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Performance improvement of remanufacturing systems operating under N-policy

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Performance improvement of remanufacturing systems operating under

N-policy

By

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N-policy

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July 26, 2018

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ABSTRACT

This thesis deals with N-policy M/G/1 queueing remanufacturing system with general server breakdown and start-up time, where the value of returned products exponentially deteriorates since received. The server will instantly turn on the system, but the system requires a start-up period to prepare for remanufacturing when returned products in the queue reach the value of N. Otherwise, the system keeps in turn-off status. During the remanufacturing process, the machines may break down and will return back to service immediately after repairing. The procedures that will be used to achieve the target are as follows. Firstly, the expression of cost function will be derived and solved. Next, the simulation software ProModel will be used to simulate this problem. Finally, a sensitivity analysis is used on a numerical example to show the applicability of the methodology and quality of results.

ACKNOWLEDGEMENTS

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1.1 Reverse logistics and remanufacturing

1.1.1 Background.

Although there are different definitions of reverse logistics, the most commonly accepted one was defined by Rogers and Tibben-Lembke (1998): "The process of planning, implementing, and controlling the efficient, cost-effective flow of materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal." The origin of reverse logistics was still not clear, but the term of reverse logistics first came out in 1992. Since that period, the topic of reverse logistics has attracted more attention from scholars, companies, and governments.

Reverse logistics has three common characteristics:

1) The purpose of reverse logistics is to recover the value of defeated or returned products or to correctly dispose the final scrap products.

2) The targets of reverse logistics are products, containers, package materials, and related information, which are driven backward through the related points in the supply chain.

3) Although reverse logistics are the physical flow of goods, reverse logistics also involve the flow of funds, information, and business, like forward logistics.
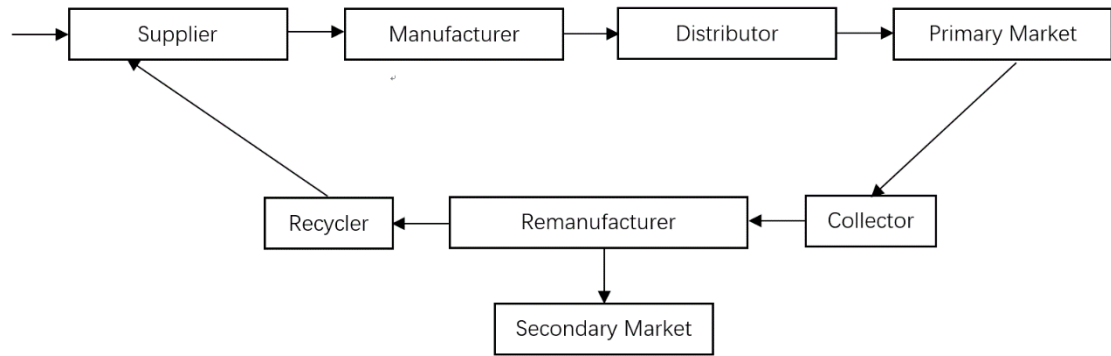
Figure 1: Product Flow

The reverse logistics and forward logistics comprise the closed loop supply chain (Pandian & Abdul-Kader, 2017). In forward logistics, manufacturers obtain raw materials and components from suppliers. Following their manufacturing, the new products are sent to distributors to sell into the primary market. Afterward, the end-life products, defected products, and returned products are collected into reverse logistics. The original manufacturers or the third-party companies will take the responsibility of collection. The third-party companies specially focus on collecting the used products and selling them to the original producers or independent producers. The recovered products may be sent to the primary markets or secondary markets according to the involved activities. When some returned products are not worth recovering, the valuable materials and parts in them may be recycled and sold.

1.1.2 Activities of reverse logistics.

Collecting the used products is usually the first step of reverse logistics. Just like raw materials to the forward logistics, the returned products are the input for reverse logistics.

The next step is to inspect (evaluate) the condition of returned products and sort them into different classes according to their qualities. This step is usually done by the producer. Nikolaidis (2009) states that some third-party companies might evaluate and sort the returned products before selling them to the producers with different prices related to the quality categories. According to the conditions of returned products, they would be sent to different destinations. If the packages are not opened or the products are never used, the returned products may be sold to other customers or outlet markets. If the quality of returned products is not sufficient to be sold directly, the companies may perform the activities like reconditioning, refurbishing, or remanufacturing to increase the selling price (Rogers & Tibben-Lembke,1998). If the returned products are not worth remanufacturing due to the extremely poor condition or control policies, the companies may recycle any valuable materials of goods and send the remainder parts for landfill or incineration.

1.2 Recovery options and processes

After inspection, according to the quality level of returned products, the producers must make the decision to choose a recovery option, such as reuse, refurbishing, remanufacture, or recycle. There still is not a standardized explanation of each term of recovery options as companies may name their refurbishing and remanufacturing activities differently according to their field (Pandian & Abdul-Kader, 2017). Figure 2 shows an example of a general process flow.

Legend:

	- Companies
	- Processing station
	- Departments

```
Collector
   │
   ▼
OEM/ IR
   │
   ▼
Sorter ──────────────────────────────────────────┐
   │                                              │
Good            Moderate              Bad         │
   ▼                ▼                  ▼           │
 Reuse         Remanufacture        Recycle ◄─────┘
   │                │                  │
   ▼                ▼                  ▼
 Reset         Disassemble          Shredder
   │                │                  │
   ▼                ▼                  ▼
 Polishing        Clean          Furnace Heating
   │                │                  │
   ▼                ▼                  ▼
Tech Update ◄   Inspection     Chemical Processing
   │                │                  │
   ▼                ▼                  ▼
Quality Test      Repair      Materials Separation
   │                │                  │
   ▼                ▼                  ▼
 Packing      Parts Inspection  Processed Pellets
   │                │
   ▼          ┌─────┴─────┐
Remanufactured │           │
  Inventory  Reusable    Parts
   │          Parts     Harvested
   │            └────┬─────┘
   │                 ▼
   │            Reassemble ◄──── Supplier
   ▼
Distributor
```

Figure 2: Generic process flow of reverse logistics (Pandian, 2015)

1.2.1 Reuse.

Usually, the reuse option is applied to high quality returned products. The returned products will only go through a few steps of the process, such as cleaning, testing, and repackaging. These processes are varied in companies, but the reuse option only involves simple activities.

1.2.2 Remanufacturing and refurbishing.

Currently, there is not a standard definition of remanufacturing. In a narrow definition, the remanufacturing is an important part of reverse logistics. In a broad sense, the remanufacturing may include not only the re-production but also the collection and distribution (Xing &Gao, 2014). Therefore, terms of the remanufacturing and reverse logistics have been referred to as the same thing in some literatures and industries.

The processes of refurbishing are similar to remanufacturing. Although some companies and scholars use 'refurbishing' and 'remanufacturing' interchangeably, there are differences between the terms. According to Gobbi (2011), the differences are the disassembly level and final quality. As for refurbishing, the structure of returned products is preserved integrally as much as possible, but the remanufacturing tends to disassemble the returned products and repair them in part level. Remanufacturing also rises the returned products to the same quality standards as the new product because it involves more processing during the recovery activities.

1.2.3 Recycle.

As mentioned above, the remanufacturing cost may be larger than the final selling price of returned products through the reverse logistics. Once a company decides that the returned products are not worth recovering as new products, the returned products will be recycled to recapture the remaining materials or undamaged parts. After that, the company could reuse the materials and parts or just sell them to other companies.

1.3 Time sensitive

The returned products usually need to wait several weeks to several months for remanufacturing process: the length of the period depends on the type of products or the field of companies. During this period, the selling price of a new product, which is the same type of the returned one, will decrease because of the release of new generation products or the change of market trend. This is more important to the products with a short life cycle, especially for high-tech products such as computers, cellphones, and tablets. Reverse logistics will generate negative value if the delay is too long because the remanufacturing costs will be larger than the final selling price. In other words, the products are not worth remanufacturing. Therefore, the companies will achieve more profits by reducing remanufacturing delays. The next chapter will be dedicated to literature review dealing with quality and deterioration value of returned products and other related aspects such as control policies, and methodology used to address this research problem.

Chapter 2: Literature Review

To better understand the background, concepts, methodology, and gaps in the current research related to reverse logistics, it is critical to conduct a thorough literature review. The review will be divided into five topics:

1. the uncertain quality of returned products,

2. the deterioration time value of returned products,

3. control policies,

4. methodology, and

5. research gaps.

Understanding each of these will not only help identify gaps but also provide insights into which methodologies that can be used and how existing methodologies can be improved.

2.1 Uncertain qualities of returned products

In the network of reverse logistics, the quantities and qualities of returned products are always uncertain (Denizel, Ferguson, & Souza 2010; Teunter & Flapper, 2011). Due to the complexity of analyzing both uncertain qualities and quantities simultaneously, some authors simplified the problem by only considering one single quality level, which means only the uncertain quantity will be considered (Ferguson, Guide, Koca, & Souza, 2006). However, multiple quality grades were taken into account in the following published works

(Denizel, Ferguson, & Souza, 2010; Galbreth & Blackburn, 2010; Teunter & Flapper, 2011).

Denizel, Ferguson, and Souza (2010) applied aggregate production planning to model the problem with the deterministic quantity and stochastic quality. Based on the concept that higher quality of returns will result in less cost of remanufacturing, Galbreth and Blackburn (2010) found that obtaining a larger quantity of used items could be profitable. The reason was that companies could select better quality used items to remanufacture. Therefore, the object was to determine the optimal quantity by comparing remanufacturing and acquiring costs. Galbreth and Blackburn (2010) assumed the uncertain quality with continuous function and the determined quantity. Afterward, Teunter and Flapper (2011) considered both the uncertainty of qualities and quantities for the returned products in reverse supply chain. The quality of returns was treated as a discrete function

2.2 Deteriorating time value and optimal disposition decision

The value of returned products will deteriorate due to the time delay. Voutsinas and Pappis (2002) considered that there was a parameter of returns called job value with an exponential deterioration function. They focused on finding a sub-optimal processing sequence to minimize the total decline value of returns by considering time value. Voutsinas and Pappis (2002) assumed that all jobs were available at time zero and processed in a single machine without set-up time, idle time, and down time after machine start. After that, the optimal algorithm was achieved by treating sub-optimal solution as an

initial solution with a branch and bound method (Voutsinas and Pappis 2010). Blackburn, Guide, Souza, and Van Wassenhove (2004) hypothesized that the marginal value of time is the most important parameter that affects the profit of returned products. They used case study to prove that redesigning reverse supply chain could reduce the loss of time value, which is caused by the lengthy delay. A simulation model was built to find how the delay affects costs and profits (Guide, Souza, Van Wassenhove and Blackburn, 2006). Two cases from HP and Bosch are used in this model to validate the cost-efficient (centralized) network and responsive (decentralized) network. The result is that responsive network is more appropriate in short product lifecycle by reducing delays. Harrison (1975) proposed a threshold to decide which class of product should be allowed to enter next process based on its current value and holding cost. Fathi, Zandi, and Jouini (2015) considered the time value in queueing models to make the disposition decision. Separate and merging models were conducted for returns that were received from two different markets. The H/M/1 and M/M/1 queueing systems have been assigned to high uncertainty returns and low uncertainty returns respectively in the separate model. The merging model combined these two queueing systems, called H2M/M/1. Pazoki and Abdul-Kader (2016) studied a mathematical model for multiple level classes of returned products that were processed in different work stations. The aim was to obtain the threshold value for deciding which class of returns should be remanufactured or sold as its salvage value. Pazoki and Abdul-Kader

(2016) assumed that the returns were received in batches at time zero with exponential

deterioration time value. In addition, the remanufacturing and manufacturing process were

treated as operating and idle periods respectively. The simulation method was used to

examine the mathematical model and the sensitivity of parameters.

2.3 Control policy

2.3.1 N-policy.

The concept of N-policy was first proposed by Yadin and Naor (1963). They

introduced M/G/1 queueing model with a removable service station that dismantled when

the queue is empty and could be reinstalled when the size of queue reaches a certain number

R. They did not use the term of N-policy in their paper. Heyman (1968) decided to use n^{opt}

to represent this policy in the M/G/1 queueing model. The objective was to find the optimal

policy to minimize the total operating cost. After that, Sobel (1969) presented a (M,m)

policy with GI/G/1 queueing system. The system stopped the service when the queue size

$\leq$ m and provided service when the queue size reaches M. Lee, Lee, Yoon, and Chae (1995)

presented a M^X/G/l queueing model under N-policy and a single-server vacation. The

server leaves the system for a time T vacation when the queue is empty. The difference

with the first type T-policy is that the server will wait in the system instead of taking another

time T vacation if the size does not reach the threshold value N after the end of vacation.

