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Remanufacturing Process Planning Considering Quality Uncertainties, Environmental Taxes and Incentives

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Abstract

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As environmental issues are gradually being valued by governments and societies, companies have begun to engage in economic sustainable practices such as remanufacturing, reuse and recycling, among other socially responsible practices. The broader impact of these practices enables companies to archive the goal of circular economies. Under normal circumstances, consumers' used products have often been released into landfills, resulting in environmental pollution. This is especially so for electronic products since most materials used in their production are non-biodegradable. This research addresses the practice of remanufacturing. The remanufacturing value of the products gradually declines with the usage–also referred to as the product resident time. So the remanufacturer must decide when to acquire these end of life products from customers, to carry out remanufacturing at maximum benefits. Companies face logistical challenges in the remanufacturing process, including uncertainties in the quality and quantity of returned products, and uncertainties in the process variables including process times and resource availability. In order to maximize expected profits, we provide a decision model for finding the optimal quality threshold to accept into the system and also show the variability in the profit percentages when products are returned at various stages in their life cycle. The model also considers a system that not only remanufactures products but also salvages components and uses them in the remanufacturing process. The model also allows for purchases of new components from suppliers as needed. The model also includes environmental factors such as emissions taxes and remanufacturing government incentives. The model is applied to a case study of a real control drive remanufacturing process, with two types of products that have interchangeable key components. The results confirm that the quality threshold is indeed of significance in the process. The demand forecast for remanufactured products in the secondary market is even more significant, driving the acceptable threshold quality to as low as 0.25 on a scale of 0 (worst quality) to 1 (best quality). Lastly, the results show that the resident time (time of return after the product was first sold in the first market) also significantly impacts the profit.

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Chapter 1

Introduction

1.1 Background

With rapid industrialization and population growth, the continuous development and abuse of land and energy have caused the global environment to be greatly affected. According to a research survey, since 1960, enterprises have released millions of tons of waste material every year, most of which have been disposed of through landfills or by incineration (U.S.EPA, 2017). The continuous pollution of land and air has also indirectly caused an increase in global climate anomalies including the greenhouse effect. It is for this reason, and continued monitoring of climatic changes due to exhaust emissions, the United Nations organizations initiated the establishment United Nations Framework Convention on Climate Change, which was an international environmental protection treaty that was adopted and open for member signatories in Rio de Janeiro in 1992. This treaty was later revised in the form of the Kyoto Protocol, which was adopted in 1997 in Kyoto Japan, and later enforced in 2005. The Kyoto Protocol's objective is to stabilize the atmospheric concentration of the six key emission pollutants by urging member companies to sign an agreement to a reduced emission goal by an agreed time frame (UNFCCC, 2008).

Besides gaseous emissions, the increasing production of electronic products (e-products) over time has necessitated directives to dictate the post-sales treatment of e-products and restrictions on their waste discharge. The European Union (EU) established the first of such directives, known as the Waste Electrical and Electronic Equipment (WEEE). Directive whose first edition was produced in 2002 (WEEE, 2002).The main content requires that motor, electronic product manufacturers and suppliers circulating products in the EU market should bear the responsibility of recycling. In addition to requiring that the recovery rate and the amount of recycling reach a certain standard, it also stipulates that recycling information of electronic products should be made public.

In order to reduce the burial of waste in landfills, in addition to enacting the relevant regulations with regards to disposal, the United States Environmental Protection Agency (EPA) advocated for the idea of source material reduction in 2003 (U.S.EPA, 2017). Esenduran et al. (2017) purposed that over the years, the number of relevant recycling regulations has increased. In addition to recommending the use of less toxic raw materials in the production process, the EPA also encourages the reuse of products especially by replacing failed or obsolete components or equipments in a system. This is the fundamental meaning of remanufacturing, which uses the steps of product returns inspection, cleaning, component replacement, reassembly and testing, restore the product function to the as new condition Butzer et al. (2016). Remanufactured products can reduce use of primary (or virgin) materials and thereby also reduce energy consumption. Manufacturers are therefore gradually paying attention to benefits of the remanufacturing process and how to accomplish it in their contexts.

Under normal circumstances, consumers' used products have often been released into landfills, resulting in wastage of resources, both material and energy as indicated earlier, but also resulting in environmental pollution, especially since most material used in the production of electronic assemblies are non-biodegradable. Under the current globalization, environmental issues affect the development of sustainable supply chains. The traditional forward supply chain refers to the production process from the first supplier, to the manufacturer, to the distributor, to the retailer and then finally delivered to the consumer so that the products are produced in the right number and delivered to the right place on time (Yadollahiniaa et al., 2018). As improvements of environmental protection have increased the renewed interests in closed-loop supply chains which require attention to products' end of life cycle after use by consumers. This has extended the traditional supply chain which focuses on the manufacture of new products to reverse the supply chains also referred to as Closed-Loop Supply Chains. Govindana and Soleimani (2017) also illustrates the relevant theories in the field of reverse logistics and closed-loop supply chain.

The outline of the closed-loop supply chain proposed by Crafoord et al. (2018), shows that manufacturers view used products on the consumer side as inputs to their processes through the process of remanufacturing, the output of which is the remanufactured products, thereby generating new value streams from used products (Guide, 2000). Whether manufacturers do the remanufacturing activity by themselves or involve a connected or independent remanufacturers, the main motivation for urging manufacturers to consider remanufacturing is the potential underlying profits and social-environmental responsibilities. When there is a value proposition in remanufacturing activities, manufacturers will naturally take the initiative to recycle/reuse used products in remanufacturing purposes. Vafadarnikjoo et al. (2018) states that on the customer side, the motivation for buying remanufactured products is the reduced price for remanufactured products with the same quality as new products. On the other hand, for the manufacturer's side, the used products returned from consumers differ in remanufacturing costs depending on their quality, and the lowest quality of products are not suitable for remanufacturing. For the above reasons, there is an inherent trade-off among the three attributes of remanufactured products, namely, used product acquisition price, quality, cost or remanufacture and selling price. It is important, therefore, to find the balance of these four factors so that manufacturers can get the maximum profit, and consumers can get satisfactory products.

Under the traditional linear economy strategy, once product ownership has been transferred to the consumer, so does the responsibility at the product's end-of-life. The recent establishment of extended producer responsibility places the onus of the product's end-of-life (EOL) status to the producer. For this reason, enterprises are being forced to rethink the entire product life cycle from the selection of front-end raw materials, to the manufacturing design and production process, mainly to ensure sustainability every step of the way. This has resulted in many enterprises adopting and even weaving the principles of active circular thinking into their processes and even mission. For instance, in the first step of the design, the circular mindset requires questions such as how sustainable and the materials in the Bill of Materials (BOM) as well as how sustainable are the design alternatives. When enterprises are committed to practicing circular economies with innovative practices, they not only reduce risks (social and environmental) but also reduce their dependence on raw materials, most of whose supply chains are being threatened by global resource constraints. Recycled products or services can also bring differentiated brand value to enterprises and allow them to establish unique competitiveness thereby bringing new opportunities for sustainable operation (Singhal et al., 2020). By the thought of circular economy, through the design, every resource is used with extreme caution.

In order to reduce pollution, the EPA encourages the use of renewable energy in addition to restricting the amount of emissions. The EPA has done so through taxes and tariffs levied on energy-related products, such as green taxes, energy taxes, environmental taxes, carbon dioxide taxes, and air and water pollution limits and taxes (Miguel et al., 2015). Green taxation has become an economic policy tool in various countries, beginning in the Nordic countries early in the 1990s. The carbon tax is one of the green rent taxes. It is a fee that is imposed on the burning of carbon-based fuels such as oil, coal, natural gas and electricity) by beneficiaries, users, and polluters. On their website, Carbontax.com indicates that placing a tax on carbon emissions gives consumers and producers a monetary incentive to reduce their carbon dioxide emissions. In accordance with the principle of expanding the tax base, Liu and Lu (2015) studies indicate that it is better to set a marginal tax rate on a carbon tax at a lower level, so that all related carbon emission economic activities will be treated uniformly. The main purpose of the carbon tax imposed by Zhang et al. (2016) is to internalize the external costs of carbon dioxide emissions, and to promote changes in energy prices, to affect energy consumption with price mechanisms, to achieve energy-saving effects with price-based measures, and to gradually guide the replacement effect of low-carbon energy. This reduces carbon dioxide emissions. The imposition of a carbon tax can internalize the external costs caused by the energy use process, promote energy conservation, and increase energy efficiency.

1.2 Research Questions, Objectives and Outline

This research is hinged on the need for original equipment manufacturers (OEM) to be involved in the production and provision of remanufactured products in the market. When the products are initially sold, the remanufacturing value of the products gradually declines with the usage, so the manufacturer must decide when to acquire products from customers to carry out remanufacturing at maximum benefits. Furthermore, another major issue besides the quality of returned products is the ability of the OEM to improve and create a consistent return rate of EOL products, that is, the products are in the final stage of service life, but still have potential for value addition, such as by remanufacturing or disassembly and sales of reconditioned reusable material and parts. The basis of this research is remanufacturing economics, which is an economically feasible way for circular economics. In this process, the value of EOL products is regained by reusing these components for remanufacturing.

Furthermore, companies face business and logistical challenges in the remanufacturing process, including changes in the quality of returned goods, uncertainty in the supply of returned goods and uncertainties in the process parameters as shown in one of our past research (A.Omwando et al., 2017). Since the remanufacturing costs for low-quality returns are much higher, the disassembly, salvage of useful parts and disposal of waste parts may be the most appropriate decision.

In this research, we seek to answer the following research questions:

- Is there an optimal resident time (time in the product's life cycle) to acquire products from customers that would maximize remanufacturing benefits?
- To what extent do uncertainties in product return quantities affect remanufacturing process planning?
- Considering remanufacturing process costs and inventory capacity constraints, is there a threshold return admittance quality?

Following the above research questions, we set the following research objectives:

Objective 1: Develop a profit-maximizing remanufacturing process.

Objective 2: Assess the impact of resident time (product acquisition time) on the remanufacturing process.

Objective 3: Propose a threshold quality of return product admittance into the remanufacturing process.

In order to maximize expected profits, companies need to find the best revenue distribution for these choices. Therefore, we provide a decision model for finding the best disposal decision, using electric motor drives as a case study. The model also considers the quality of returned products. Firstly, it is proposed that the quality variable follows a continuous quality grading method, and there are different purchase prices for different quality levels, which are also influenced by the disposal decision of the returned, and the remanufacturing cost. The proposed decision model is sufficiently versatile and can be applied to other remanufacturing applications. Finally, in order to acquire maximize the profits, we developed a model as a mixed-integer non-linear programming model, to access the minimum quality level allowable for entry into the remanufacturing facility and quantity of new component purchases from the retailer needed for the remanufacturing process planning.

This study is organized as follows: Chapter 2 reviews literature related to remanufacturing, reverse logistics, process planning and green consumption. A mathematical model for the remanufacturing process planning is presented in Chapter 3. Then, a case study of motor control drive remanufacture is presented in Chapter 4. We also discuss the model in four scenarios, i.e. considering different customer residence lengths i.e. time between the products were first purchased new to the time they were brought into the system for remanufacturing, in years, to compare the impact of the residence time on the quality, cost of remanufacturing process, and profit. Finally, result of discussion presented in Chapter 5 and conclusions and future research are discussed in Chapter 6.

Chapter 2

Literature Review

2.1 Remanufacturing and Reverse Logistics

2.1.1 Remanufacturing

Traditionally, once products have reached their end-of-life in their first service phase, they were recycled for material and part salvage or disposed of through either incineration or burial in landfills. These two methods have overtime contributed to increased environmental pollution, leading to the need for equipment manufacturers to develop environmentally friendly production, and product EOL strategies to reduce their negative environmental footprints, improve their cooperate image while still remaining competitive in the market. One strategy that has proven beneficial is by embedding the remanufacturing process into their business model. Cost savings, increase in revenue stream and fulfillment of cooperating and social environmental responsibilities have been key factors that manufacturers consider engaging in remanufacturing processes. As indicated in the introduction, the impact of remanufacturing toward environmental protection is two-fold, the reduction in virgin material usage by increasing secondary material consumption and in the reduction of energy usage. Remanufacturing not only provides reuse of multiple materials but also provides secondary products with requisite quality and functional integrity. The resultant cost savings in remanufacturing are about 40% to 60% of the cost to produce new products (Mitra, 2007). Remanufacturing activities are also seen as a strategy to resist competitors entering the market. Ferguson and Toktay (2006) believes that when a manufacturer has a First-Mover Advantage for a certain product, the manufacturer can choose to recycle products early on in toward their EOL to prevent potential competitors from remanufacturing and recycling these products. Whether this strategy is suitable for remanufacturing depends on the level of remanufacturing costs.

