7-26-2018

Performance improvement of remanufacturing systems operating under N-policy

Fengtian Gu

University of Windsor

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Performance improvement of remanufacturing systems operating under

N-policy

By

Fengtian Gu

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive & Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2018

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Performance improvement of remanufacturing systems operating under N-policy

by

Fengtian Gu

APPROVED BY:

__________________________
M. Hlynka
Department of Mathematics & Statistics

__________________________
A. Fartaj
Department of Mechanical, Automotive & Materials Engineering

__________________________
W. Abdul-Kader, Advisor
Department of Mechanical, Automotive & Materials Engineering

July 26, 2018
DECLARATION OF ORIGINALITY

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

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I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.
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

This master study has enriched my knowledge in the field of Industrial Engineering and more specifically the field of reverse logistics. It has given me the great opportunity to expand my horizon and related background.

I am deeply grateful and truly thankful to my supervisor Dr. Walid Abdul-Kader for his care, encouragement, and patience. Dr. Abdul-Kader has excellent knowledge that has guided me throughout this work.

I would like to express my gratitude to the committee members Dr. Myron Hlynka and Dr. Amir Fartaj for their constructive criticisms and willingness to positively enrich this report.

My earnest gratitude to my respected parents for their unconditional love and endless care. My purest form of love to my beautiful wife for her understanding, support, devotion, and patience.
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Chapter 1: Introduction

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.
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.
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, 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 $n_{\text{opt}}$
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/1 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

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Objective</th>
<th>Method</th>
<th>Uncertain Quality</th>
<th>Control Policy</th>
<th>Deterioration Value</th>
<th>Remanufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voutsinas &amp; Pappis, 2002-2010</td>
<td>Find the optimal processing sequence for components of one type product</td>
<td>Mathematical (Scheduling model with heuristic &amp; branch and bound algorithm)</td>
<td>NO</td>
<td>NO</td>
<td>Exponential Deterioration</td>
<td>YES</td>
</tr>
<tr>
<td>Souza, Ketzenberg, &amp; Guide, 2002</td>
<td>Find the optimal mixed product grade to achieve a certain service level</td>
<td>Analytical queueing &amp; Simulation</td>
<td>Multi-level</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Guide, Souza, Van Wassenhove &amp; Blackburn, 2004-2006</td>
<td>Comparing the centralized and decentralized model</td>
<td>Analytical &amp; ARENA model for validation (Closed-Loop Supply Chain Model)</td>
<td>Two Levels (New and remanufactured)</td>
<td>NO</td>
<td>Exponential Deterioration</td>
<td>YES</td>
</tr>
<tr>
<td>Guide, Gunes, Souza, &amp; van Wassenhove, 2008</td>
<td>Find the threshold value of processing time</td>
<td>Mathematical (Closed-Loop Supply Chain Model)</td>
<td>Multi-level</td>
<td>NO</td>
<td>Exponential Deterioration</td>
<td>YES</td>
</tr>
<tr>
<td>Karamouzian, Teimoury, &amp; Modarres, 2011</td>
<td>Find the proportion of each class should be processed to maximize the total revenue</td>
<td>Analytical queueing model (mixed integer nonlinear programming)</td>
<td>Multi-level</td>
<td>NO</td>
<td>Exponential Deterioration</td>
<td>YES</td>
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<tr>
<td>Author</td>
<td>Year</td>
<td>Objective</td>
<td>Method</td>
<td>Uncertain Quality</td>
<td>Control Policy</td>
<td>Deterioration Value</td>
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<tr>
<td>Ferguson, Fleischmann, &amp; Souza</td>
<td>2011</td>
<td>Find the optimal quantities of return to be remanufactured</td>
<td>Mathematical (Closed-Loop Supply Chain Model)</td>
<td>Two Levels</td>
<td>NO</td>
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<tr>
<td>Fathi, Zandi, &amp; Jouini</td>
<td>2015</td>
<td>Find the threshold value of processing time</td>
<td>Analytical queueing model (Merged and separated)</td>
<td>Two Levels</td>
<td>NO</td>
<td>Exponential Deterioration</td>
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<tr>
<td>Pazoki &amp; Abdul-Kader</td>
<td>2016</td>
<td>Find the optimal decision variables for achieve maximum profit</td>
<td>Analytical queueing &amp; Simulation</td>
<td>Multi-level</td>
<td>NO</td>
<td>Exponential Deterioration</td>
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<tr>
<td>Savaliya</td>
<td>2017</td>
<td>Performance evaluation of remanufacturing systems</td>
<td>Simulation (ProModel &amp; ANOVA)</td>
<td>Multi-level</td>
<td>NO</td>
<td>NO</td>
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<tr>
<td>Pandian &amp; Abdul-Kader</td>
<td>2017</td>
<td>Performance evaluation of reverse logistics enterprise</td>
<td>Agent-based Simulation</td>
<td>Multi-level</td>
<td>NO</td>
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Table 2: Summary of literature review about N-policy

