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A SIMULATION STUDY ON TELEPHONE REMANUFACTURING PROCESSES

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This paper focuses on modeling and simulation of two real telephone remanufacturing processes with the objective of improving the system throughput. We start with the system description and then build the corresponding simulation models. A series of simulation experiments are done with different values for the model parameters and the results show that they are close to reality. In particular, the bottleneck processes are the same as those of the real systems. Using the simulation results, a method to improve the system throughput is proposed by adding more workstations to the bottlenecks. Also, we extend the basic simulation models to include multiple telephone types. Comparisons of dispatching rules are performed using the extended models and the result shows that the suggested rules are much better than the existing one.

INTRODUCTION

Due to the exponential increase of waste streams, environmental issues are becoming increasingly important to manufacturing firms. In particular, several governments have introduced legislation for environmental responsibilities of companies to protect the environment imposing the obligation to collect and upgrade products at their end-of-life (EOL) in an environmentally conscious way. For example, in Germany and US, a new legislation was planned to force automotive and electronics manufacturers to recover and recycle their products at the end of their life [1]. In general, all the legislation can be summarized as the originator-principle, which means that he who inflicts harm on the environment should pay for fixing the damage [2]. Therefore, to give value to the EOL of their products, the manufacturers are forced to recover and recycle their products upon disposal.

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Under such circumstances, a number of manufacturing firms are paying considerable attention to remanufacturing, which can be defined as an industrial process in which worn-out products are restored to like-new condition [3]. Through a series of industrial processes in a factory environment, a discarded product is partially or completely disassembled. Among disassembled parts, usable ones are cleaned, refurbished, and put into inventory. Then, the new product is reassembled from both old and, where necessary, new parts to produce a unit equivalent and sometimes superior in performance and expected lifetime to the original new product. Haynsworth and Lyons [4] summarize the benefits obtained from remanufacturing as follows: (a) the sale of the lower priced remanufactured item can significantly expand the total market for the product and expand total market share; (b) design for future new unit production can be improved; (c) there are savings in both energy use and raw material consumption; and (d) employment opportunities are created, especially for low and moderately skilled workers because remanufacturing is highly labor intensive. However, there is a general tendency that customers are averse to use second-hand or remanufactured goods, which makes the concept of remanufacturing difficult to be implemented. In general, such remanufacturing firms have several complicating factors that make traditional planning and scheduling methods difficult to direct use. Guide [5] indicates two important factors that limit the effectiveness of traditional planning and scheduling methods. They are: (a) probabilistic recovery rates of the parts from the used products, which implies high degree of uncertainty in materials planning, and (b) unknown condition of the recovered parts until inspected, which leads to stochastic processing times and lead times.

Several case studies for scheduling problems in various remanufacturing systems can be found in the literature. Guide [6,7,8] applies a synchronous manufacturing technique called drum-buffer-rope (DBR) to a military depot in remanufacturing environment and reports that the suggested DBR outperforms the existing method under various performance measures. Here, DBR, which is based on the theory of constraint, is a bottleneck scheduling heuristic for a manufacturing facility with a stable and dominant bottleneck resource. With the developed simulation model, several extensions are done on the comparison of priority dispatching rules under DBR [9,10]. Later, Guide [11] compares several disassembly release mechanisms, and reports that disassembly release mechanisms had very little impact on the system performances. Erdos and Xirouchakis [12] develop a parametric Petri net model for a telephone remanufacturing line and report their simulation results. Several successful case studies on various aspects of remanufacturing can be found in the literature, which covers electronics, automobiles, and military industries [13, 14,15,16,17,18].