Several prior researchers have presented various definitions of remanufacturing, but all of them have a common concept of the process of rebuilding a used product to like-new state both functionally and quality-wise (Lund, 1984), (Gungor and Gupt, 1999), (Ijomah et al., 2007), and (A.Omwando et al., 2017). They defined remanufacturing and describe the steps of remanufacturing. Lund (1984) defines remanufacturing as a series of industrial processes that allow waste products to be rebuilt to conditions similar to new products. Any discarded products, not suitable for remanufacturing are either entirely disposed or their components are salvaged by cleaning, renovation, and added into the inventory of reusable components. Products routed for remanufacturing are inspected, cleaned, disassembled, reassembled and tested, some of whose performance and life expectancy end up being better than the original products.

Ijomah et al. (2007) stated the definition remanufacturing as a process that usually begins with the used product reaching the remanufacturer, and then goes through a series of industrial processes, including disassembly, cleaning, part remanufacture and replacement of non-remanufacturable parts, reassembly and testing to produce the remanufactured product.

It is therefore possible that more value can be created if the remanufacturing or recycling process is well-strategized and timed within the product life cycle. Georgiadis et al. (2006) present a dynamic modeling approach for strategic remanufacturing and collection capacity planning for a single product supply chain. They analyze the results using a two-array Taguchi experiment in which the inner array consists of control factors namely, product life cycle length, life cycle pattern and residence index, the latter which is described as the length of time the consumer possesses the product. The outer array on the other hand consists of noise factors namely, collection capacity (inventory) and collection costs, remanufacturing capacity (inventory) and remanufacturing costs, inspection time, failure percentage and remanufacturing process time. They emphasize that the remanufacturing process outcomes (such as revenue and cost) are affected by the product life cycle and the time and quality status when the product is returned from (or by the customer). Their results show that the capacity of the collection inventory is more significant than that of remanufactured products inventory. They also find that the residence index significantly affects the decision to remanufacture, indicating that after a certain index value, remanufacturing becomes uneconomical.

Geyer et al. (2007) established a model that simultaneously considers product durability and product life cycle. The model analyzes the economic benefits of both factors on remanufacturing and use heuristic algorithms to that integrates both factors into the recovery rate. The results confirmed that if the goal is to save costs of remanufacturing process, the model must consider the collection rate, product life cycle, and product durability.

For remanufacturing activities, in addition to considering the time point of recycling, the question of whether remanufacturing can meet the market demand for products is also an important issue. Ostlin et al. (2009) pointed out that the key to the success of remanufacturing activities lies is whether the demand for remanufactured products is in tandem with the return rate of the Core Component. It uses the product life cycle model to discuss the supply and demand for remanufactured products. The results show that the demand for remanufactured products is limited by the pricing strategy of the remanufactured products and product recovery options, and when the product recovery time can be predicted, it can meet the demand of the remanufacturing market. Debo et al. (2006) also shows that considering the product life cycle, the sale of the remanufactured product will affect profitability in the market and the time point of product recovery will affect whether the remanufactured product can meet the market demand.

Based on the above scholars' research of remanufacturing, we see a common point of view, that is, the state, quality, and specifications of remanufactured products must reach the same level as new products. However, there are many uncertainties in the quality, and time point of returns.

2.1.2 Reverse Logistics

Since it is difficult to control recovery time and quality of returned products, as well as the need for disposal after recovery, some scholars have proposed models that address reverse logistics management which include: (1) Decisions on what should be remanufactured vis what should be Recycled (2) Models to calculate remanufacturing feasibility of products (3) Models to forecast core acquisition and the demand in the remanufactured products' market, among others. Other challenges that impact reverse logistics management include the product type and its life cycle.

For reverse logistics management, Thierry et al. (1995) proposed some management implications as follows:

- Manufacturers should be more committed to integrating their business chain and collecting relevant product components supply chain information from their suppliers and the available repair stations among other resources, in order to make the best decision.

- Manufacturers may choose different remanufacturing options as determined by the product recovery rate, product types and technical remanufacturing needs.

- Products may need to be redesigned to increases their remanufacturability, by making more components detachable and using more standardized materials and components.

Atasu and Çetinkaya (2006) indicates that product recovery rates and return point do affect production planning and inventory management of a remanufacturing facility. Their research uses different intervals for recycling in a limited life cycle. Their model assumes that the product residence is not influenced by the products' remanufacturability. Their results show that when the product is held by the customer for longer periods (increased residence time), the recovery rate are reduced. To keep up with increasing demands, the manufacturers should increase quantities of returns by providing incentives to customer to return products as soon as they fail.

Guide et al. (2006) used a closed network model to treat the time of the returned product as the product arrival rate and discuss how to maximize profits for the remanufacturer should the product return delay. The results show that the overall profit of the manufacturer will be affected by the value attenuation factor of the product and the return ratio of the returned products to the comparable new products. In addition, the problem of product remanufacturability, due to the different quality status of the recovered products, some scholars proposed to make remanufacturing choices in a classified manner.

To address the effect on product return quality on the remanufacturing disposition, some researchers propose various quality classifications Farahani et al. (2020). Galbreth and Blackburn (2006) believes that by classifying return quality, the optimal recycling and remanufacturing ratio can be found. They construct a single-phase model and assume that the product status is a function of distribution, the recycling cost is linear and the demand deterministic. Their model results show that the best reproducible ratio of the recovered products can be founded.

2.2 Production Planning and Inventory Control in Remanufacturing System

2.2.1 Closed Loop Supply Chains

In the field of production management, enterprises reuse material resources, to address issues of environmental protection, in several ways, including recycling, repairing and remanufacturing as shown in Figure 2.1. Through such a hybrid manufacturing/remanu-

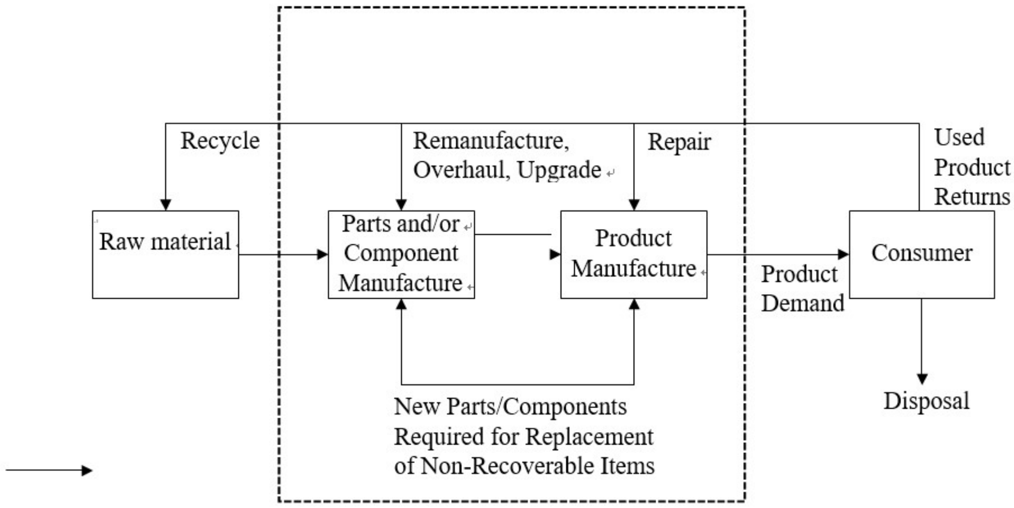

Figure 2.1: Recoverable manufacturing system (Guide et al., 2000).

facturing system, consumers have the opportunity to return used products to the remanufacturers who in turn re-process them to their original functional integrity and resells them at a lower price (Guide et al., 2000). Several researchers have presented work related to reverse logistics 2.1.2, production planning control (Honga et al., 2006), forecasting, inventory control and management (Takahashi et al., 2007) and (Farahani et al., 2020) among others.

Closed-loop supply chain management is mainly composed of both forward and reverse supply chains. The forward process is the process of traditionally delivering new products from the manufacturer to the consumer. And the reverse process on the other hand refers to the delivery of used products from consumers to back to the manufacturers to be restored back to like new condition, or be disassembled for component or material salvage before disposal.

According to Guide et al. (2003), closed-loop supply chain management is a system that combines design, control, and operation to create the maximum value in the entire life cycle from different types and quantities of used products, emphasizing on the reverse logistics, that enables a circular economy.

2.2.2 Return Methods

The key to the success of remanufacturing processes, lies in whether the product can be successfully retrieved from the customers and be remanufactured within its life cycle. The return rate not only affects the ability to fulfill used products' demand but also affect other process decisions such as process planning, staffing and inventory capacity costs, but also affects the overall process feasibility (Guide and Wassenhove, 2001). Therefore, a clear remanufacturing strategy should be established to use the minimum cost to restore the product's maximum economic value.

Considering the two cases of remanufacturing, outsourcing or OEM remanufacture, Karakayali et al. (2007) models a decentralized remanufacturing process in a single period, for a system that has (i) a homogeneous and (ii) heterogeneous sets of durable products. The goal of their paper is to present conditions when and why an OEM should collect and remanufacture or outsource either the collection or the processing to an independent third party remanufacturer in the presence of environmental regulations. Their results show that this decision is significantly influenced by the core acquisition and remanufactured products' price points.

Toyasaki et al. (2011) purposed that under the remanufacturing regulations, the recycling problems of manufacturers and recyclers can be divided into two categories: (1) Monopolistic, using a non-profit organization to configure the recycling products; (2) Competition, each manufacturer can establish a cooperative relationship with the recycler; Using a two-stage competition model to analyze the strategy between the manufacturer and the recycler, it is found that under the competitive situation, a win-win situation can be achieved for both. When the original product of the manufacturer has a high substitution rate and the economic scale of recycling activities is high, the recycler will tend to adopt a monopolistic strategy.

2.2.3 Inventory Control Management

When the product is used and recycled from the customer, the manufacturer's production and remanufacturing plan will be affected by the product recovery rate. At this time, the product will face remanufacturing or disposal, so some scholars have discussed the inventory problem of remanufacturing production. Vlachos and Dekker (2003) studied the inventory of single-cycle products within a specific period of time, which explored the optimal order quantity of manufacturers when profit was maximized. The results indicate that the traditional news-vendor model cannot be applicable when considering the product recovery rate. When inventory issues are concerned, more consideration must be given to whether the recovery rate and market demand are consistent with the choice of remanufacturing.

Toktay et al. (2000) use a closed network model to study inventory issues. Their goal is to model a remanufacturing system of the Kodak cameras that minimizes procurement, inventory and lost order costs, in the presence of factors that influence these costs, including product life cycle length, demand rate, procurement delay and information structure. They use statistical techniques to estimate products returns, and the return ratio is used to make the best inventory control decision of the supply chain. The results confirm that the product return ratio and the probability of procurement delayed affect the overall supply chain inventory management.

Bayındıra et al. (2007) constructed a single-period model to discuss the profitability of production and remanufactured products in their own markets when production capacity is limited. The results of their research found that when remanufacturing costs and capacity requirements are high, manufacturers will choose to produce new products. But when the cost of remanufacturing is high and the capacity of remanufacturing is low, then they choose to tighten production capacity to replace new products.

2.2.4 Green Consumption

Research into green consumption has increased with increasing government-driven environmental regulation and civic engagement into sustainable development and environmental degradation. do Paço and Raposo (2010) investigates the impact of age, educational attainment and income levels in a bid to model the green consumer archetype. The purchase behavior of this type of customer will be based on his/her environmental awareness and knowledge of whether the product of interest can be recycled and reused. For green customer types, manufacturers should consider product design, recyclability and feasibility for remanufacturing as a way to attract the customer into purchasing remanufactured products.

