

January 01, 2001

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Hasan Kivanc Aksoy
Northeastern University

Surendra M. Gupta
Northeastern University

Recommended Citation

Aksoy, Hasan Kivanc and Gupta, Surendra M., "Capacity and buffer trade-offs in a remanufacturing system" (2001). . Paper 25.
<http://hdl.handle.net/2047/d10003150>

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Bibliographic Information

Aksoy, H. K. and Gupta, S. M., "Capacity and Buffer Trade-Offs in a Remanufacturing System", *Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing II*, Newton, Massachusetts, October 28-29, pp. 167-174, 2001.

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Contact Information

Dr. Surendra M. Gupta, P.E.
Professor of Mechanical and Industrial Engineering and
Director of Laboratory for Responsible Manufacturing
334 SN, Department of MIE
Northeastern University
360 Huntington Avenue
Boston, MA 02115, U.S.A.

(617)-373-4846 **Phone**
(617)-373-2921 **Fax**
gupta@neu.edu **e-mail address**

<http://www.coe.neu.edu/~smgupta/> **Home Page**

Capacity and Buffer Trade-offs in a Remanufacturing System

Hasan Kivanc Aksoy and Surendra M. Gupta *
Laboratory for Responsible Manufacturing
334 SN, Department of MIME
Northeastern University
360 Huntington Avenue
Boston, MA 02115.

ABSTRACT

In this paper, we examine the tradeoffs between increasing the number of buffers and increasing the capacity at the remanufacturing stations under numerous circumstances on such performance measures as expected total cost, average WIP inventory, throughput and average processing (remanufacturing) time when the remanufacturing stations are operating in uncertain environments. We model the remanufacturing system using an open queueing network with finite buffers and unreliable servers. In order to analyze the queueing network, we use the decomposition principle and expansion methodology. Each server in the system is subject to breakdown and has a finite buffer capacity.

Keywords: Remanufacturing, recycling, disassembly, production planning and inventory control, reusable rate, disposal, open queueing network, expansion methodology, throughput, throughput approximation, buffering, capacity.

1. INTRODUCTION

The characteristic of manufacturing has changed in recent years. A growing number of manufacturing companies have begun to consider recycling and remanufacturing of their products after they are discarded by their customers. This is a direct result of rising public awareness about the environment, an increasing number of environmental regulations employed by more and more countries, competition between companies and the popularity of the extended manufacturer responsibility concept. All this has been further energized by the economic attractiveness that comes with reuse, recycling and remanufacturing of end-of-life products as opposed to disposing them of.

Extended manufacturer concept puts the responsibility of product recovery management on the manufacturing company. The objective of product recovery management as stated by Thierry *et al.* is "to recover as much of the economic (and ecological) value as reasonably possible, thereby reducing the ultimate quantities of waste"¹⁶. The product recovery options include repairing, refurbishing, remanufacturing, cannibalizing and recycling. 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. Recycling on the other hand is a process performed to retrieve the material content of used and non-functioning products without retaining their identity.

Remanufacturing operations are 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 is 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

*Correspondence: e-mail: gupta@neu.edu; URL: <http://www.coe.neu.edu/~smgupta>
Phone: (617)-373-4846; Fax: (617)-373-2921

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 aforementioned uncertainties include undersupply or obsolescence of inventory, improper remanufacturing plan and loss of competitive edge in the market.

Given the presence of uncertainties, in this paper, we examine the tradeoffs between increasing the number of buffers and increasing the capacity at the remanufacturing stations on such performance measures as expected total cost, average WIP inventory, throughput and average processing time (remanufacturing time). We model the remanufacturing system using an open queueing network with finite buffers and unreliable servers¹. In order to analyze the queueing network, we use the decomposition principle and expansion methodology^{7, 8, 10, 11}.