This means that even if the queue size reached the number N during the server vacation,

the system would not start manufacturing until time T ends. Parthasarathy and Sudhesh (2008) found the transient solution for state probability under N-policy in the M/M/C queueing system.

2.3.2 D-policy.

Balachandran (1973) was the first to present the D-policy in his research. The system turns on the server when the total service time of the customers who wait in the queue reaches the threshold value D. He compared the performance of N-policy and D-policy in the M/M/1 and M/G/1 queueing model.

2.3.3 T-policy.

With respect to T-policy, there are several different explanations. For example, Heyman (1977) was the first to introduce the term of T-policy under the M/G/1 queueing system and defined it as the sever vacation. After the busy period, the server becomes inactive, but it will check the system after time T. If there are customers in the queue, the server becomes activated. Otherwise, the server keeps inactive and checks the system after time T again. Heyman (1977) found that in order to minimize the cost rate, the N-policy must be better than the T-policy. The weakness of pure T-policy in his paper is that it cannot effectively reduce the fixed start-up cost because the server will be activated for even one customer. After that, Wang, Wang, and Pearn (2009) extended the research with server breakdowns and general start-up times based on the same concept of T-policy. The Second

configuration of T-policy is to define the T as the elapsed time units since the end of busy period or the end of previous T time unit (Gakis, Rhee, and Sivazlian, 1995). The final type of T-policy considered the time T as the waiting time of the first customer in the queue (Alfa and Frigui, 1996).

2.3.4 Combined policies.

The single control policy may have some weakness when applied to the real problem. For example, the system will become active even if only one customer arrives during the time T period under pure T-policy. Therefore, combined policies will effectively solve this problem.

Lee and Seo (2008) considered a min (N,D) Policy with M/G/1 queueing model. The server will resume the service if either N customers wait in the queue or the total backlog of the service times of the waiting customers exceeds threshold value D, whichever occurs first. After that, they compared combined (N,D) policy with pure D-policy and pure N-policy under the mean workload and mean queue length separately.

Alfa and Li (2000) extended the research by considering M/G/1 system with cost structures under (N,T)-policy with two type definitions of T: the threshold value T is the waiting time of leading customer and the time units elapsed since the end of last busy period. The system will turn on when any of the policies reaches the threshold value. This means that the system will activate as soon as the queue size reaches the threshold value N

or the time T has reached. After that, Ke (2006) extend (N,T)-policy in M/G/1 with a start-up time and unreliable server. The system needs a start-up time to activate after reaching the requirement of the threshold value. In addition, the server will break down during the service.

The primary weakness of these combined policies is that the complexity of calculation will significantly increase. Because it is difficult to directly calculate the joint optimal value of both threshold values, these authors derive the cost expression of both threshold values at first and then used numerical methods to achieve the optimal value of (N,T).

2.4 Methodology

2.4.1 A Poisson input queue under N-policy and with a general start up time (Medhi &Templeton, 1992).

Introduction:

Medhi and Templeton (1992) studied the M/G/1 queueing system under N-policy in the steady state and presented the expressions of system parameters as they relate to the performance measure. The system was divided into three different periods: turn-off period, start-up period, and busy period. A service discipline of FIFO with exhaustive service was used in this study.

Strength of this study:

Medhi and Templeton (1992) made some key assumptions that have been generally

adopted in subsequent research on related topics. One commonly used assumption is the exhaustive service discipline with the control operating policy. They also assumed the start-up time can be treated as an extended vacation. They derived the generating function of M/G/1 with start-up time under N-policy at first and found the expressions of expected length of busy period and the probability that the server is busy. Their study provided basic theoretical results and formula to support future research.

Limitation of this study:

Medhi and Templeton (1992) only presented the expression of system parameters as they did not find a way to calculate the optimal value of N. In addition, it only presented the limited number of system parameters.

2.4.2 The optimal control of an M/G/1 queueing system with server vacations, start-up and breakdowns (Ke, 2003).

Introduction:

Ke (2003) tried to achieve the optimal solution for an M/G/1 queueing system. In this system, the server takes a random length vacation while the system becomes empty. After the vacation is finished, the size of queue is checked to decide whether to take another random length vacation again if size is less than N or to wait a general start-up time to start the service otherwise. The server will break down at any moment during the working period with a Poisson breakdown rate. The repair time for the broken down server is generally

distributed. FIFO and exhaustive service disciplines are also applied in this system. The first step that Ke (2003) used to find optimal N is to derive the probability generating function of the number of customers in the system when the server starts the service. After that, he presented the function of several system characteristics that will be used in the final expected cost function. Finally, he determined the optimal N by using numerical methods to solve the expected cost function.

Strength of this study:

Ke's (2003) study involved the server breakdown, which commonly occurs in (re)manufacturing. This combination will be helpful to the current study as it provides a numerical method to solve the final expected cost function, which is convex. This method will provide potential and possible solutions to our model if the deterioration time value in included in the final expected cost function.

Limitation of this study:

The server vacation in Ke's (2003) study is similar to the T-policy, so it involved more uncertainty and complexity in the final expected cost function.

2.4.3 Optimal control of the N-policy M/G/1 queueing system with server breakdowns and general start-up times. (Wang, Wang, & Pearn, 2007).

Introduction:

Wang, Wang, and Pearn (2007) researched the M/G/1 queueing system under N-policy

with server breakdowns and start-up times. They extended Ke's (2003) research and narrowed down the scope that the random vacation time did not consider together with N-policy. They assumed that the breakdown rate of the server is a negative exponential distribution and the repair time and start-up time is a general distribution. As a result, they derived the several characteristics used to measure the system performances and then differentiated the expected cost function per unit time per customer with respect to N to achieve the optimal value of N.

Strength of this study:

This paper provided a numerical method that differentiated the expected cost function to find the optimal value of N. They also verified that the optimal solution is unique for the expected cost function and the best positive integer N will be close to optimal N if the optimal N is not an integer.

Limitation of this study:

Despite the important insights offered by Wang et al. (2007), they did not discuss the N-policy in the remanufacturing system. Thus, the cost parameter did not involve the deterioration time value.

2.4.4 Cost-minimization analysis of a working vacation queue with N-policy and server breakdowns. (Yang & Wu, 2015).

Introduction:

Yang and Wu (2015) studied the M/M/1 queueing system, which combined the N-policy and server vacations and breakdowns. They treated the queueing system as a quasi-birth–death process. The definitions of server vacations and breakdowns are different from other researches. The server will take a vacation after the system becomes empty, but it will not completely stop the service. This means that the server will keep a lower service rate during its vacation. Moreover, the server will have different breakdown rates in each period. The vacation times and repair times are all assumed to be exponentially distributed. The procedures that Yang and Wu (2015) used to reach the optimal value N are similar to previous studies. Finally, they adopted the particle swarm optimization algorithm to minimize the final cost function regarding the decision variables of threshold N and mean service rates.

Strength of this study:

Yang and Wu (2015) presented a powerful algorithm to solve final cost function with multiple decision variables. They provided different assumptions about service rates and breakdown rates. Moreover, they discussed two levels of service rates that occurred in the busy period and vacation period.

Limitation of this study:

The final cost function is too complex to have an explicit solution because it involved three decision variables: threshold N, service rate in the busy period, and service rate in the

vacation period. Yang and Wu (2015) based their findings on the M/M/1 queueing model instead of the M/G/1 queueing model, which will be used in the current research.

2.4.5 Optimal N-policy for Finite Queue with Server Breakdown and State-dependent Rate. (Agrawal, Jain & Singh, 2017).

Introduction:

Agrawal, Jain and Singh (2017) presented a unique queueing model in which the arrival rates were based on the system state. They assumed that the customers will have different Poisson arrival rates when they arrive in the turn-off state, operating state, and breakdown state respectively. The distributions of service time, life time and repair time are exponential. After that, Agrawal et al. (2017) used the generating function method to determine the system parameters. Finally, the recursive method is used to determine the optimal N for minimizing the total expected cost.

Strength of this study:

Agrawal et al. (2017) provide another unique model of N-policy by presenting steps to solve the N-Dpolicy problem. Some methods, such as the probability generating technique and the recursive method, may be useful to the current study. Thus, the state-dependent arrival rate provides concepts that have the potential to enhance the current study.

Limitation of this study:

This research does not use a typical M/M/1 queueing model. It increased the

complexity by involving additional variables of arrival rates. There is no relation between start-up time and remanufacturing. Besides, these authors did not present the detailed numerical method to minimize the final cost function.

2.5 Research Gaps

During the literature review, we only found two papers that involved both N-policy and remanufacturing together. These papers more concentrated on the buffer allocation problem. Most literature that focused on the N-policy is in forward logistics. There was no research that combined N-policy and deterioration time value of products together. Therefore, and to the best of our knowledge, this thesis is the first to combine N-policy and deterioration value of products together in the remanufacturing system. In a real situation, the value of returned products always decreases during the time since they go into the reverse logistic system, so reducing the time delay in the remanufacturing stage is necessary and profitable. Besides, it is common that factories wait to collect enough returned products to start the remanufacturing in the real world, but this action will increase the average waiting time for returned products to be processed. Consequently, studying to control the waiting time (the N-policy to control it in this research) to minimize the loss of time value is imperative. This research will contribute to this gap in the literature.

Table 1: Summary of literature review about remanufacturing

Author	Year	Objective	Method	Uncertain Quality	Control Policy	Deterioration Value	Remanufacturing
Voutsinas & Pappis	2002 2010	Find the optimal processing sequence for components of one type product	Mathematical (Scheduling model with heuristic & branch and bound algorithm)	NO	NO	Exponential Deterioration	YES
Souza, Ketzenberg, & Guide	2002	Find the optimal mixed product grade to achieve a certain service level	Analytical queueing & Simulation	Multi-level	NO	NO	YES
Guide, Souza, Van Wassenhove & Blackburn	2004 2006	Comparing the centralized and decentralized model	Analytical & ARENA model for validation (Closed-Loop Supply Chain Model)	Two Levels (New and remanufactured)	NO	Exponential Deterioration	YES
Guide, Gunes, Souza, & van Wassenhove	2008	Find the threshold value of processing time	Mathematical (Closed-Loop Supply Chain Model)	Multi-level	NO	Exponential Deterioration	YES
Karamouzian, Teimoury, & Modarres,	2011	Find the proportion of each class should be processed to maximize the total revenue	Analytical queueing model (mixed integer nonlinear programming)	Multi-level	NO	Exponential Deterioration	YES

Table 1: Summary of literature review about remanufacturing, cont'd

Author	Year	Objective	Method	Uncertain Quality	Control Policy	Deterioration Value	Remanufacturing
Ferguson, Fleischmann, & Souza	2011	Find the optimal quantities of return to be remanufactured	Mathematical (Closed-Loop Supply Chain Model	Two Levels	NO	NO	YES
Fathi, Zandi, & Jouini	2015	Find the threshold value of processing time	Analytical queueing model (Merged and separated)	Two Levels	NO	Exponential Deterioration	YES
Pazoki & Abdul-Kader	2016	Find the optimal decision variables for achieve maximum profit	Analytical queueing & Simulation	Multi-level	NO	Exponential Deterioration	YES
Savaliya	2017	Performance evaluation of remanufacturing systems	Simulation (ProModel & ANOVA)	Multi-level	NO	NO	YES
Pandian & Abdul-Kader	2017	Performance evaluation of reverse logistics enterprise	Agent-based Simulation	Multi-level	NO	NO	YES

Table 2: Summary of literature review about N-policy

Author	Year	Objective	Method	Uncertain Quality	Control Policy	Deterioration Value	Remanufacturing
Yadin & Naor	1963	Find the optimal procedure to eliminate idle time	Inventory model	NO	N-policy	NO	NO
Heyman	1968	Find the optimal policies to minimize the total operating cost	Inventory model	NO	N-policy	NO	NO
Sobel	1969	Examing the stationary policy	Inventory model	NO	(M,m)-policy	NO	NO
Balachandran	1973	Creat D-policy and compare it with N-policy	Inventory model	NO	N-policy D-policy	NO	NO
Heyman	1977	Find the minimum cost rate under T-policy and compare with N-policy	Inventory model	NO	T-policy	NO	NO
Lee et al.	1995	Performance Measures	Mathematical method	NO	N-policy Server vacation	NO	NO
Alfa& Frigui	1996	Performance Measures	Mathematical method	NO	(N,T)-policy	NO	NO

