OPTIMAL BUFFER ALLOCATION FOR REMANUFACTURING SYSTEM USING META-HEURISTIC ALGORITHM

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Abstract- Remanufacturing system is complicated due to its stochastic nature. Random customer demand, return product rate and system unreliability contribute to this complexity. Remanufacturing systems with unreliable machines usually contain intermediate buffers which are used to decouple the machines, thereby reducing mutual interference due to machine breakdowns. Intermediate buffers should be optimized to eliminate waste of resources and avoid loss of throughput. The problem deals with finding optimal buffer sizes to be allocated into buffer locations to achieve specific objectives. We develop a model for remanufacturing system based on realistic assumptions, with finite buffers, unbalanced and unreliable servers. We utilize the decomposition principle and expansion method for evaluating system performance and implement an efficient Meta-heuristic search algorithm to find an optimal buffer allocation. The computational experiments show a better quality, more accurate, efficient, reliable and fast of solutions obtained by the proposed algorithm. Finally, we apply proposed method on Toner cartridge Remanufacturing Company as a case study and present numerical results based on proposed methodology. Numerical experiments which are performed on our method are provided to show the efficiency and accuracy of the proposed algorithms.

Keywords- Buffer Allocation, Finite capacity, Meta-heuristic Algorithm, Remanufacturing.

I. INTRODUCTION

Remanufacturing process restores used product (which's called "core") to like-new condition. The process is disassembling used product down to its components, dividing non-usable from reusable parts, and reassembling a combination of new parts with reusable parts to remanufacture the product. Remanufacturing of single use cameras, car engines, computer parts, pallets, and containers could be successful examples where no differences are made between remanufactured and manufactured products. Obviously, study on the system characteristics, inventory management, scheduling and product recovery network design are important issues in remanufacturing mode. In this study, we consider the remanufacturing mode which is based on customer demand and does not consider recycling and waste products. USA navy and the UK remanufacturing industry are two well-known successful examples of remanufacturing systems in the world. They have reduced maintenance costs and saved millions of dollars since 2001.

Based on the report published by Naeem, M.A., et al, 2012, remanufacturing cost is approximately 30–50% of manufacturing new parts cost in order to raw materials, energy and labor is saved. In remanufacturing system, system fluctuations could be handled by means of buffering and inventory control policies. Also, buffering contributes in enhancing level of customers' services, continuing operations sequentially, reducing the risk of loss, and making working capital to be utilized efficiently. Therefore, one of the most challenging issues is the optimization of remanufacturing system performance in which the intermediate buffers are introduced to make an improvement in the efficiency of such systems and thereby to make flow of material balance and smooth. Buffer allocation problem (BAP) is an NP-hard combinatorial optimization problem which deals with finding optimal buffer sizes to be allocated in buffer areas in a production line to achieve a specific objective. So far, three forms of buffer allocation problem (BAP) regarding the objective function have been considered in the literature. Minimizing the WIP inventories, maximizing throughput rate of the system and minimizing the total available buffer spaces are three objective functions which have been concerned. Solution approaches to solve buffer allocation problem involve applying a generative method and an evaluative method in an iterative manner. Obviously, remanufacturing systems face more uncertainties (due to stochastic return rate and unreliable workstations) for achieving the desirable throughput rate and optimizing the buffer allocations effectively and efficiently.

In this paper, because of the system complexity, evaluative method is combined with a Meta-heuristic search algorithm to address the problem. Evaluative method is used to model the remanufacturing facilities whereas a Meta heuristic algorithm is used to analyze the simulated results. Modified simulated annealing approach (SA) is employed in attempting to quickly work out the best solutions for buffer allocation problem.

II. LITERATURE REVIEW

Determining optimum buffer allocation is an important optimization problem faced by manufacturing and remanufacturing system designers. Koenigsberg, in 1959, investigated internal storage in production lines for the very first time, in which the basic problems and the efficient operation of production systems have been analysed and reviewed. Evaluative methods (analytical methods and simulation) are applied to estimate performance measures in both manufacturing and remanufacturing systems. There are two classified; exact and approximate methods for analytical methods in which the approximate methods are usually employed for solving combinatorial buffer allocation large-sized problems and the exact methods could be applicable only for small-sized problems.