2. LITERATURE REVIEW

In recent years, there have been attempts devoted to the design and control of remanufacturing systems. Many authors have discussed the requirements to enhance recycling activity: such as ease of disassembly, modularity, material selection and compatibility, material identification and efficient cross-industrial reuse of common parts/materials. Thierry *et al.*¹⁵ present various case studies of firms who are implementing remanufacturing of post-consumed products from a range of industries.

The first crucial step of product recovery is disassembly. Disassembly is a methodical extraction of valuable parts/subassemblies and/or 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 the raw-materials suppliers and the residuals are disposed of. The problems associated with disassembly and scheduling have been investigated by Brennan *et al.*², Gupta and Taleb⁶, Lee *et al.*¹². Moyer and Gupta¹³ provide a comprehensive review of recycling and disassembly efforts in the electronics industry. Gungor and Gupta⁵ review the literature in the area of environmentally conscious manufacturing and product recovery. The problems associated with remanufacturing have been addressed by Guide and Srivastava³. Guide *et al.*⁴ compared capacity planning techniques and conclude that variability in the remanufacturing process is a significant issue, which must be considered for a successful capacity planning approach.

Classical models of production planning and inventory control are not appropriate for remanufacturing and need to be modified for it. Several authors have made such attempts. Heyman⁹ analyzed the continuous-review inventory control problem where incoming returnables are disposed of whenever the inventory reaches a predefined level. The author assumed zero repair times and did not consider procurement lead times. Muckstadt and Isaac¹⁴ developed an approximate control strategy with respect to order points and order quantities for a single product case where returned products are remanufactured. They considered fixed lead times but without disposal of returned products. Van der Laan *et al.*¹⁷ present a general approach to production planning and inventory control for a combination of traditional manufacturing and remanufacturing. The authors proposed an (s, Q) inventory control model in which used products can be remanufactured into new ones. They developed two alternative approximation methods for cost evaluation and the optimization instead of an exact analysis. They also showed that disposition is a necessary option because inventory levels may rise to very high values because of the variability in the return stream and imperfect correlation between the demand and remanufacturing process. Van der Laan *et al.*¹⁸ considered a single-product, single-echelon production and inventory system with product returns, product remanufacturing, and product disposal. For the proposed system three different procurement and inventory control strategies were considered, namely the (s_p, Q_p, s_d, N) strategy, the (s_p, Q_p, s_d) strategy, and the (s_p, Q_p, N) strategy. The control parameters in these strategies relate to the inventory position at which an outside procurement order is placed (s_p), the inventory position at which returned products are disposed of (s_d), the outside procurement order quantity (Q_p), and the capacity of the remanufacturing facility (N). The authors derived exact expressions of the total expected costs as functions of the control parameters and compared the performance of the alternative strategies with respect to cost, under different system conditions.

3. THE REMANUFACTURING MODEL

The remanufacturing model for this research is a collection of cellular based service areas where jobs arrive at different rates and demand service with unequal processing times. The remanufacturing system considered here is presented in Figure 1. In this paper, we utilize an open queuing network (OQN) with finite buffers and unreliable servers to model the system. Once the used products return to the remanufacturing system they first go to the disassembly operation (station 1). After disassembly, used parts are tested (station 2) and with expected rate r directed to the remanufacturing shop. Products that do not satisfy a certain quality level for recovery or are unusable are either disposed of or sold as a recoverable material for recycling. The remanufacturing shop 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 by remanufactured and new products. We assume that the demand rate γ is greater than the product return rate, λ_{ar} . 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 queuing network, all the stations have finite buffer capacities and are prone to breakdowns

We use the decomposition principle and the expansion methodology in order 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. After decomposing the network, we use the expansion methodology to analyze each node individually^{7, 8, 10}. Formulation and analysis of the expansion methodology will be briefly discussed next.