Debo et al. (2006) studied the integrated dynamics managing a portfolio that consists of new and remanufactured products, where the latter is an imperfect substitute of the former but still affects the market dynamics. They point out that the choice of production technology and market segmentation will affect the customer's willingness to buy the product. They also believe that because customers in the market have different views on new products and remanufactured products, their willingness to purchase remanufactured products will be affected by the customer's influence such as by word of mouth propagation.

Michaud and Llerena (2011) purposed that remanufactured products can reduce the load on the environment and increase benefits, so they are also regarded as green products. They use surveys to study customers' purchase intentions for green products, (i) when the customer is informed prior on which products are green, in which case customers' preference was for green products, and (ii) when they do not know, in which case the decision to purchase a product is highly driven by its price.

Robotis et al. (2005) believe that remanufactured products have a cost-saving impact by reducing unit production costs, especially when there is an adequate secondary market. The consider two options for a reseller: (1) Sell used product (or part of it) into the developing market. (2) Invest in remanufacturing and sell the remanufactured products directly to the developing market at a higher price. It is found that if remanufacturing can serve the secondary market, the number of remanufactured products sold in the first market can be reduced. They conclude that in most modeled scenarios, remanufacturing emerges as the best choice.

Chapter 3

Methodology

As environmental issues are gradually being valued by governments and society, companies have begun to engage in sustainable practices such as remanufacturing, to improve their corporate image, social responsibility and achieve circular economies. One of the key aspects to companies engaging in remanufacturing the expected returns on investments, at times measure by profit maximization, which is dependent on all cost metrics and revenues expected from the process. As mentioned in Chapter 2, the factors that make remanufacturing profitable include the time of remanufacturing (defined by either residence time or life cycle time, the quality of the product being remanufactured, and all the costs involved in the remanufacturing process.

Furthermore, when the products are used and returned from the customer, the remanufacturer's remanufacturing plan will be affected by the product recovery rate. Vlachos and Dekker (2003) research results indicate that inventory control strategies must consider both the recovery rate and market demand for remanufactured products. Ferguson et al. (2009) and Farahani et al. (2020) also found out that the remanufacturing process profits are improved when the returns are classified according to their quality, and by having a quality threshold that determines if a returned core should be remanufactured or routed for part salvage and disposal.

At the disassembly site, according to the product's bill of materials (BOM), the products are disassembled into their components. However, not all components are reusable or can be used in remanufactured products. Therefore, the remanufacturer is responsible for the disposal costs or waste costs of the products or components. If components can be repaired, it is added to the inventory of components. In addition, if there are any missing components, new components are purchased from the supplier to be used in the reassembly of the remanufactured product. Finally, components are delivered to the factory according to the production plan. The overall remanufacturing system is shown in Figure 3.1.

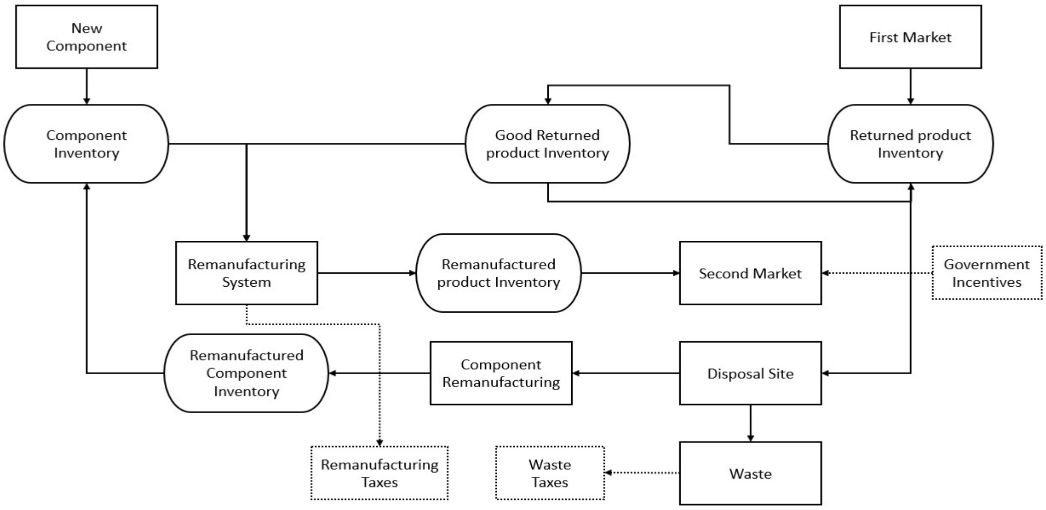

Figure 3.1: Conceptual framework of remanufacturing system, adopted from (Kim et al., 2006).

The remanufacturer has two choices to obtain the components required for remanufacturing: (1) Order new components from a supplier. (2) Use stock of refurbished components. Therefore, in order to obtain maximum profit, the remanufacturer must determine the best quality and return quantity of the product that can be accepted at the remanufacturing site, the number of products disassembled into components and the new components that should be purchased from suppliers. These strategic decisions mainly depend on the set quality and quantity of returned, the remanufacturing costs and the inventory costs which depend on the inventory capacity. This is the basis of the proposed model in this research. We propose a nonlinear program (NLP)-based model and apply it to the production planning of a real company scenario that remanufactures motor control drives.

3.1 Model Assumptions

The following assumptions have been made in the optimization model.

- The quantity of demand for remanufactured products and the quantity of returned products are considered to be deterministic.
- The quality of a returned product is assumed to have a normal distribution.
- The grading process of the returned product quality is assumed to be accurate (which determines the remanufacturing process cost) and the scale of quality is between 0 to 1, where 0 implies the worst quality, 1 implies the best quality.
- The price of the returned product and remanufacturing cost depends on product quality. The former increases while the latter decreases linearly as the quality level increases.
- All process costs, which include: the returned product cost, remanufacturing costs, inventory costs and the cost of disposal non-zero and deterministic.
- The model includes four different inventories: returned products, good-returned products, remanufactured products and remanufactured components.
- These inventories have finite capacity

3.2 Model Variables

Sets

$P = \{1, 2, 3, \cdots, P\}$ set of products;

$C = \{1, 2, 3, \cdots, C\}$ set of components;

$T = \{1, 2, 3, \cdots, T\}$ set of time periods;

Constant Variables

A_p acquisition cost of product p with the worst possible quality, from first market;

B_p remanufacturing costs associated with the worst quality returned product p;

M_{Ap} slope of product p acquisition cost and quality linear relationship;

M_{Bp} slope of remanufacturing product p cost and quality linear relationship;

α_p actual quality of returned product p;

D_p unit operation cost of disposal product p;

R_c unit operation cost of remanufactured component c;

W_c unit operation cost of waste component c;

H_{1pt} unit holding cost of product p for returned product in period t;

H_{2pt} unit holding cost of product p for good quality returned product in period t ;

H_{3pt} unit holding cost of product p for remanufactured product in period t ;

H_{4ct} unit holding cost of component c for remanufactured component in period t ;

Q_{pt} quantity of product p in period t from first market;

P_c unit price of new component c;

O_{pt} estimated sales target for product p in period t;

U_{pt} cost of back-log for remanufactured product in period t;

P_p unit sales price of remanufactured product p in second market;

G_p percent of government incentive for unit product p;

E_p emission tax for unit of remanufactured product p;

E_c emission tax for unit of waste component c;

F_{pc} number of component c from disposal of unit product p;

U_{ct} required quantity of component c in period t;

Decision variables

- α_{pt} minimum allowable quality of returned product p into the returned product inventory in period t;
- α'_{pt} minimum allowable quality of returned product p to the good quality returned product inventory in period t;
- Q^{+}_{pt} quantity of product p accepted into good quality returned product site in period t;
- Q^{-}_{pt} quantity of product p routed to the disposal site in period t;
- q'_{ct} quantity of component c disposed off in period t;
- q^{+}_{ct} quantity of component c remanufactured in period t;
- q^{-}_{ct} quantity of component c wasted in period t;
- I_{1pt} inventory level at the end of period t for returned product p;
- I_{2pt} inventory level at the end of period t for good quality returned product p;
- I_{3pt} inventory level at the end of period t for remanufactured product p;
- I_{4ct} inventory level at the end of period t for remanufactured component c;
- E_{pt} inventory level at the end of period t for exchanged returned product p due to quality difference;
- W_{ct} quantity of component c purchased in period t;
- R_{pt} actual number of remanufactured product p sold to secondary market in period t;

3.3 Objective Function

Our research objective is to maximize the total expected profit over all types of products and components during the remanufacturing planning horizon. The profit maximization function is shown in Equation 3.1. Profit here refers to the difference between the process revenue and all of the costs in the remanufacturing process including the emission taxes. These costs include operation costs, inventory costs, return and purchase costs, and emission costs. The revenue includes income from selling remanufactured products in the secondary market and government incentives. It is assumed that any remanufactured components are consumed in the process. Next, we discuss the three different costs terms of the model in Section 3.4.

$$Profit = \frac{\sum_{i=1}^{I} Revenue_i - \sum_{i=1}^{I} Cost_i - \sum_{i=1}^{I} EmissionTax_i}{\sum_{i=1}^{I} Cost_i + \sum_{i=1}^{I} EmissionTax_i} \cdot 100\% \tag{3.1}$$

Where the index i indicates the revenue, cost or tax components as will be seen in the subsequent sections.

3.4 Costs

3.4.1 Operational Cost

The operational cost consists of remanufacturing cost (Equation 3.2), disposal cost (Equation 3.3), component remanufacture cost (Equation 3.4), and component waste cost (Equation 3.5) using model parameters defined in Section 3.2.

Remanufacturing Cost: the total remanufacturing process costs of good quality returned product that are admitted to the remanufacturing process.

$$\sum_{p=1}^{P}\sum_{t=1}^{T}\int_{\alpha_{pt}}^{1} Q_{pt}^{+} \cdot [B_p - M_{Bp} \cdot \alpha_p] \cdot f_\alpha(\alpha_p)_p \cdot d\alpha \tag{3.2}$$

Disposal cost: the total disposal costs of the returned products which rejected by the remanufacturing site.

$$\sum_{p=1}^{P}\sum_{t=1}^{T}\int_{0}^{\alpha_{pt}} Q_{pt}^{-} \cdot D_p \cdot f_{\alpha}(\alpha_p)_p \cdot d\alpha \tag{3.3}$$

Component of remanufacturing cost: the total remanufacturing costs of the components that can be remanufactured from the disposal site.

$$\sum_{c=1}^{C}\sum_{t=1}^{T} q_{ct}^{+} \cdot R_c \tag{3.4}$$

Waste cost: the total waste costs of the components that cannot be used and are therefore routed to the disposal site.

$$\sum_{c=1}^{C}\sum_{t=1}^{T} q_{ct}^{-} \cdot W_c \tag{3.5}$$

3.4.2 Inventory Cost

This costs consists of returned products inventory cost (Equation 3.6), good quality returned products inventory cost (Equation 3.7), remanufacturing products inventory cost (Equation 3.8), components remanufacturing inventory cost (Equation 3.9), and exchange quality inventory cost (Equation 3.10) as follows:

Returned products inventory: the inventory costs of the returned products from first market.

$$\sum_{p=1}^{P}\sum_{t=1}^{T} I_{1pt} \cdot H_{1pt} \tag{3.6}$$

Good quality returned products inventory: the inventory costs of the good quality returned products from returned products site.

$$\sum_{p=1}^{P}\sum_{t=1}^{T} I_{2pt} \cdot H_{2pt} \tag{3.7}$$

Remanufactured products inventory: the inventory costs of the remanufactured products after the remanufacturing process.

$$\sum_{p=1}^{P}\sum_{t=1}^{T} I_{3pt} \cdot H_{3pt} \tag{3.8}$$

Remanufactured components inventory: the inventory costs of the remanufactured components after the remanufacturing process.

$$\sum_{c=1}^{C}\sum_{t=1}^{T} I_{4ct} \cdot H_{4ct} \tag{3.9}$$

Exchange quality inventory: This is the cost of inventory that results from a case when say a returned product at time t is of a better quality than a previously returned product at time t-i, and are therefore exchanged. I.e. updating the returned good product inventory and sending the lower quality product back to the returned product inventory.

