Modeling and Analysis of a Hybrid Production System in Electronics Industries Using System Dynamics

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Abstract

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Industries Using System Dynamics

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Sustainable production has become a significant concern over recent years due to environmental considerations and material scarcity. Consequently, the closed-loop supply chain concept has been developed to reduce waste, decrease environmental issues, and maximize material utilization. Manufacturers attempt to add different recovery strategies to the traditional production system and close the forward production flow to create a closed-loop supply chain. In this research, a hybrid production system applied in an electronics manufacturing company is studied. Two recovery strategies, remanufacturing and recycling, are considered to make a hybrid production system. Although remanufacturing and recycling are recognized in the literature as promising recovery strategies, the profitability of using them for the manufacturers is still controversial. This research presents a system dynamics model addressing the analysis of a hybrid production system in an electronics manufacturing company. The objective of the system dynamics simulation is to evaluate impacts resulting from using remanufacturing and recycling on two critical parameters, including total profit and cost per unit. For this purpose, the model is run using parameters and information related to a laptop manufacturing company to compare production scenarios, evaluate the system performance in terms of economic benefits, and provide insights for policymakers for designing policies that align with the manufacturers' benefits.

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CHAPTER 1 INTRODUCTION AND MOTIVATION

This chapter proposes a summary of the performed research in the thesis. First, the closed-loop supply chain and two main recovery strategies are described. Then, the problem's motivation is discussed. In the end, we provide our contribution to the discussed issue.

1.1 Introduction

Environmental concerns and respective government regulations, and on the other hand, the problem of raw material limitation from an economic perspective, has entailed manufacturers to focus on sustainable manufacturing more than ever. As a result, they attempted to use product and material recovery strategies to close the production supply chain's forward flow. Consequently, the Closed-Loop Supply Chain (CLSC) idea was established to create value over the product's whole life cycle. Considering what is issued by the United Nations, the Electronic Waste (E-waste) amount will be risen to over 52 million metric tons by 2021 (Aboelmaged, 2021). Statistics show 20% of Canadians household waste in the year 2017 was related to unwanted computers that only 9% of them were returned to the manufacturers or collection centers responsible for the E-waste treatment (Statistics Canada, 2019). The hazards of discarded e-waste to the environment, also their precious and scarce materials have forced their treatment a challenging but attractive issue for policymakers. Maximization of resource utilization and reducing hazardous material impacts are possible through recovery strategies (Zhang et al., 2020). There are several kinds of recovery strategies, such as remanufacturing, reuse, refurbishment, and recycling. These strategies are different from each other, and in selecting them, factors such as the condition of return products and factory objectives must be regarded. Manufacturing industries require to increase their ability to select recovery strategies that align with profitability. In this research, a hybrid production system including remanufacturing and recycling in electronics industries is studied. A system dynamics (SD) model is used to make informed decisions about the production system's future through modeling the system's behavior throughout time.

1.2 Manufacturer performance modeling and system dynamics

Remanufacturing and recycling are among promising recovery strategies used by manufacturers in the supply chain of electrical and electronic products to form a CLSC. Remanufacturing and refurbishing are incorrectly used interchangeably on some occasions while they are entirely different. The output of the remanufacturing process is a kind of product with high quality close to the quality level of new products, while the quality of refurbished products is less than new products.

Recycling offers recovered materials from worn out and non-operating products through sorting, disassembly, shredding, and separation processes. More value is captured for the manufacturer in remanufacturing process compared to recycling (Tan et al., 2014).

Remanufacturing is defined by Wang et al (2014) as a process to recover used products and sell them as good as new products in the same or separate markets. According to what Krystofik et al (2018) believe, remanufacturing in a hybrid production system generates profit through material cost reduction and complementary revenue flows. Although remanufacturing is a profitable recovery strategy, it cannot be used in some conditions. Remanufacturing is not practical in all cases due to the low quality of returned products and remanufacturing impacts on production systems variables. Profit generation through recovery strategies in hybrid production systems is a critical issue from the manufacturers' perspective; therefore, applying an approach to study the behavior of the production system and predict profit in different production scenarios over time is necessary. Using different recovery strategies in any hybrid production system makes more complexity and interrelations in the production system that could be studied by system dynamics modeling.

System Dynamics (SD) simulation was introduced by Forrester in the 1960s as an approach in dynamic management problems to increase the utilization of systems (Georgiadis & Besiou, 2010). System analysis for system components when they are highly interdependent is possible through SD modeling. Indeed, the causal relationships are identified and modelled to show the effect of changing the system's components on the system's future behavior.

1.3 Motivation

In recent years, a question regarding hybrid production systems (including recovery strategies besides traditional manufacturing) has been raised among original equipment manufacturers (OEM). Indeed, they are concerned about whether using the recovery strategies is beneficial over time and how they generate more profit. Original manufacturers first require knowing the most appropriate recovery strategies from an economic perspective and then how to combine them to make more profit. Mohamad-Ali et al. (2018) articulated economic factors such as recovery cost and generated revenue as important influences to attract manufacturers and the other stakeholders' attention to establish recovery strategies. Therefore, it is necessary for manufacturing companies that are applying a hybrid production to predict estimated profit resulting from using the recovery strategies. In other words, it is crucial in hybrid production systems to find the best production strategy and analyze the manufacturer performance under the different production scenarios over time.

1.4 Contribution

This study proposes a system dynamic model associated with electronics industries when they use remanufacturing and recycling in addition to traditional manufacturing operations. In our model, two recovery strategies are added to the conventional production system to observe what would occur for critical variables over time after considering the strategies. Moreover, the comparison of different production scenarios is possible through dynamics simulation.

Most literature concerning recovery strategy decision-making methods is related to mathematical optimization methods, but they have not been effective in some practices due to the complexity of mathematical models and many input parameters (Alamerew & Brissaud, 2019). The developed system dynamics model provides an insight into selecting the best profit-oriented recovery strategy and predict each production scenario's impacts on the production system variables at any given time. The main purpose of the model is to design an optimal strategy under which the company could respect government regulations and its own financial goals.

1.5 Outline of thesis

The next chapter discusses available literature concerning CLSC, remanufacturing, recycling and system dynamic modeling. A causal loop diagram, as well as an SD model, are presented in chapter 3. Moreover, in chapter 4, we perform different scenario analyses and evaluate the system's performance under the scenarios. Also, an optimal strategy is suggested. Finally, chapter 5 summarizes the thesis and offers a conclusion.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Sustainable production has become a significant concern over recent years. Many practitioners and scholars worldwide attempted to seek sustainable actions and solutions for different kinds of industries. As a result, the Closed-Loop Supply Chain (CLSC) concept emerged to create value over products' entire life cycle. For this purpose, various End-Of-Life (EOL) product strategies were deployed.

In the literature, three sustainability dimensions, environmental, economic, and social, have been studied regarding EOL policies. Remanufacturing and recycling are among the most promising EOL strategies used to reduce waste and decrease environmental issues; however, still, there is a controversial debate regarding the profitability of these actions. Profitability can vary from different industries and different case studies. Many researchers efforted to analyze the potential profitability of remanufacturing and recycling by applying various methods. This chapter first presented a literature review related to CLSC and two EOL strategies, remanufacturing and recycling. Then, we summarized highlighted studies regarding EOL electrical and electronic products. Finally, we focused on system dynamics modeling and its application in CLSC.

2.2 Sustainable Manufacturing

Sustainable manufacturing has attracted the attention of many researchers in recent decades. This attraction's main reason is public perception development on end-of-life products' unsustainable disposal practices (Ngu et al., 2020) Sustainable manufacturing is defined in different ways and from various perspectives, but all definitions are environmental, economic, and social aspects.

Many strategies were developed to achieve sustainable manufacturing and to satisfy sustainability requirements. Johari and Hosseini-Motlagh (2019) believed that recycling, re-selling and reusing efforts are all activities performed align with environmental sustainability. Also, remanufacturing is discussed by Vogt Duberg et al. (2020) as a sustainable strategy added to the original equipment manufacturer (OEM) business to maximize profit by waste utilization. Some manufacturing firms pursue the mentioned production activities such as recycling and remanufacturing and those associated with the forwarding supply chain in their production system. Applying this kind of activity has led to the formation of a closed-loop supply chain (CLSC). According to Rezaei and Maihami (2020), the concept of a CLSC is introduced to provide a sustainable manufacturing strategy to integrate forward and reverse logistics to optimize profit and fulfilling sustainable goals simultaneously.

2.3 Closed-Loop Supply Chain (CLSC)

Raza (2020) describes the traditional supply chain as a forward supply chain, including all possible stakeholders such as suppliers, manufacturers, distributors, retailers, and customers when connected and make some processes to satisfy consumer needs. Although The traditional supply chain does not have any responsibilities for returned products, the reverse flow attempts to recover or dispose of EOL products by applying environmentally friendly measures (Govindan & Soleimani, 2017). The reverse flow occurs in collecting EOL products and then retrieving them through recovery actions such as recycling and remanufacturing. Finally, the recovered materials, components or products are returned to the forward flow (Meng et al., 2020). Value recovery is possible through recovery measures in the reverse flow. EOL products or components return to the forward flow (production system) exactly where the forward and reverse supply chains are linked.

The concept of CLSC is evolved from the integration of reverse and forward flows (Islam & Huda, 2018). Recycling and remanufacturing procedures are considered essential concepts in CLSC. Firms can recuperate the value of waste products across remanufacturing and recycling measures (Long et al., 2019). Closed-loop supply chain management is about design, control and all actions related to a system that are performed to increase value generation over the entire life cycle through recovery operations over time (Yacan Wang et al., 2020).

2.3.1 Remanufacturing

Rapid technological advancements and the expanding desire of customers to achieve the most recent technology make the life cycle of existing products shorter. The shorter life cycle has led to an increase in EOL products. As a result, extensive environmental issues such as environmental pollution have been detected in recent decades. Many sustainable operations are suggested for manufacturing firms in different industries. According to the available literature, remanufacturing is the most commonly employed action. This section reviewed the concept, challenges, and a quick summary of remanufacturing literature.

Lee et al. (2017) described remanufacturing as a sequence of activities that allow discarded products to be returned to the market as new products. The required operations are disassembling, inspecting, cleaning, repairing, replacing, and reassembling. Remanufacturing requires fewer resources and efforts than the other recovery strategies (Barquet et al., 2013).

Lee et al. (2017) listed the recent literature on remanufacturing according to the various perspectives. They recorded environmental and economic, marketing, and reverse logistics issues among managerial concerns.