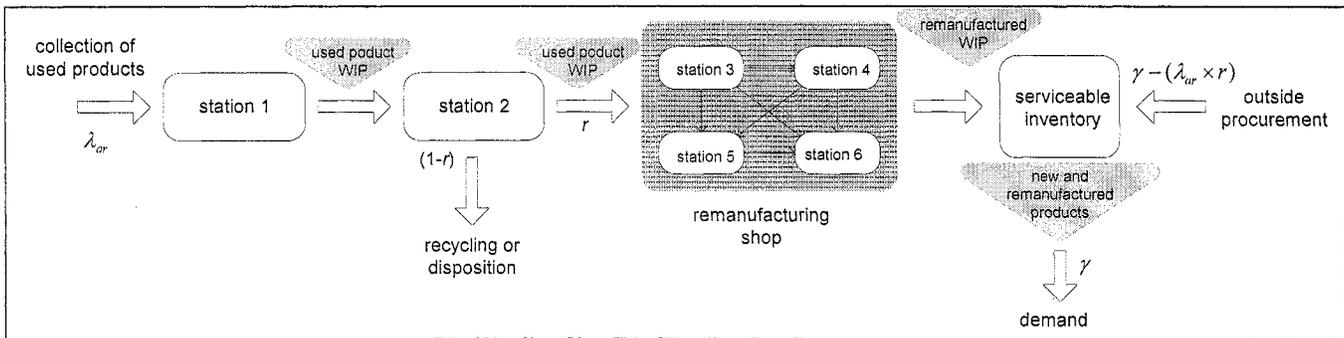


Figure 1. The model of a remanufacturing system and flow of operations.

3.1. Model Assumptions

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 γ 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 breakdown rate α_i and the repair time rate β_i for broken machines are also exponentially distributed. 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 ($i+1$ th) 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 recoverability 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.

Note that, assumptions in our model differ from the typical production line models reported in the literature. The first difference is that our model considers the buffer capacities to be finite compared to the typical assumption of being infinite. Most importantly, a common assumption in the production line models is that the first station of the production line is never starved and the last station of the line is never blocked. However, in our remanufacturing line model, since the return products arrive at the remanufacturing facility according to a Poisson arrival stream, a situation could occur when there are no products at the first station (disassembly station), i.e. the first station could starve. In addition, since there is a limited buffer capacity at the last station (serviceable inventory) and the demand follows a Poisson stream, the buffer at the last station could be full, blocking the upstream stations.

3.2. Analysis of the Remanufacturing System

The optimization of a remanufacturing system's performance is of great importance because of the above mentioned uncertainties and complexities. It is always possible to reduce the effect of uncertainties on the system's performance by increasing the number of buffers at the station that exhibits these shortcomings. However physical constraints and many other real life circumstances 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 through 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 mythical perception that the remanufacturing system is more difficult to justify economically. In this paper, we compare two alternative methods to cope with the uncertainties in the remanufacturing systems, namely buffering and capacity techniques. Buffering is a traditional way of controlling work-in-process inventory against variability and additional capacity is an effective approach against variability in manufacturing system¹⁵.

We analyze the remanufacturing system by monitoring the expected total cost, throughput rate, average WIP inventory and the mean processing time of the entire system. The analysis here is based on the steady-state behavior of the given remanufacturing system with the following parameter set: λ_{ar} , return rate of used products; γ , demand rate; μ_i , service rate at the node i ; α_i , breakdown rate of node i ; β_i , repair rate of the node i and B_i , buffer capacity of node i .

To capture the gross effect of the varied system parameters we define the total cost function based on the remanufacturing network in Figure 1.

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

where:

- $c_p E(RP)$: Expected cost of returned products to the remanufacturing system including transportation expenses. Expected rate of the returned products ($E(RP)$) is obtained by the arrival rate of returned products to the remanufacturing system (λ_{ar}) and c_p is the cost of used products/item.
- $c_{dis} E(Dis)$: Expected disassembly cost of the returned products. Expected rate of disassembled products ($E(Dis)$) is estimated by the throughput rate of the associated station (TH_1) and c_{dis} is the cost of disassembly/item.
- $c_t E(T)$: Expected cost of testing the returned products. Expected rate of the tested products ($E(T)$) is estimated by the throughput rate of the inspection station (TH_2) and c_t is the cost of testing/item. After inspection, the parts are

directed to either the remanufacturing shops with the probability of r or the disposition station with the probability of $(1-r)$.