As a common mostly used evaluative method, decomposition methodology calculates the throughput of manufacturing and remanufacturing systems quite accurately and quickly, Dallery et al. proposed an algorithm which was a development of the decomposition principles' equations called DDX to solve them. Later, Burman developed Dallery's methodology and proposed an algorithm called accelerated-DDX (ADDX) algorithm to evaluate the non-balanced lines' performance. Gershwin and Schor proposed a method in which the approximate decomposition algorithm solves the decomposition equations efficiently to determine production rate and average buffer levels. They applied decomposition method for small buffers as well as small systems to produce numerical results. In the papers published by Nahas et al., they modelled a series-parallel manufacturing line in which workstations are unreliable and proposed new approach to solve buffer allocation problem. In presented formulas, they considered large production lines with maximum average throughput as a main objective subject to a limited total cost. Recently, in a new presented approach, an analytical decomposition approximation method (as an evaluative method) has been developed to calculate the throughput rate. They implemented an adaptive tabu search (as a generative method) to maximize the throughput rate of the line for both homogeneous and non-homogeneous lines. The authors also tested the efficiency of the presented approach considering the objective function is the minimization of total available buffer slots. Dolgui et al. proposed a meta-heuristic algorithm where an approximate Markov-model aggregation approach evaluated the experimental solutions for the buffer allocation problem. They considered an unreliable and homogenous manufacturing system in which the series of workstations are divided with finite buffers, and they assumed that repair and failure rate of workstations are exponentially distributed.

Simulation is the other mostly common evaluative method to measure performance of manufacturing or remanufacturing systems. Battini et. al. in the reference proposed an efficient simulation method for flow-line manufacturing system to allocate available buffer slots between workstations. In addition, they provided a new generative method (experimental cross-matrix) to optimize buffer allocation problem. Other simulation method as an evaluative method can be reviewed in papers published by Can et al.. They proposed a simulation-based Meta modelling (as an evaluative method) in combination with an evolutionary algorithms (as a generative method) to solve buffer allocation problem. Simulation-based Meta modelling has been developed by implementing Artificial Neural Networks (ANNs) and Genetic Programming (GP). In the previous literature, almost all researchers assumed effective parameters are either deterministic or exponential distribution. However, Amiri and Mohtashami relaxed these assumptions and limitations for repair, failure rates and processing times of workstations to solve multi-objective buffer allocation problem in unreliable production lines. Due to, for such systems, decomposition technique cannot be applied in the absence of deterministic or exponential distribution for parameters, they proposed a simulation approach in which processing times and times between repairs and failures are assumed to be general function distributions. Jeong and Kim studied on a different type of buffer allocation problem involving the selection of machines for each workstation and determination of buffer capacities in a tree-structured unreliable assembly system. The authors suggested three heuristics to determine minimum cost configuration for achieving a desired throughput rate.

Lee and Ho developed a heuristic search algorithm to allocate optimum size of buffer between the workstations in complex manufacturing systems. They considered total buffer storage and total cost as objective functions which are optimized in three phases. In phase one, the capacity of buffer stage is determined using queuing statistics. Afterwards, buffer settings are optimized theoretically in the second phase. In this phase, they used constructing a second-order model of the buffer sizes and the response surface. Finally, in phase three, the derivative approximation is conducted to obtain an integral solution to solve the buffer allocation problem.

An appropriate stochastic algorithm for solving the BAP has been presented in. Two phases of the proposed algorithm are: phase 1, generating the buffer allocation based on a certain random strategy, and

phase 2, the customizing of the phase 1 according to minimization of cross-entropy. Another study employing a genetic algorithm was presented for complex production systems in that a simulator including a genetic algorithm is developed to optimize the buffer sizes. The authors introduced a new encoding method called multi-vector encoding method for genetic algorithms and stated that by using this new encoding method, the optimal buffer sizes could be obtained after a few numbers of generations.

Chehade et al. have taken two objectives into consideration: the maximization of the throughput rate and the minimization of the total size of the buffers. The resolution method is based on a multi-objective ant colony algorithm but using the Lorenz dominance instead of the well-known Pareto dominance relationship. In the studies published in They developed a multi-objective approach for the buffer allocation and throughput and overall server rate trade-off problem for single server queuing networks.