2.3.1.1 Production planning and design concerns

The remanufacturing procedure is complicated due to the uncertainties in quality, quantity, arrival time, and EOL product design. These uncertainties arise from the uncertain nature of the product life cycle. Indeed, this can affect the rate of return (Guide, 2000).

Production planning and control (PPC) will be more challenging when there is a hybrid production system, including manufacturing and remanufacturing modes. PPC should help managers coordinate and control the production of alternative sources to manage inventories, resources, and utilization efficiency. Assid et al. (2019) investigated the PPC problem for a hybrid production system. This study aimed to offer better production and control policies when there is an unreliable production facility in a stochastic and dynamic environment. As a result of this environment, it is necessary to take set up actions each time to shift between manufacturing and remanufacturing. The used approach was the combination of optimization and simulation to develop the best production and setup control strategy concerning costs. The researchers compared the impacts of a wide range of system settings on the optimal control factors. An appropriate design can mitigate many potential barriers in remanufacturing. Indeed, design features can ease the remanufacturing process. The role of designing products that are more re-manufacturable is the responsibility of OEMs.

2.3.1.2 Marketing concerns

One of the challenges of remanufacturing is marketing and selling remanufactured products when there is no clear right perception of these kinds of products among consumers (Hazen et al., 2017). Singhal et al. (2020) attempted to investigate customers' willingness to purchase remanufactured products. They considered the effects of personal attitudes (micro-level) and macro-level factors on customer behavior. Three practical factors on customers' intention are examined in this study, price as a push factor, government intensive and environmental advantages as pull factor (refers to macro-level), and attitude as mooring factor. The research tested this hypothesis that new product price is positively linked to moving toward remanufactured products. As a result of testing the hypothesis, the authors suggested it is more likely for customers to switch to remanufactured products if they realize that the new products' price is high.

Similarly, the environmental benefits of purchasing remanufactured products affect customer adoption if they have genuinely perceived them. The authors used a questionnaire and used hierarchical regression and reached this result: Customers' attitudes on remanufactured products are positively related to shifting intentions and moderate the impacts of environmental benefits and government incentives and price. Moreover, the researchers noted that attitude was found to moderate the relationship between recognized environmental benefits and shifting.

Papachristos (2014) believed that although both the original equipment manufacturer (OEM) and third-party can perform remanufacturing, the customers' willingness to buy the OEM remanufactured products is more than for the remanufactured products by the third parties due to customers trust in OEM. They explored a supply chain when an OEM competes with a retailer in responding to the market needs by producing remanufactured and new products. They studied the impacts of response strategies for OEM by developing a system dynamics model. Moreover, they attempted to observe whether the strategies are consistent with the supply chain's environmental performance. Their work showed that the OEM could not compete in the market well and profit when it handled its actions persuading environmental goals.

To address this issue, the trade-off between competitiveness and environmental considerations must be considered, and OEM needs to reconsider terms of competition with the retailers. It is suggested for OEMs to cooperate with the retailers in remanufacturing or establish an effective decentralized recycling network to continue recycling and use of obtained material close to the point of collection.

2.3.1.3 Returned products and reverse logistic concerns

Singhal et al. (2020) considered an effective reverse logistics system a crucial factor of successful remanufacturing. They stated that this is the remanufacturer and government's responsibility to develop efficient collection channels. They should both attempt to inform customers about collection centers.

Since the remanufacturing process's raw materials are from returned products, providing an appropriate collection method and easy accessibility to returned products play an essential role in the remanufacturing process. Uncertainties in both aspects, quantities and qualities of returned products, are being studied in the relevant literature. Raihanian Mashhadi et al. (2015) stated that variations in quality, quantity, and market demand for returned products affect remanufacturing's cost-effectiveness. They focused on uncertainties regarding remanufacturing returns, such as the quality, quantity, and arrival of returns. The authors introduced a stochastic optimization model to make better decisions concerning the most profitable upgrade level for incoming EOL(s). The application of the model is presented by an illustration of a computer returns with five different quality grades. Finally, the researchers solved the model using the chance-constraint programing method and proposed the optimized upgrade strategy.

2.3.1.4 Environmental and economic concerns

The sustainable approach regards social and environmental impacts and economic benefits in deciding. Sustainability is commonly considered each firm's responsibility; this means that every part of the supply chain optimizes its operations despite its effects on others. A more comprehensive approach is required to optimize the entire supply chain's performance (Sarkar et al., 2017). Firms can gain economic and environmental benefits from remanufacturing activity if they apply the correct measures at the right time.

Many scholars discussed the potential benefits of remanufacturing. According to the relevant literature, some research presented that remanufacturing leads to more profits and reduced total environmental impacts. However, some scholars revealed contrary results.

Sarkar et al. (2017) developed an analytical model to assess remanufacturing's economic and environmental impacts. They focused on a green supply chain that included a single vendor and multi retailers to reduce environmental effects and improve resource utilization. A hybrid manufacturing remanufacturing system was examined. The solved model provided optimal order quantity from the size of the container, retailers, cycle time, and shipment schedule for different retailers. Finally, a hybrid policy was stated as optimal. The results showed that transportation and emission costs have severe effects on the remanufacturing rate. The result of their work showed that remanufacturing is usually a remarkably advantageous action from an eco-efficiency view. According to this research, remanufacturing increases the firm's benefits, and in most cases, it can decrease environmental effects. Although in some tested cases in the paper, negative environmental impacts were observed due to the negative effective cannibalization. Overall, the authors encouraged remanufacturing as an efficient way to touch both the economic and environmental goals of the firm.

On the other hand, Bagalagel and ElMaraghy (2020) discovered a contrary result in remanufacturing profitability. They developed a mathematical model to obtain the optimum number of products in a hybrid manufacturing-remanufacturing system to maximize its profit. They analyzed three different remanufacturing scenarios by solving the mathematical model. Finally, they discovered that the firm's net profit when there is a portion for remanufactured products was significantly less than the scenario with no amount of remanufactured products. Several studies focused on the potential environmental benefits of remanufacturing; most of them are case-based and attempted to assess environmental impacts.

Ardente et al. (2018) introduced a comprehensive systematic method, a life cycle assessment approach, to assess the environmental effects of remanufacturing activity. The method assisted in analyzing possible trade-offs among potential environmental impacts and energy efficiency. Indeed, it evaluated all life cycle stages of remanufactured products compared with a new product. The authors used the environmental effects of a product's life cycle stages as input parameters. The result of a proposed case study of an enterprise server showed that the remanufactured servers have lower environmental impacts even when they are less energy-efficient compared to new products.

2.3.2 Recycling

Different decisions can be made for the collected EOL; recycling is one of the potential choices providing more raw material and raw parts (Golroudbary & Zahraee, 2015). Different methods, such as melting the material, are used to restore the material through the recycling process (Noman & Amin, 2017). Bringing used products to the market through recycling activity offers customer and environmental benefits to OEM. Also, it can decrease their production cost. Manufacturers can save between 40% to 60% of the cost while paying for only 20% of the manufacturing work than traditional production (Habuer et al., 2014).

2.4 Electrical and Electronic products Waste Management

Nowadays, electrical and electronic EOL(s), titled E-waste, is among the most critical environmental issues worldwide (Habuer et al., 2014).The growing amount of E-waste, especially from ICT (Information and Communication Technologies) products, arose from rapid technological developments and innovations that lead to a shorter life span (Jayaraman et al., 2019). As a result of declining electronics product life span, growing consumer desire, and swift innovation cycles, it is anticipated that the world faces a massive increase in waste generation and material utilization in the future (Althaf et al., 2019). United Nations published a report indicating that the E-waste quantity would increase to more than 52 million metric tons by 2021 (Aboelmaged, 2021).

Many governments have enacted regulations to force producers to adopt strategies in this area. Therefore, in many countries, producers are financially and physically responsible for managing and treating end-of-life products (Islam & Huda, 2018). Recovery measures could effectively decrease the environmental effects of ICT waste (André et al., 2019).

2.4.1 E-waste recycling and remanufacturing

Although EOL EEE (Electrical and Electronic Equipment) contains valuable and rare materials, it can be a major threat to the environment if it is not controlled or properly processed. Many substances in EOL EEE are potentially hazardous to the environment, such as lead (Pb), mercury (Hg), cadmium (Cd), nickel (Ni) and so on (Habuer et al., 2017). Recycling e-waste can cut the amount of harmful waste and recover valuable metals to produce new electronic products (Arain et al., 2020).

WEEE (Waste Electrical and Electronic Equipment) recycling is challenging in containing different hazardous materials such as cadmium, lead, and even some restricted materials; however it could be economically and environmentally valuable (Gonul Kochan et al., 2016).

According to what the EPA (The Environmental Protection Agency) issued, saving energy from recycling one million laptops is equivalent to using more than 3,500 US homes in one year (Gonul Kochan et al., 2016).Sustainability must be considered in E-waste recycling. It is possible by establishing an efficient E-waste recycling system, and in this way, the recycling process can be advantageous to the environment and public health (Miao et al., 2017).

Remanufacturing is one of the most suggested recovery strategies in the literature, especially for discarded electronic products. Tan et al. (2014) believed that remanufacturing provides considerable economic and social benefits, even if the remanufacturing operation handles a small portion of E-waste. The concept of E-waste has been highlighted in academic studies since 2004 due to theoretical concerns about the cost and benefits of cell phone waste and customer attitude to the recovered products (Aboelmaged, 2021).

The literature concerning RL and CLSC of E-waste was categorized by Islam and Huda (2018) into different main topics: designing and planning RL, decision-making and performance assessment, and qualitative research. The following section focuses on the studies associated with decision-making concerns and performance evaluation due to the similarity with the research topic. Making an appropriate decision on EOL strategy selection is one of the critical actions in CLSC. To this end, Ma et al. (2018) employed an approach combination of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and fuzzy logic to create a decision-making framework. The comprehensive decision-making tool used fourteen evaluation criteria focusing on sustainability dimensions to assess seven EOL strategies. A refrigerator was applied as an example to find the best EOL strategy for each product's components. Finally, reuse, remanufacturing, primary recycling, and secondary recycling were suggested as the most appropriate EOL strategies for the refrigerator case study.

The research conducted by Yang et al. (2016) offered a holistic decision support tool to assist EOL strategy planning. The focus of the study was on remanufacturing strategy. To illustrate the proposed decision-making approach, the authors used two types of desktop phones. First, the checklist method was used to evaluate the possibility of performing remanufacturing for the products and their components. The study then provided an optimization model to determine the Pareto set of optimal EOL strategies related to maximum economic profit and environmental impacts. The genetic algorithm was applied to perform quick calculations regarding the set of EOL solutions. Finally, a sensitivity analysis was performed to detect the impacts of situational variables on EOL strategies. The results presented that the remanufacturing operations related to business IP telephone had economic and environmental benefits. Indeed, the EOL strategy could save 86% of the business telephone's embodied energy, while only 15% of the product energy could be reserved for the second type, the consumer telephone.