- $c_m E(OP)$: Expected cost of outside procurement of the new products. Expected rate of outside procurement ($E(OP)$) is estimated by the difference in the demand rate and the return rate ($\gamma - \lambda_{ar} \times r$) and c_m is the cost of new product/item.
- $c_{hs} E(I)$: Expected inventory holding cost. Expected inventory level ($E(I)$) of the remanufacturing system is estimated by the average queue length of the serviceable inventory where the demand satisfied and c_{hs} is the inventory holding cost
- $c_l E(Ls)$: Expected lost sales cost. Expected fraction of the lost sales ($E(Ls)$) is estimated by the starving probability of the serviceable inventory and c_l is the lost sales cost.
- $c_{rej} E(Rej)$: Expected penalty cost of rejected items from the remanufacturing system due to buffer unavailability. Expected fraction of the rejected items ($E(Rej)$) is estimated by the probability of experiencing full buffer at the first station and c_{rej} is the penalty cost/item.
- $c_{ri} E(Ri)$: Expected remanufacturing costs at station i ($i=3, 4, 5, 6$). Expected rate of the remanufactured parts ($E(Ri)$) at each station is estimated by its throughput rate ($TH_i, i=3, 4, 5, 6$) and c_{ri} is the cost of remanufacturing.

To obtain the approximate throughput rates (TH_i) of each server and the entire remanufacturing network, we utilize the expansion methodology. For details of the method and the necessary derivations for unreliable production lines see Gupta and Kavusturucu^{7, 8} and Kavusturucu and Gupta¹⁰. A brief discussion of expansion method is as follows. The expansion methodology is an efficient tool for the analysis of nodes with finite buffers. In order to analyze the remanufacturing system, which is presented in Figure 1, we first decompose the network and examine each server separately. After isolating each node we expand the network by adding a node in front of the each server. 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 calculated¹¹.

4. NUMERICAL EXPERIMENTATION AND RESULTS

In order to compare how well the two techniques (buffering and capacity) respond to uncertainties in a remanufacturing system, we experimented with the system given in Figure 1. We used the following data for the experimentation:

- Return rates were assumed to be either low ($\lambda_{ar} = 0.5$) or high ($\lambda_{ar} = 0.9$).
- Similarly, reusable rates were assumed to be either low ($r = 0.4$) or high ($r = 0.8$).
- We performed four sets of experiments using return and usable rates as follows. 1) low return rate and low reusable rate, 2) low return rate and high reusable rate, 3) high return rate and low reusable rate and 4) high return rate and high reusable rate.
- For each set of experiments, we compared the performance measures using the buffering and capacity techniques under four levels (viz., the base level, the low level, the medium level and the high level).
- For the buffering technique, the total number of available buffer slots (N) for the four levels were 8, 10, 12, and 14 allocated as (2-2-1-1-1-1), (2-2-2-2-1-1), (2-2-2-2-2-2) and (3-3-2-2-2-2) among the six stations respectively. In addition, the service rate (μ_i) was equal to 1.5. The rest of the data is as given in Tables 1 and 2.
- For the capacity technique, the service rates (μ_i) for the four levels were 1.5, 1.88, 2.25, and 2.63 respectively. In addition, the number of available buffer slots (N) was equal to 8 allocated as (2-2-1-1-1-1). The rest of the data is as given in Tables 1 and 2.