Table 2: Summary of literature review about N-policy, cont'd

Author	Year	Objective	Method	Uncertain Quality	Control Policy	Deterioration Value	Remanufacturing
Alfa & Li	2000	Find the optimal policies to minimize long-run average cost per unit time	Mathematical method	NO	(N,T)-policy	NO	NO
Ke	2006	Find the optimal N and T to minimize the total cost	Mathematical method Numerical method	NO	(N,T)-policy	NO	NO
Lee & Seo	2008	Performance Measures	Mathematical method Numerical method	NO	Min(N, D)-policy	NO	NO
Parthasarathy & Sudhesh	2008	Find the transient solution of a multi-server Poisson queue with N-policy	Mathematical method Numerical method	NO	N-policy	NO	NO
Feyaerts et al.	2014	Performance Measures	Mathematical method Numerical method	NO	(N,T)-policy	NO	NO
Shaojun & Yinghui	2017	Optimization of system capacity	Numerical Method based on MATLAB	NO	Min(N, D)-policy	NO	NO
Fengtian Gu (This thesis)	2018	Find optimal value of decision variables	Mathematical method Simulation method	YES	N-policy	YES	YES

Chapter 3: Problem statement

3.1 Problem definition and assumption
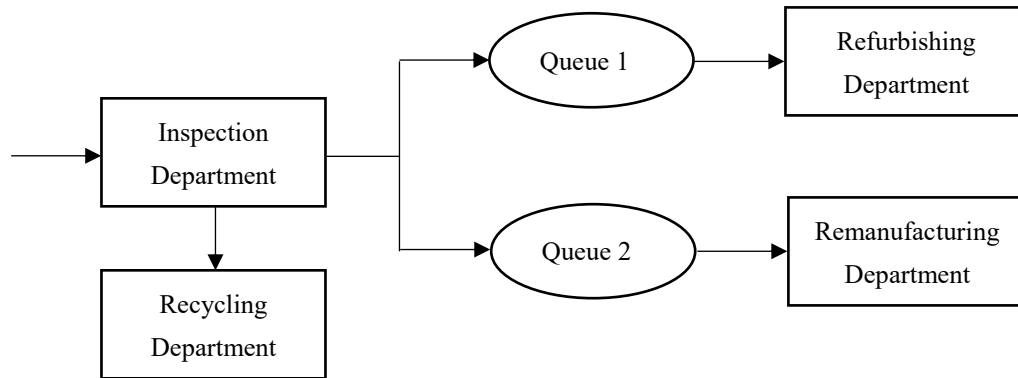
Figure 3: General concept of the model

The multi-class M/G/1 queueing system is used in this model with N-policy. The received returned products will continue to arrive at the inspection station with a total Poisson arrival rate λ. According to their qualities, it is assumed that the inspection station will evaluate these returns and sort them into three classes: good, moderate and bad. The inspection department is assumed with an infinite capacity, which means no delay in this stage, so returned products will be sent to the next position immediately. Returned products with bad quality, which are not worth refurbishing or remanufacturing, will be sent to the recycling department to capture the final value of them. The good and moderate returned products will cumulate in queue 1 and queue 2, respectively. Besides, each queue has its own threshold value: N_1 for queue 1 and N_2 for queue 2, which are independent of each other. Once one queue reaches its own threshold value, the corresponding department becomes activated. In other words, the activation of an individual system will only depend on its own decision variable.

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There are other definitions and assumptions made for this model:

1) The whole system consists of two independent systems. System 1 includes queue 1 and the refurbishing department, while system 2 includes queue 2 and the remanufacturing department.

2) Only one type of returned product is assumed to be received in this problem.

3) Refurbished and remanufactured products are assumed to be the same selling price at time zero. The selling price at time zero is assumed to be a constant value. For example, the company decide to receive the computer series A with selling price of $1000 at beginning of the year. After three months, the company chooses to receive the computer series B, a new generation of series A, with the selling price of $1000.

4) The good condition returns will be sent to the refurbishing department to undergo fewer processes than the moderate returned products in the remanufacturing department. The service rates of the refurbishing and remanufacturing departments are different.

5) The final quality of recovered products meets the same standard as new products. In other words, the final selling prices of refurbished products and remanufactured products are the same.

6) The service department will need a start-up time before starting processing. During the start-up period, the departments will not be able to process any items.

7) The server can break down at any moment during the service. Once the server breaks down, it will be sent to repair immediately. After a generally distributed repair time, the server will return back to the system and serve the customers again until the server encounters its next breakdown or the system becomes empty.

8) The service time, start-up time, and repair time are generally distributed. The arrival rate and breakdown rate are Poisson distributed.

9) The system is in a steady state. This thesis is only focusing on the long-run behaviour of the system. The service rate must be larger than the arrival rate, otherwise the system will be blocked. Hence, the traffic intensity ρ is less than one.

10) The probability of each class will be known based on historical data. Each arriving product could be labelled only with one class in the inspection station according to its condition. The assigned class would not change during the following remanufacturing process.

11) Even though no service will be provided during the server breakdown period, returned products continue to arrive at the inspection station even during the breakdown period.

12) The value of returned products will continue to decrease since they were received with an exponential deterioration rate θ. The deterioration function is $re^{-\theta t}$, where t is the delay time, r represents the selling price at time zero and θ is deterioration rate.

13) FIFO with exhaustive service. The system processes the items with first-in and first-out discipline. Once service is started, the system continues to run until the queue is empty.

3.2 Refurbishing and remanufacturing period
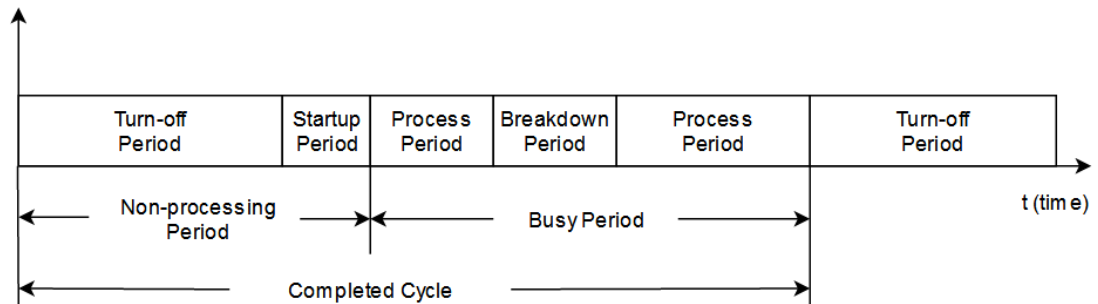
Figure 4: Refurbishing and remanufacturing period

The refurbishing and remanufacturing processing is divided into (see also Figure 4):

● Turned-off period,

● Start-up period,

● Process period,

● Breakdown period,

● Busy Period. The sum of process period and breakdown period,

● Completed cycle or run. Since the last end of the busy period to the next end of the busy period, includes the turn-off period, start-up period, process period and breakdown period. This is true for both refurbishing run and remanufacturing run in this thesis.

3.2.1 Turn-off period.

Each time when the system becomes empty, the server leaves from the primary tasks. The server may be assigned other tasks, such as maintenance work or secondary work. In hybrid (re)manufacturing companies, the secondary tasks can be the production of new products while the primary task is remanufacturing. Therefore, the turn-off period is the period in which the server is unavailable for the primary task in this case.

During the turn-off period, the customers will continue to arrive in the queue. After the number of cumulated customers in the queue reaches the pre-set threshold value N, the system will enter the start-up period.

3.2.2 Start-up period.

The start-up period is a common situation in the real factories. In a department, the start-up period means the time to place raw materials and position workers before beginning the service. As for a machine, it means the time to power on and warm up the machine.

In this case, once the queue size reaches its threshold value, the server turns on the system and is ready for the incoming refurbishing and remanufacturing activities. However, the system requires a generally distributed start-up time to complete some preparation work, such as switching from secondary work to primary work or adjusting the equipment. After the start-up time, the system will enter the process period.

3.2.3 Process period with exhaustive service.

After the start-up period is completed, returned products will be processed with the generally distributed service rate. The server will not only process the N returned products that cumulate during turn-off period, but also will deal with the products that arrive during the startup period and busy period. This is called exhaustive service discipline, which was commonly used in N-policy research.

3.2.4 Breakdown period.

The server can randomly break down with a Poisson rate at any moment during the process period. Once the server fails, it will be sent to the repair department immediately. The repair time of a failed server follows a general distribution. After repair action, the server will immediately resume service.

3.3 Deterioration value

The most important assumption of this thesis is the deterioration value of returned products because the purpose is to find the optimal value N_1 and N_2 to minimize the total cost during the remanufacturing. The value of returned products is assumed to be exponentially decreasing during the whole remanufacturing since they have been received. Many research papers, such as Pazoki and Abdul-Kader (2014), and Guide et al. (2008), considered that the deterioration rate includes both revenue decay, holding cost, and processing cost. In this case, only the revenue decay and holding cost will be considered

into the deterioration rate. Other costs that occur during the refurbishing and remanufacturing process will be set as independent cost parameters.

In the next chapter, the expected cost function is derived by using analytical method at first. However, there is not explicit expression of the optimal decision variable N_i. After that, the simulation method is used to find the optimal value of the decision variable N_i.

Chapter 4: Methodology

4.1 Analytical method to find the expected cost function

In this section, the primary objective is to derive the formulation of the system characteristics.

(1) Expected time spent in the system.

(2) Expected length of each period.

(3) Expected length of completed cycle or run.

4.1.1 Parameters and notations.

In order to distinguish the different departments, the suffix "i" of parameters is used.

Decision variable

N_i The threshold value of the queue size to start remanufacturing

System parameters

P_i Probability of the qualities of returned product, i=1,2, 3.

λ Total arrival rate, so arrival rate for each department $\lambda_i = \lambda * P_i$

$E(S_i)$ Mean service time for each department, equals to $1/\mu_i$

$E[U_i]$ Mean start-up time

α_i Breakdown rate for server

$E[D_i]$ Mean repair time

Cost parameters

θ Deterioration rate

C_s Setup cost per complete cycle

C_{sp} Cost per unit time for the start-up period

C_b Operation cost per unit time

C_d Breakdown cost per unit time

r   Selling price of finished product at time zero, which is the time of receiving

Notations

ρ_i Traffic intensity of original M/G/1 system, equals to λ_i / μ_i

ρ_H Traffic intensity of M/G/1 system with server breakdowns

$E[W_{qi}]$ Mean waiting time spent in the queue

$E[L_{qi}]$ Expected number of returned products waiting in the queue

$E[T_i]$ Mean waiting time spent in the system

$E[H_i]$ Mean busy time for one job

$E[R_{Si}]$ Mean residual service time

$E[R_{Ui}]$ Mean residual start-up time

$E[R_{H_i}]$ Mean residual busy time

$E[S_i^2]$ The second moment of the service time

$E[U_i^2]$ The second moment of the start-up time

$E[D_i^2]$ The second moment of the repair time

$E[H_i^2]$ The second moment of the busy time

$E[V_i]$ Expected length of busy period

$E[M_i]$ Expected length of process period

$E[K_i]$ Expected length of breakdown period

$E[I_i]$ Expected length of turn-off period

$E[C_i]$ Expected length of one run

$F[N_i]$ Expected cost per time unit

4.1.2 Expected time spent in the system.

From the results of Adan and Resing (2015), the mean time spent in system $E[W_{qi}]$

of one job in an original M/G/1 queueing system with generally distributed start-up times

will satisfy Equation (1).

$$E[W_{qi}] \ = \ E[L_{qi}] \ \times \ E[S_i] \ + \ \rho_i \ \times \ E[R_{S_i}]$$

$$+ \ P \ (\text{Returns arrive in turn-off period}) \ \times \ E[U_i]$$

$$+ \ P \ (\text{Returns arrive in start-up period}) \ \times \ E[R_{U_i}] \tag{1}$$

where $E[R_S]$ and $E[R_U]$ denote the mean residual service and mean residual start-up

time, $\rho_i = \lambda_i \times E[S_i]$, and $E[L_{qi}]$ denotes the expected number of returned products waiting

in the queue which equals to $\lambda_i \times E[W_{qi}]$, so the Equation (2) and (3) are obtained.

$$E[R_{S_i}] = \frac{E[S_i^2]}{2 \times E[S_i]} \tag{2}$$

$$E[S_i^2] = \sigma_{S_i}^2 + E[S_i]^2 \tag{2a}$$

$$E[R_{U_i}] = \frac{E[U_i^2]}{2 \times E[U_i]} \tag{3}$$

$$E[U_i^2] = \sigma_{U_i}^2 + E[U_i]^2 \tag{3a}$$

where $E[S_i]$ and $E[S_i^2]$ are the first and second moments of the service time respectively, and $E[U_i]$ and $E[U_i^2]$ are the first and second moments of the start-up time. For example, the second moment of service time with an exponential distribution is $2E[S_i]^2$ because the $\sigma_{S_i}^2$ equals to $E[S_i]^2$ in the exponential distribution.