Habuer et al. (2017) introduced a decision-making framework to select the best recovery measure. Deciding on whether recovery measure is the best option depends on two main factors, profitability and environmental impacts. According to the framework, price, cost, and market demand affect profitability directly. Factors such as return volume and product condition are influential on cost; therefore, they indirectly affect profitability.

Zhang et al. (2020) studied the effects of the policy concerning government funds on CLSC decisions. For this purpose, they studied CLSC of WEEE involving a manufacturer, a recycler third party, and a retailer. The role of the manufacturer was both manufacturing and remanufacturing. Also, it could permit the retailer to remanufacture discarded WEEE products. Four dynamic Stackelberg game models of the CLSC were developed to address how the government fund policy influences decisions related to CLSC, remanufacturing modes and gained profits of each part of the CLSC. Finally, the authors noticed that the manufacturer remanufacturing mode could be better for all CLSC parts in the absence of government fund policy. On the contrary, the retailer remanufacturing mode is the best option in the presence of government fund policy.

2.5 System Dynamics (SD)

Forrester introduced system dynamics at the Massachusetts Institute of Technology in the 1960s. This approach, including simulation and modeling, helps policymakers make long-term decisions in the Industrial management area (Chaudhary & Vrat, 2020). The objective of SD methodology is to analyze and conceptualize the behavior of the complex systems in the presence of feedback loops, auxiliary variables, stocks, and flows (Giannis et al., 2017).

Moreover, seeking policies to improve the system performance is another objective of SD methodology. Policies are defined as strategic long-term decision procedures applied by top management (Vlachos et al., 2007). It is possible to recognize the causes behind the behavior of the system by using system dynamics (Georgiadis & Besiou, 2010).

To summarize the application, SD is typically used to perceive how and why the dynamics of concerns are created and seek improvement policies to boost the system performance (Vlachos et al., 2007).The available literature on studies performed in the past decade demonstrates an interest in modeling supply chains by applying the SD approach. Still, most of the researches are related to the traditional supply chain (forward supply chain) (Das & Dutta, 2016). Many researchers attempted to apply mathematical modeling in CLSC and focused on optimization. Georgiadis and Besiou (2010) believed that optimization is associated with static and free of feedback problems.

Many problems of CLSC are dynamic, and they need to use approaches considering feedbacks and continuous time.

2.5.1 Application of SD in CLSC and reverse supply chain

Although there is still a necessity to study the traditional supply chain to design more efficient systems and optimize the current forward activities, the most recent studies' primary focus is CLSC. Indeed, CLSC has highlighted more than the traditional supply chain in recent years. This section attempted to summarize studies performed on the application of SD in CLSC. Mostly those studies which are emphasized remanufacturing and recycling operations as recovery strategies.

Some scholars attempted to use SD in CLSC management matters to provide insights for decision-makers and policymakers dealing with long-term strategic issues. Vlachos et al. (2007) developed an SD model to assess different capacity planning policies concerning CLSC of a single product, including supply, production, distribution, collection, and remanufacturing activities. The authors recommended leading capacity strategies to balance the trade-off of market share maximization and utilizing capacity more. Moreover, the research revealed the negative effect of green image on the supply chain's total profit.

Poles and Cheong (2009) studied the impact of returns rate on the total production cost in a single product CLSC, including remanufacturing. Uncertainty in quantity and EOL(s) arrival time were investigated in the research. To this end, the researchers considered two variables, residence time and return index. According to the results, product characteristics and customer behavior significantly affected total production costs by influencing the returns rate. Finally, the authors suggested that policymakers focus on product design and encourage customers to return the used products using incentives.

Poles (2013) considered total system capacity, inventory coverage, manufacturing and remanufacturing lead time in an SD model of a system concerning production and inventory of in a CLSC. The major objective of the research was to investigate the dynamics of remanufacturing process to provide production system improvement strategies. The results presented that higher capacity allocation to remanufacturing causes a rapid increase in the total system cost. Moreover, it has shown that more system efficiency is possible through an increment in remanufacturing capacity and a decrement in remanufacturing lead time. It was notable that changing manufacturing lead time has a significant impact on the system efficiency compared to alter remanufacturing lead time.

Yixuan Wang et al. (2014) extended boundaries of the SD model related to CLSC. They added four different types of subsidies allocated to remanufacturing and recycling to the model to investigate the behavior of the system. The quantity of collected re-manufacturable products, the quantity of remanufactured, and remanufacturing production speed were used to study the impact of subsidy policies on recovery strategies such as remanufacturing and recycling. To this end, the authors developed different scenarios by using individual subsidy policies and mixed policies.

Ghisolfi et al. (2017) designed a system dynamics model to examine the effect of the Brazilian Solid Waste Policy and bargaining power to formalize waste pickers. The sustainability of the CLSC, including desktop computers and laptops, was studied by considering recycling as an EOL strategy. According to the result, the formalization of waste pickers is possible even without bargaining power. It happens because of legal incentives.

Das and Dutta (2016) developed an SD model for CLSC to analyze the effectiveness of incentive offers, particularly the incentive offer on customer satisfaction and profit. The researchers first established a recovery structure for CLSC, which obtains the probability of returning EOL(s) according to the assigned incentive amount. The developed recovery structure is then used for modeling the demand function for new products on the forward flow and return function of the EOL products in the reverse channel by considering the incentive. Finally, the authors incorporate the structure to the SD model of the multi-period CLSC. The simulation results showed that the demand for the new products, collection rate, and the average total profit of CLSC was increased after including incentive offer to customers. The research suggested a trade-off between the more revenue resulted from remanufacturing and the cost of collection. Statistical tools and sensitivity analysis were employed to study the importance of critical factors, their interactions, and their effect on profit and performance of fill rate.

The research ends by comparing the total profit of CLSC in two different scenarios; first, when there is an incentive for returning the used products. At the same time, the other scenario focuses on profitability in the absence of the offer.

Some researchers efforted to study the competition between different OEMs or OEMs and third parties and retailers in remanufacturing and selling recycled or remanufactured products. Miao et al. (2017) designed an SD model to assess the competitiveness behavior of two corporations in the UK while recycling and remanufacturing their household appliances in different recycling ways. They tried to explore two recycling modes' impact on the supply chain's market share and total revenues. In other words, the authors examined the effects of recycling strategies and modes on corporations' competitiveness by comparing two recycling modes employed by two corporations. One of the recycling modes associated with Midea Crop considered the third party's role for recycling and disposing of EOL products.

On the other hand, retailers lead the different recycling mode. It means that the retailers are responsible for recycling E-waste and selling the products, while the manufacturer is only obliged to manufacture and remanufacture. According to the SD simulation results, the supply chain's total revenue increased by enhancing environmental awareness in specific areas and increasing third parties' coverage points.

Various scenarios were simulated in Chaudhary and Vrat (2020) research to review the critical internal policy variables such as gold reserve, the efficiency of the organized collectors, recovered gold from e-waste and sustainability index. The researchers defined scenarios by changing the initial value of demand for cell phones and the organized sector. According to the model, recycled gold from EOL cell phones can supply gold for manufacturing new cell phones. As per the result, the efficiency of the organized sector is critical for the accomplishment of the circular economy. When it increases leads to an increase in sustainable benefits. Expanding the collection capacity of organized players enhances collection efficiency.

2.6 Study Gap

The primary focus of the studies performed on recovery policies is about environmental aspects of them. According to what we described in previous sections of this chapter, some scholars attempted to consider the economic element on the entire CLSC or the competition issues between OEM and third parties. Still, there is a question regarding the profitability of remanufacturing and recycling for different industries and cases, particularly the profitability of OEM in CLSC. To address this question, there is a necessity to employ a comprehensive approach to analyze the long-term financial trends of an OEM.

Moreover, according to the research conducted by Govindan and Soleimani (2017) eighty-three papers were selected from one of the most functioning journals in this area, the Journal of Cleaner Production (JCP), from 2001- 2015. The authors classified the papers according to the research problems' major topic. They noticed that decision-making and simulation are from research topics in RL studies that still require work on them. According to our knowledge, the number of published papers in this area still is low in recent years.

Lastly, many studies concerning making EOL strategy selection are qualitative analysis, and there is a lack of quantitative EOL strategy decision-making approaches in the relevant literature (Ma et al., 2018).

This research attempts to apply SD modeling to perceive interconnected components in the production system after using two recovery strategies, remanufacturing and recycling. Indeed, the behavior of the production system could be examined by using this approach. Moreover, the developed model helps top managers make reliable long-term decisions about using the recovery strategies to generate more profits.

CHAPTER 3: PROBLEM DESCRIPTION AND MODEL DEVELOPMENT

In this chapter, details of designing system dynamics modeling in a hybrid production system are studied. We explain the general definitions and concepts used in this problem. Moreover, we explore relationships and interactions of variables in the production system when integrated with remanufacturing and recycling processes. In the end, we offer a developed SD model.

3.1 Problem description

In this research, a hybrid production system concerning an electronic manufacturing company is studied. Remanufacturing and recycling are added to the current supply chain (forward flow) to close the loop. The CLSC that is created using the recovery activities is assumed to be an ideal CLSC. Asif et al. (2012) believed that a perfect form occurs when the remanufacturer is OEM or an authorized third party. The distribution channel and the market of remanufactured products and new products are the same. Therefore, the price of one set of remanufactured components (equal to one unit of the product) is the same as one unit of the new product. In other words, there is no difference between new products and remanufactured products that are considered as good as new. EOL products are collected by a third party that is not considered in this problem's system boundary. We assumed that the returned products are from the same model and brand, and they should have manufactured by the company. Figure 3.1 is an overview of the hybrid production system which is being discussed in this research.