Table 1. System parameters and cost variables

| | |
|---------------------------------|-------------------------------|
| $\gamma = 1.0$ | $c_p = 4$ |
| $\alpha_i = 0.1$ (1, . . . , 6) | $c_t = 1$ |
| $\beta_i = 0.1$ (1, . . . , 6) | $c_{ri} = 5$ ($i=1, 2, 3$). |
| $c_{dis} = 6$ | $c_{hs} = 1$ |
| $c_l = 5$ | $c_{rej} = 5$ |
| $c_m = 25$ | |

Table 2. Routing probabilities p_{ij} in the remanufacturing shop.

| i/j | 1 | 2 | 3 | 4 |
|-------|---|-----|-----|-----|
| 1 | - | 0.5 | 0.4 | 0.1 |
| 2 | - | - | 0.8 | 0.2 |
| 3 | - | - | - | 1 |
| 4 | - | - | - | - |

Tables 3-6 summarize the performance of the remanufacturing system. We note that as the buffer capacity increases, WIP inventory, throughput rate and average process time also increase. On the other hand, as the capacity increases at each station, the throughput of the system increases while the average WIP inventory and process time decrease (Figures 2-5). If throughput is considered as a performance measure, the buffering technique always dominates the capacity technique for all cases of return flow and reusable rate combinations. The products return rate (λ_{ar}) has a significant effect on the average WIP inventory level. When the return rates are high, the average WIP inventory levels are close to each other regardless of technique used. However, when the return rates are low, the average WIP inventories are significantly different depending on the technique used.

Another way of comparing the performances of these techniques is by contrasting their expected total costs (Figure 2b-5b). When the return rate is low, both techniques perform in a similar manner whether there is an increase in the buffer level or capacity. On the hand, as the return rate becomes higher the difference between the two techniques become significant.

Table 3. Low return rate ($\lambda_{ar} = 0.5$) and low re-usable rate ($r=0.4$).

| | Base level | | Buffering | | Capacity Increasing | | |
|------------|------------|--------|-----------|--------|---------------------|--------|--------|
| | low | high | medium | high | low | medium | high |
| WIP inv. | 7.199 | 7.244 | 7.296 | 7.461 | 7.066 | 6.912 | 6.732 |
| Throughput | 0.184 | 0.189 | 0.194 | 0.198 | 0.188 | 0.191 | 0.195 |
| TC | 32.849 | 32.963 | 33.028 | 33.023 | 32.901 | 32.947 | 32.984 |
| PT | 4.569 | 4.700 | 4.857 | 5.072 | 4.003 | 3.374 | 2.671 |

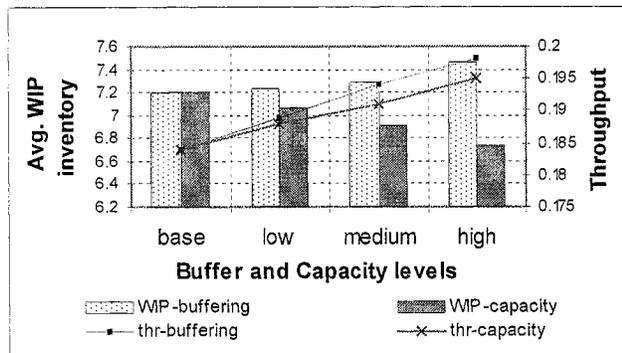


Figure 2a. Average WIP inventory and throughput for low return ($\lambda_{ar} = 0.5$) and low re-usable ($r=0.4$) rate.

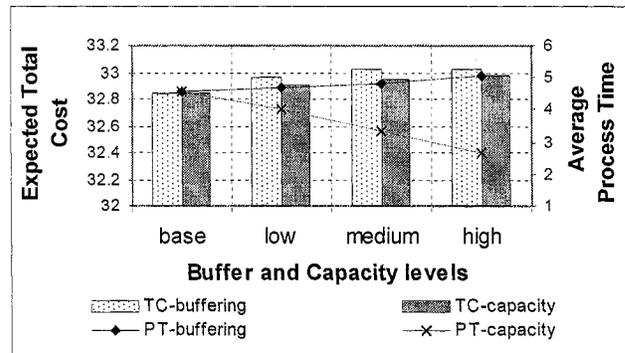


Figure 2b. Expected total cost and average process time for low return ($\lambda_{ar} = 0.5$) and low re-usable ($r=0.4$) rate.