$$\sum_{p=1}^{P}\sum_{t=1}^{T} E_{pt} \cdot (H_{1pt} + H_{2pt}) \tag{3.10}$$

3.4.3 Return and Purchase Cost

This cost consists of returned products cost (Equation 3.11), new component cost (Equation 3.12) and cost of stock back-log (Equation 3.13) as follows:

Returned products cost: the total costs of the returned products from the first market or customer.

$$\sum_{p=1}^{P}\sum_{t=1}^{T} \int_{0}^{1} Q_{pt} \cdot [A_p + M_{Ap} \cdot \alpha_p] \cdot f_\alpha(\alpha_p)_p \cdot d\alpha \tag{3.11}$$

New component: the total costs of the new components bought from the supplier.

$$\sum_{c=1}^{C}\sum_{t=1}^{T} W_{ct} \cdot P_c \tag{3.12}$$

Cost of stock back-log: the total costs of the shortage of remanufactured products in the second market.

$$\sum_{p=1}^{P}\sum_{t=1}^{T}(O_{pt} - R_{pt}) \cdot U_{pt} \tag{3.13}$$

3.5 Emission Cost

This cost consists of the remanufacturing system emission tax (Equation 3.14) and the waste emission tax (Equation 3.15) as follows:

Remanufacturing system emission tax: the total emission tax of remanufacturing a unit product.

$$\sum_{p=1}^{P}\sum_{t=1}^{T} R_{pt} \cdot E_p \tag{3.14}$$

Waste emission tax: the total emission tax levied on any component that is routed to the disposal site.

$$\sum_{c=1}^{C}\sum_{t=1}^{T} q_{ct}^{+} \cdot E_c \tag{3.15}$$

3.6 Revenue

This consists of the revenue from selling remanufactured products in the second market (Equation 3.16), and the government incentives (Equation 3.17) for remanufacturing a product as follows:

Revenue from the sales of remanufactured products in the second market:

$$\sum_{p=1}^{P}\sum_{t=1}^{T} R_{pt} \cdot P_p \tag{3.16}$$

Government incentive provided for every product that is remanufactured:

$$\sum_{p=1}^{P}\sum_{t=1}^{T} R_{pt} \cdot P_p \cdot G_p \tag{3.17}$$

3.7 Model Constraints

The model is set to various constraints using the model parameters defined in Section 3.2 as follows:

Returns Constraints:

$$Q^{+}_{pt} \leq \int_{\alpha_{pt}}^{1} Q_{pt} \cdot f_{\alpha}(\alpha_p)_p \cdot d\alpha \qquad \forall p, \text{ and } t = 1, ..., T \tag{3.18}$$

$$Q^{-}_{pt} \leq \int_{0}^{\alpha_{pt}} Q_{pt} \cdot f_{\alpha}(\alpha_p)_p \cdot d\alpha \qquad \forall p, \text{ and } t = 1, ..., T \tag{3.19}$$

During period t, Constraint 3.18 makes sure that the remanufacturing system will only do the remanufacturing process on good quality returned products from the primary market. Constraint 3.19 ensured that the quantity of returned products from customers that do not reach the minimum quality level or exceed the capacity of remanufacturing site inventory are sent to the disposal site.

$$q'_{ct} = \sum_{p=1}^{P} F_{pc} \cdot Q^{-}_{pt} \qquad \forall c, \text{ and } t = 1, ..., T \tag{3.20}$$

$$q^{-}_{ct} + q^{+}_{ct} = q'_{ct} \qquad \forall c, \text{ and } t = 1, ..., T \tag{3.21}$$

Constraint 3.20 calculates the quantity of the components from the disposal of returned products are not accepted for remanufacture. Constraint 3.21 ensures that the quantity of components from the products that are sent to disposal equals the sum of components that are sent to waste and the remanufactured components.

$$Q_{pt} + I_{1p,t-1} = Q^{+}_{pt} + Q^{-}_{pt} + I_{1pt} \qquad \forall p, \text{ and } t = 1, \ldots, T \tag{3.22}$$

$$Q^{+}_{pt} + I_{3p,t-1} = R_{pt} + I_{3pt} \qquad \forall p, \text{ and } t = 1, \ldots, T \tag{3.23}$$

$$W_{ct} + q^{+}_{ct} + I_{4c,t-1} = I_{4ct} + U_{ct} \qquad \forall c, \text{ and } t = 1, \ldots, T \tag{3.24}$$

Constraint 3.22 ensures a balance in the quantity of returned products and the sum of the returned products accepted for remanufacture and those rejected and thus sent for disposal. Constraint 3.23 ensures that the quantity of products remanufactured equals those that are sold in the secondary market i.e. a perfect remanufacturing system. Constraint 3.24 ensures that there is a balanced equation of the component inventory.

$$R_{pt} \leq O_{pt} \qquad \forall p, \text{ and } t = 1, \ldots, T \tag{3.25}$$

Constraint 3.25 ensures that the quantity of remanufactured products sold in the secondary market does not exceed the estimated target sales.

$$R_{pt} \geq 0,\ Q^{+}_{pt} \geq 0,\ Q^{-}_{pt} \geq 0 \qquad \forall p, \text{ and } t = 1, \ldots, T \tag{3.26}$$

$$W_{ct} \geq 0,\ q^{+}_{ct} \geq 0,\ q^{-}_{ct} \geq 0,\ q'_{ct} \geq 0 \qquad \forall c, \text{ and } t = 1, \ldots, T \tag{3.27}$$

Constraint 3.26 and constraint 3.27 ensure that the decision variables are all greater or equal zero.

$$0 \leq \alpha_{pt} \leq 1 \qquad \forall p, \text{ and } t = 1, \ldots, T \tag{3.28}$$

Constraint 3.28 ensures that the scale of quality is between 0 to 1. Where 0 implies the worst quality and 1 implies the best quality.

In Chapter 4 the model formulated above will be tested in a real case remanufacturing scenario of motor control drives.

Chapter 4

Model Application and Results

4.1 Case Study

This chapter illustrated the application of the model that was formulated in Chapter 3. In Chapter Chapter 2.1, we mentioned that the two most important factors that determine how profitable the remanufacturing process is are: the residence time (time of acquisition in the products' life cycle) and the quality of the returned product. Therefore, the purpose of this study is to develop a general model that remanufacturers can use to determine if a returned product is suitable for remanufacture considering the cost, inventory, return quality and quantity as well as the environmental taxes and incentives. The model is applied to real scenarios in the remanufacture of motor control drives. Two types of control drive are considered, and we refer to them as CON 1 and CON 2. The Bill of Material for each control drive considering only key components is shown in Table 4.1. Both of them are composed of four main components namely, the Control board (CB), Power Module (PM), Printed Circuit Board (PCB), and Cooling Fan. In addition, the components of these two control drives are interchangeable.

Table 4.1: Number of components in each product (F_{pc}).

These are the key components that can be disassembled and either salvaged or wasted.

	Control Board	Power Module	Printed Circuit Board	Cooling Fan
CON 1	1	1	1	1
CON 2	1	1	1	2

As indicated earlier, the product is assessed and categorized in the range of 0 (worst) to 1 (best). In this study, we set the quality threshold for a product to be admissible for remanufacture at 0.25. According to the remanufacturer's data and return status over the years, the distribution of returned product quality approximately follows the normal distribution. We also set the quality degradation (quality level reduction) over the residence period to be 0.1 every five years. Furthermore, we differentiate the two products as follows: CON 1 is mature in the market (more than 5 years) while CON 2 is the latest control drive in the market (less than 5 years) A.Omwando et al. (2017). Table 4.2 provides the forecast of returned products from consumers during the four-time periods (in months). The forecast is adjusted based on past sales data. Table 4.3 presents different holding costs per product/component for each inventory site. Furthermore, the remanufactured product inventory site has a limited capacity. The remanufactured product inventory capacity is set at 210 for CON 1 and 500 for CON 2. These are arbitrary numbers set for modeling purposes and can be altered. If there is insufficient inventory to meet the requirement of customers in the secondary market, the back-log cost is set at $89 and $179 for CON 1 and 2 respectively.

Table 4.2: Quantity of returned product forecast for 4 months (Q_{pt}).

Months	1	2	3	4
CON 1	344	332	268	310
CON 2	512	511	488	497

Table 4.3: Unit cost of CON 1 and CON 2.

*1: Unit operation cost of disposal (D_p)
*2: Unit cost of returned product inventory (H_{1pt})
*3: Unit cost of good quality returned product inventory (H_{2pt})
*4: Unit cost of remanufactured product inventory (H_{3pt})

Cost Term	*1	*2	*3	*4
CON 1	30	4.5	6.75	10
CON 2	50	6	9	15

Table 4.4 represents the number of main components required during each period, and Table 4.5 provides the cost associated with new component purchases, remanufacturing process, disposal and waste. The estimated sales target of remanufactured products is also shown in Table 4.6.

Table 4.4: Quantity of required component in period t (U_{ct}).

Months	1	2	3	4
CB	232	265	270	254
PM	245	235	249	249
PCB	219	228	235	235
Fans	398	415	397	399

Table 4.5: Unit cost of each component.

*1: Unit price of new component (P_c)
*2: Unit operation cost of remanufactured component (R_c)
*3: Unit operation cost of waste component (W_c)
*4: Unit cost of component pf remanufacturing inventory (H_{4ct})

Cost Term	*1	*2	*3	*4
CB	150	15	1	4
PM	80	8	1	2
PCB	80	8	1	3
Fans	50	5	1	1

Table 4.6: Quantity of estimate sales target for 4 months (O_{pt}).

Months	1	2	3	4
CON 1	225	205	198	201
CON 2	447	444	423	432

As mentioned earlier, CON 1 is mature in the market while CON 2 is the latest model hence still early in the market. We also assume that there is a higher demand for CON 2 than there is for CON 1, implying that the secondary market unit sales price for CON 2, which is set at \$599 is higher than that of CON 1 set at \$429. The government also has incentives for manufacturers that implement remanufacturing or sustainable practices, so the amount of incentive is assumed to be 1.5% of the sales price in our model.

This study discusses scenarios in different periods. As explained earlier there is a 0.1 reduction in quality for every year a product remains with the customer (i.e. residence time). We therefore consider the following four scenarios with the product quality assumed to be normally distributed with the following parameters:

- Scenario 1: The product is returned on the fifth year after it was sold in the first market.

  CON 1 quality ~ Norm ($\mu = 0.6; \sigma = 0.2$); CON 2 quality ~ Norm ($\mu = 0.7; \sigma = 0.2$)

- Scenario 2: The product is returned on the tenth year after it was sold in the first market.

  CON 1 quality ~ Norm ($\mu = 0.5; \sigma = 0.2$); CON 2 quality ~ Norm ($\mu = 0.6; \sigma = 0.2$)

- Scenario 3: The product is returned on the fifteenth year after it was sold in the first market.

  CON 1 quality ~ Norm ($\mu = 0.4; \sigma = 0.2$); CON 2 quality ~ Norm ($\mu = 0.5; \sigma = 0.2$)

- Scenario 4: The product is returned on the twentieth year after it was sold in the first market.

  CON 1 quality ~ Norm ($\mu = 0.3; \sigma = 0.2$); CON 2 quality ~ Norm ($\mu = 0.4; \sigma = 0.2$)

The model assumes that the quantity of returns, the quantity of required components and all costs remain constant across the time period in the four scenarios. The results of the model, i.e. profits for each scenario is discussed in detail in the Section 4.2.

4.2 Model Results

4.2.1 Scenario 1

As mentioned in the previous section, scenario 1 set to mimic returns of products fifth years after they were first sold. For this scenario, this section discusses the quality of returned products, minimum standard quality allowable for remanufacture, number of sales and profits from the remanufacturing process. Figures 4.1 and 4.2 shows the quality distribution of the returned product types, CON 1 and CON 2 respectively. The average quality of CON 1 is about 0.6 and the standard deviation is 0.2. the average quality of CON 2 is about 0.7 and the standard deviation is 0.2.