After involving the N-policy, the equation of mean waiting time is changed to Equation (4).

$$
\begin{aligned}
E[W_{qi}] \;=\; & E[L_{qi}] \times E[S_i] + \rho_i \times E[R_{S_i}] \\
& + \sum_{m=1}^{N} P \text{ (Arriving return is number m)} \times \left(\frac{N_i - m}{\lambda_i} + E[U_i] \right) \\
& + \; P \text{ (Returns arrive in start-up period)} \times E[R_{U_i}] \tag{4}
\end{aligned}
$$

The probability that a return will arrive in a non-processing period is equal to $1 - \rho_i$. By assuming the start-up period is an extended vacation, the non-processing period now consists of the turn-off period and the start-up period. In other words, this period includes (N-1) interarrival times and a start-up time. Therefore, the probability that a return is the *i*-th one, given that the return arrives in a non-processing period, is equal to $1/\lambda_i$ divided by the mean length of a non-processing period. So,

$$P(\text{Arriving return is number m}) = (1 - \rho_i) \times \left(\frac{1/\lambda_i}{N_i/\lambda_i + E[U_i]} \right) \tag{5}$$

$$P(\text{Returns arrive in start-up period}) = (1 - \rho_i) \times \left(\frac{E[U_i]}{N_i/\lambda_i + E[U_i]}\right) \tag{6}$$

When considering the server breakdowns, the busy time of one customer is assumed to include both the service time of the customer and repair time for server breakdowns. $E[H_i]$ is assumed to be the mean busy time for one job under N-policy so the $E[R_{H_i}]$ is the residual busy time. The Equation (8) and (9) about the first and second moments of busy time are obtained from Ke's(2003) research. By replacing the service time of original function with the busy time, the following results can be obtained.

$$
\begin{aligned}
E[W_{qi}] \;=\; & E[L_{qi}] \times E[H_i] + \rho_{H_i} \times E[R_{H_i}] \\
& + \sum_{m=1}^{N} P\,(\text{Arriving return is number m}) \times \left(\frac{N_i - m}{\lambda_i} + E[U_i]\right) \\
& + \; P\,(\text{Returns arrive in start-up period}) \times E[R_{U_i}] \tag{7}
\end{aligned}
$$

where $\rho_{H_i} = \lambda_i \times E[H_i]$, ρ_{H_i} is assumed to be less than one.

$$E[H_i] = E[S_i] \times (1 + \alpha_i \times E[D_i]) \tag{8}$$

$$E[D_i^2] = \sigma_{D_i}^2 + E[D_i]^2 \tag{8a}$$

$$E[H_i{}^2] = E[S_i{}^2] \times (1 \; + \; \alpha_i \times E[D_i])^2 + \alpha_i \times E[S_i] \times E[D_i{}^2] \tag{9}$$

$$E[R_{H_i}] = \frac{E[H_i{}^2]}{2 \times E[H_i]} = \frac{E[S_i{}^2] \times (1 \; + \; \alpha_i \times E[D_i])^2 + \alpha_i \times E[S_i] \times E[D_i{}^2]}{2 \times E[S_i] \times (1 \; + \; \alpha_i \times E[D_i])} \tag{10}$$

$$P(\text{Arriving return is number m}) = \left(1 - \rho_{H_i}\right) \times \left(\frac{1/\lambda_i}{N_i/\lambda_i + E[U_i]}\right) \tag{11}$$

$$P(\text{Returns arrive in start-up period}) = \left(1 - \rho_{H_i}\right) \times \left(\frac{E[U_i]}{N_i/\lambda_i + E[U_i]}\right) \tag{12}$$

Where $1 - \rho_{H_i}$ is the probability that time is not in busy period. $N_i/\lambda_i + E[U_i]$ is the length of turn-off period plus start-up period.

Hence, by using Little's law to Equation (7), the mean waiting time spent in the queue for one job under N-policy with server breakdown and start-up time for each department is obtained.

$$E[W_{qi}] = \frac{\lambda_i \times (E[S_i^2] \times (1 + \alpha_i \times E[D])^2 + \alpha_i \times E[S_i] \times E[D_i^2])}{2(1 - \lambda_i \times E[S_i] \times (1 + \alpha_i \times E[D_i]))}$$

$$+ \frac{1}{N_i + \lambda_i \times E[U_i]} \times \left(\frac{N_i \times (N_i - 1)}{2 \times \lambda_i} + N_i \times E[U_i] + \frac{\lambda_i \times E[U_i^2]}{2} \right) \qquad (13)$$

Finally, $E[T_i]$, which is the mean time spent in the system, is achieved by adding the mean service time $E[S_i]$ to mean time spent in the queue $E[W_{qi}]$.

$$E[T_i] = E[S_i] + E[W_{qi}] \qquad (14)$$

4.1.3 Expected length of turn-off period.

As mentioned above, the turn-off period will end when the Nth customer presents in the queue. Because the interarrival time between two returned products is independently, identically and exponentially distributed with mean $1/\lambda_i$, the expected length of the turn-off period only relates to decision variables N_i and arrival rates λ_i.

$$E[I_i] = \frac{N_i}{\lambda_i} \qquad (15)$$

4.1.4 Expected length of process period and breakdown period.

According to the research of Wang et al. (2007), $E[V_i]$ the expected length of busy period under N-policy with start-up times and server breakdowns is the product of the expected length of busy period of original M/G/1 system with server breakdowns and the total number of arrivals in turn-off period and start-up period.

$$E[V_i] = (N_i + \lambda_i \times E[U_i]) \times (\frac{E[S_i] \times (1 + \alpha_i \times E[D_i])}{1 - \rho_i \times (1 + \alpha_i \times E[D_i])}) \qquad (16)$$

As mentioned above, the busy period includes both the process period and breakdown period; thus, the expected length of process period $E[M_i]$ and breakdown period $E[K_i]$ can be separated from Equation (16).

$$E[M_i] = \frac{(N_i + \lambda_i \times E[U_i]) \times E[S_i]}{1 - \rho_i \times (1 + \alpha_i \times E[D_i])} \qquad (17)$$

$$E[K_i] = \frac{(N_i + \lambda_i \times E[U_i]) \times \alpha_i \times E[S_i] \times E[D_i])}{1 - \rho_i \times (1 + \alpha_i \times E[D_i])} \qquad (18)$$

4.1.5 Expected length of the run (completed cycle).

The completed cycle contains the turn-off period, start-up period, process period and breakdown period. Therefore, the expected length of the run is the sum of the length of each period that is presented in Equation (19).

$$E[C_i] = E[V_i] + E[I_i] + E[U_i] = \frac{(N_i + \lambda_i \times E[U_i]) \times E[S_i] \times (1 + \alpha_i \times E[D_i])}{1 - \rho_i \times (1 + \alpha_i \times E[D_i])} + \frac{N_i}{\lambda_i} + E[U_i]$$

$$= \frac{N_i + \lambda_i \times E[U_i]}{\lambda_i \times (1 - \rho_i \times (1 + \alpha_i \times E[D_i]))} \qquad (19)$$

4.1.6 Expected cost function.

The expected cost function per unit time is developed for a single system under N-policy with server start-up and breakdown, which is based on the decision variables N_i. The target is to find the optimal decision variables to minimize the cost function. At first, the cost function is defined as the sum of the deterioration cost, setup cost, start-up cost, operation cost, and breakdown cost.

Deterioration cost per run = $r \times (1 - e^{-\theta \times E[T_i]}) \times \lambda_i \times E[C_i]$ \qquad (20)

Deterioration cost per unit time $= \frac{\text{Deterioration cost per run}}{\text{Expected length of one run}} = \lambda_i \times r \times (1 - e^{-\theta \times E[T_i]})$ (21)

Therefore, the expected cost per unit time is expressed as Equation (22).

$$F(N_i) = \lambda_i \times r \times (1 - e^{-\theta \times E[T_i]}) + \frac{1}{E[C_i]} \times C_s + \frac{E[U]}{E[C_i]} \times C_{sp} + \frac{E[M_i]}{E[C_i]} \times C_b + \frac{E[K_i]}{E[C_i]} \times C_d$$ (22)

Wang et al. (2007) has proved that the expression of operation cost per unit time $\frac{E[M_i]}{E[C_i]}$ and breakdown cost per unit time $\frac{E[K_i]}{E[C_i]}$ are not function of decision variable N_i. Hence, these cost functions can be omitted in the final cost function.

$$F(N_i) = \lambda_i \times r \times (1 - e^{-\theta \times E[T_i]}) + \frac{C_s}{E[C_i]} + \frac{E[U_i]}{E[C_i]} \times C_{sp}$$ (23)

This model is comprised of refurbishing and remanufacturing departments; the total cost is the sum cost of two departments. However, the two are independent systems. Hence, the solution is the same for both departments. In other words, if the solution is found for the refurbishing department, it also can be found for the remanufacturing department.

The final expected cost function is presented as the Equation (24) after substituting Equation (13), (14) and (19) into the Equation (23):

$$F(N_i) = \lambda_i \times r \times \left(1 - e^{-\theta \times \left(\frac{\lambda_i \times (E[S_i^2] \times (1+\alpha_i \times E[D_i])^2 + \alpha_i \times E[S_i] \times E[D_i^2])}{2 \times (1-\lambda_i \times E[S_i] \times (1+\alpha_i \times E[D_i]))} + \frac{1}{N_i + \lambda_i \times E[U_i]} \left(\frac{N_i \times (N_i-1)}{2 \times \lambda_i} + N_i \times E[U_i] + \frac{\lambda_i \times E[U_i^2]}{2}\right) + E[S_i]\right)}\right)$$
$$+ \frac{(C_{sp} \times E[U_i] + C_s) \times \lambda_i \times (1 - \rho_i \times (1+\alpha_i \times E[D_i]))}{N_i + \lambda_i \times E[U_i]}$$ (24)

4.2 Simulation method

4.2.1 Reason for simulation.

This final expected cost function is too complex and time-consuming to be solved by mathematical methods. To find the optimal threshold value N_i, the expression of the

decision variable N_i should be derived by differentiating the expected cost function (24).

However, this work is challenging to implement because it is unable to find an explicit

solution with respect to N_i by using the software packages MATLAB and MAPLE, after

differentiating equation (24).

The main challenges for using the mathematical method in the N-policy

remanufacturing system with deterioration value are the following:

- Cost function while involving exponential deterioration rate.

- Implementation of N-policy.

- More complicated model in the remanufacturing system than primary production.

Because of the above-indicated complexities, simulation modeling is a better

modeling approach to solve this problem as compared with mathematical method.

According to Golinska-Dawson and Pawlewski (2018), the common methods of simulation

are Agent Based System (ABS) simulation, Discrete Event System (DES) simulation and

System Dynamics (SD) simulation.

The model in this thesis is considered as a dynamic, stochastic, and discrete event

simulation model. Promodel, a commercial simulation software package, is used to

simulate this problem. It is a DES simulator in which the system events are recorded at

specific points of time. This software provides powerful tools for constructing, debugging,

and analyzing the model.