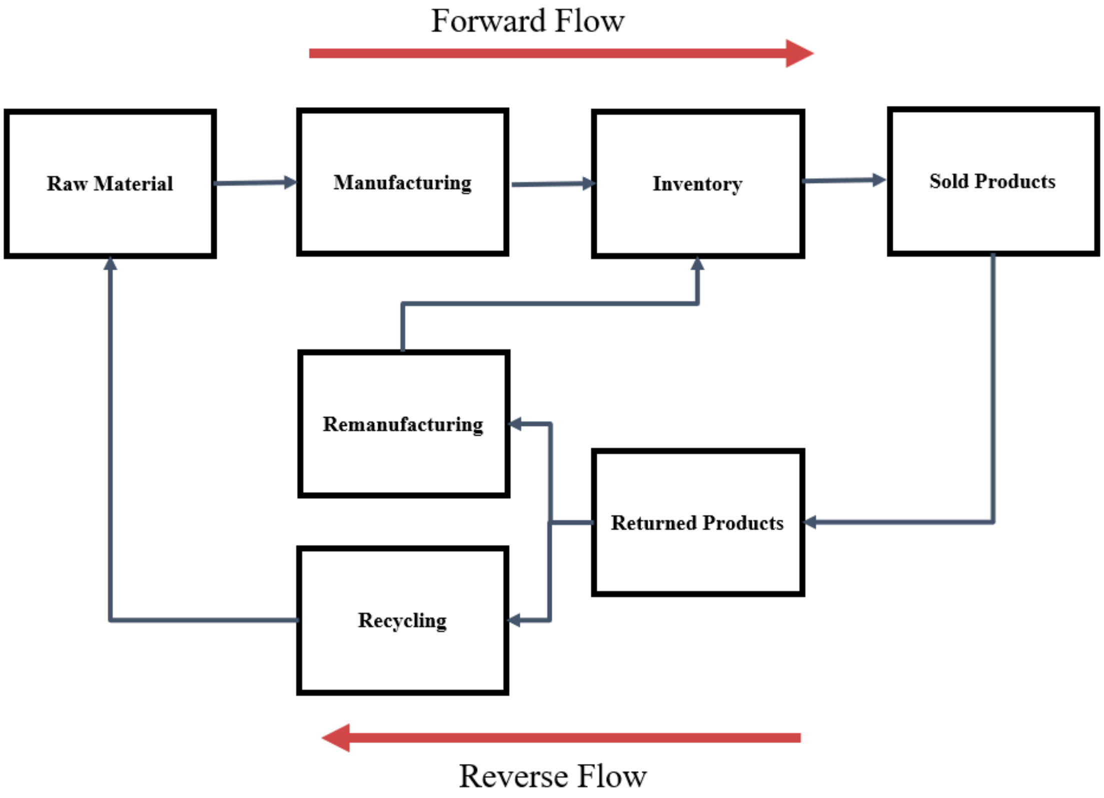

Figure 3.1 The overview of the hybrid production system

Generally, in electronics industries, the returned products are first disassembled to their components. Then following the disassembly process, the inspection process starts to detect components' quality. High-quality disassembled components will be forwarded to the remanufacturing flow, and the remaining will be transferred to the recycling flow. There is also another option for the components that are not functional for either remanufacturing or recycling. These components will be moved for disposal.

Andrew-Munot and Ibrahim (2013) articulated inspection, disassembly, reprocessing, and reassembly as fundamental activities that create remanufacturing process. According to what the authors mentioned, when OEM performs remanufacturing, the remanufactured products will be sold in the primary market and at the new products' same price. Our model defines remanufacturing cost as an auxiliary variable related to the cost of all the required activities related to remanufacturing process. All remanufactured products are kept in the same inventory of original products. On the other hand, the low-quality components are forwarded to the recycling process. The raw material inventory contains both original materials purchased and recycled raw materials that have been recovered through the OEM recycling process.

As a result of adding the recovery strategies, the production system becomes more complicated due to the causal relationships and interactions among the system elements. Therefore, it is vital to apply an approach to study these complexities considering the dynamic manufacturing environment. We develop a system dynamics model for the hybrid production system to evaluate the impacts of using the recovery strategies on the critical economic variables. The two performance variables, profit and cost per unit, are selected from the manufacturers' perspective to be studied. We evaluate the production system under the various production scenarios and then design an improvement production strategy.

3.2 Definitions

Some of the terms used in developing the model are explained in detail in this section. Following definitions and explanations are according to Sterman (2000).

3.2.1 Dynamic System

Contrary to the static systems, the current outputs in dynamic systems depend on both the current inputs and past inputs. It means that there is a memory in dynamic systems.

3.2.2 State, rate, and auxiliary variables

State variables (stock variables) are selected according to the problem objectives; these variables that are shown by boxes indicate the system's state; therefore, the system's decisions and activities are all based on them. On the other hand, rate variables (flow variables) represent the rate of change in state variables. The amount of the state variable is the accumulation of past events. In other words, by changing the inflow or outflow rate variables, the amount of the state variable changes; otherwise, the amount of the state variable will not change.

The variable is categorized into auxiliary when it cannot be defined in terms of state or rate expressions at the current time. The mathematical structure of the system cannot be changed by adding or excluding an auxiliary variable.

3.2.3 Dynamic Hypothesis

The dynamic hypothesis is a description of the behaviour of the system. It must be meaningful given to the purpose of the model. A designer can extract and test the consequences of feedback loops using a dynamic hypothesis. He can also create diagrams that show the main mechanisms that drive the dynamic behaviour of the system. The diagrams are the main structure of the model. A model only can be well designed when there is a proper understanding of feedback loops.

3.2.4 Feedback Loop

A dynamic model cannot be made without understanding the feedback loops. They are the main idea in system dynamics that can capture interactions between the system elements that create an overall behaviour pattern. The real system usually has numerous loops (system dynamics model loops), but many do not directly create important patterns; therefore, the model designer must remove many loops and variables that are not influential for the defined problem. There are two kinds of feedback loops:

Reinforcing loop: When the feedback loop intensifies the loop's generated effects, the feedback loop is a reinforcing feedback loop.

Balancing loop: When the feedback loop stabilizes the created effects within the loop, the feedback loop is a balancing loop. An odd number of negative linkages (arrows) specifies a negative feedback loop.

3.2.5 Causal Loop Diagram

The causal loop diagram or causal model is the diagram of all feedback loops associated with the problem and within the boundary. This diagram presents the causality between elements of the system. A Causal loop diagram of a system can be plotted differently by different researchers; it shows how model makers observe the system and conceptualize it.

3.2.6 Stock and Flow Diagram

The stock and Flow diagram, also known as the flow diagram, illustrates the parts of the system and how they affect each other. Indeed, the stock and flow diagram is a more complex form of a causal diagram. The main difference is that causal diagrams focus on the feedback structure of a system, and stock and flow diagrams focus on the physical structures that make the feedback structure. In other words, the flow diagram provides a visual representation of how a system operates. Key stocks or accumulations are identified with the boxes. These stocks can go up and down based on their flows or rates of change.

3.3 Modeling approach using system dynamics

To conduct this research, first, we review available literature in this area. In the next step, the stock and flow diagram (SFD) is designed given the literature and experts' opinions. According to the parameters and collected information, respective equations are applied to SFD and provide a quantitative format of the model. In the next chapter, different production scenarios are simulated and compared through running the model. Tow economic critical variables are examined to evaluate the production system performance. Finally, an improvement strategy is designed to make improvements in the production system.

3.3.1 Defining the system boundary and dynamic hypothesis

System boundary specifies the part of the environment that is concerned with the study interest. The boundary has to be set according to the problem definition and its objective. Thy boundary in the hybrid production system starts from receiving EOL(s) and ends by selling products. Table 3.1 presents details of the system boundary. The table shows the main endogenous and exogenous variables, as well as excluded issues in the model boundary.

Table 3.1 Model boundary chart

Endogenous	Exogenous	Excluded
EOL inventory	Disposal Ratio	Different models of products
Disassembled products	Demand	Training of human resource
Inspected EOL - Remanufacturing	Inspection ratio	The number of factory human resources
Remanufactured Inventory	Recycling Ratio	Different marketing strategies
Inspected EOL - Recycling	Inspection unit cost	
Recycled Inventory	Recycled raw material ratio	
Raw Material Inventory	Cycle time	
WIP	WIP adjustment time	
FGI	Remanufacturing unit cost	
Sold Products	Production unit cost	
Disassembly Rate	Shipment unit cost	
Shipment Rate		

The dynamic hypothesis of this research concerns all dynamics of the reference mode. It is assumed that EOL(s) are collected by a third party and then returned to the OEM. The original manufacturer uses remanufacturing and recycling activities in addition to the conventional production system. Indeed, the manufacturer aims to satisfy part of the demand through the remanufactured products recovered from EOL(s). Moreover, part of the required raw material is satisfied by recycled materials obtained from the recycling process. There is no difference in the price of remanufactured and new products. The remanufactured products' quality is as good as new; the only difference between new and remanufactured products is the offered warranty for remanufactured products. Both manufactured and remanufactured products are sold in the same market, and they will return to OEM.

All the above mentioned are the dynamics of this system that creates the dynamic hypothesis.

3.3.2 Designing subsystem diagram

The subsystem diagram demonstrates how the system coordinates workflows. The system usually includes several subsystems that operate to obtain the predefined objective of the system. It is necessary to design a subsystem diagram before creating a causal loop diagram. The subsystem diagram provides a big picture of the system and critical variables that are required for modeling. Figure 3.2 shows the subsystems of our model and available workflows between them. Five main subsystems are considered in this research: production, financial, demand, recycling, and remanufacturing. The production subsystem includes production rate, raw material inventory, finished good inventory, and shipment rate as critical variables. Costs and product delivery are outputs of the production subsystem, which enter the financial subsystem and demand-side subsystem, respectively. The costs' information flows enter the financial subsystem as an input.

According to the costs and payment flows obtained from the production subsystem and the demand subsystem, profit, total revenue, and total cost can be calculated in the financial subsystem.

Demand, sold products, and unusable products (EOL products) are considered as main variables of the demand-side subsystem. The demand subsystem makes order flows as an input of the production subsystem.

The critical subsystems of this model are those related to recovery activities. EOL flows are the input of the recycling and remanufacturing subsystems, which originates from the demand-side subsystem. According to the disassembly rate and inspection rate, the recycling rate and the remanufacturing rate will be determined. As a result of recovery subsystems, recycled materials and remanufactured parts will be entered as inputs of the production system, and this cycle continues.