This paper focuses on modeling and simulation of two real telephone remanufacturing processes. The main concern is to improve the system throughput. Here, the system throughput is defined as the number of remanufactured telephones per unit time. We start with the system descriptions and then build the simulation models. By use of the developed models, a series of simulation experiments are done with different values for the model parameters. Then, the basic simulation models are extended to include multiple telephone types. Comparison of scheduling methods is performed using the extended models and the results are also reported

Now, the objectives of this study can be summarized as follows:

- Developing simulation models for the two real systems
- Validating the simulation models
- Providing the methods to improve the system throughput
- Comparing scheduling methods in the case that the systems are extended to include multiple telephone types

SYSTEM DESCRIPTION

The company considered in this paper remanufactures various used telephones and telephones at their EOL [19]. The services of the company include repairs, development and planning, fabrication, and disposal or recycling for electronic telecommunication, IT terminals and modules, and systems. The company has one major customer that subcontracts various telephones. Also, it has agreements with computer companies and IT enterprises and performs warranty repairs for them. In fact, the company is a repair center that is equipped with remanufacturing machines and workforce. In 1995, the company performed about 370,000 repairs of 6,800 different modules that include 240,000 phones. This amount is up to 318 tons of rebuilt materials, 149 tons of electronic circuits, and 81 tons of plastic. The company handles from 250 to 1000 standard, cordless or mobile phones a day.

The products remanufactured in the company can be classified into two categories, which have their own remanufacturing processes and resources. The first one is the *standard and cordless telephones*, which are remanufactured with mass production rates through disassembly, test, repair, refreshing, reassembly, and packing operations. The second one is the *mobile phones*, which are processed with test and repair operations with highly variable operation processing times. Actually, the products in the second category should be repaired in a short delay and hence makespan (the time required to complete all jobs) is considered as an important measure. Nevertheless, makespan is not taken into account in this paper, because the system throughput plays the same role as makespan from the scheduling point of view.

As stated earlier, this paper focuses on *the problem of improving the system throughput of the two telephone remanufacturing processes*. In general, the improvement of the system throughput can be achieved by optimizing its flow. For the flow optimization, there may be three general approaches that can be summarized as follows:

- Simplifying the physical flows
  - Removing non-valuable operations
  - Reorganization of the flow, etc.
- Accelerating the physical flows
  - Reducing machine breakdowns or transportation time
  - Improving product quality or workers' skill
  - Developing partnership between suppliers and dealer, etc.
- Creating a coherent and relevant management information system that includes the production management function

Among the three approaches, this study focuses on the first and second ones, i.e., simplifying and accelerating the physical flows. As mentioned earlier, the goal of this case study is to improve the system throughput without much investment for the company. In this study, this can be achieved by identifying bottleneck processes and reorganizing remanufacturing process. Also, in the case that the systems are extended to include multiple telephone types, scheduling methods are needed in order to accelerate the product flows.

One of the main difficulties for modeling and simulation of the telephone remanufacturing is the lack of information. It is very difficult to obtain required information of the used telephones, i.e., composition of materials, fixation methods, quality of used telephones, and technical specifications. This is because most products have not been designed for disassembly or remanufacturing. Another difficult point lies in the cost estimation. That is, it is not easy to estimate the recycling cost of EOL products due to the highly uncertain conditions of the recovered parts. That is, even for the same product, the condition of the used products can be much different depending on their ages and usages. For example, the surface can be damaged, a fixation can be wrapped or jammed, and a subassembly may be out of order, which could lead to highly variable processing times in remanufacturing systems.

In this study, we selected two types of telephones, each of which has interesting product flows. More specifically, the first one, called *telephone A* in this paper, follows a remanufacturing process and has a large production volume. This is selected because it has a high potential to improve the productivity from the optimization point of view. On the other hand, the second one, called *telephone B*, follows a unitary repairing process. That is, repairing operations of telephone B is done with a lot size of one.

Now, the two telephone remanufacturing processes are described in more detail. Figure 1 shows the remanufacturing flow description of telephone A. The telephones of type A are processed with batch size of 120. In this type, all of its parts are exchangeable, which means that the parts need not be reassembled to the same unit from which they are disassembled. Each telephone arrives at the system randomly after some parts, such as battery, cables and charger, are sorted by an external organization. When a used telephone arrives at the system, the two main parts, telephone base and mobile part, are disassembled (Step 1) and sent to test or cleaning steps. In the test step, the printed circuit board (PCB) is tested to determine whether it needs to be repaired (Step 2). In the other branch, the soft parts and the plastic box are cleaned (Step 3). During the disassembly process, there may be some defective parts that are caused by the workers. In this case, subsequent used parts are substituted for the defective parts, since the missing parts can be replaced with new ones in the real process. After this step, all parts are reassembled (Step 4), and tests are carried out twice (Steps 5 and 6). If a defect is found during the test, the part is disassembled again (Step 7) and the PCB is repaired (Step 8). Otherwise, the telephone is bonded (Step 9) and finally repacked with its battery, cable and charger (Step 10).