4.2.2 Description of simulation model.
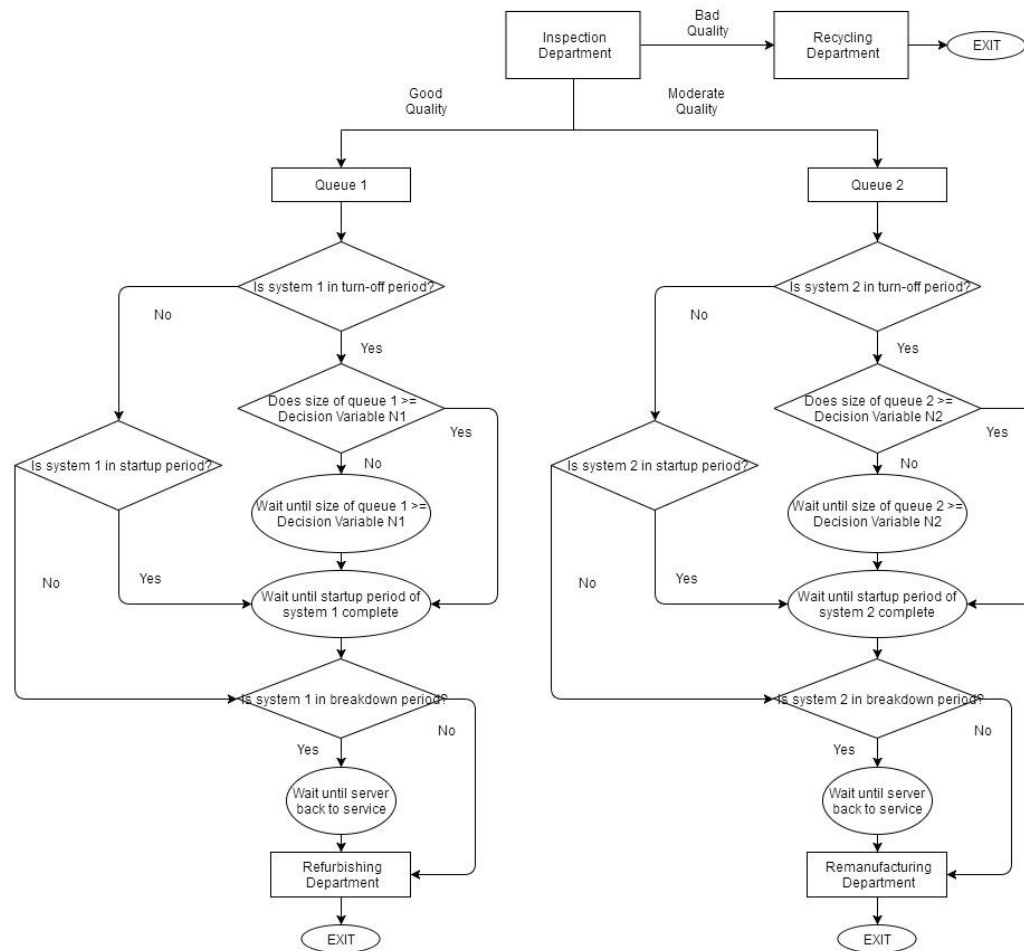
Figure 5: Flowchart of process logic

When a returned product enters a system in the turn-off period, it must wait in the

queue until the queue size reaches the decision variable of the current queue. After the

threshold value of the decision variable is achieved, the server will not be available until

the start-up period is completed. Under the exhaustive service, any returned products that

arrive during the start-up period and busy period will be processed. To better understand

the exhaustive service, the following equation about the number of processed products in

one run is given:

Processed products per complete cycle

$$= \text{Decision Variable } N_i + \lambda_i * (1 \text{ busy period} + 1 \text{ Start-up period})$$

4.2.3 Simulation object function.

The model aims to minimize the total cost function by obtaining the optimal decision

variables N_1 and N_2. The tool called SimRunner, which is available in Promodel, is used to

find the optimal decision variables.

The analytical objective function is the same as Equation (23):

$$F(N_i) = \lambda_i r(1 - e^{-\theta E[T_i]}) + \frac{C_s}{E[C_i]} + \frac{E[U_i]}{E[C_i]} \times C_{sp}$$

Where the mean time spend in system $E[T_i]$ and expected length of one run $E[C_i]$ are

obtained from the simulation results.

In order to obtain the expected length of the completed cycle, extra variables are

defined to record the total cycle (run) times during the simulation running time. After that,

the expected length of the completed cycle (run) equals to simulation running time divided

by total cycle (run) times.

$$E[C_i] = \frac{\text{simulation running time}}{\text{total cycle (run) times}}$$

Due to limitations of default objective function in SimRunner, extra variables are also

defined to record the mean time of one product spent in the system $E[T_i]$. To minimize the

total cost of the two departments, the minimized costs are required for each department,

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which can be achieved independently.

4.2.4 Model verification and validation.

It is critical to perform the model verification and validation after building a simulation model. During the translation from a conceptual model to a simulation model, there are many chances to make errors. Model verification is to ensure the model is running correctly without errors. Model validation is to prove that the result data is the accurate presentation of the conceptual model.

The Promodel software provides powerful debugging tools to track each step of the simulation model during the running. The debug command and trace option are used during the model construction. After carefully debugging and testing, every part functioned correctly. However, there is not a mathematical model or real system that can be used to validate the simulation model. Therefore, two methods are used to validate the simulation model. The first method is to assume the same input parameters and conditions that are used in Chapter 5 and change the decision variable N_1 from 10 to 100 with interval value of 10. After that, the differences of analytic and simulation results are compared in Table 9. The differences of results are very small between the analytic method and the simulation method. After adjusting some small parts of variables, cost functions, and logical routes to examine the model from Wang et al. (2007), the simulation results are similar to the mathematical results of Wang et al. (2007). Thus, this simulation model can perform the optimization process of the problem that is stated in this thesis.

Table 3: Comparison of analytical and simulation results

N_1	10	20	30	40	50
$F(N_1)$ (Analytical results)	29.9883	16.5295	12.6704	11.2275	10.7522
$F(N_1)$ (Simulation results)	29.8972	16.5207	12.7073	11.2455	10.8156
Difference(%)	0.0030	0.0005	0.0029	0.0016	0.0059

Table 3: Comparison of analytical and simulation results, cont'd

N_1	60	70	80	90	100
$F(N_1)$ (Analytical results)	10.7600	11.0428	11.4964	12.0630	12.7077
$F(N_1)$ (Simulation results)	10.7268	11.0409	11.5526	11.9839	12.7358
Difference(%)	0.0031	0.0002	0.0049	0.0066	0.0022

Chapter:5 Case study

5.1 Input data for numerical experiments

    5.1.1 System parameters.

Guide et al. (2008) present a study about HP printers. They assume the returned

products will arrive in batches of 250 units with an arrival rate 0.08 to 0.099 batches per

day. The remanufacturing process will finish within ten days. Therefore, the arrival rate is

1.25 units per hour by using the arrival rate of 0.08 batches per day. The service rate of

remanufacturing is 3.125 units per hour while the company is assumed to work eight hours

per day for refurbishing and remanufacturing. After that, the service rate of refurbishing is

assumed to be 3.5 units per hour, which is a slightly larger than the remanufacturing service

rate because of fewer operations. The parameters of breakdown, repair, and start-up are

adopted from Wang et al. (2007). The service time and repair time are exponentially

distributed. The arrival rate and breakdown rate follow a Poisson process.

Table 4: Input data - system parameters

Parameter	Value
λ	1.25 per hour
μ_1	3.5 per hour
μ_2	3.125 per hour
α	0.05 per hour
$E[D]$	1/3 hour
$E[U]$	1/3 hour

5.1.2 Cost parameters.

The cost parameters C_s and C_{sp} are also retrieved from the paper of Wang et al. (2007).

Guide et al. (2008) define that the deterioration rate is the sum of discount rate and revenue

decay rate in the HP printer case, in which the discount rate is 5% per year and revenue

decay rate is 1% per week. Thus, the hourly deterioration rate in this thesis is assumed to

be 0.0002 when deterioration rate is considered to include the holding cost.

Table 5: Input data - cost parameters

Parameter	Value
C_s	1000 dollars
C_{sp}	100 dollars
θ	0.0002 per hour
r	1000 dollars

5.1.3 Probabilities of returned product quality.

Table 6: Probability of each class (Data adopted from Nikolaidis,2009)

Probability		
Good	Moderate	Bad
0.25	0.6	0.15

5.1.4 Simulation time and warmup period.

The company is assumed to operate eight working hours per shift, two shifts per day, five days per week, 48 weeks per year. Therefore, the length of simulation is assumed to be one year, which equals to 3,840 hours.

Considering a warmup period in the simulation is imperative because it can reduce the bias data at the beginning of simulation. The warmup period is determined by using SimRunner with moving average window, w=12. This is based on Welch's method. After tracking the mean service time of the refurbishing department, the statistics (green line) in Figure 6 become stable after eight periods with the time interval of 80 hours. Thus, the warmup time is set as 640 hours. The calculation of replication number is presented in Appendix 2. The calculation result is 20.41 replications when considering with 95% confidence interval and error level 0.075. Therefore, the number of replication is set at 25 to achieve higher precision.
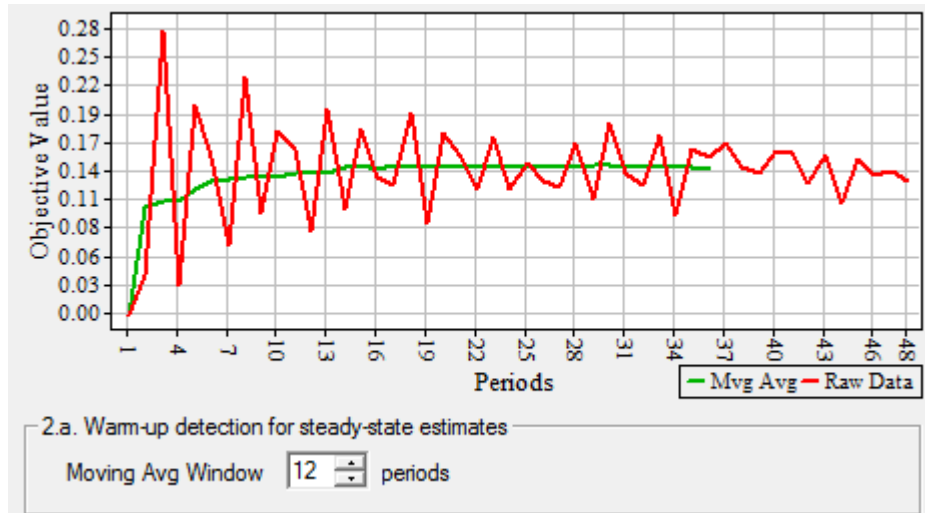
Figure 6: Simulation warmup time

5.2 Simulation results data and discussion

Per the simulation result, the cost function will rapidly decrease to the lowest point first and then rise slowly when the value of decision variable increases. The length of turn-off period and the average waiting time of returned products in the system will significantly rise when decision variables increase. This will cause the ascent of deterioration cost because of the longer average waiting time in the queue. However, the larger decision variable will result in a smaller number of completed cycles. Hence, the setup cost and start-up cost will decrease. In other words, the average length of each completed cycle will increase. The mean waiting time spent in the queue is approximately linear with respect to the decision variable N_i. The deterioration cost per unit time seems linear to the value of decision variable because of the limited boundary of axes.

