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Near optimal buffer allocation in remanufacturing systems with *N*-policy

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ABSTRACT

We introduce a near optimal buffer allocation plan (NOBAP) specifically developed for a cellular remanufacturing system with finite buffers where the servers follow *N*-policy. The term *N*-policy is used for the situation where the server leaves primary work to tend to an external workload assigned to him (such as processing additional tasks or performing preventive maintenance of equipments) every time the server becomes idle and does not return back to his primary work until the queue size in front of the primary work reaches a threshold value of $N\ (\geqslant 1)$. The remanufacturing system considered here consists of three modules, viz., the disassembly module for returned products, the testing module and the remanufacturing module. In order to analyze the system we propose an algorithm that uses an open queueing network, decomposition principle and expansion methodology. The buffer allocation algorithm distributes a given number of available buffer slots among the remanufacturing system stations to optimize the system's performance. The algorithm has been rigorously tested using a variety of experimental conditions. From the results, it is clear that the algorithm's performance is robust, consistent and produces excellent results.

1. Introduction

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. Recycling, on the other hand, is a process performed to retrieve the material content of used and non-functioning products without retaining the identity of the original product. Remanufacturing of durable goods has become an important alternative to assembling new products. This is a direct consequence of the implementation of extended manufacturer responsibility, together with the new more rigid legislation and public awareness of the environment. In addition, the economic attractiveness of remanufacturing products, instead of disposing them, has further fueled this phenomenon.

Remanufacturing is an important element of product recovery. Product recovery management is concerned with the collection of used and discarded products and the exploration of the opportunities to remanufacture the products, reuse the components or recycle the materials. The objective of product recovery management, as stated by Thierry, Salomon, van Nunen, and van Wassenhove (1995), 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 levels 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 (re-usable 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. See Fig. 1 for a schematic diagram of typical remanufacturing operations and their flows.

The need to optimize a remanufacturing system's performance is most desirable because of the aforementioned uncertainties and complexities. One can always reduce the effect of uncertainties on

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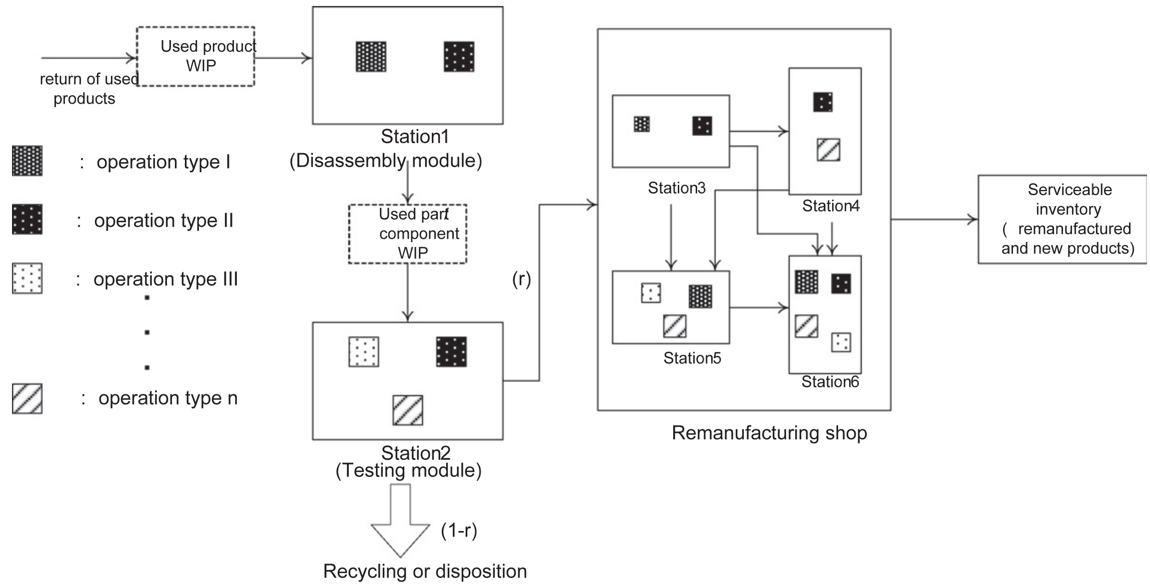