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Objective</th>
<th>Method</th>
<th>Uncertain Quality</th>
<th>Control Policy</th>
<th>Deterioration Value</th>
<th>Remanufacturing</th>
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<tbody>
<tr>
<td>Yadin &amp; Naor</td>
<td>1963</td>
<td>Find the optimal procedure to eliminate idle time</td>
<td>Inventory model</td>
<td>NO</td>
<td>N-policy</td>
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<td>Heyman</td>
<td>1968</td>
<td>Find the optimal policies to minimize the total operating cost</td>
<td>Inventory model</td>
<td>NO</td>
<td>N-policy</td>
<td>NO</td>
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<td>Sobel</td>
<td>1969</td>
<td>Examining the stationary policy</td>
<td>Inventory model</td>
<td>NO</td>
<td>(M,m)-policy</td>
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<td>Balachandran</td>
<td>1973</td>
<td>Create D-policy and compare it with N-policy</td>
<td>Inventory model</td>
<td>NO</td>
<td>N-policy</td>
<td>D-policy</td>
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<tr>
<td>Heyman</td>
<td>1977</td>
<td>Find the minimum cost rate under T-policy and compare with N-policy</td>
<td>Inventory model</td>
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<td>T-policy</td>
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<td>Lee et al.</td>
<td>1995</td>
<td>Performance Measures</td>
<td>Mathematical method</td>
<td>NO</td>
<td>N-policy</td>
<td>Server vacation</td>
<td>NO</td>
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<td>Alfa &amp; Frigui</td>
<td>1996</td>
<td>Performance Measures</td>
<td>Mathematical method</td>
<td>NO</td>
<td>(N,T)-policy</td>
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Table 2: Summary of literature review about N-policy, cont’d

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<th>Author</th>
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<th>Objective</th>
<th>Method</th>
<th>Uncertain Quality</th>
<th>Control Policy</th>
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<tr>
<td>Alfa &amp; Li</td>
<td>2000</td>
<td>Find the optimal policies to minimize long-run average cost per unit time</td>
<td>Mathematical method</td>
<td>NO</td>
<td>(N,T)-policy</td>
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<td>Ke</td>
<td>2006</td>
<td>Find the optimal N and T to minimize the total cost</td>
<td>Mathematical method, Numerical method</td>
<td>NO</td>
<td>(N,T)-policy</td>
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<td>Lee &amp; Seo</td>
<td>2008</td>
<td>Performance Measures</td>
<td>Mathematical method, Numerical method</td>
<td>NO</td>
<td>Min(N, D)-policy</td>
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<td>Parthasarathy &amp; Sudhesh</td>
<td>2008</td>
<td>Find the transient solution of a multi-server Poisson queue with N-policy</td>
<td>Mathematical method, Numerical method</td>
<td>NO</td>
<td>N-policy</td>
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<td>Feyaerts et al.</td>
<td>2014</td>
<td>Performance Measures</td>
<td>Mathematical method, Numerical method</td>
<td>NO</td>
<td>(N,T)-policy</td>
<td>NO</td>
<td>NO</td>
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<td>Shaojun &amp; Yinghui</td>
<td>2017</td>
<td>Optimization of system capacity</td>
<td>Numerical Method based on MATLAB</td>
<td>NO</td>
<td>Min(N, D)-policy</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Fengtian Gu (This thesis)</td>
<td>2018</td>
<td>Find optimal value of decision variables</td>
<td>Mathematical method, Simulation method</td>
<td>YES</td>
<td>N-policy</td>
<td>YES</td>
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</table>
Chapter 3: Problem statement

3.1 Problem definition and assumption

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 $\lambda$. 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.
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 $\rho$ 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 $\theta$. The deterioration function is $re^{-\theta t}$, where $t$ is the delay time, $r$ represents the selling price at time zero and $\theta$ 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](image)

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, \( i=1,2,3 \).

\[ \lambda \]  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

\[ \alpha_i \]  Breakdown rate for server

\[ E[D_i] \]  Mean repair time
Cost parameters

\( \theta \)  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

\( \rho_i \)  Traffic intensity of original M/G/1 system, equals to \( \lambda_i / \mu_i \)

\( \rho_H \)  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

\( E[R_{Hi}] \)  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).

\[ E[W_{qi}] = E[L_{qi}] \times E[S_i] + \rho_i \times E[R_{S_i}] \]
\[ + \ P \ (\text{Returns arrive in turn-off period}) \times E[U_i] \]
\[ + \ P \ (\text{Returns arrive in start-up period}) \times E[R_{U_i}] \]  

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.