47
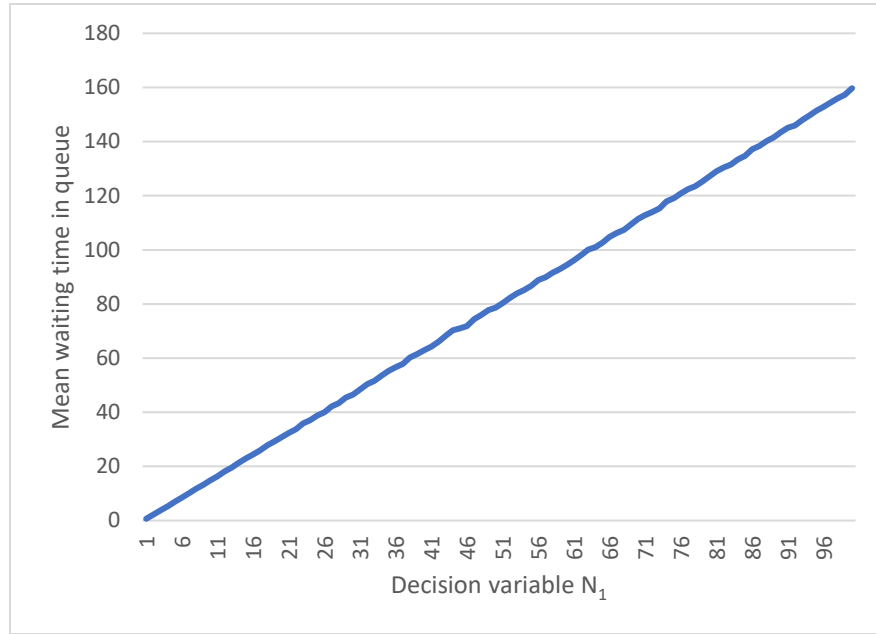
Figure 7: Mean waiting time in queue for refurbishing department
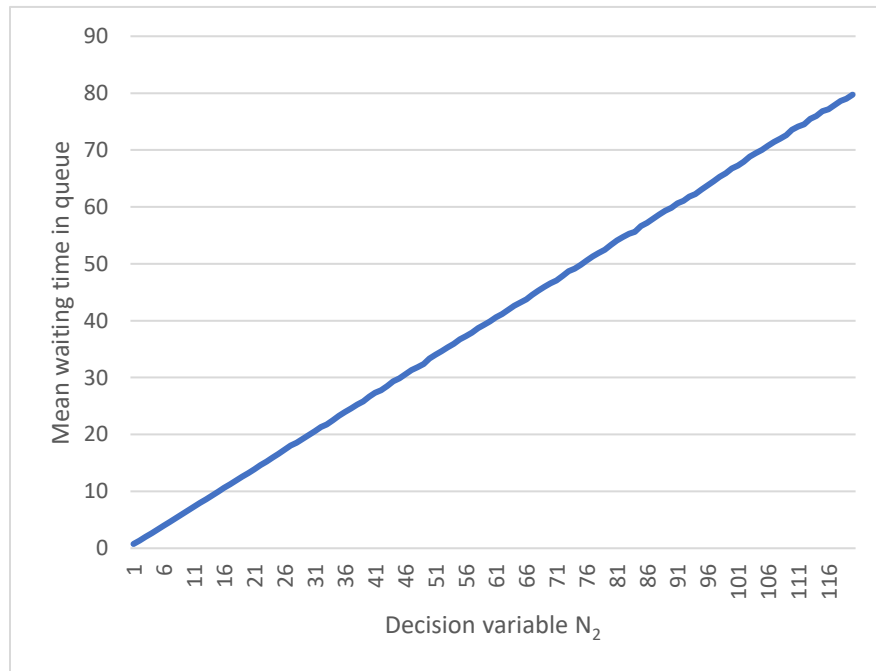
Figure 8: Mean waiting time in queue for remanufacturing department
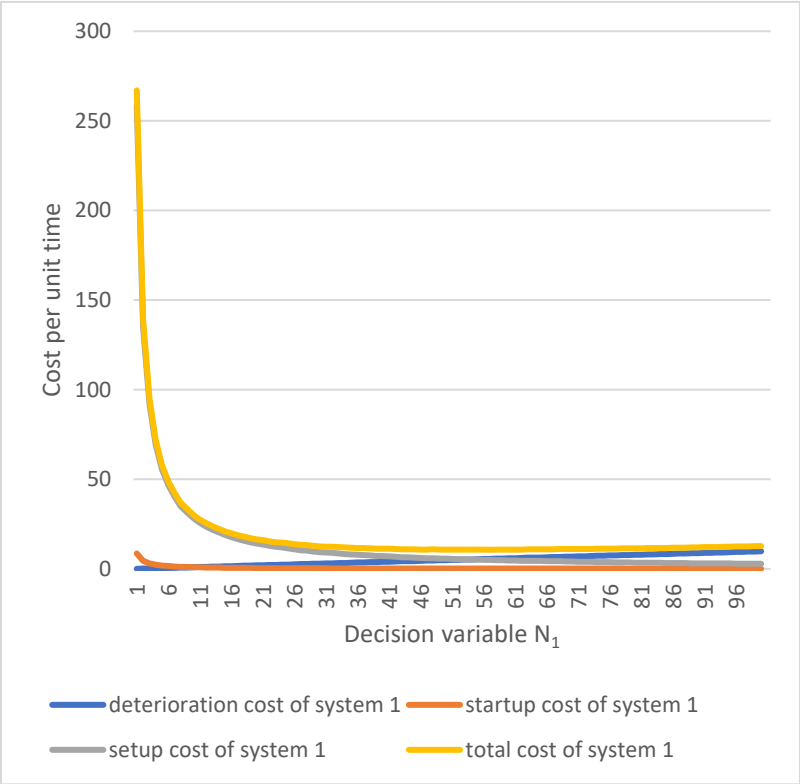
Figure 9: Refurbishing cost per unit time
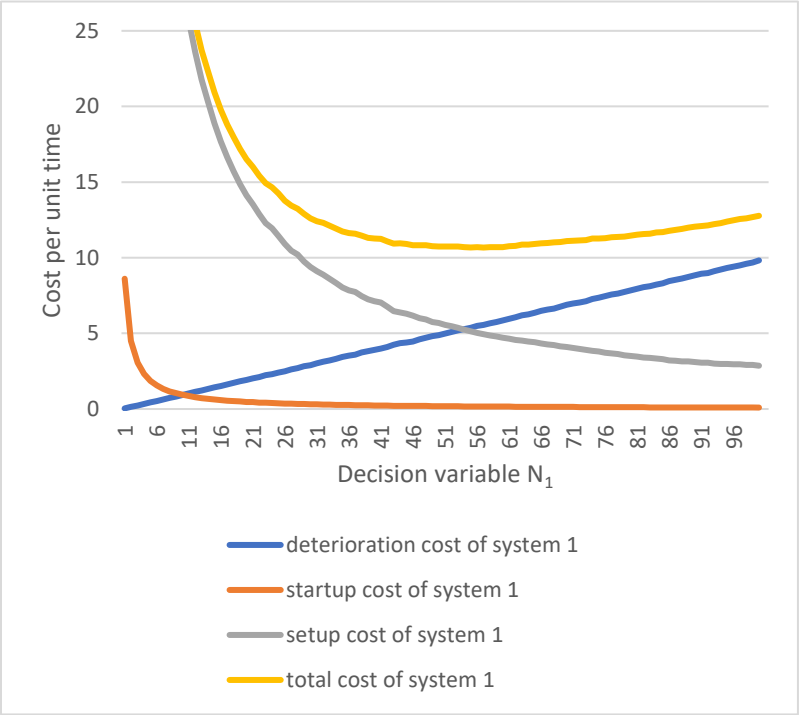
Figure 10: Magnification of refurbishing cost per unit time
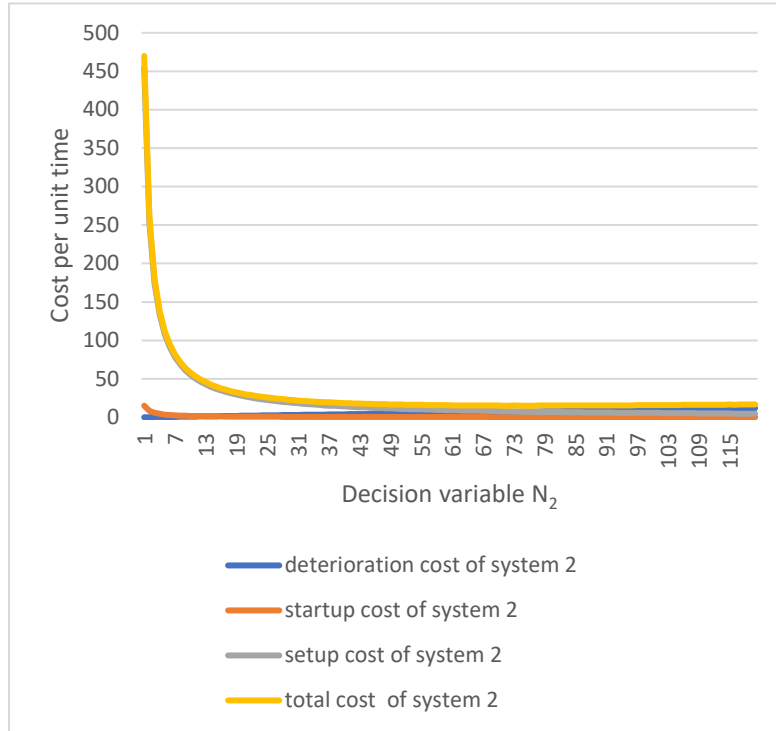
Figure 11: Remanufacturing cost per unit time
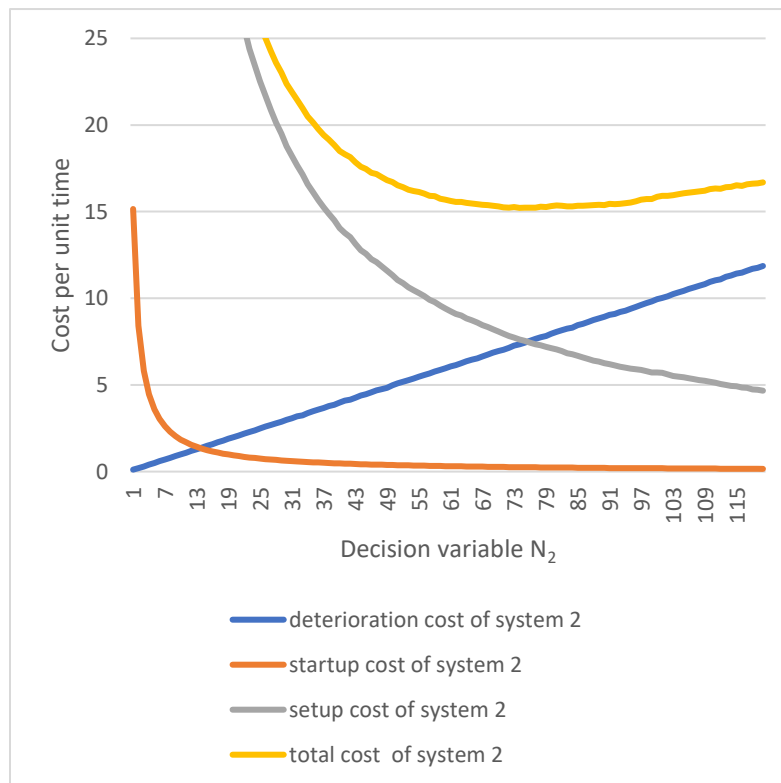
Figure 12: Magnification of remanufacturing cost per unit time

During the one-year simulation, the refurbishing and remanufacturing department processed 1199.12 and 2868.00 returned products separately. Besides, 714.68 return products were sent to recycling department. This is also illustrated in Table 13 below.

Table 7: Processed products of each department (Data is average of 25 replications)

	Refurbishing	Remanufacturing	Recycling
Processed products	1199.12	2868.00	714.68

Table 8: Summary of simulation results (Data is average of 25 replications)

	Refurbishing	Remanufacturing	Unit
Optimal decision variable N	57	74	count
Avg. number of runs	18.92	29.12	count
Avg. length of run	203.15	131.95	hour
Mean waiting time in queue	89.82	48.78	hour
Turn-off time	3444.67	2878.13	hour
Percentage of turn-off	89.70%	74.95%	
Breakdown time	5.49	15.38	hour
Start-up time	6.51	10.5	hour

The optimal values of decision variables are obtained from simulation results by minimizing the cost function. The refurbishing department and remanufacturing department require optimal value 57 and 74, respectively. With the optimal decision variables, the average number of refurbishing and remanufacturing runs during one-year simulation time are 18.92 and 29.12, respectively. These numbers are also equal to the number of turn-off periods in the one-year simulation, which is obtained by counting the number of times the systems become empty. The average length of each run is calculated

by dividing simulation time 3840 hours by the average number of runs. The mean waiting time in queue is achieved by using entity attributes to first record the clock time when return products enter and exit the queues. After that, the waiting time in queue for each product of the refurbishing department and remanufacturing department are known, so they must then be divided by the number of products exiting corresponding queue. This means that any returned products need to wait in the queue for 89.82 hours to be refurbished and 48.78 hours to be remanufactured. The percentages of turn-off time are 89.70% and 74.95% for refurbishing and remanufacturing separately, which are the turn-off time to be divided by simulation time. During the turn-off time, the departments can switch to manufacturing new products. This situation is caused by the low traffic intensity, which usually happened in the remanufacturing area. Due to the distribution of qualities, the remanufacturing department will process more returned products. Thus, the breakdown time of the remanufacturing department is higher than that of the refurbishing department. Besides, the higher average number of runs, the more start-up time presents.