Fig. 1. The model of a remanufacturing system and flow of operations. Returned product operations sequence S1→S2→rS3→$P(r_{34})$S4→$P(r_{45})$S5→$P(r_{56})$S6→Serv. Inv.

the system's performance by increasing the number of buffers at the remanufacturing system's station that exhibits these shortcomings. However physical limitations and many other real life situations impose an upper limit on the number of buffers that can be accommodated in the system. For instance, as the number of buffers in the system increases, the mean processing time and the WIP inventory throughout the system also increase which directly affects the system's operating costs and due date performance. While the throughput rate, the work-in-process (WIP) inventory and the mean processing times are typical performance measures in traditional production lines, for the remanufacturing systems, the performance measure representing the average expected total cost is equally important because of the deceiving perception that the remanufacturing system is more difficult to justify economically. Therefore, one of the critical problems is to allocate a given number of buffer slots among the remanufacturing stages in a way so as to minimize the total cost of the system. As mentioned previously, unknown conditions of the returned products lead to different routings and highly varied processing times within the remanufacturing system. Together, the variation in processing times and the allocation of limited buffers play an important part in the system's performance. Buffer allocation problem has to be solved in the presence of many conflicting objectives including minimizing the remanufacturing costs and processing times and maximizing the throughput rate. The serviceable inventory level coordination between remanufactured products and the new products which are procured from outside further complicates the optimization of the system performance.

To address the issues raised above, we incorporate various stochastic factors, such as used product return rate, service rate, setup rate for the servers and re-usable rate of returned products to model a remanufacturing system. When used for analysis, the model developed here provides for a near optimal buffer allocation plan (NOBAP) for the remanufacturing system.

A remanufacturing system typically consists of three modules, viz., a disassembly module for returned products, a testing module and a remanufacturing module for recoverable items. In this paper, an open queuing network model is developed to represent the remanufacturing operations with finite buffers and exponential service time. Fig. 1 depicts an illustrative example for the remanufacturing system with three modules and six stations. We demonstrate the various phases of remanufacturing operations via four stations and associated routings in the remanufacturing shop. The servers in the system follow N-policy. The term N-policy is used for the situation where the server leaves primary work to tend to an external workload assigned to him (such as processing additional tasks or performing preventive maintenance of equipments) every time the server becomes idle and does not return back to his primary work until the queue size in front of the primary work reaches a threshold value of N ($\geqslant 1$). Once the queue size reaches that threshold level, the server continues to process the currently assigned external workload instead of stopping it abruptly. This means that there is start-up time required to start serving the primary jobs waiting in the queue. Service is provided to one job at a time and it continues till the service station becomes empty. The motivation for N-policy comes from the need to reduce the idle time of the server and use him more efficiently. The threshold level (N) constitutes one of the design problems for the performance of the system. The size of the threshold level directly affects the queue lengths and the waiting times in the system.

This paper is organized as follows. In Section 2 we briefly review the literature on buffer allocation in production lines and production planning and inventory control models for remanufacturing systems. In Section 3 we present the notation of all the variables and parameters used in the paper. In Section 4 we briefly describe the expansion methodology used to calculate the system performance measures in the buffer allocation algorithm. In Section 5 we describe the model formulation, assumptions and the buffer allocation algorithm. In Section 6, the performance of the algorithm developed in Section 5 and the results obtained from exhaustive search are compared. Finally, we present the conclusions in Section 7.

2. Literature review

There is an expanding body of literature in the area of remanufacturing/manufacturing systems and product recovery due to operational challenges surrounding such systems. There are many factors that enhance product recovery, remanufacturing and recycling activities. Examples include: ease of disassembly, modularity, material selection and compatibility, material identification and efficient cross-industrial reuse of common parts/materials. The