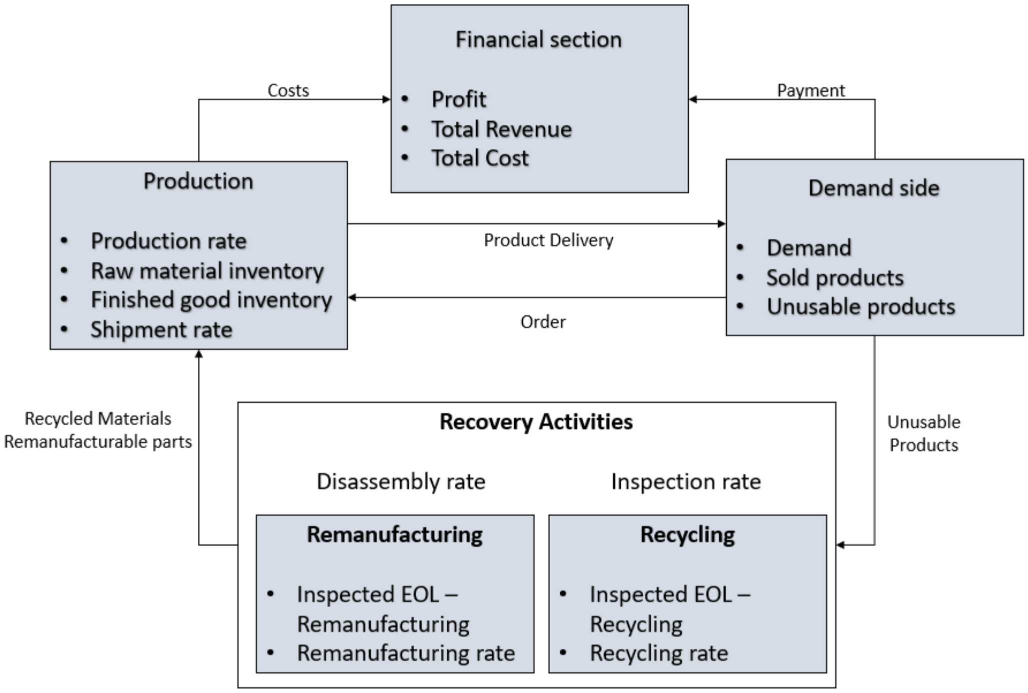

Figure 3.2 The subsystem diagram of the model

3.3.3 Assumptions

Following assumptions are considered to design the model:

We assumed that one unit of recycled material is equivalent to one set of recycled parts that can be used to manufacture one unit of a product. Also, one unit in the remanufacturing process is supposed to be equal to one set of remanufactured components to make one product. These assumptions are used due to the simplification of the research.

One unit of original raw materials purchased from suppliers is equivalent to one batch of all required materials for manufacturing an original product.

The original raw material purchasing rate is considered zero at the initial time.

Demand is considered an exogenous variable due to the model's boundary and objective of the model. The main focus of the designed model is on production activities in the presence of recycling and remanufacturing.

3.3.4 Variables and mathematical formulation

As we mentioned in section 3, there are three types of variables in SD models. State variables, rate variables and auxiliary. Table 3.2 presents variables used in the model, their types, and their respective formulas.

Table 3.2 Information of variables of the model

Variable	Type	Formula
Discarded Rate	rate	$\text{Sold Products}_t / Average\ life\ cycle\ of\ product$
Disposal rate	rate	$Disposal\ ratio \times EOL\ Inventory$
Unusable products (EOL inventory)	state	$\int_{t_0}^{t} [Discarded\ Rate(s) - Disassembly\ Rate(s) - Disposal\ Rate(s)]\, ds + EOL\ inventory(t_0)$
Disassembly rate	rate	$\min\left(\left((1 - DR) \times EOL\ Inventory\right), SMOOTHI\ (Shipment\ Rate, Average\ time, initial\ value\ )\right)$
Shipment rate	rate	$\min\left(FGI, Demand(Time)\right)$
Disassembled products	state	$\int_{t_0}^{t} [Disassembly\ Rate(s) - Disposal\ Rate1(s) - "Inspection\ EOL\ Rate - Recycling(s)"$ $- "Inspection\ EOL\ Rate - Remanufacturing(s)"]\, ds + \ Disassembled\ products(t_0)$
Disposal rate 1	rate	$(1 - INS\ Ratio) \times Dissassembled\ Products$
INS Ratio	auxiliary	0 ≤ INS Ratio ≤ 1
Inspection EOLRate Remanufacturing	rate	$INS\ Ratio \times Disassembled\ Products \times (1 - Recycling\ Ratio)$
Inspection EOLRate Recycling	rate	$Disassembled\ Products \times INS\ Ratio \times Recycling\ Ratio$
Recycling Ratio	auxiliary	0 ≤ Recycling Ratio ≤ 1
Inspected EOL Remanufacturing	state	$\int_{t_0}^{t} ["Inspection\ EOL\ Rate - Remanufacturing(s)" - Remanufacturing\ From\ EOL\ Rate(s)] ds$ $+ \ \text{Inspected EOL Remanufacturing}(t_0)$
Inspected EOL Recycling	state	$\int_{t_0}^{t} ["Inspection\ EOL\ Rate - Recycling"(s) - Recycling\ From\ EOL\ Rate(s)] ds$ $+ \text{Inspected EOL Recycling}(t_0)$
Recycling From EOL Rate	rate	$\min\Big(\max\left(0, Desired\ Recycled\ Material\ Inventory - Recycled\ Inventory\right), "Inspected\ EOL - Recycling$
Recycled Inventory	state	$\int_{t_0}^{t} [Recycling\ From\ EOL\ Rate(s) - Raw\ Material\ Arrival\ From\ Recycled\ Rate(s)]\, ds +$ $\text{Recycled Inventory}(t_0)$
Desired Recycled Material Inventory	auxiliary	$RRMR \times Desired\ Raw\ Material\ Inventory$

Table 3.2 Information of variables of the model (Continued)

Variable	Type	Formula
Raw Material Arrival From Recycled Rate	rate	$\min(\mathit{Raw\ Material\ Gap} \times \mathit{RRMR}, \mathit{Recycled\ Inventory})$
RRMR (Recycled raw material ratio)	auxiliary	0 ≤ RRMR ≤ 1
Desired Raw Material Inventory	auxiliary	Constant value
Raw Material Gap	auxiliary	$\max(0, \mathit{Desired\ Raw\ Material\ Inventory} - \mathit{Raw\ Material\ Inventory})$
Raw Material Inventory	state	$\int_{t_0}^{t} [\mathit{Raw\ Material\ Arrival\ From\ Recycled\ Rate}(s) + \mathit{Raw\ Mateial\ Arrival\ From\ OEM\ Rate}(s) - \mathit{Raw\ Material\ Consumption\ Rate}(s)]\, ds + \mathit{Raw\ Material\ Inventory}(t_0)$
Raw Material Arrival From OEM Rate	rate	$\mathit{DELAY1I}\left((1 - \mathit{RRMR}) \times \mathit{Raw\ Material\ Gap} + \max(0, \mathit{Raw\ Material\ Gap} \times \mathit{RRMR} - \mathit{Raw\ Material\ Arrival\ From\ Recycled\ rate})\ 1{,}0\right)$
Recycling Cost	auxiliary	$\mathit{Recycling\ cost\ for\ one\ unit\ of\ product} \times \mathit{Recycling\ From\ EOL\ Rate}$
Raw Material Cost	auxiliary	$\mathit{Raw\ material\ purchasing\ cost\ for\ manufacturing\ one\ unit} \times \mathit{Raw\ Material\ Arrival\ From\ OEM\ Rate}$
Production Cost	auxiliary	$\mathit{Production\ cost\ for\ one\ unit\ of\ product} \times \mathit{Production\ Rate}$
FGI Inventory Cost	auxiliary	$\mathit{holding\ cost\ for\ one\ unit\ of\ product} \times \mathit{FGI}$
Shipment Cost	auxiliary	$\mathit{Shipment\ cost\ for\ one\ unit\ of\ product} \times \mathit{Shipment\ Rate}$
Remanufacturing Cost (reprocessing)	auxiliary	$\mathit{Remanufacturing\ cost\ for\ one\ unit\ of\ product} \times \mathit{Remanufactured\ Rate}$
Total Cost	rate	$\mathit{Disassembly\ Cost} + \mathit{FGI\ Inventory\ Cost} + \mathit{Inspection\ Cost} + \mathit{Production\ Cost} + \mathit{Raw\ Material\ Cost} + \mathit{Recycling\ Cost} + \mathit{Remanufacturing\ Cost} + \mathit{Shipment\ Cost}$
Profit	State	$\int_{t0}^{t} [\mathit{Total\ Revenue}(s) - \mathit{Total\ Cost}(s)]\ ds + \mathit{profit}(t_0)$
Total Revenue	rate	$\mathit{Product\ price} \times \mathit{Shipment\ Rate} \times \mathit{Profit\ margin}$
Raw Material Consumption Rate	rate	$\min(\mathit{Desired\ Production\ Start\ Rate}, \mathit{Raw\ Material\ Inventory})$
Desired production start rate	auxiliary	$\mathit{Adjustment\ for\ WIP} + \mathit{Desired\ Production}$

Table 3.2 Information of variables of the model (Continued)

Variable	**Type**	**Formula**
WIP (Work in process)	state	$\int_{t_0}^{t} [Raw\ Material\ Consumption\ Rate(s) - \text{Production Rate}(s)]\, ds + WIP(t_0)$
Production Rate	rate	$\min\big(WIP, \max\big(0, DELAY3(Raw\ Material\ Consumption\ Rate, Cycle\ time)\big)\big)$
FGI (Finished good inventory)	state	$\int_{t_0}^{t} [Production\ Rate(s) + Remanufactured\ Rate(s)\ - Shipment\ Rate(s)] + FGI(t_0)$
Sold Products	state	$\int_{t_0}^{t} [\text{Shipment rate}(s) - \text{Discarded Rate}(s)]\ \text{ds} + sold\ products\ (t_0)$
Disassembly Cost	auxiliary	$Disassembly\ cost\ for\ one\ unit \times Disassembly\ Rate$
Inspection cost	auxiliary	$Inspection\ cost\ for\ one\ unit \times \text{"Inspection EOLRate } - \text{ Remanufacturing"} + \text{"Inspection EOLRate } - \text{ Recycling"}$
Cycle time	auxiliary	Constant
Desired WIP	auxiliary	$Cycle\ Time \times Desired\ Production$
Desired production	auxiliary	$Demand(Time) - SMOOTHI(Remanufactured\ Rate, average\ delay\ time, initial\ value)$
WIP adjustment time	auxiliary	Constant
Adjustment for WIP	auxiliary	$\max\big((0, Desired\ WIP - WIP)/WIP\ adjustment\ time\big)$

3.3.5 Model loops

Decision-making depends on understanding the system's current conditions, and any change in decision-making creates new situations that affect our following decisions. A dynamic system often consists of several feedback loops, and they are functional to dynamic modeling. Feedback loop thinking as the basis of system dynamics focuses on identifying dominant reinforcing and balancing loops in the system that can help the system grow or limit. Figure 3.2 represents two critical loops in the model which are concerned with recovery activities. Both of them are reinforcing loops that are created based on the dynamics of recycling and remanufacturing. The other feedback loops are disregarded in this section. In the next section, all feedback loops of the model are observed in the form of a stock and flow diagram.