According to research conducted on the buffer allocation problem, there were a very limited (only three) studies published by Aksoy et al. They modelled an unreliable remanufacturing system to find a near optimal buffer allocation plan (NOBAP) in which buffer capacities are finite. They analyzed the system performance using expansion methodology, approximate decomposition method (as an evaluative method) and open queueing network. They also proposed a specific search algorithm to find near optimal buffer allocation and implemented Taguchi method (orthogonal array) to design appropriate factorial experiment for their numerical study. In this paper, we extend the work of other researchers by proposing an efficient modified simulated annealing algorithm as a generative method and decomposition method as an evaluative method for maximizing the throughput rate in series-parallel remanufacturing systems. The rest of the paper is structured as follows. In the following section, we will introduce the area of remanufacturing and analyse the process. Then it is explained how to implement the decomposition technique to evaluate the performance measures of proposed queuing network and a simulated annealing algorithm. In the next section, we will describe the numerical and case study of toner cartridge remanufacturing company and analyse obtained results. Conclusions and an outlook on further research goals are afforded in the concluding segment.

III. MODEL DESCRIPTION AND ASSUMPTIONS

In this paper, we define a remanufacturing system as an independent group of dissimilar modules. Classification and disassembly module for returned products, testing module for recognizing which returned item is either reusable or non-reusable are the first group. Moreover, the remanufacturing module for reusable returned items, the collection for recycling module for non-reusable items and final test & packaging module for finished remanufactured products are categorized in the second group (Fig. 1).

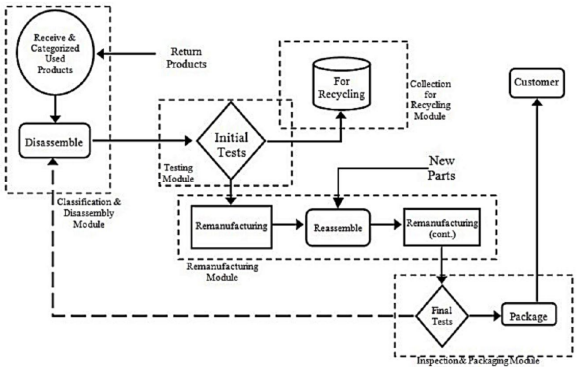


Figure 1. Remanufacturing Process Model

The fundamental properties of the series-parallel remanufacturing system are assumed as follows: Each module in the current modelling, considered in the proposed queuing network, consists of one or more unreliable servers arranged in series-parallel with finite capacities and are prone to breakdowns. Returned parts are routed into the system via the first workstation, follow through and are processed by all or partial workstations in turn and finally depart from the system by way of the last one. The total factory area that can be used to set up the buffer capacities is finite. As a result, buffer capacity (including the one in service) of all workstations in the queuing network is restricted in size, and thus the blocking phenomenon exists. Returned products inter the system from outside with a Poisson distribution with a known average rate, ƛrp, for a certain period of observation. Each queue has a single server with exponential service time distribution in which servicing the returned items are done continuously and independently with average rate, μi. In addition, service disciplines are on a first-come-first-served basis for all queues. Once the operation on a part (job) is finished at the ith queue, the part is routed to the (i+1)th queue, where it enters into service immediately if the server is idle; otherwise, it joins the queue if there is a place in the buffer capacity. We use an isolation technique, decomposition principle and expansion methodology in an open queueing network (OQN) to analyse the remanufacturing system. Once the used products return to the remanufacturing system they are directed to the disassembly module. After disassembling, components are inspected visually at first. Then electrical parts are tested by tools and technicians. Those items, which do not satisfy a determined level of

quality for remanufacturing, are directed to collection for recycling module with expected rate R1, R2 from visual and technical test workstations, respectively. Damaged items, collected in this module, can be either disposed of, land filled or sold as a scrap part for recycling. Reusable disassembled and inspected parts are transferred to the remanufacturing module to be remanufactured with expected rate, 1-R2, from electrical test station. In Toner Cartridge Company, after the remanufacturing operations such as Cleaning, Repairing, Refurbishing and Reassembling, items are directed to refill section. Refilling process is started by adding cleaning solution and then continued by spinning, vacuuming and finished by refilling. In addition, there are two final inspections (Weighting and test page print) and packaging module for finished remanufactured products to be stocked where satisfies the product demand. We outline our system patterns as demonstrated in Fig. 2.