Figure 2 shows the remanufacturing flow description of telephone B. In this process, each telephone is managed individually because it is processed by the repairing operations. Also, unlike type A, its parts are not exchangeable. In fact, the telephone is a mobile phone and hence is composed of only one part. When a telephone arrives, it is unpacked (Step 1) and sorted (Step 2). In the sorting step, the telephones are sorted into two categories: those that need to be repaired and those that need repairing price estimation. The telephones in the latter category are no more under warranty and hence their customers ask how much it will cost if the telephones are repaired (Step 3). In the real system, Step 3 is a cupboard that stores telephones, which are waiting for an answer from customers before being repaired. If a negative answer is received or the telephone has spent more than one month in the cupboard, the telephone is shredded. Note that the shredding process is not depicted in Figure 2. Also, Step 3 is not considered in the simulation model because we could not acquire the required information and the shredding process is beyond our research scope. Otherwise, it goes back to the normal flow, i.e., the telephone is sent to the repair step. Here, the workers do the repair step and then the telephone is configured if it is an old version (Step 4). These two operations can be done at the same workstation and there are two workstations for this operation. Then, there is a test step that checks if the telephone works (Step 5). If the telephone works, it is personalized (Step 6). That is, the required parameters are reintroduced to the repaired telephones. Then, the repairing report is recorded (Step 7). Finally, the telephone is packed for customer delivery (Step 8).