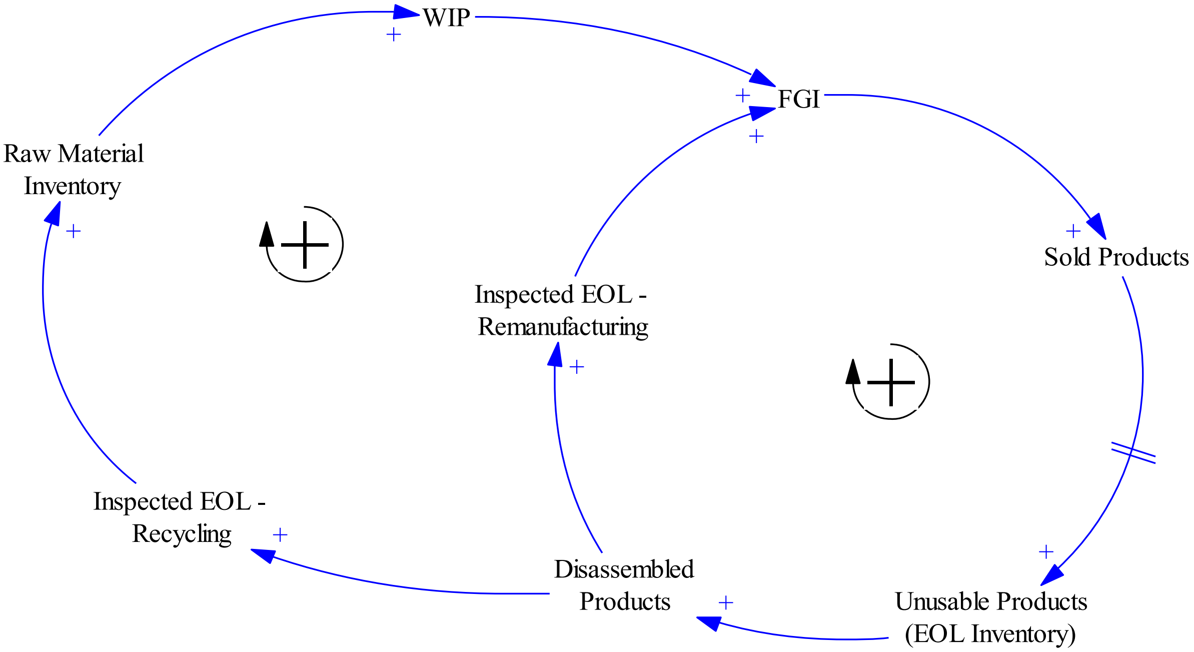

Figure 3.3 Two important feedback loop of the model

Figure 3.3 shows the causal relationships between variables in two crucial feedback loops. The first loop starts with sold products. When the number of sold products released in the market increases, subsequently, EOL inventory will be increased. It should be mentioned that there must be a lag in this process as it takes more time than the model's time step (one week) to use the products and collect them as EOL(s). The second positive link shows the positive relationship between EOL inventory and disassembled products. It is evident that with the increase of collected EOL(s), disassembled products also increase. The positive association is due to the fact that the first step of the recovery process is disassembling. As a result of the rise in disassembled products, accepted inspected components for each candidate EOL strategy will be increased. In the first loop, when inspected EOL(s) related to remanufacturing process raises, then finished goods inventory will be increase. It occurs since we supposed the distribution channel and market of new products and remanufactured ones are the same.

Regarding the second loop in figure 3.2 on the left, there is an increment in raw material inventory when the inspected components available for recycling increased. The reason for this positive relation is that recycled materials are forwarded to raw material inventory. In other words, raw material inventory is a combination of original raw material and raw materials recovered by recycling. As a result of this enhancement, work in process (WIP) is increased, and finally, it affects the number of finished goods in inventory positively.

These two positive feedback loops affect the growth of the company positively. In the above figure, only the dynamics related to recycling and remanufacturing are presented. More details of the model will be explained in the model's stock and flow diagram.

3.3.6 Stock and flow diagram

After detecting model structure, feedback loops and their behaviour in the system, it is necessary to translate the causal loop diagram to stock and flow diagram. It is possible by using mathematical equations and determining stocks or levels according to the model objectives. In other words, a stock and flow diagram is a quantitative form of a causal loop diagram. Figure 3.4 presents state variables in the boxes and their inflow and outflow (marked by valves on the arrows), which can change stocks' states.

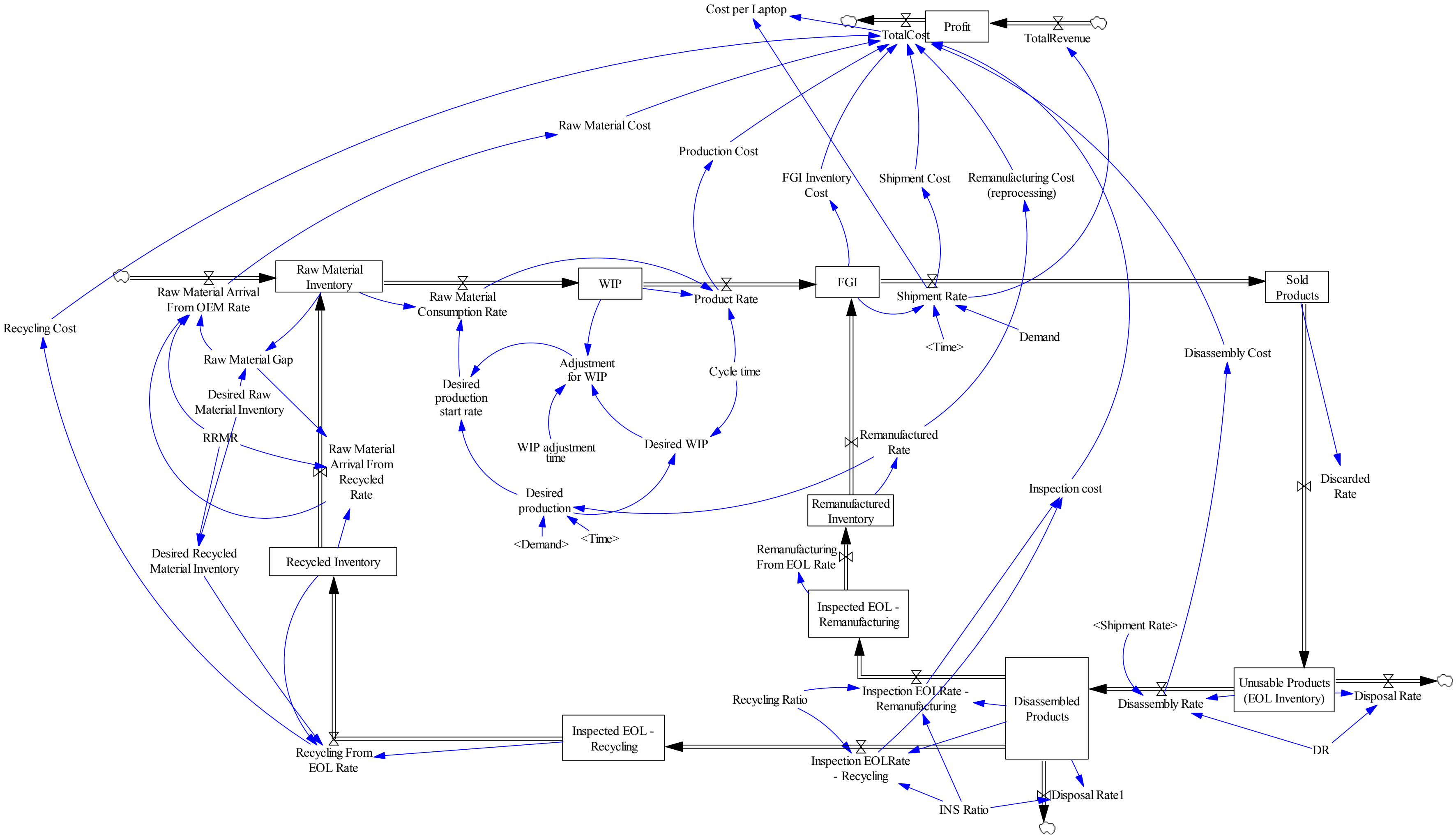

Figure 3.4 Stock and Flow Diagram (SD model)

3.4 Conclusion

This chapter first describes the dynamic system concepts and definitions. Then, we determine the variables of the model according to the problem and previous studies. In the next step, interactions among these variables are examined, and a stock and flow diagram is created subsequently. In the next chapter, we will offer the results of running the model, comparing different production scenarios and an offered strategy to improve the production system.

CHAPTER 4: SIMULATION AND ANALYSIS

4.1 Introduction

This study considers an electronics manufacturing company that plans to use two recovery strategies to make a hybrid production system. The candidate recovery strategies are recycling and remanufacturing. The main problem for decision-makers is whether using the recovery strategies makes profits for the company over time. Moreover, they need to know what the best production strategy is. In the previous chapter, we developed the model using Vensim PLE 8.2.1 software. In this chapter, we apply the model to the laptop manufacturing company's production system as an example of the electronics industries to analyze the system behavior and evaluate the impacts of using different production strategies on critical two variables. A proposed optimized strategy to enhance the profit of the laptop manufacturing company is offered in the end.

4.2 System dynamics model description

This section describes the critical steps and processes that are considered in the hybrid production system. The details of information, parameters and figures related to the laptop manufacturing company are explained.

4.2.1 Disassembly and inspection

According to the presented model (figure 4.1), recycling and remanufacturing added as recovery strategies to the traditional production system to close the forward loop and make a closed-loop supply chain (CLSC).

It is assumed that a third-party company collects end-of-life (EOL) laptops from the end-users. Collected laptops must be from the same brand and model, and they should have been produced by the company. After delivering EOL laptops to the company, they will be first disassembled to proper components for inspection. Disposal ratio (DR) is defined in the model to compare EOL laptops quantity that is either kept or disposed by the consumers and the number of returned that considered for disassembly. We assumed that DR is equal to 0.6 (1/week) for the base run of the model. It means that the consumers did not deliver 60% of EOL products for being considered for recovery. The remaining were collected by the third party and are available for the first step, disassembly. After the components got disassembled, they will be transferred for inspection to find which components are appropriate for the next steps. It should be noted that, after disassembly, it is possible for the components to be detected as non-functional. In this case, they will be regarded for disposal. Disposal Rate1 shows available components for disposal in the model.

The company must decide on the disassembled components according to the quality and grade of them. The parts with high quality forwarded for remanufacturing flow, and the low quality considered for recycling flow. The inspection ratio (INS ratio) presents the ratio of accepted components for inspection to the components for disposal. INS ratio in the base run is equal to 0.8. It means that 80% of the component are proper for the second step, inspection.