Table 4. Low return rate ($\lambda_{ar} = 0.5$) and high re-usable rate ($r=0.8$).

| | Base level | | Buffering | | Capacity Increasing | | |
|------------|------------|--------|-----------|--------|---------------------|--------|--------|
| | low | high | medium | high | low | medium | high |
| WIP inv. | 7.495 | 7.652 | 7.822 | 7.998 | 7.343 | 7.163 | 6.947 |
| Throughput | 0.332 | 0.353 | 0.382 | 0.39 | 0.344 | 0.357 | 0.371 |
| TC | 29.384 | 29.913 | 30.295 | 30.377 | 29.599 | 29.823 | 30.056 |
| PT | 4.569 | 4.807 | 5.086 | 5.304 | 4.003 | 3.374 | 2.671 |

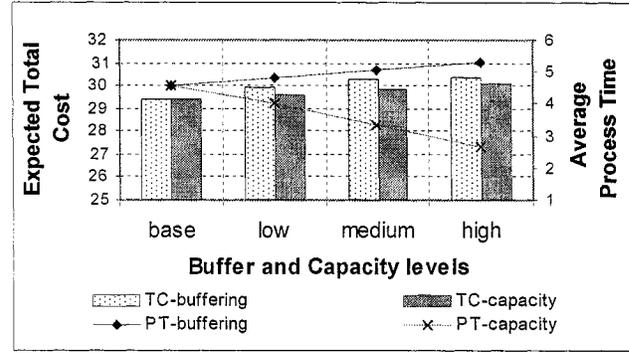
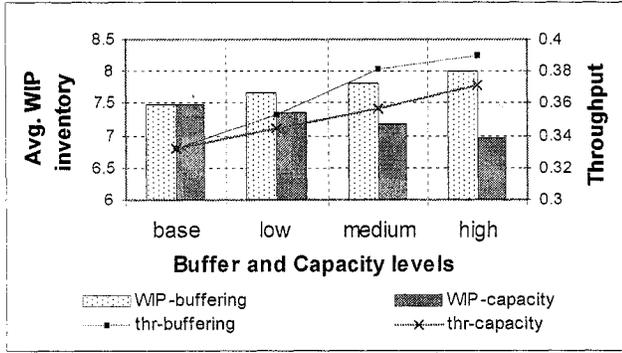


Figure 3a. Average WIP inventory and throughput for low return ($\lambda_{ar}=0.5$) and high re-usable ($r=0.8$) rate.

Figure 3b. Expected total cost and average process time for low return ($\lambda_{ar}=0.5$) and high re-usable ($r=0.8$) rate.

Table 5. High return rate ($\lambda_{ar} = 0.9$) and low re-usable rate ($r=0.4$).

| | Base level | | Buffering | | Capacity Increasing | | |
|------------|------------|--------|-----------|--------|---------------------|--------|--------|
| | low | high | medium | high | low | medium | high |
| WIP inv. | 7.962 | 8.076 | 8.198 | 8.779 | 7.787 | 7.569 | 7.292 |
| Throughput | 0.281 | 0.297 | 0.315 | 0.337 | 0.296 | 0.312 | 0.33 |
| TC | 34.253 | 34.642 | 34.88 | 35.243 | 34.557 | 34.868 | 35.163 |
| PT | 5.18 | 4.942 | 5.18 | 5.654 | 4.149 | 3.491 | 2.756 |