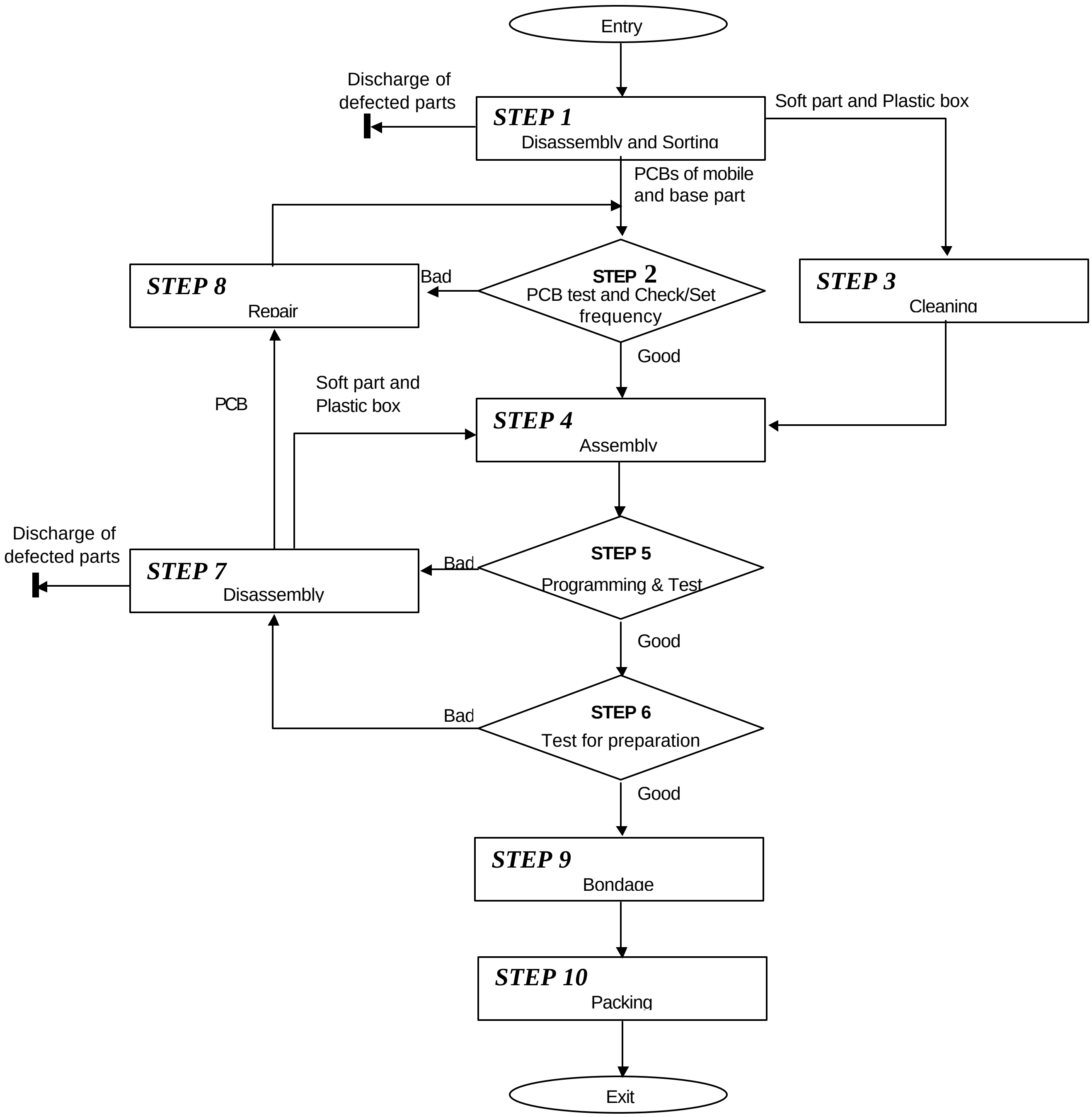

Figure 1. Remanufacturing flow description of telephone A

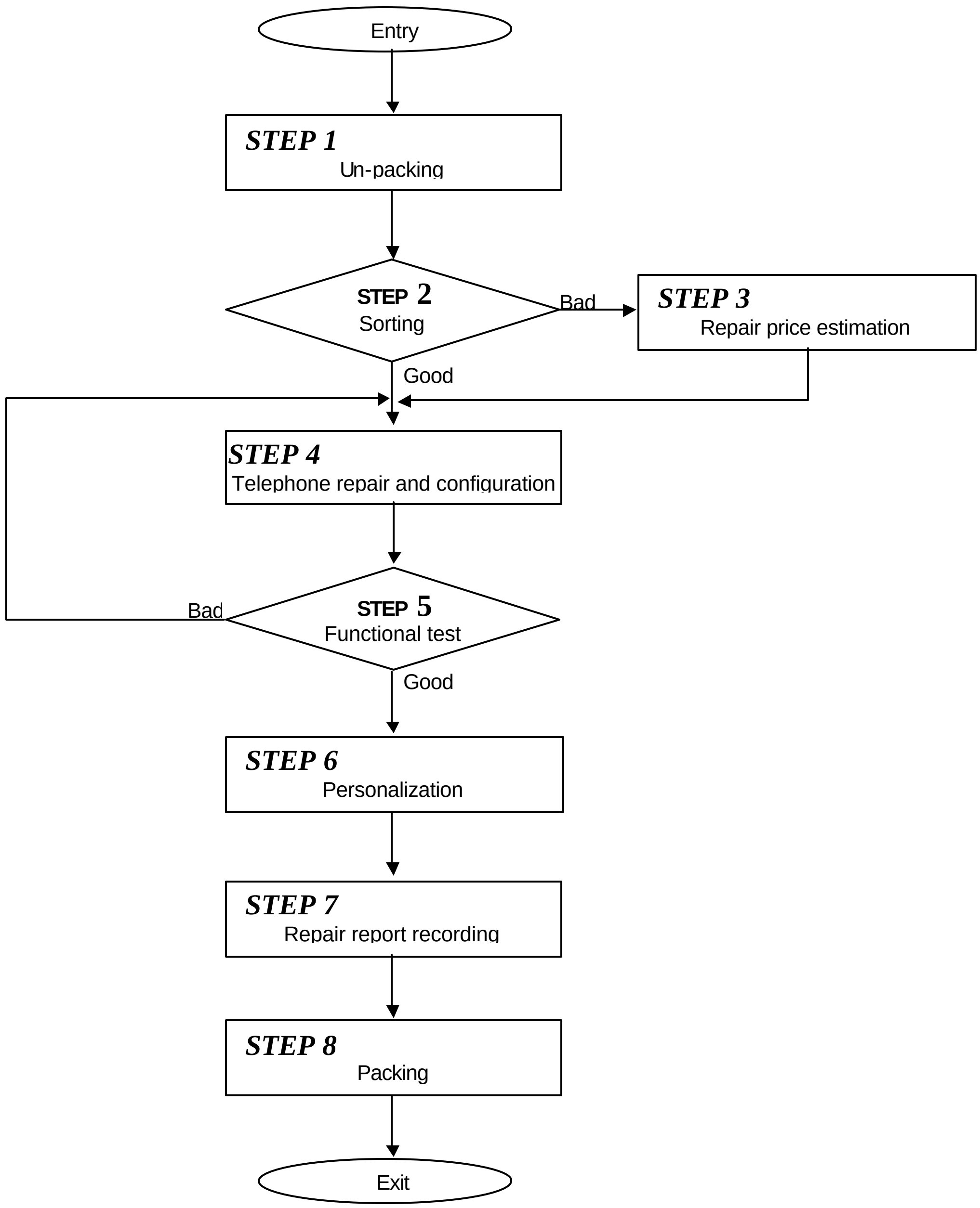

Figure 2. Remanufacturing flow description of telephone B

SIMULATION EXPERIMENTS

In this section, we first explain the simulation models based on the flow descriptions of the two telephone remanufacturing processes. Then, a series of experiments are done using the simulation models and the results are reported together with the methods to improve the system throughput. Finally, the simulation models are extended to include multiple telephone types. Using the extended models, a test for comparison of the suggested scheduling methods is done.

Basic Models and Results

As mentioned earlier, we develop a simulation model for each telephone remanufacturing process with the objective of evaluating the current system and suggesting methods to improve the system throughput. Using the developed simulation models, we simulate and investigate the remanufacturing processes under various values for the system parameters. Here, the main parameter is the number of workstations at each processing step and hence the variation of the parameter implies the number of workstations in the bottleneck process. Each simulation model contains only one telephone type, i.e., single product type. In general, the simulation models include three types of modeling entities that organize the processes, which can be summarized as follows.

- Products: they correspond to a physical part, i.e., telephones to be remanufactured.
- Operations: they are activities required for the telephone remanufacturing, such as storage, disassembly, repair, update, assembly, etc. In fact, operations correspond to steps described in this paper.
- Workstations: they are places with certain required equipment, in which the operations (steps) are performed.