4.2.2 Remanufacturing and recycling processes

The recycling ratio determines the ratio of accepted components for recycling to the accepted components for remanufacturing. The recycling ratio is considered 0.6 for the base run to illustrate this assumption that 60% of inspected EOL(s) are forwarded for recycling flow, and the remaining moved to remanufacturing flow.

It is assumed in this research that there is no difference between the quality and price of remanufactured products and new products due to the ideal closed-loop supply chain that OEM generated. The remanufactured products are kept in the same inventory of new products (finished goods inventory, FGI). Also, they can be sold in the primary market similar to the new products. The laptops' components must be disassembled (if required), cleaned, reprocessed, and reassembled in the remanufacturing process.

On the other hand, the low-quality components are forwarded to the recycling process. All components of a laptop, including glass, plastic, metal, and batteries, are recyclable. First, hazardous and toxic components such as batteries are removed in the separation process. The remaining will be moved for shredding. Some rare and precious materials, plastics, and glass are recovered as raw materials for manufacturing laptops or other products. In this research's recycling process, we focus on all laptop components that can be manufactured from recovered raw materials. Most of the laptop's components can provide recycled plastics, magnets (to produce hard drive), glass and gold (to produce motherboard) used in original products. The purchasing costs of those laptop raw materials that cannot be obtained from the recovered materials are included in the recycling cost.

The raw material inventory contains both original materials purchased and recycled raw materials that are recovered through the OEM recycling process. The recycled raw material ratio (RRMR) shows an allowed amount of recycled material that can be used in the product so that the quality of the product is satisfactory. The initial value of RRMR is assumed to be 0.3; this means that 30% of the used material in one laptop can be supplied from the recycled material. The raw material inventory can be included original raw material and recycled material. We defined raw material arrival from recycled rate *(rrm)* to show the number of the recycled sets that were recovered through the recycling process. Raw material gap *(rmg)* is defined to present the gap between desired raw material inventory and available inventory. Also, ri indicates recycled inventory. rrm is calculated as follows:

$$rrm = min(rmg \times RRMR, ri) \tag{4.1}$$

On the other hand, raw material arrival from OEM rate *(orm)* is defined to show the number of original raw materials sets that are purchased from suppliers as original raw materials. It is calculated according to formula 4.2:

$$orm = DELAY1I\left((1 - RRMR) \times rmg + max(0, rmg \times RRMR - rrm)\ 1{,}0\right) \tag{4.2}$$

We considered one week delay for the original raw material arrival, as is shown in formula 4.2. FGI represents the number of finished goods that are kept in the inventory that includes both new products and remanufactured products.

In this model, profit is defined as a state variable. In other words, the defined variable presents the cumulative amount of profit over the time horizon. It is calculated as follows:

$$Profit = \int_{t0}^{t} [Total\ Revenue(s) - Total\ Cost(s)]\ ds + profit(t_0) \tag{4.3}$$

Initial values and parameter ranges that are used in this thesis are according to experts' opinions, similar studies, and manufactures reports. Table 4.1 shows the initial values and constant values of the model according to the defined time step (one week).

Table 4.1 Initial values of model variables

Name	Value/Initial value
The average life cycle of a laptop	104
EOL inventory	5000
Disposal ratio (DR)	0.6
Disassembled products	200
Inspection Ratio (INS ratio)	0.8
Recycling ratio	0.6
Inspected EOL-remanufacturing	80
Inspected EOL-recycling	80
RRMR (Recycled raw material ratio)	0.3
Desired Raw Material Inventory	350
Recycling Cost	100
Raw Material Cost	150
Production Cost	25
FGI Inventory Cost	3
Shipment Cost	20
Remanufacturing Cost	100
The average price of a laptop	700
WIP	200
FGI	200
Sold Products	1000
Disassembly Cost	15
Inspection cost	15
Average weekly sales	270

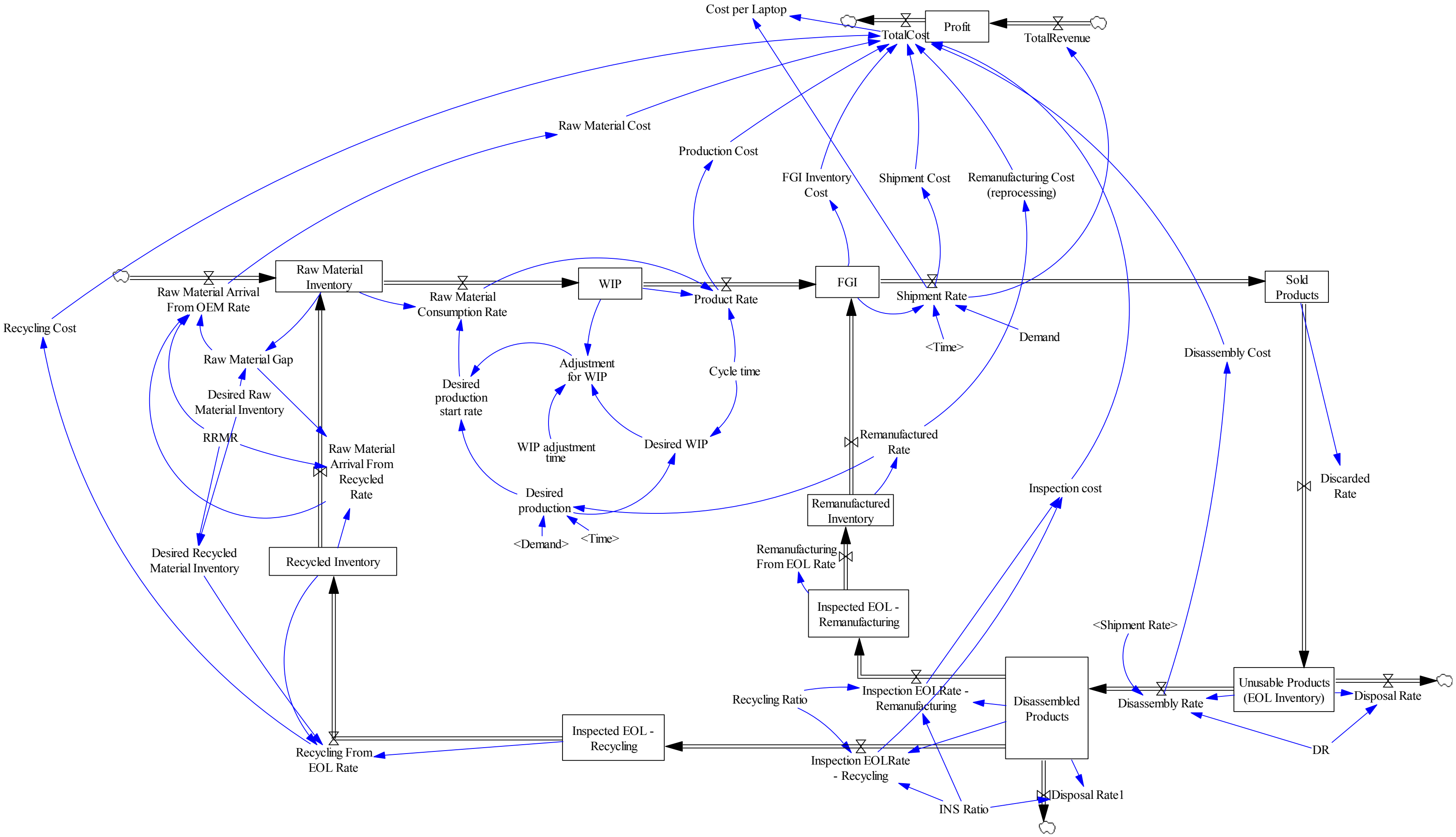

Figure 4.1 System dynamic model of the laptop OEM production system

4.3 Production scenarios

The model is run for 52 weeks (one year) as a time horizon and one week as a time step. Different scenarios are defined to observe the behavior of the production system in the presence and absence of remanufacturing and recycling. First, the best production scenario is detected through the simulation, and then we attempt to improve the best scenario to discover under what conditions it generates more profit. The defined scenarios are according to the following:

Remanufacturing

Recycling

Without a recovery action

Remanufacturing and recycling

The first scenario is about remanufacturing as a single recovery strategy. According to figure 4.2, the predicted cumulative profit is higher than either the second scenario, recycling strategy or without a recovery action. It is sensible due to the low cost of material and production. However, it might be impossible when the quality of returned products is not high enough to be remanufactured.

The second scenario is defined when the only recovery strategy is recycling. Though the profit is higher than the case without a recovery action, it is lower than both scenarios, "remanufacturing" and "recycling and remanufacturing ".

The next one is associated with the traditional production system when there is no recovery activity. Indeed, we studied this scenario to compare it with other situations in using recovery strategies. The lowest profit is predicted for this scenario.

It has shown in Fig 4.2 that the company can maximize profit when applies both recovery actions. It means that remanufacturing and recycling strategies can be the most profitable for the production system when used simultaneously.

To summarize the comparison of different scenarios, most profit is gained in "remanufacturing and recycling" scenario. Remanufacturing scenario is in the second rank in terms of making profits, and the third place is related to recycling due to the high cost of recycling. Moreover, as it was supposed, "without a recovery action scenario" makes the lowest profit compared to the other scenarios.