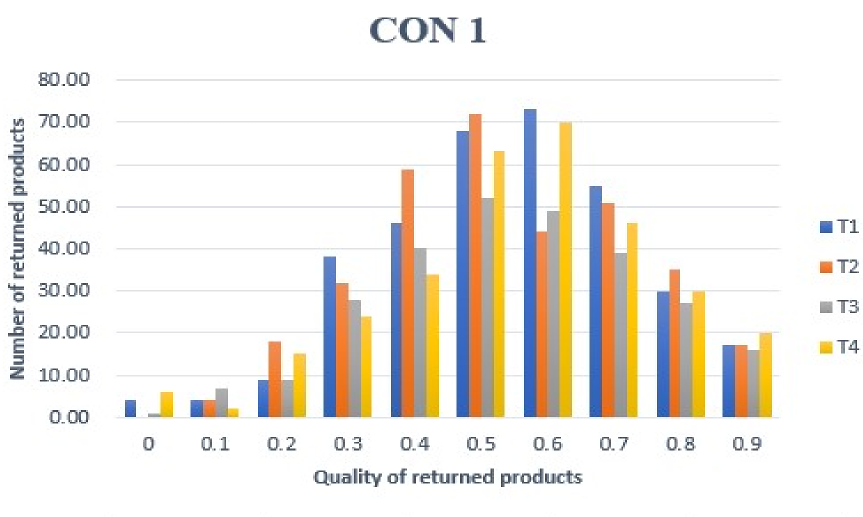

Figure 4.1: Con 1: Scenario 1 quality distribution of returned products.

Table 4.7 presents the minimum quality of returned products allowable for remanufacture in the system and Table 4.8 shows the percentage of the returned products that are accepted into the good returned product inventory for the given time periods in months. Since we set CON 2 as new in the market and hence it has a high demand in the secondary market, the results also concur by showing a larger percentage of CON 2 enters into the remanufacturing process than that of CON 1. Therefore, CON 1 is mainly accepted into the system to enable the system to salvage components from CON 1 for remanufacture. Table 4.9 provides the number of products that were rejected from the remanufacturing system and routed for disposal.

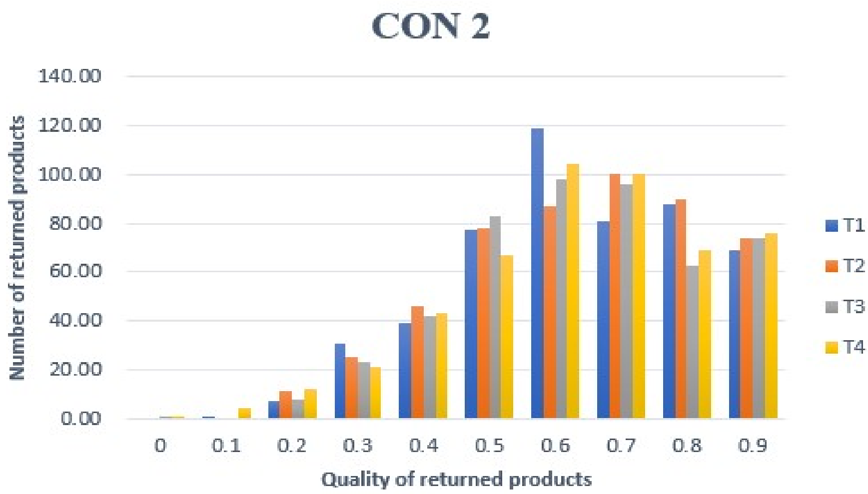

Figure 4.2: Con 2: Scenario 1 quality distribution of returned products.

Table 4.7: Minimum quality of product p to returned product inventory in scenario 1.

Months	T1	T2	T3	T4
CON 1	0.53	0.52	0.48	0.55
CON 2	0.48	0.48	0.5	0.47

Table 4.8: The percentage of good returned product in scenario 1.

Months	T1	T2	T3	T4
CON 1	62.5%	59.9%	73.5%	64.5%
CON 2	87.1%	86.5%	84.8%	86.5%

Table 4.9: Quantity of product p rejected from the remanufacturing site and routed to disposal in scenario 1 (Q^{-}_{pt}).

Months	T1	T2	T3	T4
CON 1	129	133	71	110
CON 2	66	69	74	67

It was noted earlier that for modeling purposes, the capacity of the good returned products inventory is set at 210 and 500 units for CON 1 and CON 2 respectively. Table 4.10 shows the actual sales quantities of remanufactured products. In light of the inventory capacities, we can see that during the first month, CON 1 product type had enough returns to fills its capacity, all of which were remanufactured successfully and re-sold. Considering that the return forecast for CON 1 at T1 was 344, and 62.5% (i.e. 215) were accepted as good returns, this means that only 210 were routed to the remanufacturing system and five remained in the good returns inventory for consideration for remanufacturing in T2. Table 4.11 provides the number of remanufactured components.

Table 4.10: Actual number of remanufactured product p sales to secondary market scenario 1 (R_{pt}).

Months	T1	T2	T3	T4
CON 1	210	204	197	200
CON 2	446	442	414	430

Table 4.11: Quantity of remanufactured component c scenario 1 (q^{+}_{ct}).

Months	T1	T2	T3	T4
CB	190	195	144	170
PM	180	195	135	186
PCB	185	193	130	177
Fans	241	248	212	246

In this scenario, we can see that due to the high quality of the returned products, there are many products that are remanufactured to meet the requirement of customers in the secondary market across all four periods (see Table 4.8. Therefore, only a few returned products are sent to the disposal site. With an insufficient inventory of salvaged components, it is necessary to purchase new components from material suppliers. The quantity of purchased components is shown in Table 4.12. Finally, Table 4.13 shows the resulting profits in this scenario as percentage values of the total remanufacturing cost plus emissions taxes. These percentages are relative to the systems cost and hence the impact is relative also to the volume of returned products.

Table 4.12: Quantity of purchased component c scenario 1 (W_{ct}).

Months	T1	T2	T3	T4
CB	42	70	126	84
PM	65	40	114	63
PCB	34	35	105	58
Fans	157	167	185	153

Table 4.13: Profit of remanufacturing process in scenario 1.

Months	T1	T2	T3	T4
Profit	8.3%	6.4%	2.7%	6.3%

4.2.2 Scenario 2

As mentioned in Section 4, Scenario 2 is set to mimic returns on the tenth year after the products were sold in the first market. Figures 4.3 and 4.4 shows the quality distribution of the returned products for CON 1 and CON 2 respectively. The average quality of CON 1 is about 0.5 and the standard deviation is 0.2. while the average quality of CON 2 is about 0.6 and the standard deviation is 0.2.

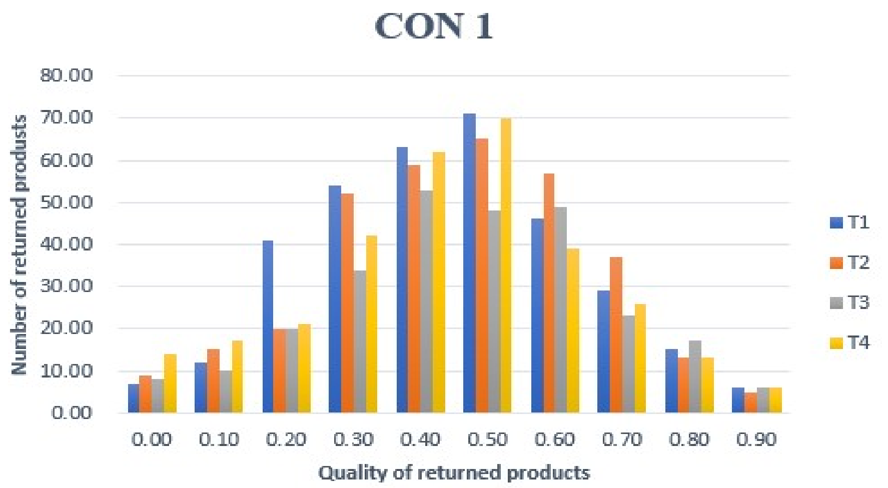

Figure 4.3: Con 1: Scenario 2 quality distribution of returned products.

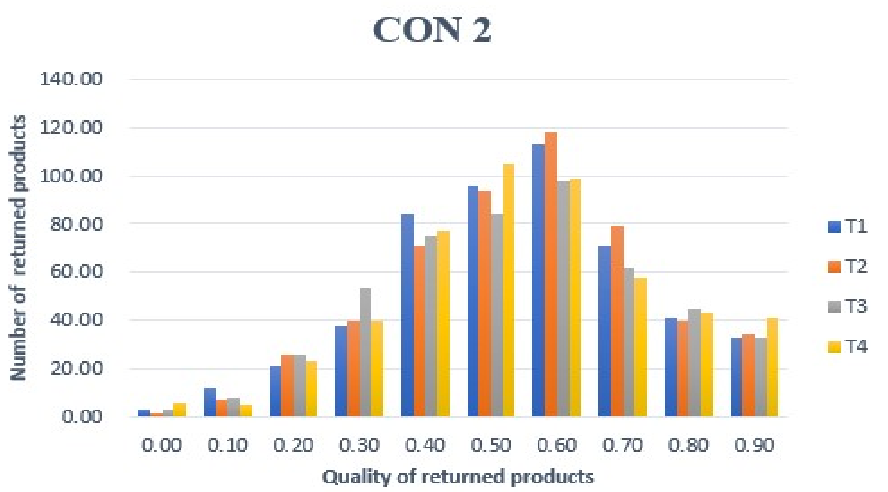

Figure 4.4: Con 2: Scenario 2 quality distribution of returned products.

Table 4.14 presents the minimum quality of returned products acceptable for remanufacturing and Table 4.15 presents the percent of the returned products that are accepted into the good returned product inventory. These percentage numbers reflect the demand of CON 2 (higher) and Con 1 (lower) in the secondary market. Compared with scenario 1, the percentage of CON 1 accepted into the good returned product inventory has decreased in all the four-time periods (see 4.8. Therefore, CON 1 is once again mainly used to fulfill the demand of CON 2 in providing salvaged (remanufactured) components. Table 4.16 provides the number of products that were rejected from the remanufacturing system and routed to the disposal site for component salvage and later into the waster stream.

Table 4.14: Minimum quality of product p to returned product inventory in scenario 2.

Months	1	2	3	4
CON 1	0.52	0.52	0.44	0.47
CON 2	0.39	0.4	0.36	0.39

Table 4.15: The percentage of good returned product in scenario 2.

Months	1	2	3	4
CON 1	43.3%	50.0%	67.2%	57.4%
CON 2	86.7%	85.3%	85.5%	86.9%

Table 4.16: Quantity of product p rejected to remanufacturing site and go to disposal in scenario 2 (Q^{-}_{pt}).

Months	1	2	3	4
CON 1	195	166	88	132
CON 2	68	75	71	65

The actual sales number of remanufactured products are shown in Table 4.17. Considering that the demand forecasts for CON 1 for the four-time periods are 225, 205, 198, and 201, respectively, the results show that the system did not receive sufficient CON 1 returns with acceptable quality for remanufacture and hence the secondary market for CON 1 was starved. Table 4.18 provides the number of remanufactured components.

Table 4.17: Actual number of remanufactured product p sales to secondary market in scenario 2 (R_{pt}).

Months	1	2	3	4
CON 1	149	166	180	178
CON 2	444	436	417	432

Table 4.18: Quantity of remanufactured component c in scenario 2 (q^{+}_{ct}).

Months	1	2	3	4
CB	224	257	172	189
PM	237	217	141	192
PCB	212	219	137	189
Fans	307	315	231	242

In this scenario, we can see that due to the shortage of good quality returned of CON 1, a larger percentage is routed for disposal for component remanufacture. In the First month to the fourth month, it is necessary to purchase new components from material suppliers as shown in Table 4.19. Finally, for four-month profits in this scenario are shown in Table 4.20.

Table 4.19: Quantity of purchased component c in scenario 2 (W_{ct}).

Months	1	2	3	4
CB	8	8	98	65
PM	8	18	108	57
PCB	7	9	98	46
Fans	91	100	166	157

Table 4.20: Profit of remanufacturing process in scenario 2.

Months	1	2	3	4
Profit	5.6%	6.4%	2.5%	4.8%

The rest of the results from scenarios (3 and 4) can be see in the Appendix section of this Thesis.