In this paper, to narrow down the research scope to what the company is interested in, we simplify the real system using the following assumptions: (a) the model for telephone A includes only one of the two main components, i.e., telephone base or mobile part, because both of them have the same flow and similar processing times; (b) the external operations, which have much longer processing time, are not included in the model; (c) transportation times to move a part from one workstation to another are not taken into account, since transportation times are small enough to be ignored; (d) each workstation can process only one operation at the same time, i.e., there are no batch operations at each workstation; and (f) machine breakdown is not considered in this study, since the company was not interested in it in terms of optimizing the values of the system parameters.

The most important data for this simulation study is operation processing time, which implies the time required to process the tasks on the required workstation. Also, for the sorting or test steps, it is necessary to know the ratio of sorting or successful inspection, which means the ratio among the different outgoing flows. Also, the defective part rates that occur at each step should be included in the simulation model. Note that, even if the defect in itself may be incurred at every step, the discharge of defective parts is modeled at only Steps 1 and 7 for telephone A. This is because the discharge of defective parts exists at the two disassembly steps in the real process. On the other hand, there are no defective parts in the model of telephone B, since no parts are thrown away in the remanufacturing process. As stated earlier, Step 3 (repair price estimation step) of telephone B was excluded in the simulation model, since there was no required information for the step. Table 1(a) summarizes the information required to model the remanufacturing process of telephone A, which includes processing times, defective part rates, and ratio of sorting or successful inspection.

In the table, $U(a,b)$ denotes the continuous uniform distribution ranged from a to b. Also, Table 1(b) summarizes the required information to model the system for telephone B.

