station is being repaired. After the repair of the station, the part is reprocessed from the beginning.

The total cost function (*TC*) for a remanufacturing network of the type illustrated in Figure 1. consists of the following types of recovery and remanufacturing costs:

$E(R_t)$: Expected rate of the returned products is represented by the arrival rate of returned products to the remanufacturing system (λ_{ar}).

$E(dis.)$: expected number of disposed items per unit of time.

$E(P_t)$: Expected rate of manufacturing/outside procurement is estimated by the difference in the demand and the return rate ($d - \lambda_{ar} \times r$).

$E(S_t)$: Expected serviceable inventory level of the remanufacturing system is estimated the average queue length of the serviceable inventory where the demand, *d* is satisfied. Serviceable inventory designed as a dummy station with the service rate equal to demand (*d*) rate with two arrival streams.

$E(L_s)$: Expected rate of the lost sales is estimated by the starving probability of the serviceable inventory.

$E(Rm_t)$: Expected rate of the remanufactured parts in each station is estimated by the throughput rate of the associated stations. The expected total cost expression can then be written as:

$$E(TC|r_i) = c_p E(R_t) + c_{dis} E(dis) + c_h E(S_t) + c_l E(L_s) + c_r E(Rm_t) + c_m E(P_t) \quad (1)$$

Since each node is analyzed independently and in isolation, the throughput of each node is also calculated independently. The throughput of node i is calculated as follows [15].

$$TH_i = (L_i - Lq_i)\mu_{i_i} + \lambda j_i (1 - P'_{K_i})^{\rho_i + \rho_{i-1}} (1 - P_{K_i}) \quad (2)$$

where the expected number of jobs in node i,

$$L_i = \sum_{s_i=0}^{K_i} s_i P_{si} \quad (3)$$

the expected number of jobs in the queue at node i,

$$Lq_i = \sum_{s_i=1}^{K_i} (s_i - 1) P_{1s_i} + \sum_{s_i=1}^{K_i} s_i P_{0s_i} = L_i - \sum_{s_i=1}^{K_i} P_{1s_i} \quad (4)$$

P_{K_i}, P'_{K_i}, P_{qs_i} are depicts probability of having K_i jobs at the destination node i, feedback blocking probability in the expansion method and probability that there are s_i $(0 < s_i < K_i)$ jobs at node i and the server is either taking a vacation (q=0) or serving (q=1) respectively.

The throughput of the last node represents the throughput of the entire system.

4. NUMERICAL RESULTS AND CONCLUSIONS

In this section we examine the effect of return rate and recovery rate update on the performance of the system. In the model that we studied single production order decision made before the period to persuade the demand. Used products may be returned to the remanufacturing system and they follow a stochastic recovery rate. Unfulfilled demand at the end of the period is considered as lost sales.

In the remanufacturing process, a low reusable rate of products does not, by itself, create a major problem since it is always possible to supplement the deficient amount with new parts/materials bought from outside suppliers to satisfy the demand in a given period. However, the variable recovery rate of a product complicates production and inventory planning. We considered that core recovery rate in consecutive periods are independent and identically distributed (i.i.d) stochastic variables depicted by $r_i$for periods t. In Figure 1, r_i represents the reusable rate of the parts (cores), which are disassembled from returned products and (1-r_i) corresponds to the scrap rate. $r_i$is a stochastic variable with mean $\bar{r}$, standard deviation σ_r and density function $f(r)$ such that $0 \le r \le 1$.

The main objective of this paper is investigating the effect of return rate and recovery rate variation on the system performance measures. In this study we consider system operation cost and throughput rate of the remanufacturing system. To assess the effect of recovery rate on the remanufacturing system performance we defined the expected cost of the system, which comprises of the variable and fixed remanufacturing and outside procurement costs, disassembly, testing, disposal and remanufacturing costs, holding costs for serviceable inventory and lost sales costs. The following notation is used for the steady state cost function.

The cost variables are; purchasing cost of returned products (c_p=4), disassembly cost (c_{dis}=5), inventory holding cost for serviceable items (c_h=1), lost sales cost for unfulfilled demand (c_l=5), remanufacturing operation cost (c_r=3) and cost of procured/manufactured items (c_m=25). In order to reflect the effect of return and recovery rate variation on major system performance measures, total system cost (TC) and system throughput (TH) we use different combinations of return, demand and recovery rates are utilized and the results are summarized in Table 1.

Table 1. Performance measures under various system parameters

λ_{ar}	d	r	γ_i	TC	TH
0.3	0.5	0.4	1	19.1108	0.0931
0.3	0.5	0.4	2	19.367	0.102
0.3	0.5	0.6	1	17.542	0.1398
0.3	0.5	0.6	2	17.7968	0.1467
0.3	0.8	0.4	1	26.771	0.0982
0.3	0.8	0.4	2	27.0588	0.102
0.3	0.8	0.6	1	24.882	0.1358
0.3	0.8	0.6	2	25.626	0.1467
0.6	0.5	0.4	1	18.8205	0.15.03
0.6	0.5	0.4	2	19.0704	0.1588
0.6	0.5	0.6	1	14.76	0.1886
0.6	0.5	0.6	2	15.3876	0.219
0.6	0.8	0.4	1	26.0361	0.1407
0.6	0.8	0.4	2	27.321	0.1588
0.6	0.8	0.6	1	22.864	0.205
0.6	0.8	0.6	2	23.90	0.219
0.9	0.5	0.4	1	17.1045	0.174
0.9	0.5	0.4	2	18.1057	0.188
0.9	0.5	0.6	1	12.1587	0.1996
0.9	0.5	0.6	2	13.1021	0.2531
0.9	0.8	0.4	1	25.6459	0.151
0.9	0.8	0.4	2	26.6612	0.188
0.9	0.8	0.6	1	20.459	0.1996
0.9	0.8	0.6	2	21.499	0.2531

In Table 1. it's clear that system's operation cost is sensitive to return rate and recovery rate. As the return rate increases associated with high recovery rate there is a significant decline on the total cost. Also, for the low return rate associated with a low recovery rate the total remanufacturing cost increases meaningfully. Another observation from the experiments suggests that as the server vacation time increases (or in other words, γ_i decreases) there is a significant decrease in the system's throughput.

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