WS_i : Workstation i, $(i=1,...,m)$
α_i : Failure rate for workstation i
β_i : Repair rate for workstation i
K_i : Capacity for buffer ith (B_i)
P_{qs_i} : Probability of existing s_i jobs at node i and if the machine is serving, q=0, if not, q=1
R_{cr} : Recollect rate for imperfect finished products
λ_i^t : Input rate of node i
r_{ij} : Probability of routing from node i to j
R_{np} : New part rate for reassembling
λ_i^{re} : Input rate of jobs which are not rejected
λ_i^{ho} : Input rate of the visual station

IV. EVALUATIVE METHOD

Decomposition method is the most widely used method for solving BAP when a closed form solution for the network does not exist. The common idea of this method is to decompose the analysis of the original model into the analysis of a set of smaller subsystems that are easier to deal with. After decomposing the network, we use the expansion methodology to analyze each node individually, which is used under restrictive assumptions and it can be applied to split and merge configurations as well as serial configurations. 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 for each finite buffer node. These extra nodes are modelled as infinite buffer nodes with zero processing time for those jobs, which cannot enter the destination node because the buffer is full. The blocked jobs stay in holding node until a space becomes available in the full buffer. Next, the parameters that define the expanded network, such as the actual arrival rate of the system, the probability of a job being blocked by the full buffer are calculated. Eventually, through the newly defined variables, the throughput of the node is set. Once the throughput of the first node is calculated, this value is used in the analysis of the second node (if it is in tandem to the first node) where it is processed as the arrival rate to that node. If the first node is a split node, the arrival rate to any one of the parallel nodes following the first node is the product of the throughput from the first node multiplied by the branching probability to that node. If the second node is a merge node, the arrival rate to that node is the sum of the throughputs of all its immediately preceding nodes. The expansion methodology calls for applying this procedure to each node and eventually the throughput of the final node is calculated. This throughput becomes the throughput of the entire network.

V. THROUGHPUT CALCULATION

Based on the Markov chain theory and transition phenomena in queueing network with failure probability Equilibrium Equations can be written as follows:

$$\begin{aligned}
&\lambda_i^t P_{00_i} = \mu_i P_{01_i} \\
&(\lambda_i^t + \mu_i + \alpha_i) P_{0s_i} = \lambda_i^t P_{0s_i-1} + \mu_i P_{0s_i+1} + \beta_i P_{1s_i} \qquad 1 \le S_i \le K_i - 1 \\
&(\mu_i + \alpha_i) P_{0k_i} = \lambda_i^t P_{0k_i-1} + \beta_i P_{1k_i} \\
&(\lambda_i^t + \beta_i) P_{11_i} = \alpha_i P_{01_i} \\
&(\lambda_i^t + \beta_i) P_{1s_i} = \lambda_i^t P_{1s_i-1} + \alpha_i P_{0s_i} \qquad 2 \le S_i \le K_i - 1 \\
&\beta_i P_{1k_i} = \lambda_i^t P_{1k_i-1} + \alpha_i P_{0k_i}
\end{aligned} \tag{1}$$

Where Pqsi is the probability that si number of jobs exist at node i. Also, q=1 is representing that the workstation is not operating and q=0 means the workstation is serving. With following accumulated condition:

$$\sum_{q=0}^{1} \sum_{s_i=0}^{k_i} P_{qs_i} = 1 \tag{2}$$

In addition, we assumed that if S_i jobs exist at node i, and we do not concern that the workstation is under operation or not, then

$$P_{s_i} = P_{0s_i} + P_{1s_i} \quad , \quad 0 \le S_i \le K_i \tag{3}$$

According to the above equations we use following systems of equations in 2 variables to calculate approximate values for total input rate λ_i , feedback blocking probability P'_{Ki} at node i [36].

$$P'_{k_i} = \left(2 - \frac{\lambda_i (r_{2_i}^{k_i} - r_{1_i}^{k_i}) - (r_{2_i}^{k_i-1} - r_{1_i}^{k_i-1})}{\mu_i (r_{2_i}^{k_i+1} - r_{1_i}^{k_i+1}) - (r_{2_i}^{k_i} - r_{1_i}^{k_i})} \right)^{-1} \tag{4}$$

$$\lambda_i = \lambda_i^{re} - \lambda_i^{ho}(1 - P'_{k_i}) + \alpha_i + \beta_i$$