(a) Telephone A

Step	Processing time (minutes)	Defective part rates	Flow ratio	
			Good	Bad
1	0.5	0.08		
2	3.0		0.75	0.25
3	4.0			
4	3.0			
5	3.5		0.80	0.20
6	1.5		0.90	0.10
7	0.5	0.08		
8	U(9.0, 15.0)	0.04		
9	3.0			
10	1.5			

(b) Telephone B

Step	Processing time (minutes)	Flow ratio	
		Good	Bad
1	U(2.0, 3.0)		
2	U(0.5, 1)		
4	U(20.0, 27.0)		
5	0	0.75	0.25
6	3.0		
7	U(5.0, 10.0)		
8	3.0		

Table 1. Data for the simulation models

In this study, the simulation models were developed using ProModel 4.0. In the simulation model, each step was modelled as a multi-capacitated facility, which means that one can operate a number of parts equal to its capacity at the same time. That is, the capacity of a step can be interpreted as the number of workstations that can process the step in parallel. Note that the capacity of each step is one of the system parameters that should be determined in order to optimize the product flow. In the basic model, the capacity of each step was set to 1 except for Step 4 of telephone B. This reflects the assumption that each workstation can process one operation at the same time. Each workstation has its own buffer in order to store the parts that wait for processing. When a workstation becomes available, one part among those in the buffer is selected and processed using FCFS (first-come-first-served). Telephones arrive at the system with batch sizes of 120 and 1 for telephones A and B, respectively, and the arrived telephones are stored in the buffer of Step 1. In addition, it is assumed that the arrival of telephones follows the Poisson process, that is, the inter-arrival time follows the exponential distribution. In the simulation experiments, the average inter-arrival times of products were set to 400 minutes and 5.2 minutes for Telephone A and B, respectively.

For the steady-state analysis, the warm-up period and the run length were predetermined by the Welch's graphical method [20]. To carry out the method, a series of preliminary simulation runs were done with five replications and the cumulative throughput values were observed. From the results, the warm-up period and the simulation run length were set to 1488 hours and 2928 hours for telephone A, and 744 hours and 1464 hours for telephone B, respectively. Due to the assumptions made in this paper, the problem data are not exactly the same as those of the real cases. Nevertheless, we can take out some interesting results from the simulation experiments.

Now, the results obtained from the simulation experiment can be summarized as follows:

Telephone A

- We found that Step 8 is the bottleneck process that affects the system throughput the most significantly. In fact, the utilization of the workstation of Step 8 was 100 percent during the simulation period in the steady state. Therefore, if we reduce the processing time in this step or increase the capacity of the step, we can increase the system throughput.
- An additional test was done to show the effect of the change of the capacity of the bottleneck step and the results are summarized in Table 2(a). In the table, we can see that the system throughput (the number of telephones remanufactured per hour) is improved by the amount of 9.7% by adding one more workstation to the bottleneck step.

Telephone B

- The utilization of the workstations for Step 4 was maintained at 100 percent in the simulation results. Thus, the repair time in Step 4 is the most important one compared with the other processing times and hence this step is the bottleneck process.
- To find the adequate number of workstations in the bottleneck step, additional tests were done and the results are summarized in Table 2(b). In the table, it can be seen that the adequate number of workstations in Step 4 is four.

(a) Telephone A

NW†	Average throughput‡	Improvement (%)
1	9.34	-
2	10.29	9.715
3	10.29	9.725

† number of workstations in the bottleneck step
‡ number of remanufactured telephones per hour (averaged over the number of replications)

(b) Telephone B

NW†	Average throughput ‡	Improvement (%)
2	3.81	-
3	5.69	49.3
4	7.59	99.2
5	7.93	108.1
6	7.93	108.1

See the footnotes of Table (a).

Table 2. The impact of the number of workstations in the bottleneck processes

Extended Models and Results

The basic models explained in the earlier section consider one telephone type and hence there are no conflicts among different telephone types when they are processed on the same workstation. Therefore, this section extends the basic models to include multiple telephone types to investigate the effectiveness of production scheduling. That is, the extended models are used to compare several scheduling methods in order to manage the flows of different telephone types.