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

(2)
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 $\sigma^2_{S_i}$ 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).

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

(4)

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,

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

(5)
\[ P(\text{Returns arrive in start-up period}) = (1 - \rho_i) \times \left( \frac{E[U_i]}{N_i/\lambda_i + E[U_i]} \right) \]  \hspace{1cm} (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.

\[
E[W_{qi}] = E[L_{qi}] \times E[H_i] + \rho_{H_i} \times E[R_{H_i}]
 + \sum_{m=1}^{N} P(\text{Arriving return is number } m) \times \left( \frac{N_i-m}{\lambda_i} + E[U_i] \right)
 + P(\text{Returns arrive in start-up period}) \times E[R_{U_1}] \]
\hspace{1cm} (7)

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

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

\[
E[D_i^2] = \sigma_{D_i}^2 + E[D_i]^2 \]
\hspace{1cm} (8a)

\[
E[H_i^2] = E[S_i^2] \times (1 + \alpha_i \times E[D_i])^2 + \alpha_i \times E[S_i] \times E[D_i^2] \]
\hspace{1cm} (9)

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

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

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

\[
E[W_{qi}] = \frac{\lambda_i \times (E[S_i^2] \times (1 + \alpha_i \times E[D_i])^2 + \alpha_i \times E[S_i] \times E[D_i^2])}{2(1 - \lambda_i \times E[S_i] \times (1 + \alpha_i \times E[D_i]))} \\
+ \frac{1}{N_i + \lambda_i \times E[U_i]} \times \left(\frac{N_i \times (N_i - 1)}{2 \times \lambda_i} + N_i \times E[U_i] + \frac{\lambda_i \times E[U_i^2]}{2}\right)
\]

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 \(E[W_{qi}]\).

\[
E[T_i] = E[S_i] + E[W_{qi}]
\]

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 \(\lambda_i\).

\[
E[I_i] = \frac{N_i}{\lambda_i}
\]

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

(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).

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

(17)

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

(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).

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

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

(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.

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

(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]}) \quad (21)

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

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

(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):

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

(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

\[ = \text{Decision Variable } N_i + \lambda_i \times (1 \text{ busy period} + 1 \text{ Start-up period}) \]

**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,
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 N1 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

<table>
<thead>
<tr>
<th>$N_1$</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>F($N_1$) (Analytical results)</td>
<td>29.9883</td>
<td>16.5295</td>
<td>12.6704</td>
<td>11.2275</td>
<td>10.7522</td>
</tr>
<tr>
<td>F($N_1$) (Simulation results)</td>
<td>29.8972</td>
<td>16.5207</td>
<td>12.7073</td>
<td>11.2455</td>
<td>10.8156</td>
</tr>
<tr>
<td>Difference(%)</td>
<td>0.0030</td>
<td>0.0005</td>
<td>0.0029</td>
<td>0.0016</td>
<td>0.0059</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$N_1$</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>F($N_1$) (Analytical results)</td>
<td>10.7600</td>
<td>11.0428</td>
<td>11.4964</td>
<td>12.0630</td>
<td>12.7077</td>
</tr>
<tr>
<td>F($N_1$) (Simulation results)</td>
<td>10.7268</td>
<td>11.0409</td>
<td>11.5526</td>
<td>11.9839</td>
<td>12.7358</td>
</tr>
<tr>
<td>Difference(%)</td>
<td>0.0031</td>
<td>0.0002</td>
<td>0.0049</td>
<td>0.0066</td>
<td>0.0022</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>1.25 per hour</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>3.5 per hour</td>
</tr>
<tr>
<td>$\mu_2$</td>
<td>3.125 per hour</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.05 per hour</td>
</tr>
<tr>
<td>$E[D]$</td>
<td>1/3 hour</td>
</tr>
<tr>
<td>$E[U]$</td>
<td>1/3 hour</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_s$</td>
<td>1000 dollars</td>
</tr>
<tr>
<td>$C_{sp}$</td>
<td>100 dollars</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0.0002 per hour</td>
</tr>
<tr>
<td>$r$</td>
<td>1000 dollars</td>
</tr>
</tbody>
</table>
5.1.3 Probabilities of returned product quality.