Where

$$\begin{aligned}
&\lambda_i^{re} = \lambda_i^t (1 - P_{k_i}) \\
&\lambda_i^{ho} = \lambda_i^t P_{k_i} \\
&r_{1_i} = \frac{\left[(\lambda_i + 2\mu_i) - \sqrt{z_i} \right]}{2\mu_i} \\
&r_{2_i} = \frac{\left[(\lambda_i + 2\mu_i) + \sqrt{z_i} \right]}{2\mu_i} \\
&z_i = (\lambda_i + 2\mu_i)^2 - 4\lambda_i \mu_i = \lambda_i^2 + 4\mu_i^2
\end{aligned} \tag{5}$$

The expected numbers of jobs in the queue and in the node *i* would be achieved by following formulas which are used to calculate the throughput of each node independently [31]:

$$L_i = \sum_{s_i=0}^{K_i} s_i P_{si}$$

$$Lq_i = \sum_{s_i=1}^{k_i} (s_i - 1) P_{0s_i} + \sum_{s_i=1}^{k_i} s_i P_{1s_i} \Rightarrow Lq_i = L_i - \sum_{s_i=1}^{k_i} P_{1s_i} \quad (6)$$

$$TH_i = (L_i - Lq_i)\mu_i + \lambda_i^j (1 - P'_{k_i})^{\rho_i + \rho_{i\sim}} (1 - P_{k_i}) \quad (7)$$

VI. MODEL FORMULATION

As it mentioned in section 2, the buffer allocation problem can be expressed mainly in three forms depending on the objective functions. These objective functions may consider maximizing the throughput rate of the system, minimizing the total buffer size in the system or minimizing the work-in process inventory. The model for the formulation of the problem in this paper is provided below:

$$Find \ \mathrm{B}=(\mathrm{B}_1, B_2, ..., B_{k-1}) \text{ so as to}$$

$$Ma\ x \ \mathrm{f(B)}$$

Subject to

$$\sum_{i=1}^{k-1} B_i = N$$

$$B_i \text{ non negative integers } (i = 1, 2, ..., k\text{-}1)$$

This formulation of the problem indicates maximization of the throughput rate for a given fixed amount of buffers, where N is the total number of buffer space available, which is nonnegative integer and fixed amount. This amount of buffers has to be allocated among the buffer locations so as to maximize the throughput rate. In this formulation, B represents a buffer size vector, and f(B) is the system final throughput rate which is based on the buffers' size vector.

VII. SIMULATED ANNEALING ALGORITHM

Simulated annealing is suitable for combinatorial minimization problems and its idea is about simulating the cooling of material in a heat bath. Kirkpatrick, in took the idea and applied it to optimization problems. They used simulated annealing to search for feasible solutions and converge to an optimal solution. Simulated annealing method starts with a non-optimal initial configuration (which may be chosen at random) and works on improving it by selecting a new configuration using a suitable mechanism (at random in the simulated annealing case). If the cost is reduced, then the new configuration is accepted and the process repeats until a termination criterion is satisfied. The main structure of the proposed simulated annealing algorithm is presented in Fig. 3.

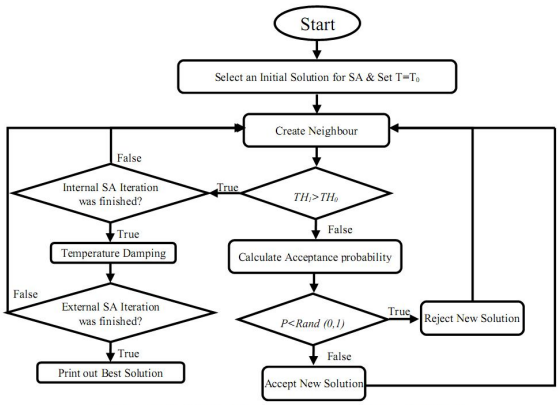


Figure 3. Simulated Annealing algorithm Flowchart

VIII. NUMERICAL STUDY

For an evaluation of the potentials of our approach, a case study was carried out in collaboration with a Toner Cartridge Remanufacturing Company. We collected all parameters' value including; the return rate, failure and repair rates of workstations, new parts input rate, recollect rate of imperfect finished products and the routing probabilities in the toner cartridge remanufacturing system (See Table 1, 2).