Each of the extended models contains five telephone types with different processing times and the same process flow as the basic one. For each extended model, we generated four additional telephone types randomly. Here, the processing times were randomly generated by changing those of the basic models. More specifically, the processing times were generated using *U*(*á*(1–*â*),*á*(1+*ã*)), where *á* denotes the original processing time, and *â* and *ã* denote the range parameters generated using *U*(0,1). Also, the number of workstations for Step 4 of telephone B was set to 4 from the simulation results of the basic model. Table 3 summarizes the operation processing times of the five product types for telephones A and B.

(a) Telephone A

Step	Product types				
	A1	A2	A3	A4	A5
1	0.5	0.6	0.7	0.8	0.9
2	3.0	4.0	3.5	2.5	3.0
3	4.0	5.0	6.0	3.0	2.0
4	3.0	2.0	1.0	3.0	4.0
5	3.5	3.0	2.5	2.0	1.5
6	1.5	2.0	2.5	3.0	3.5
7	0.5	1.0	0.7	0.8	0.6
8	*U*(9.0, 15.0)	*U*(8.0,20.0)	*U*(11.0,15.0)	*U*(6.0,17.0)	*U*(4.0,14.0)
9	3.0	1.0	2.0	3.0	2.0
10	1.5	2.0	2.5	3.0	3.5

(b) Telephone B

Step	Product types				
	B1	B2	B3	B4	B5
1	*U*(2.0, 3.0)	*U*(1.0,4.0)	*U*(2.0,3.0)	*U*(1.0,2.0)	*U*(2.0,4.0)
2	*U*(0.5, 1.0)	*U*(1.0,2.0)	*U*(1.0,1.5)	*U*(0.5,1.5)	*U*(0.5,2)
4	*U*(20.0, 27.0)	*U*(10.0,30.0)	*U*(20.0,25.0)	*U*(15.0,30.0)	*U*(15.0,25.0)
5	0.0	0.0	0.0	0.0	0.0
6	3.0	2.0	4.0	3.0	4.0
7	*U*(5.0, 10.0)	*U*(7.0,8.0)	*U*(3.0,12.0)	*U*(4.0,8.0)	*U*(7.0,12.0)
8	3.0	4.0	3.0	2.0	3.0

Table 3. Processing times of the five product types (unit: minutes)

In general, there may be various ways for selecting a telephone type among those in the buffer of each workstation. Since it is difficult to find optimal schedules, we use a list scheduling method that is easy to implement and requires very short computation time. This method lists telephones that wait for a workstation and selects one by a priority rule when the workstation becomes available. In other words, it is the priority dispatching rule that determines the sequence of operations that are processed on each workstation. More specifically, a priority rule is applied to select a telephone type among those waiting in a buffer when the workstation becomes available. The comparison of dispatching rules was carried out in terms of the system throughput, which is the performance measure adopted in this study.

In this research, we suggest and test seven dispatching rules that are usually used for scheduling job shop and flexible manufacturing systems [22,23]. Before describing priority rules that are included in the test, we define some terms needed in the description. In the description of these priority rules given below, *part processing time* of a telephone denotes the sum of processing times of the operations required to remanufacture the telephone, *remaining processing time* of an operation denotes the sum of processing times of successor operations including itself, while *remaining operations* of an operation denotes the number of successor operations including itself. Note that in this paper, the term operation is used as the same meaning as step. Now, the priority dispatching rules are briefly described in the following.

FCFS (First Come First Served): select a telephone type with the longest waiting time

SPT (Shortest Processing Time): select a telephone type with the shortest operation processing time

SPPT (Shortest Part Processing Time): select a telephone type with the shortest part processing time

MOR (Most Operation Remaining): select a telephone type with the longest remaining processing time

PORW (Processing time Over Remaining Work): select a telephone type with the smallest ratio of the operation processing time to remaining processing time

OTOPT (Operation processing Time Over Part processing Time): select a telephone type with the smallest ratio of the operation processing time to part processing time

OTMPT (Operation processing Time Multiplied by Part processing Time): select a telephone type with the smallest value of the operation processing time multiplied by part operation time

A series of simulation experiments were done to compare the dispatching rules. To determine the warm-up period and the simulation run length, the graphical method explained earlier was also carried out, and they were set to the same as those of the basic models. Like the basic models, it is assumed that each telephone type arrives randomly and independently with batch sizes of 120 and 1, and their inter-arrival time follows the exponential distribution with the mean values of 2000 minutes and 26 minutes for telephone A and B, respectively.