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

<table>
<thead>
<tr>
<th>Probability</th>
<th>Good</th>
<th>Moderate</th>
<th>Bad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
<td>0.6</td>
<td>0.15</td>
</tr>
</tbody>
</table>

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.
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.
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)

<table>
<thead>
<tr>
<th>Processed products</th>
<th>Refurbishing</th>
<th>Remanufacturing</th>
<th>Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1199.12</td>
<td>2868.00</td>
<td>714.68</td>
</tr>
</tbody>
</table>

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

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

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 $\lambda_1$.

- 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 $\alpha$, and require an exponential distribution time with mean $E[D_1]$ to be repaired.

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


55
**Case 1:** Fixing the following cost parameters $C_s = $1000, $\theta = 0.0002$ per hour, $C_{sp} = $100, $r = $1000 and system parameters $\lambda_1 = 0.3$ per hour, $\alpha = 0.05$ per hour, $E[D_1] = 1/3$ hours, $E[U_1] = 1/3$ hours and changing in specific values $\mu_1$. 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>
<thead>
<tr>
<th>$\mu_1$(per hour)</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>4</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>48</td>
<td>50</td>
<td>52</td>
<td>54</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$9.18$</td>
<td>$9.78$</td>
<td>$10.08$</td>
<td>$10.54$</td>
<td>$10.70$</td>
<td>$10.77$</td>
</tr>
</tbody>
</table>

**Case 2:** Fixing the following cost parameters $C_s = $1000, $\theta = 0.0002$ per hour, $C_{sp} = $100, $r = $1000 and system parameters $\mu_1 = 1$ per hour, $\alpha = 0.05$ per hour, $E[D_1] = 1/3$ hours, $E[U_1] = 1/3$ hours and changing in specific values $\lambda_1$. 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>
<thead>
<tr>
<th>$\lambda_1$(per hour)</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>46</td>
<td>48</td>
<td>53</td>
<td>55</td>
<td>52</td>
<td>47</td>
<td>39</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$8.04$</td>
<td>$9.18$</td>
<td>$10.14$</td>
<td>$10.15$</td>
<td>$10.01$</td>
<td>$9.49$</td>
<td>$8.60$</td>
</tr>
</tbody>
</table>
Case 3: Fixing the following cost parameters $C_s = $1000, $\theta=0.0002$ per hour, $C_{sp} =$ $100$, $r =$ $1000$ and system parameters $\lambda_1=0.3$ per hour, $\mu_1=4$ per hour, $\alpha=0.05$ 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>
<thead>
<tr>
<th>$E[U_1]$ (hours)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.5</th>
<th>1</th>
<th>1.25</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>55</td>
<td>56</td>
<td>56</td>
<td>55</td>
<td>56</td>
<td>55</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$10.41$</td>
<td>$10.49$</td>
<td>$10.62$</td>
<td>$10.87$</td>
<td>$10.99$</td>
<td>$11.34$</td>
</tr>
</tbody>
</table>

Case 4: Fixing the following system parameters $\lambda_1=0.3$ per hour, $\mu_1=4$ per hour, $E[D_1]=0.5$ hours, $E[U_1]=1/3$ hours and cost parameters $C_s = $1000, $\theta=0.0002$ per hour, $C_{sp} =$ $100$, $r =$ $1000$ changing in specific values $\alpha$. The optimal decision variables almost keep stable when $\alpha$ 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>
<thead>
<tr>
<th>$\alpha_1$ (per hour)</th>
<th>0.005</th>
<th>0.01</th>
<th>0.05</th>
<th>0.1</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>55</td>
<td>56</td>
<td>56</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$10.57$</td>
<td>$10.56$</td>
<td>$10.52$</td>
<td>$10.53$</td>
<td>$10.46$</td>
<td>$10.34$</td>
</tr>
</tbody>
</table>
**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>
<thead>
<tr>
<th>$E[D_1]$ (hours)</th>
<th>0.2</th>
<th>1/3</th>
<th>1</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>54</td>
<td>55</td>
<td>56</td>
<td>53</td>
<td>55</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$10.51$</td>
<td>$10.51$</td>
<td>$10.46$</td>
<td>$10.41$</td>
<td>$10.18$</td>
</tr>
</tbody>
</table>