Chapter 5

Discussion

The case study in this research uses a realistic remanufacturing situation at a motor control drive facility. The case study has two product types namely, CON 1 and CON 2. CON 1 is a product that is mature in the market and hence has lower quantities of returns and lower secondary market demand in comparison to CON 2 which is newer in the market. It is assumed in this case study that the two products have interchangeable common key components, which include the control board (CB), the power module (PM), the printed circuit board (PCB) and the cooling fans. CON 1 and CON 2 product types have one of each of these key components, but CON 2 has two cooling fans.

The model execution also considers four scenarios, mimicking the resident time, i.e. the time between the products were first sold to the market and when they were acquired for remanufacture. These four scenarios mimic returns after 5, 10, 15 and 20 years of resident time. The difference between the scenarios being a 10% reduction in the average quality of the product at each subsequent year.

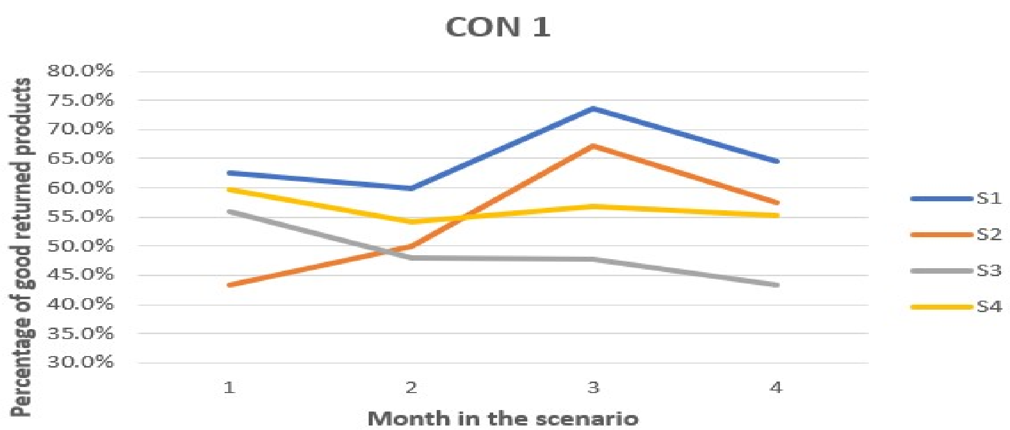

Figure 5.1: CON 1: percentage of good returned products

In all these scenarios, the systems adapt to the higher demand for CON 2 in the secondary market by not only accepting a larger percentage of CON 2 returns for remanufacture as seen in Figure 5.1. In addition, Figure 5.2 shows that the system accepts more of CON 1 in order to salvage the components to remanufacture CON 2.

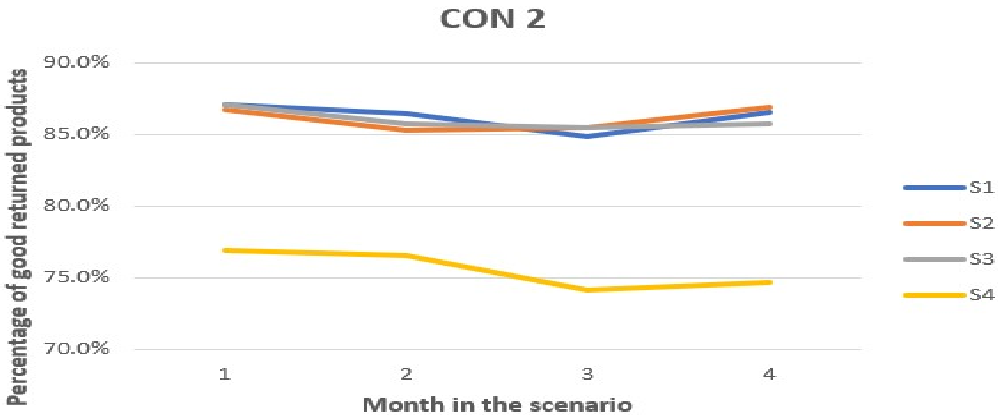

Figure 5.2: CON 2: percentage of good returned products

Figure 5.2 also shows that the percentage of accepted CON 2 products for remanufacture for scenarios 1,2 and 3 are markedly different (higher) than the percentage of good returns in scenario 4. This is an indication that the resident time is indeed a significant factor to consider for any remanufacturing system. Ideally, it is very important to understand the resident time in light of the product life cycle. Particularly, it is best to enable the acquisition of the returned products sooner in their life cycle than later. Figure 5.1 on the other hand, indicates a clear trade-off being made by the system, between lowering the threshold quality (accepting more of CON 1) for component salvage so us to remanufacture more CON 2 rather than starve the secondary market.

Figures 5.3 to 5.6 indicate the number of new components that were purchased from the supplier so as to remanufacture CON 1 and CON 2, at each month of each scenario. It can be seen that the system purchase the most number of components in scenario 1, in a bid to satisfy the demand of the secondary market. The quality of each of these key components was independent of each other so the difference in the trends of purchases for scenarios 2, 3, and 4 could be attributed to the randomness in the quality assignment in the simulation model.

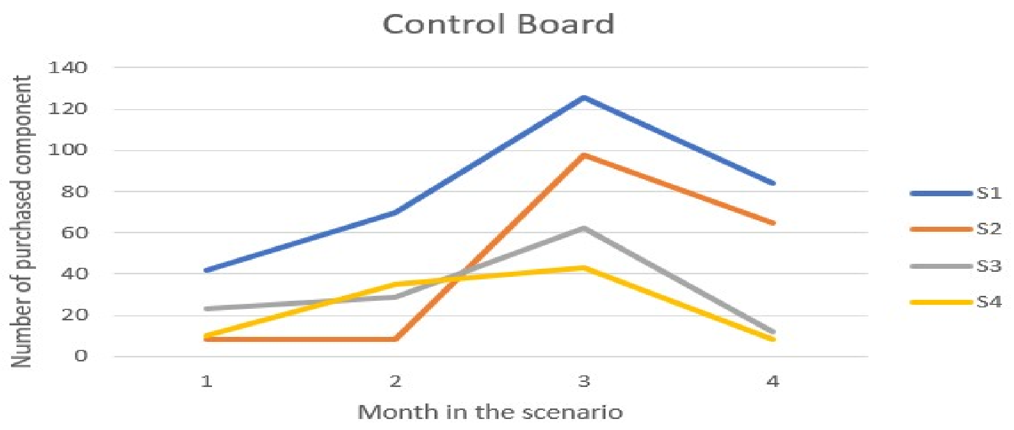

Figure 5.3: Number of control boards purchased

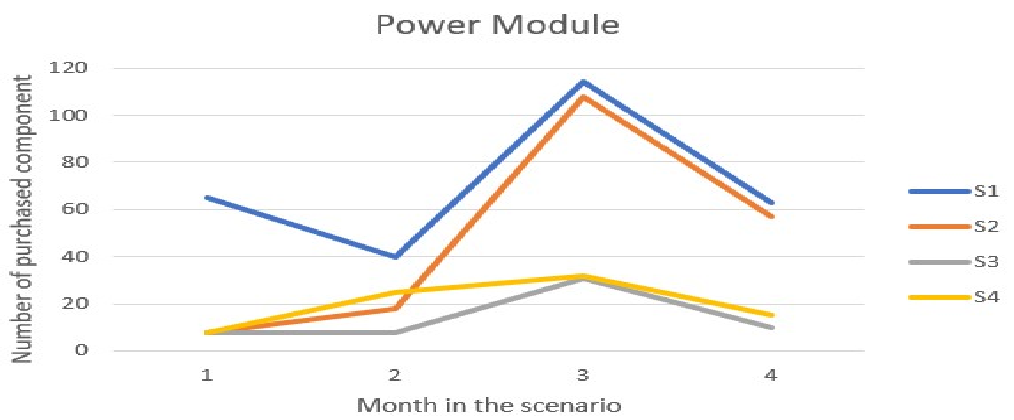

Figure 5.4: Number of power modules purchased

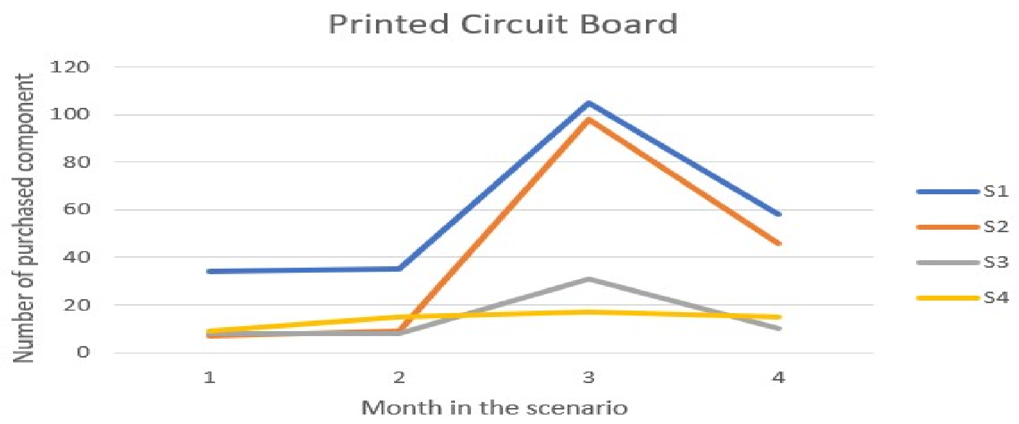

Figure 5.5: Number of printed circuit boards purchased

Figures 5.7 to 5.10 indicate the number of components that were routed as waste in the system. As expected, the system responded to the decrease in quality of returns by routing the most components as waste in the 4^{th} scenario. It is however interesting to

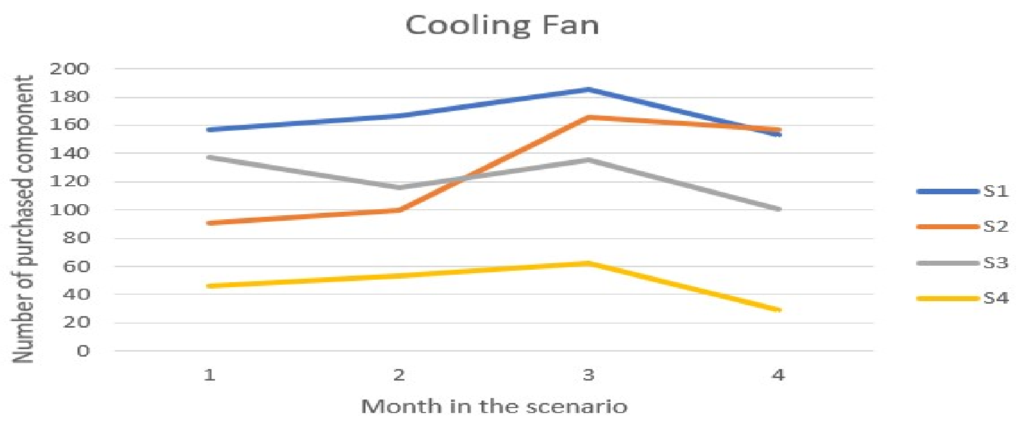

Figure 5.6: Number of cooling fans purchased

note that between scenarios 1 and 3, the trend in the number of wasted components was not consistent for the four key components. The next step in the research would be to include realistic component degradation functions in the models to study the changes in the trend of wasted components.