Test results for the comparison of dispatching rules are summarized in Table 4, which shows averages and standard deviations of the system throughput out of the 20 replications. From the test results, we found that no one rule dominates the others. In overall average, however, OTOPT and PORW worked better than the others for telephone A, while OTOPT performed the best for telephone B. However, for telephone B, there was not significant difference between OTOPT and SPT/PORW/ OPTMP. In particular, all the newly suggested rules (SPT, SPPT, MOR, PORW, OTOPT, OTMPT) outperformed the existing FCFS. Therefore, we can conclude that the newly suggested dispatching rules, particularly OTOPT, can be used effectively if the telephone remanufacturing processes are extended to include multiple telephone types.

(a) Telephone A

Throughput†	OTOPT	PORW	SPPT	OPTMP	SPT	MOR	FCFS
Average	10.609	10.609	10.309	10.314	10.306	9.817	8.904
Standard deviation	0.263	0.263	0.134	0.186	0.155	0.167	0.315

† number of remanufactured telephones per hour

(b) Telephone B

Throughput	OTOPT	SPT	PORW	OPTMP	MOR	SPPT	FCFS
Average	8.685	8.658	8.566	8.558	8.171	7.855	7.619
Standard deviation	0.476	0.381	0.272	0.435	0.287	0.692	0.336

See the footnote of Table (a)

Table 4. Performance of dispatching rules

Results of paired-*t* tests given in Table 5(a) show that there was statistically meaningful difference between OTOPT/PORW and the other dispatching rules for telephone A. However, in Table 5(b) for telephone B, there was no statistical difference among OTOPT, SPT, PORW, and OPTMP, although OTOPT performed the best. Also, it can be seen from the tables that the newly suggested rules are always statistically better than the existing FCFS. Consequently, it can be argued from the test results that the operation sequencing in each workstation affects the system throughput and it can be improved by adopting efficient scheduling algorithms.

(a) Telephone A

Dispatching rules	Average throughput†	OTOPT	PORW	SPPT	OPTMP	SPT	MOR
OTOPT	10.609						
PORW	10.609						
SPPT	10.309	*	*				
OPTMP	10.314	*	*				
SPT	10.306	*	*				
MOR	9.817	*	*	*	*	*	
FCFS	8.904	*	*	*	*	*	*

* There is a difference at the significant level of 0.01.
† number of remanufactured telephones per hour (averaged over the number of replications)

(b) Telephone B

Dispatching rules	Average throughput†	OTOPT	SPT	PORW	OPTMP	MOR	SPPT
OTOPT	8.685						
SPT	8.658						
PORW	8.566						
OPTMP	8.558						
MOR	8.171	*	*	*	*		
SPPT	7.855	*	*	*	*		
FCFS	7.619	*	*	*	*	*	

See the footnotes of Table (a)

Table 5. Results of the paired-t test of dispatching rules

CONCLUDING REMARKS

In this paper, we considered modeling and simulation of two real telephone remanufacturing processes with the objective of improving the system throughput. We developed simulation models based on the real processes and data. Several simulation experiments were performed with different values of the model parameters and the results show that they are close to reality. Particularly, the bottleneck processes were the same as found in practice. Using the simulation results, a method to improve the system throughput was proposed by adding more workstations to bottlenecks. Also, we extended the simulation models to include multiple telephone types. Comparisons of dispatching rules were performed using the extended simulation models and the results show that the newly suggested rules performed better than the existing one.

The contribution of this paper is that a simulation study was performed on the real telephone remanufacturing processes. With the developed simulation models, we can evaluate and apply new scheduling methods for the systems. In particular, this study can be extended to a simulation-based real time scheduling mechanism in order to cope with the inherent uncertainty of the remanufacturing systems. However, in order to extend the case study, it is necessary to develop a more accurate model that includes transportation time, required tools, detailed tasks, and human factors. Furthermore, to improve the system throughput, it is also necessary to develop scheduling algorithms that can consider highly variable processing times and the uncertainty of product conditions.

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