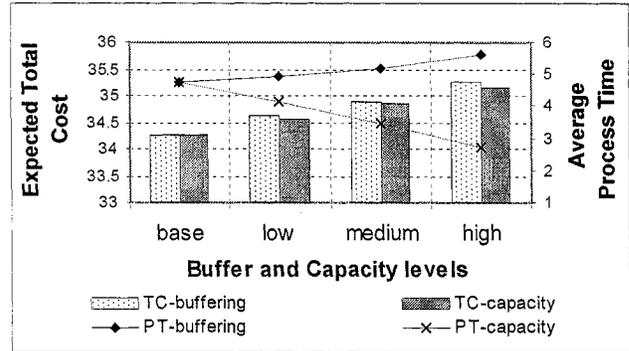
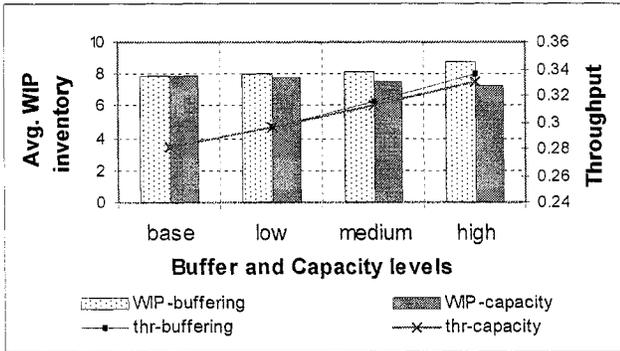


Figure 4a. Average WIP inventory and throughput for high return ($\lambda_{ar}=0.9$) and low re-usable ($r=0.4$) rate.

Figure 4b. Expected total cost and average process time for high return ($\lambda_{ar}=0.9$) and low re-usable ($r=0.4$) rate.

Table 6. High return rate ($\lambda_{ar} = 0.9$) and high re-usable rate ($r=0.8$).

| | Base level | | Buffering | | Capacity Increasing | | |
|------------|------------|--------|-----------|--------|---------------------|--------|--------|
| | low | high | medium | high | low | medium | high |
| WIP inv. | 8.335 | 8.675 | 9.023 | 9.651 | 8.149 | 7.911 | 7.603 |
| Throughput | 0.465 | 0.517 | 0.597 | 0.633 | 0.499 | 0.54 | 0.589 |
| TC | 26.385 | 27.717 | 28.765 | 29.486 | 27.056 | 27.856 | 28.785 |
| PT | 4.74 | 5.086 | 5.483 | 5.966 | 4.149 | 3.491 | 2.756 |

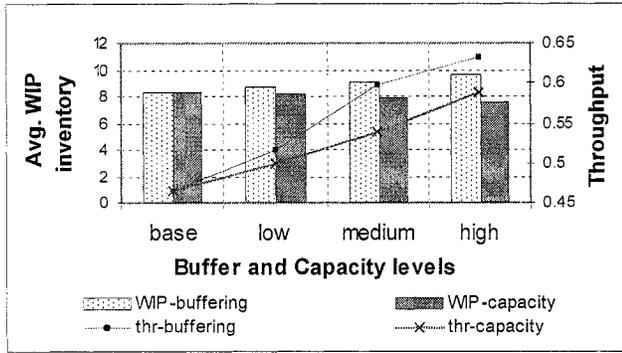


Figure 5a. Average WIP inventory and throughput for high return ($\lambda_{ar} = 0.9$) and high re-usable ($r = 0.8$) rate.

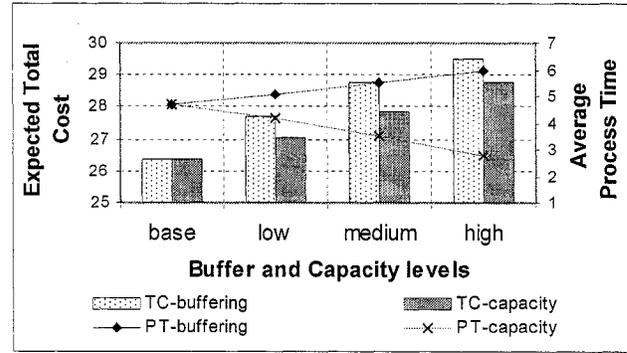


Figure 5b. Expected total cost and average process time for high return ($\lambda_{ar} = 0.9$) and high re-usable ($r = 0.8$) rate.

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