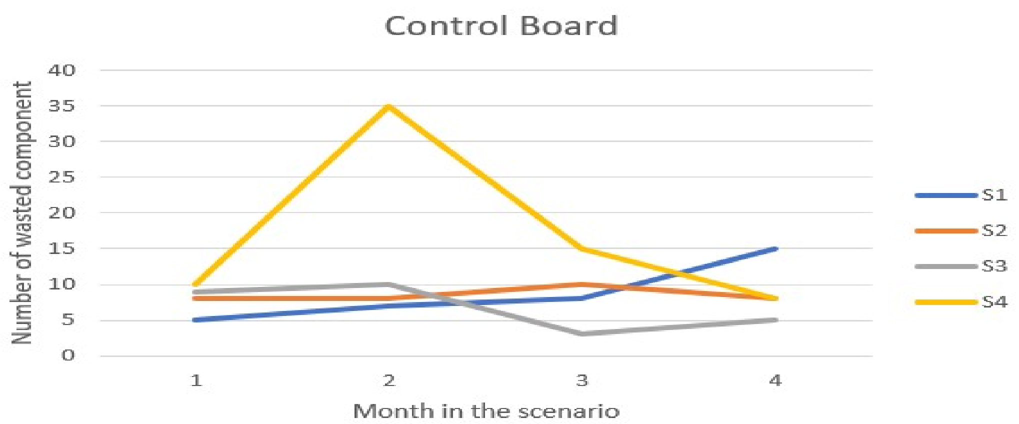

Figure 5.7: Number of control boards wasted

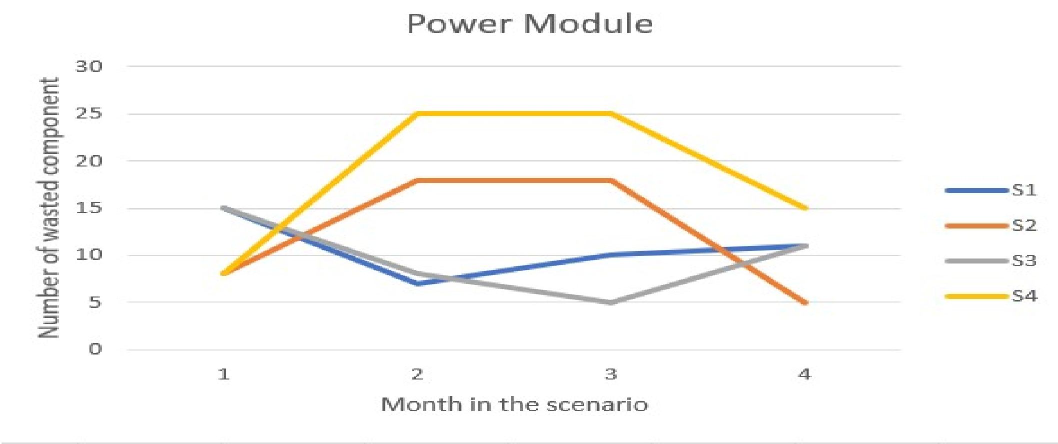

Figure 5.8: Number of power modules wasted

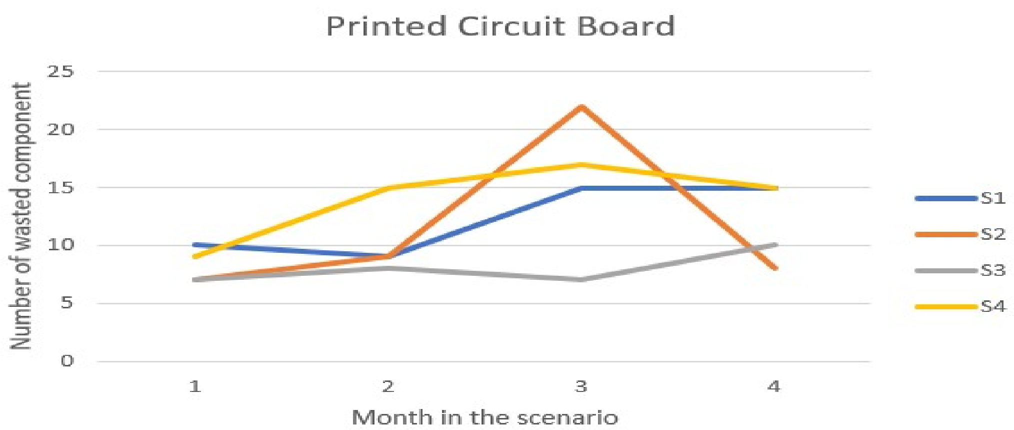

Figure 5.9: Number of printed circuit boards wasted

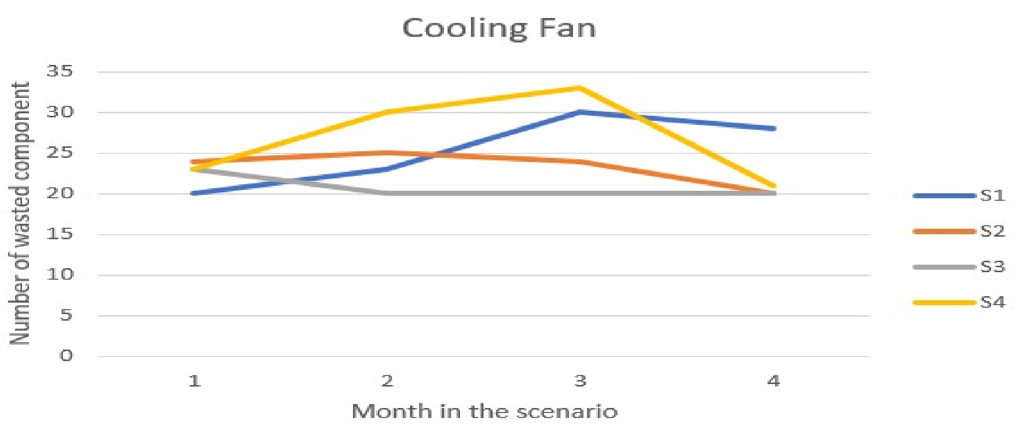

Figure 5.10: Number of cooling fans wasted

In a previous research by our team that was published in Farahani et al. (2020), the simulation was not set to enable an exchange of a good returned product of a higher quality with the lowest quality good returned product in the inventory. This was ac-

Table 5.1: Quantity of exchanged good returned product for 4 months in scenario 1 (E_p).

Months	1	2	3	4
CON 1	0	0	0	25
CON 2	0	2	13	0

Table 5.2: Quantity of exchanged good returned product for 4 months in scenario 2 (E_p).

Months	1	2	3	4
CON 1	0	2	0	14
CON 2	0	4	0	11

Table 5.3: Quantity of exchanged good returned product for 4 months in scenario 3 (E_p).

Months	1	2	3	4
CON 1	0	5	15	0
CON 2	0	11	0	3

Table 5.4: Quantity of exchanged good returned product for 4 months in scenario 4 (E_p).

Months	1	2	3	4
CON 1	0	0	0	0
CON 2	0	0	0	0

complished in this research and Tables 5.1 to 5.4 show the record of products that were exchanged. Considering that the good return inventory capacities of CON 1 and CON 2 were set at 210 and 500 respectively, the most exchanges for CON 1 (25 units, approximately 11% of the inventory) occurred in scenario 1 at T_4 There were exchanges done for both product types in scenarios 1 to 3. However, it is interesting to see that scenario 4 did not register any exchanges. This may be possible because of carry over inventory from scenarios 1 to 3, which had better quality than the incoming returns at scenario 4.

Figure 5.11 depicts the profit percentages for the four months in each scenario. First, we see that overall, the most profits were obtained during scenario 1, as a result, if increased quality of returns, while the lease profits were realized at scenario 4 which had the least quality of returns. This shows once again that higher profits are attained when products are remanufactured earlier at their end-of-life. The demand forecast for CON 1 and 2 were set in Table 4.6 where the range is between 198 to 225 with the lowest value at T3) for CON 1. For CON 2, the demand forecast ranges from 423 to 447, with the lowest value also at T3. Figure 5.11 shows that the profit trend follows that demand forecast trend for both product types. These results show that for the set conditions (the constant variables such as cost, taxes and purchase price), the demand generally has a higher influence on the remanufacturing system production plan.

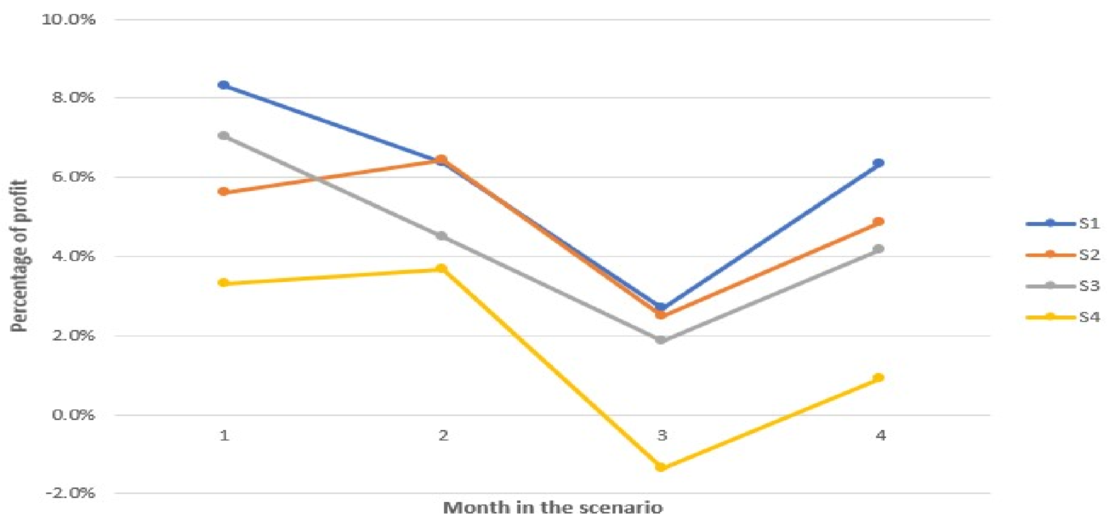

Figure 5.11: Profit comparison for each time period T (months) across four scenarios.

From the analysis of the total profit in the four scenarios, shown in Figure 5.12, the profit in scenario 1 is the highest as expected, due to the higher quality of returned products, closely followed by scenarios 2 and 3. However, the profit in scenario 4 is the least because at this point, the product's life cycle is close to the end, and the proportion of products that can be remanufactured is lowest. Therefore, finding the best time to remanufacture the product is most important for the remanufacturer because it directly influences the profitability of the system.

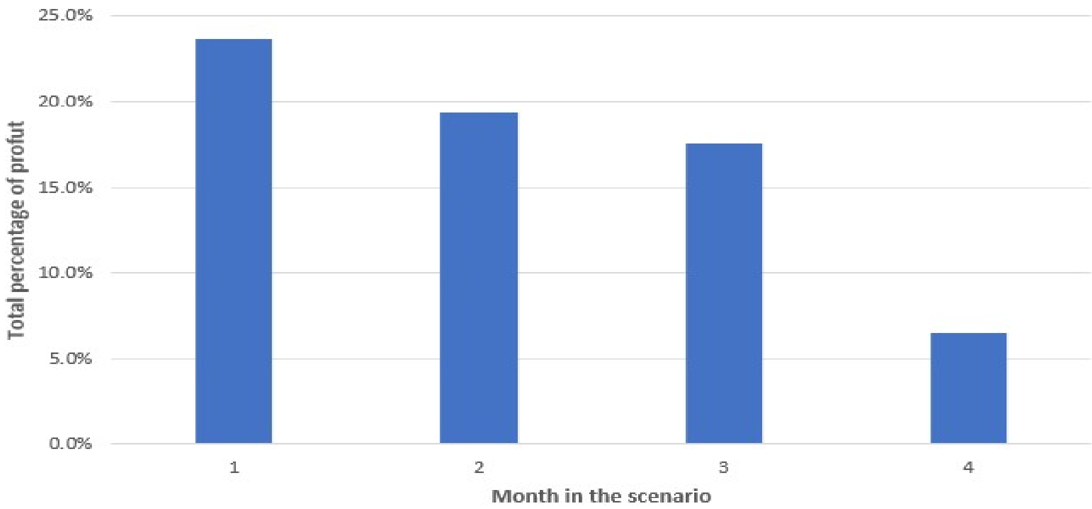

Figure 5.12: Total profits for each scenario.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In conclusion, this thesis presents the findings of a research study whose goal was to model a remanufacturing system that receives the end of life product returns from the customers. Once received, the returns are inspected and their quality classified from 0 (worst quality) to 1 (best quality), following a normal distribution. The remanufacturing system contains several capacitated inventories that have holding costs. The good return inventory houses return that have been cleared as meeting the threshold (minimum) quality acceptable for remanufacturing. This threshold quality in set a decision variable in the system which is reached at by maximizing the systems' profit. Therefore the threshold quality adopts the trade-off between the system and the system revenue. The system revenue includes revenue from sales of remanufactured products and government incentives for sustainable production. The system costs on the other hand include: cost of product acquisition, cost of remanufacturing, inventory holding costs, emissions taxes, cost of waste and cost of system starvation–when the system cannot meet the demand for remanufactured products. The results indicate that when the quality of the returned product is higher, the minimum acceptable quality level at the manufacturing site increases.