TABLE 1: Workstation's parameters

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
μ_i	1.3	1.7	1.5	1.3	1.3	1.7	1.5	1.3	1.7	1.7	1.3	1.7	1.7	1.5
α_i	0.1	0.02	0.05	0.02	0.01	0.02	0.05	0.1	0.01	0.01	0.1	0.02	0.02	0.05
β_i	0.2	0.1	0.15	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.15

Table 2: Routing Probabilities

Routings	r_{45}	r_{46}	r_{47}	r_{56}	r_{57}	R_1	R_2	R_{np}	R_{cr}
Rates	0.25	0.15	0.6	0.7	0.3	0.1	0.15	0.25	0.05

Once the used products return to the remanufacturing system they first go to the disassembly operation. After disassembling, components are inspected visually at first.

Then electrical parts are tested by tools and technicians in another workstation. Those items, which do not satisfy a determined level of quality for remanufacturing, are directed to collection for recycling module with expected rate R1, R2 from visual and technical test workstations, respectively. Damaged items could be either disposed of, land filled or sold as a scrap for recycling. Reusable disassembled and inspected parts are transferred to the remanufacturing module to be remanufactured with expected rate 1-R2 from electrical test station. In Toner Cartridge Company, after the remanufacturing processes such as cleaning, repairing, refurbishing and reassembling, items are directed to refill section. Refilling process is started by adding cleaning solution and then continued by spinning, vacuuming and finished by refilling. Also, there are two final inspections (Weighting and test page print) and packaging module for finished remanufactured

products to be stocked in the serviceable inventory from where the demand is satisfied.

Currently, the volume of remanufactured cartridges is about 1400 (ƛar = 1.94) a month, but the goal is to reach 5000 and total available buffers for allocation is 36 (N=36). The remanufacturing process at 24 Hour Toner Services starts when the empty cartridges are received in which the processes are mostly manual and only few machines are used. According to the facility manager's statement, it is the cleaning step that takes more time in the remanufacturing process in order to many components need to be cleaned in the cartridges. The filling process is also time consuming, and appears to be the step where efficiency could be improved.

Table 3: Summarized results

Approach	Run	Opt. Buffer Allocation	Opt. Throughput	Run Time (seconds)
Simulated Annealing	1	[1, 1, 1, 1, 2, 3, 2, 4, 4, 1, 2, 4, 4, 6]	1.3435	598.4
	2	[2, 1, 2, 3, 1, 2, 2, 1, 5, 3, 2, 4, 3, 5]	1.2579	603.5
	3	[3, 1, 2, 1, 3, 1, 2, 2, 7, 2, 1, 2, 5, 4]	1.2513	613.9
	4	[1, 1, 1, 6, 1, 1, 2, 1, 2, 1, 4, 3, 8, 4]	1.2946	592.8
	5	[2, 3, 1, 2, 1, 4, 2, 1, 3, 3, 1, 4, 4, 5]	1.3060	594.9

The proposed algorithm is coded in the Matlab,7 software. The implementation is executed on a computer having 2.4 GHz Core i5 CPU processor and 4 GB of RAM. Table, 3 represents the results of the computational runs.

The performance of the algorithms is evaluated with respect to solution time (the CPU time in seconds) and solution quality (the throughput rate). Our experiment concerned non-balanced and unreliable lines for a case where exact solution for optimal buffer allocation is not known. Simulated annealing algorithm optimizes a single solution (specific case indicated in Table 2 and 3) in 5000 iterations. The solution's throughput value oscillates as both better and worse solutions while the oscillation width decreases following the algorithm's exponential cooling schedule and converges towards the optimal value.

CONCLUSION

In this study, an accurate, fast, and a reliable simulated annealing algorithm is proposed to solve buffer allocation problem in non-balanced unreliable remanufacturing system for maximizing throughput. In addition, we include total available buffer slot constraint in our problem. A nonlinear programming approach is adopted to model the problem. Experimental results are also provided to show the accuracy and efficiency of our algorithm. It should be noted that the test problem includes quite long remanufacturing line which has a wide range of variety both in processing times and reliability parameters so that the efficiency of the proposed algorithm can be tested thoroughly on a wide range of problem instances. The results of observational studies are found to be quite encouraging. Namely, it has been observed that the proposed algorithm always converges to the optimal. There is several research directions to which we can extend our algorithm in the future. In this study, only the throughput maximization problem is considered. Therefore, especially, if there is a budget constraint, minimizing the total buffer size could be very valuable.

Also, this study can be extended to minimize the total buffer size and customer waiting time by using the proposed meta-heuristic method or hybrid algorithm. In this respect, the proposed algorithm can be employed as a decision support tool to decide on the total buffer capacity to allocate to each machine in the line.

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