**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>
<thead>
<tr>
<th>$C_s$</th>
<th>$$300$</th>
<th>$$500$</th>
<th>$$800$</th>
<th>$$1200$</th>
<th>$$1600$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>31</td>
<td>38</td>
<td>46</td>
<td>59</td>
<td>72</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$5.97$</td>
<td>$7.56$</td>
<td>$9.48$</td>
<td>$11.51$</td>
<td>$13.33$</td>
</tr>
</tbody>
</table>
**Case 7:** 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, $r=$ $1000$, $C_s =$ $1500$ 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 $C_{sp}$

<table>
<thead>
<tr>
<th>$C_{sp}$</th>
<th>$25$</th>
<th>$50$</th>
<th>$100$</th>
<th>$200$</th>
<th>$500$</th>
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</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>59</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$12.72$</td>
<td>$12.78$</td>
<td>$12.92$</td>
<td>$13.06$</td>
<td>$13.45$</td>
</tr>
</tbody>
</table>

**Case 8:** 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 $C_{sp} =$ $100$, $C_s =$ $1000$, $r=$ $2000$ and changing in specific values $\theta$. The optimal decision variable will decrease by increasing the deterioration rate $\theta$. 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 $\theta$

<table>
<thead>
<tr>
<th>$\theta$ (per hour)</th>
<th>0.00005</th>
<th>0.0001</th>
<th>0.0002</th>
<th>0.0005</th>
<th>0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>77</td>
<td>59</td>
<td>36</td>
<td>25</td>
<td>17</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$7.46$</td>
<td>$10.57$</td>
<td>$14.92$</td>
<td>$23.43$</td>
<td>$32.80$</td>
</tr>
</tbody>
</table>

**Case 9:** 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 $C_{sp} =$ $100$, $C_s =$ $1000$, $\theta=0.0003$ 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 $r$

<table>
<thead>
<tr>
<th>$r$</th>
<th>$$200$</th>
<th>$$500$</th>
<th>$$1000$</th>
<th>$$2000$</th>
<th>$$3000$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_1^*$</td>
<td>89</td>
<td>68</td>
<td>42</td>
<td>29</td>
<td>26</td>
</tr>
<tr>
<td>$F(N_1^*)$</td>
<td>$5.74$</td>
<td>$9.21$</td>
<td>$12.88$</td>
<td>$18.25$</td>
<td>$22.24$</td>
</tr>
</tbody>
</table>

**Special Case:** Fixing the system parameters $\lambda_1=0.3125$ per hour, $\mu_1=3.5$ per hour, $\alpha=0.05$ per hour, $E[D_1]=1/3$ hours, $E[U_1]=1/3$ hours and cost parameters $C_{sp} = \$100$, $C_s = \$1000$, $\theta=0.0002$ 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

<table>
<thead>
<tr>
<th>$N_1$</th>
<th>30</th>
<th>57</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. selling price per product</td>
<td>$990.72$</td>
<td>$982.16$</td>
</tr>
<tr>
<td></td>
<td>Mean time spent in system per product</td>
<td>46.60 hr</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Setup cost per product</td>
<td>$30.21</td>
<td>$15.78</td>
</tr>
<tr>
<td>F(N_1) (cost per hour)</td>
<td>$12.71</td>
<td>$10.72</td>
</tr>
</tbody>
</table>

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.
References


Table 19: Number of processed products per refurbishing run

<table>
<thead>
<tr>
<th>Number of returned products processed per refurbishing run</th>
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<tbody>
<tr>
<td>N=57</td>
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<tr>
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<tr>
<td>85</td>
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<tr>
<td>72</td>
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<tr>
<td>80</td>
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<tr>
<td>83</td>
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</tbody>
</table>
Table 20: Number of processed products per remanufacturing run

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<tbody>
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</tbody>
</table>

N2 = 74, Mean = 86.025, Standard deviation = 7.3567, Max = 124, Min = 81, Total Observations = 839
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 \( \alpha \) 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

\( \alpha \) = Significance level

\[
m = \left[ \frac{t_{20-1,0.05/2}0.1619}{0.075} \right] = 20.4131
\]
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---

Gowtham Ravi Sankara Pandian,
Master of Applied Science,
Mississauga, Ontario,
Canada
Ph: 519-980-2529
Vita auctoris

NAME: Fengtian Gu

PLACE OF BIRTH: Hengyang, Hunan, China

YEAR OF BIRTH: 1991

EDUCATION: NO. 8 High School of Hengyang, Hengyang, Hunan, China, 2009

University of South China, B.Sc., Hengyang, Hunan, China, 2013

University of Windsor, M. Eng., Windsor, ON, 2016

University of Windsor, M.A.Sc., Windsor, ON, 2018