At the optimal value of decision variables (N_1 =57, N_2=74), we derive the data of the number of returned products processed per each refurbishing run and remanufacturing run during the total 25 replications of simulation (Appendix 1). Because the number of products processed in each run includes the value of decision variable and the number of returned products that arrive during the start-up period and busy cycle, the theoretical

minimum values are the values of decision variable. During the 25 replications, there are

546 observations of the number of returned products processed per refurbishing run in the

range from 57 to 73 and 839 observations of the number of returned products processed

per remanufacturing runs in the range from 81 to 124. In the first entry of Figure 13, for

example, this means that there are four refurbishing runs that only processed 57 returned

products.
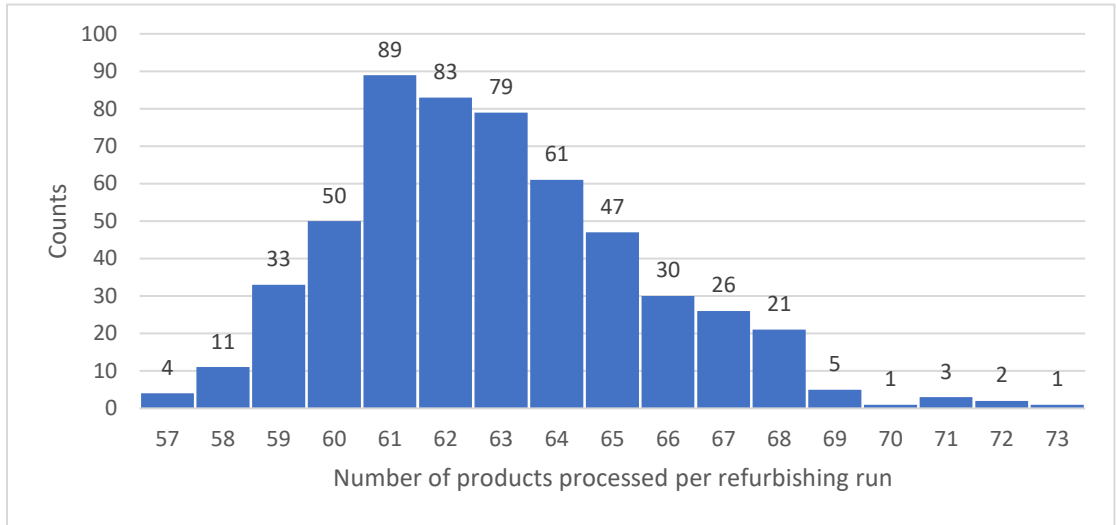
Figure 13: Distribution of products processed per refurbishing run
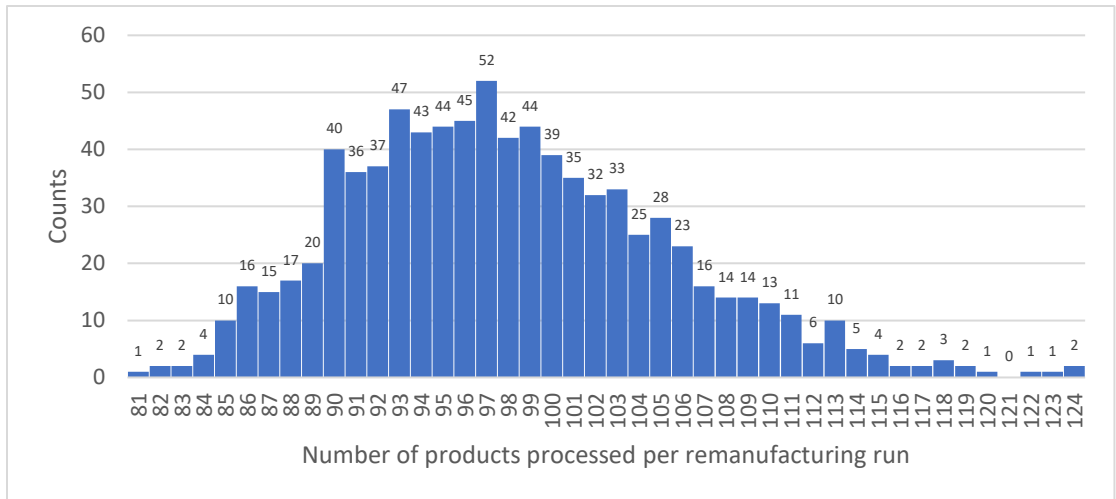
Figure 14: Distribution of products processed per remanufacturing run

Chapter 6: Sensitivity analysis

Some numerical examples are presented in this chapter to demonstrate parameters that affect the optimal decision variable based on minimizing the cost function. Since the refurbishing department and remanufacturing department are modelled in the same model, the example of the refurbishing department is used in this analysis. The units that used to sensitivity analysis are "dollar" for the cost unit and "hour" for the time unit.

Recall the problem: the company will not start the refurbishing process until at least a number of decision variable N_1 returned products appear in queue 1 during the turn-off period. The company may utilize this turn-off period to produce new products. After accumulating N_1 products in queue 1, the server requires a start-up period to prepare the work for refurbishing.

- The arrival of returned products follows the Poisson arrival rate λ_1.

- The service time of returned products follows an exponential distribution with mean $E[S_1] = 1/\mu_1$.

- The start-up time is an exponential distribution with mean $E[U_1]$.

- The server may breakdown with a Poisson breakdown rate α, and require an exponential distribution time with mean $E[D_1]$ to be repaired.

- The current value of finished product at time zero, is r.

Case 1: Fixing the following cost parameters Cs = $1000, θ=0.0002 per hour, Csp = $100, r =$1000 and system parameters λ_1=0.3 per hour, α=0.05 per hour, $E[D_1]$=1/3 hours, $E[U_1]$=1/3 hours and changing in specific values μ_1. With a fixed arrival rate, the optimal value of N_1 and the cost function will increase rapidly and then keep a stable range when service rate increased. Results are presented in Table 9.

Table 9: The optimal N_1^* and minimum expected $F(N_1^*)$ with various μ_1

μ_1(per hour)	1	1.5	2	4	7	10
N_1^*	48	50	52	54	55	56
$F(N_1^*)$	$9.18	$9.78	$10.08	$10.54	$10.70	$10.77

Case 2: Fixing the following cost parameters Cs = $1000, θ=0.0002 per hour, Csp = $100, r =$1000 and system parameters μ_1=1 per hour, α=0.05 per hour, $E[D_1]$=1/3 hours, $E[U_1]$=1/3 hours and changing in specific values λ_1. When fixing the service rate, the optimal value of N_1 and cost function will first rise and then fall off by increasing the arrival rate. Results are presented in Table 10.

Table 10: The optimal N_1^* and minimum expected $F(N_1^*)$ with various λ_1

λ_1(per hour)	0.2	0.3	0.4	0.5	0.6	0.7	0.8
N_1^*	46	48	53	55	52	47	39
$F(N_1^*)$	$8.04	$9.18	$10.14	$10.15	$10.01	$9.49	$8.60

Case 3: Fixing the following cost parameters Cs = $1000 , θ=0.0002 per hour, Csp = $100 , r =$1000 and system parameters λ_1=0.3 per hour, μ_1=4 per hour, α=0.05 per hour, E[D$_1$] =1/3 hours and changing in specific values E[U$_1$]. The optimal decision variables wave around 55 to 56 when E[U$_1$] increased from 0.1 to 4 hours. The cost function slightly decreases by increasing E[U$_1$]. Results are presented in Table 11.

Table 11: The optimal N_1^* and minimum expected $F(N_1^*)$ with various E[U$_1$]

E[U$_1$] (hours)	0.1	0.2	0.5	1	1.25	4
N_1^*	55	56	56	55	56	55
$F(N_1^*)$	$10.41	$10.49	$10.62	$10.87	$10.99	$11.34

Case 4: Fixing the following system parameters λ_1=0.3 per hour, μ_1=4 per hour, E[D$_1$]=0.5 hours, E[U$_1$]=1/3 hours and cost parameters C$_s$ = $1000, θ=0.0002 per hour, C$_{sp}$ = $100, r =$1000 changing in specific values α. The optimal decision variables almost keep stable when α changed from 0.005 to 1 per hour, but the cost function will slowly decrease. Therefore, decision variables can be considered as insensitive to the breakdown rate and mean repair time. Results are presented in Table 12.

Table 12: The optimal N_1^* and minimum expected $F(N_1^*)$ with various α_1

α_1 (per hour)	0.005	0.01	0.05	0.1	0.5	1
N_1^*	55	56	56	55	55	55
$F(N_1^*)$	$10.57	$10.56	$10.52	$10.53	$10.46	$10.34

Case 5: Fixing the following system parameters $\lambda_1=0.3$ per hour, $\mu_1=4$ per hour, $\alpha=0.2$ per hour, $E[U_1]=1/3$ hours and cost parameters $C_s = \$1000$, $\theta=0.0002$ per hour, $C_{sp} = \$100$, r $=\$1000$ and changing in specific values $E[D_1]$. The optimal decision variables almost keep stable when $E[D_1]$ changed from 0.2 to 5 hours, but the cost function will slowly increase. Therefore, decision variables can be considered as insensitive to mean repair time. Results are presented in Table 13.

Table 13: The optimal N_1* and minimum expected $F(N_1*)$ with various $E[D_1]$

$E[D_1]$ (hours)	0.2	1/3	1	2	5
$N_1{}^*$	54	55	56	53	55
$F(N_1{}^*)$	$10.51	$10.51	$10.46	$10.41	$10.18

Case 6: Fixing the system parameters $\lambda_1=0.3$ per hour, $\mu_1=4$ per hour, $\alpha=0.05$ per hour, $E[D_1]=1/3$ hours, $E[U_1]=1/3$ hours and cost parameters $\theta = 0.0002$ per hour, r $=\$1000$, $C_{sp}=\$100$ and changing in specific values C_s. The optimal value of decision variables and cost function are sensitive to the setup cost C_s when increasing the setup cost from $300 to $1600. Results are presented in Table 14.

Table 14: The optimal N_1* and minimum expected $F(N_1*)$ with various C_s

C_s	$300	$500	$800	$1200	$1600
$N_1{}^*$	31	38	46	59	72
$F(N_1{}^*)$	$5.97	$7.56	$9.48	$11.51	$13.33

Case 7: Fixing the system parameters λ_1=0.3 per hour, μ_1=4 per hour, α=0.05 per hour, $E[D_1]$=1/3 hours, $E[U_1]$=1/3 hours and cost parameters θ = 0.0002 per hour, r =$1000, C_s =$1500 and changing in specific values C_{sp}. The decision variable is insensitive to start-up cost when changing it from $25 to $500. Results are presented in Table 15.

Table 15: The optimal N_1^* and minimum expected $F(N_1^*)$ with various C_{sp}

C_{sp}	$25	$50	$100	$200	$500
N_1^*	59	58	58	58	59
$F(N_1^*)$	$12.72	$12.78	$12.92	$13.06	$13.45

Case 8: Fixing the system parameters λ_1=0.3 per hour, μ_1=4 per hour, α=0.05 per hour, $E[D_1]$=1/3 hours, $E[U_1]$=1/3 hours and cost parameters C_{sp} = $100, Cs =$1000, r=$2000 and changing in specific values θ. The optimal decision variable will decrease by increasing the deterioration rate θ. However, the cost function will increase while the optimal decision variable decreases. Results are presented in Table 16.

Table 16:   The optimal N_1^* and minimum expected $F(N_1^*)$ with various θ

θ (per hour)	0.00005	0.0001	0.0002	0.0005	0.001
N_1^*	77	59	36	25	17
$F(N_1^*)$	$7.46	$10.57	$14.92	$23.43	$32.80

Case 9: Fixing the system parameters λ_1=0.3 per hour, μ_1=4 per hour, α=0.05 per hour, $E[D_1]$=1/3 hours, $E[U_1]$=1/3 hours and cost parameters C_{sp} = $100, Cs =$1000, θ=0.0003 per hour and changing in specific values r. The optimal value N_1 will obviously

decrease while the cost function of refurbishing will rise by increasing the parameter r.