This study set out to answer three research questions. The answers to these questions in the context of the results from the case study can be summarized as follows:

- Is there an optimal resident time (time in the product's life cycle) to acquire products from customers that would maximize remanufacturing benefits?

  The percentage of accepted products for remanufacturing for scenarios 1, 2 and 3 are markedly different (higher) than the percentage of good returns in scenario

4. This is an indication that the resident time is indeed a significant factor to consider for any remanufacturing system. It is therefore important to understand the resident time in light of the product life cycle, and incentive product returns earlier in their end-of-life.

- To what extent do uncertainties in product return quantities affect remanufacturing process planning?

  We can see that the quantity of returned products in scenario 1 is the highest and Scenario 4 is the lowest. Considering the system profitability, Scenario 1 has the highest profit in the four scenarios. Therefore, we can infer that if the quantity of the returned product is higher, there is more opportunity to meet the demand in the secondary market, which directly affects the profitability of the remanufacturing process.

- Considering remanufacturing process costs and inventory capacity constraints, is there a threshold return admittance quality?

  Due to the limited capacity of inventory and the trade-offs between the system costs (inventory holding, remanufacturing, backlog and emissions) and revenue from the secondary market and green incentives, the threshold quality is reached at by the decision model, and is dynamic from one month to the other and also varies from one resident time scenario to the other. If the minimum quality to do the remanufacturing is too low, the remanufacturing cost will increase. Therefore, the remanufacturing system must set the standard quality of the returned product.

6.2 Future Work

Some of the suggested future work following this research include:

- First, a thorough sensitivity analysis to assess the impact of changing some constant variables on the profit as a percentage of the systems costs. These constant variables include the forecast quantity of returns, the forecast quantity of demand, the inventory capacities and their holding costs, the number of key components and the quantity required for each products type, the price of products in the secondary market, the government incentives as well as the taxes on emissions.

- Second, the proposed model assumed that the quality of the components are independent from each other, and the quality values were randomly and arbitrarily set for modeling purposes. There is need to include the actual component degradation in the model. This would be made more complex, yet more realistic if the degradation of these components may be dependent on each other.

- Third, it may be useful to track which of the new components that are purchased from suppliers are used in each component type, thereby determining if the may be variability in how much the remanufacture of each product type depends on the purchases from suppliers.

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Appendix

This section of the Thesis presents the results from scenarios 3 and 4, which are set to simulate returns on the fifth and sixth year after sales in the first market respectively.

Scenario 3: Figures 1 and 2 showing the quality distributions.

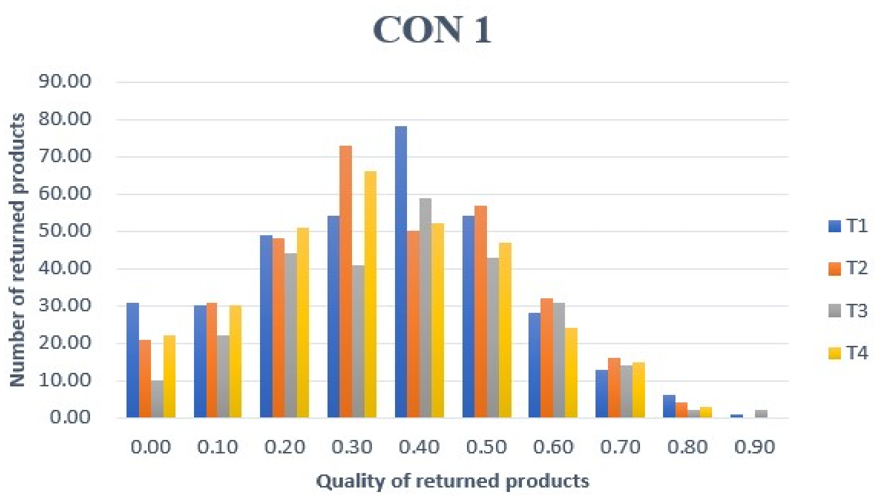

Figure 1: Con 1: Scenario 3 quality distribution of returned products.

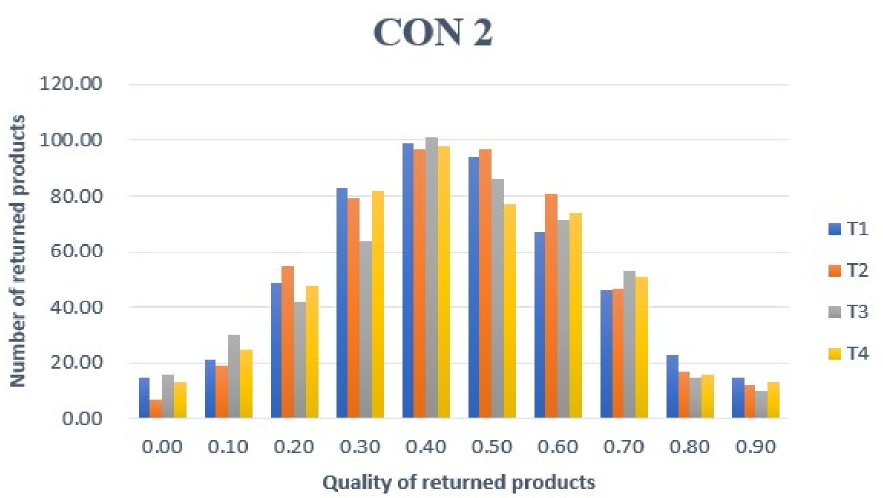

Figure 2: Con 2: Scenario 3 quality distribution of returned products.

Tables 1, 2, 3 present the minimum quality of returned products acceptable for remanufacture, the percentage of the returned products that are accepted into the good returned product inventory and the number of products that were rejected for remanufacturing and routed for disposal.

Table 1: Optimal minimum quality of product p to returned product inventory in scenario 3 (α_{pt}).

Months	1	2	3	4
CON 1	0.38	0.4	0.44	0.41
CON 2	0.26	0.29	0.26	0.27

Table 2: The percentage of good returned product in scenario 3.

Months	1	2	3	4
CON 1	55.8%	47.9%	47.8%	43.2%
CON 2	87.1%	85.7%	85.5%	85.7%

Table 3: Quantity of product p rejected to remanufacturing site and go to disposal in scenario 3 (Q^{-}_{pt}).

Months	1	2	3	4
CON 1	152	173	140	176
CON 2	66	73	71	71

Tables 4, 5 , 6 and 7 provide the actual sales number of remanufactured products, the number of remanufactured components, the number of purchase new components and the resulting profits respectively.

Table 4: Actual number of remanufactured product p sales to secondary market in scenario 3 (R_{pt}).

Months	1	2	3	4
CON 1	192	159	128	134
CON 2	446	438	417	426

Table 5: Quantity of remanufactured component c in scenario 3 (q^{+}_{ct}).

Months	1	2	3	4
CB	209	236	208	242
PM	203	227	206	236
PCB	211	220	204	225
Fans	261	299	262	298

Table 6: Quantity of purchased component c in scenario 3 (W_{ct}).

Months	1	2	3	4
CB	23	29	62	12
PM	42	8	43	13
PCB	8	8	31	10
Fans	137	116	135	101

Table 7: Profit of remanufacturing process in scenario 3.

Months	1	2	3	4
Profit	7.0%	4.5%	1.9%	4.2%

Scenario 4: Scenario four results are presented as follows:

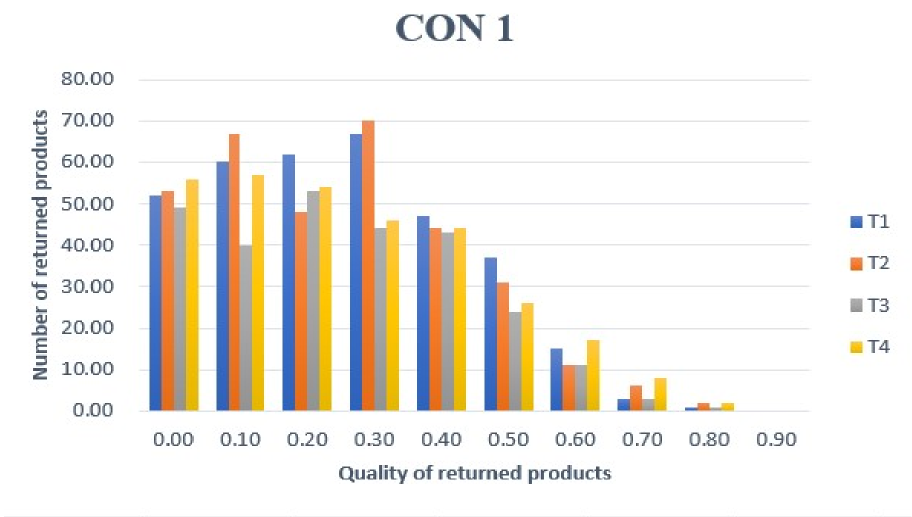

Figure 3: Con 1: Scenario 4 quality distribution of returned products.

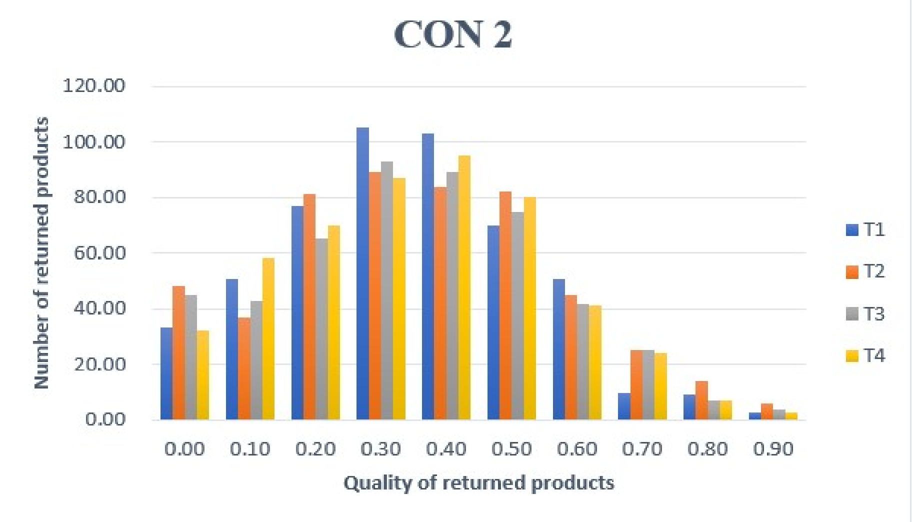

Figure 4: Con 2: Scenario 4 quality distribution of returned products.

Table 8: Optimal minimum quality of product p to returned product inventory in scenario 4 (α_{pt}).

Months	1	2	3	4
CON 1	0.25	0.25	0.25	0.25
CON 2	0.25	0.25	0.25	0.25

Table 9: The percentage of good returned product in scenario 4.

Months	1	2	3	4
CON 1	59.6%	54.2%	56.7%	55.1%
CON 2	76.9%	76.5%	74.1%	74.7%

Table 10: Quantity of product p rejected to remanufacturing site and go to disposal in scenario 4 (Q^{-}_{pt}).

Months	1	2	3	4
CON 1	139	152	116	139
CON 2	118	120	126	126

Table 11: Actual number of remanufactured product p sales to secondary market in scenario 4 (R_{pt}).

Months	1	2	3	4
CON 1	205	180	152	171
CON 2	394	391	362	371

Table 12: Quantity of remanufactured component c in scenario 4 (q^{+}_{ct}).

Months	1	2	3	4
CB	222	230	227	246
PM	237	210	217	234
PCB	210	213	218	220
Fans	352	362	335	370

Table 13: Quantity of purchased component c in scenario 4 (W_{ct}).

Months	1	2	3	4
CB	10	8	43	8
PM	8	25	32	15
PCB	9	15	17	15
Fans	46	53	62	29

Table 14: Profit of remanufacturing process in scenario 4.

Months	1	2	3	4
Profit	3.3%	3.7%	-1.4%	0.9%