Results are presented in Table 17.

Table 17: The optimal N_1^* and minimum expected $F(N_1^*)$ with various r

r	$200	$500	$1000	$2000	$3000
N_1^*	89	68	42	29	26
$F(N_1^*)$	$5.74	$9.21	$12.88	$18.25	$22.24

Special Case: Fixing the system parameters λ_1=0.3125 per hour, μ_1=3.5 per hour, α=0.05 per hour, $E[D_1]$=1/3 hours, $E[U_1]$=1/3 hours and cost parameters C_{sp} = $100, Cs =$1000, θ=0.0002 per hour, r= $1000. After that, comparing results at N_1=57 and N_1=30, which 57 is the optimal value of N_1 and 30 is the approximate half value of optimal N_1. The results are illustrated in Table 24 below. If the company choose the decision variable N_1 as 30 to instead of the optimal value 57, the average selling price per product can be higher because the mean time spent in the system per product reduced from 90.01 hour to 46.60 hour. However, the setup cost per product will significant increase from $15.78 to $30.21. In addition, the expected cost per hour will increase from $10.72 to $12.71. Results are presented in Table 18.

Table 18: Comparison when choosing N_1 as 30 and 57

N_1	30	57
Avg. selling price per product	$990.72	$982.16

Mean time spent in system per product	46.60 hr	90.01 hr
Setup cost per product	$30.21	$15.78
$F(N_1)$ (cost per hour)	$12.71	$10.72

To summarize the sensitivity analysis, the optimal values of decision variables are highly dependent on the arrival rate and service rate, setup cost, deterioration rate, and current value of finished product at time zero. The breakdown rate, mean repair time, mean start-up time, and start-up cost have limited influence on the optimal decision variables.

Chapter 7: Conclusion and recommendations for future research

The existing literature does not combine the N-policy, the deterioration of time value, and the remanufacturing environment. This thesis contributes to this gap by applying the analytical method and discrete event simulation method to solve the remanufacturing problem of a M/G/1 queueing system under N-policy with server breakdowns and start-up times when considering exponential deterioration time value of returned products. The expressions of time spent in system and cost per unit time are derived from the analytical method. After that, the simulation model is built to find out the optimal value of decision variables N_i to minimize the objective function about the expected cost per unit time. The delay time is an important factor to remanufacture returned products with short life-cycle because the value of returned products deteriorates during the delay. The hybrid remanufacturing companies need to wait several weeks to months to collect enough returned products to start a remanufacturing process. By using N-policy, the companies can control the waiting time. However, the waiting time cannot be simply minimized because the smaller N_i can cause the frequent switching between manufacturing and remanufacturing that will significantly increase the start-up and setup cost. Thus, finding the optimal value of N_i can achieve the balance between the deterioration cost and switching cost, such as setup cost and start-up cost. Moreover, this research also presents how the system parameters and cost parameters affect the optimal value of N_i.

In conclusion, this thesis will help managers to control the delay time in order to maximize company profits by choosing a suitable value of N_i. Moreover, this study will be especially useful to hybrid remanufacturing companies because they can perform the manufacturing of new products during the turn-off time. Therefore, the hybrid remanufacturing companies can manage the balance time of manufacturing and remanufacturing to achieve higher profits. In future study, there are two points can be extended. The refurbishing and remanufacturing department may share some stations, so the relationship of both departments can be focused. Besides, the priority service discipline could be considered for different qualities.

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Appendices

Appendix A: Number of return products processed per run

Table 19: Number of processed products per refurbishing run

N1= 57	Mean=62.855		Standard deviation =2.6981		Max =73		Min =57	Total Observations= 546					Number of returned products processed per refurbishing run											
Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Rep 9	Rep 10	Rep 11	Rep 12	Rep 13	Rep 14	Rep 15	Rep 16	Rep 17	Rep 18	Rep 19	Rep 20	Rep 21	Rep 22	Rep 23	Rep 24	Rep 25
65	63	67	64	65	60	61	63	68	62	68	63	61	59	65	65	64	66	59	61	63	63	66	65	59
72	63	60	62	63	61	66	67	64	61	60	62	63	63	62	65	60	68	67	59	61	61	63	67	67
66	61	62	66	63	59	64	59	65	61	63	64	65	64	61	57	63	68	61	64	62	60	63	64	66
60	59	60	66	68	61	65	65	60	64	65	61	59	65	62	59	63	64	65	61	64	64	61	63	69
62	65	63	59	63	63	61	59	64	58	63	63	69	67	62	67	66	68	64	67	60	64	61	65	62
71	61	65	61	67	62	67	62	64	60	64	63	65	65	58	68	62	64	60	60	61	59	63	65	62
63	63	66	61	61	62	64	63	68	64	64	59	66	60	61	62	60	60	67	63	65	61	64	65	62
64	61	65	63	61	59	61	62	64	59	71	63	60	63	59	62	67	63	68	61	65	63	64	66	65
62	62	64	60	62	66	57	60	62	63	61	60	61	65	63	67	64	60	66	63	60	61	63	61	60
66	65	64	63	60	62	64	63	68	61	64	59	68	60	61	66	62	62	59	61	62	59	63	63	63
62	61	59	61	61	61	59	61	61	63	57	61	67	62	64	62	60	59	63	64	61	63	58	64	63
66	62	61	65	63	67	60	61	59	60	64	59	69	61	66	62	64	65	62	62	68	65	61	62	63
59	64	63	65	66	64	61	63	63	68	67	62	58	62	62	64	58	58	61	59	66	64	60	65	61
65	66	63	65	68	60	60	68	62	65	65	60	66	61	65	60	61	64	62	62	61	68	64	63	66
67	62	62	66	63	63	62	65	63	60	60	61	68	67	64	65	64	61	63	61	64	61	66	67	62
61	61	61	62	65	58	63	61	61	63	61	64	59	66	68	63	62	67	62	60	64	62	63	62	63
63	63	63	65	68	61	59	64	58	62	70	61	64	66	64	62	62	64	65	59	64	61	65	60	64
62	61	62	71	62	64	63	62	62	58	67	61	61	62	63	59	59	57	60	67	63	60	62	65	62
61	62	61	66	72	65	58	59	61	63	60	60	62	61	62	67	61	64	61	65	60	64	62	66	60
60	68	62	62	60	63	69	62	60	67	61	68	61	65	63	61	66	69	62	60	63	61	62	62	64
60	62	61	61	62	65	73	62	61	67			63	63	58	64	61	62		63			66	61	65
63		59		62																				

Table 20: Number of processed products per remanufacturing run

| N2 = 74 | Mean=98.025 | | Standard deviation =7.3587 | | Max =124 | | Number of returned products processed per remanufacturing run | | | | | | | | | | | | | | | | | |
| Min =81 | Total Observations= 839 | | | | | | | | | | | | | | | | | | | | | | | |

Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Rep 9	Rep 10	Rep 11	Rep 12	Rep 13	Rep 14	Rep 15	Rep 16	Rep 17	Rep 18	Rep 19	Rep 20	Rep 21	Rep 22	Rep 23	Rep 24	Rep 25
104	89	110	101	91	87	92	92	99	91	91	92	102	101	95	94	106	100	97	97	94	96	94	98	90
102	100	92	99	94	90	106	94	96	93	86	100	96	98	97	87	97	111	86	88	101	102	106	101	93
107	104	93	110	115	99	100	111	95	109	99	102	90	88	97	86	97	110	100	99	90	101	88	105	95
101	101	101	113	101	98	113	88	113	106	87	115	102	83	115	101	96	114	104	90	97	92	99	95	93
91	95	101	97	100	88	103	99	101	108	108	92	92	90	99	105	94	113	96	90	114	101	93	98	103
106	89	97	105	97	94	107	99	86	100	86	107	105	81	101	100	89	104	99	104	104	104	103	93	102
103	105	109	103	94	95	90	95	111	91	98	101	94	100	94	102	105	85	82	97	100	88	103	95	100
87	90	90	93	103	97	108	97	110	104	96	101	100	93	86	109	99	102	123	106	99	96	82	98	109
104	95	96	100	97	95	93	97	95	106	84	95	85	112	104	94	93	88	98	88	89	104	98	96	86
92	105	103	101	106	93	110	104	85	91	103	97	96	101	96	85	86	107	107	95	93	99	90	103	104
108	113	96	85	95	100	90	99	103	107	112	98	91	101	103	92	92	99	108	93	96	85	96	98	98
98	94	103	94	102	100	94	106	100	97	106	94	101	99	122	92	90	93	105	105	85	90	110	105	91
96	107	99	108	96	124	105	95	88	90	97	85	112	105	93	89	94	90	105	86	97	91	94	120	86
106	91	103	91	93	95	106	111	88	98	93	105	102	91	92	95	99	97	99	105	96	107	86	91	100
93	89	100	102	90	94	88	103	90	103	95	89	91	116	102	97	94	97	93	93	87	109	98	110	97
103	101	98	103	85	94	90	93	103	96	95	91	90	118	97	88	83	93	95	93	87	94	100	103	90
89	95	101	97	91	95	92	94	100	97	95	107	91	101	104	109	104	89	96	98	89	89	105	95	101
108	108	99	109	97	94	111	110	95	101	100	91	107	97	107	110	98	92	102	88	95	94	93	96	87
103	93	95	91	99	94	119	103	93	105	102	96	95	89	103	97	99	99	93	96	108	96	90	105	92
103	102	94	111	101	94	92	106	87	93	118	92	104	115	98	104	102	107	104	98	96	108	102	92	117
96	101	111	90	103	93	109	96	104	98	106	93	97	106	104	96	99	100	84	96	100	93	98	89	108
101	108	92	92	101	98	95	94	95	94	104	97	96	96	92	110	94	90	102	92	91	96	95	95	92
106	88	106	91	102	93	94	95	100	94	101	117	97	91	111	105	102	96	91	95	90	96	100	99	96
97	106	108	93	102	100	103	92	90	91	105	90	94	97	91	99	98	100	105	90	102	110	99	97	107
98	98	91	109	93	95	94	94	86	100	102	110	94	104	100	90	90	109	99	103	102	93	99	99	89
93	94	103	96	95	91	93	90	98	104	101	94	96	106	106	98	113	92	87	114	108	99	87	100	100
84	95	105	107	90	97	88	91	93	98	94	98	95	102	86	92	96	105	90	98	89	97	97	86	90
96	93	94	92	92	91	100	97	89	92	97	113	91	93	101	105	102	91	96	87	100	95	98	87	113
109	89	97	97	97	87	86	101	101	109	89	97	94	98	93	84	103	102	112	90	114	103	103	106	104
88	98	92	116	119	105	88	107	99	98	98	91	106	90	97	99	90	96	86	100	100	98	100	99	93
101	113	87	100	91	89	99	92	112	99	118	97	98	97	95	94	94	93	93	92	102	99	93	112	106
93	96	97	85	98	92	105	92	96	103	96	87	87	97	102	124	99	99	91	97	90	100	110	96	100
92	103	92	93	101	91	93	111	99	107	94	98	105	111	109	91	89	98	102	114	97	98	95		95
					90			103	95		105	102	97		96	113	92	111	104			95	96	98

Appendix B: Calculation of replication number

The more replications of the simulation, the smaller variance of result will be obtained. Choosing a suitable replication number not only can improve the precision of results but also reduce the time consumed by the simulation. The value of expected cost function of refurbishing is used as the criterion to calculate the replication number.

First, the simulation model is run with 20 replications to generate data that will be used to calculate the suitable replication number for simulation in the same parameters of the case study by choosing $N_1 = 50$.

Then, the true mean is 10.7893 and the standard deviation is 0.1619. To ensure that the half-width 95% confidence interval results of cost function for refurbishing are no more than 0.075, the acceptable amount of error is 0.03 and the significance level α is 0.05.

$$m = \left[\frac{t_{n-1,\alpha/2} S(n)}{e} \right]$$

Where

m   = Number of replications

S(n) = Estimate of standard deviation based on sample standard deviation

e =Error amount

α = Significance level

$$m = \left[\frac{t_{20-1,\alpha/2} S(n)}{e} \right]^2 = \left[\frac{2.093 * 0.1619}{0.075} \right]^2 = 20.4131$$

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