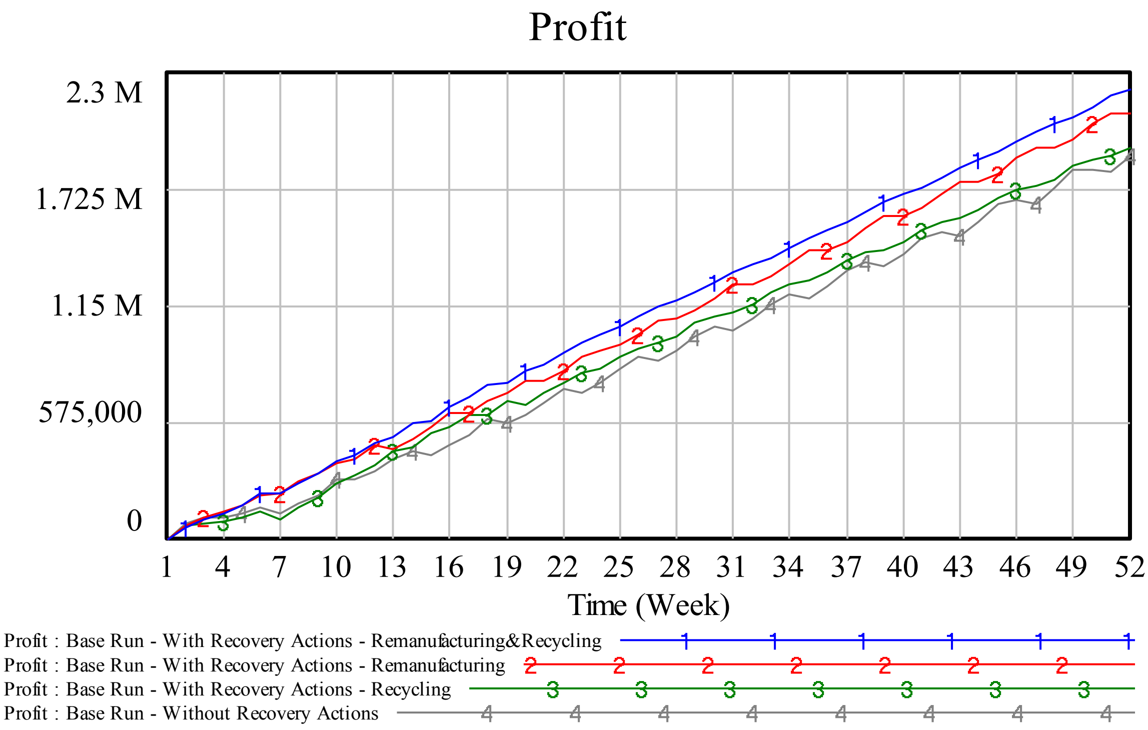

Figure 4.2 Comparison of profit in different production scenarios

Figure 4.3 shows how the shipment rate is different in each scenario. The shipment rate represents FGI and sold products as an inflow variable (rate) of sold products and outflow variable (rate) of FGI. As it is observed in figure 4.3, using both recovery strategies leads to fewer shipment rate fluctuations than other scenarios. It means that when the company supplies parts of the demand through remanufactured products and products manufactured from recycled components, the production system will be more stable in responding to the market.

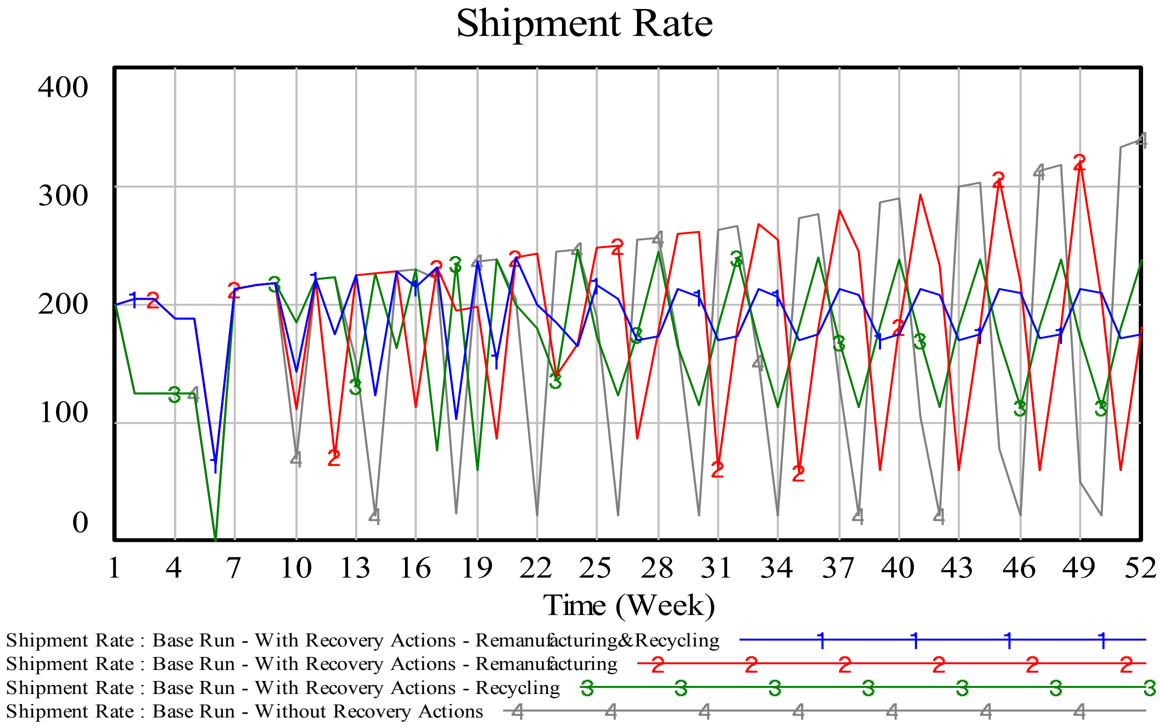

Figure 4.3 Comparison of shipment rate in different production scenarios

It is possible to compare the rate of components forwarded to recycling flow in different production scenarios through figure 4.4. There are no recycled materials for graphs 2 and 4, so the number of recycled sets is zero. Some fluctuations are observed in the first weeks, but the graphs will be smoother after that.

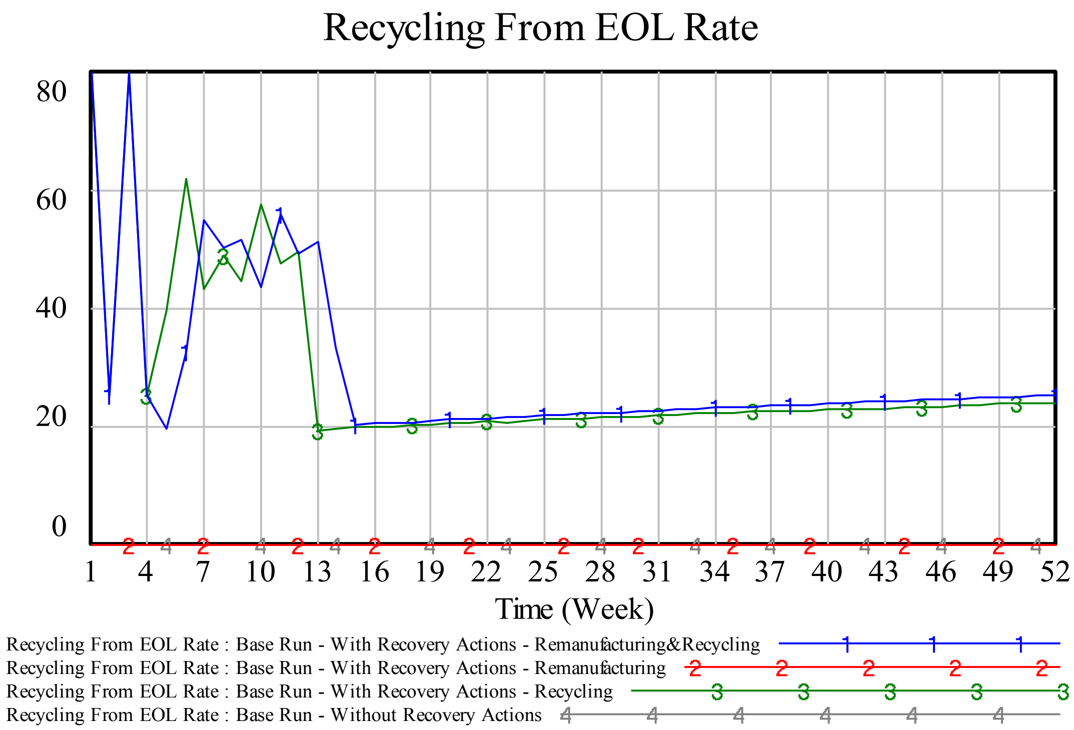

Figure 4.4 Comparison of recycling rate in different production scenarios

This study assumes that all available components for remanufacturing can be remanufactured and sent to finished good inventory to satisfy demand. There are no remanufactured products in graphs 3 and 4 in figure 4.5. The figure shows that graphs 1 and 2 follow a fairly similar pattern throughout the whole time frame.

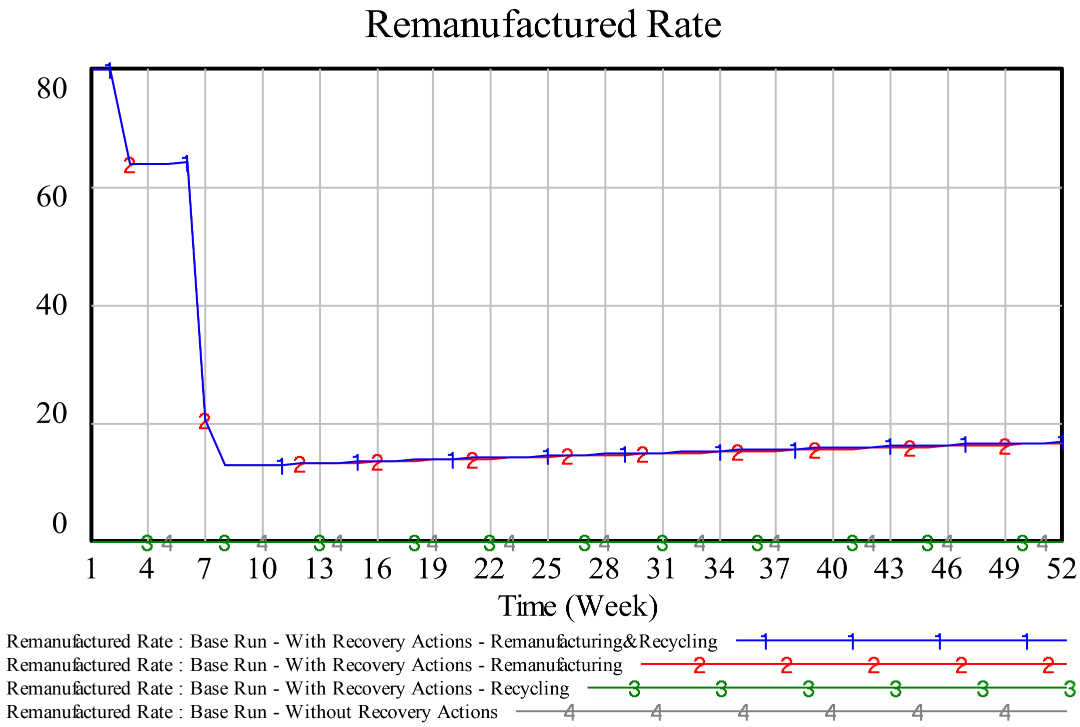

Figure 4.5 Comparison of remanufactured rate in different production scenarios

From figure 4.6, it is evident that the number of purchased raw material sets fluctuates for the whole time horizon; however, there is less fluctuation for the candidate of best production scenario, "remanufacturing and recycling". It is sensible because when the company uses both recovery strategies simultaneously, supplying raw material will have fewer fluctuations. Indeed, the original raw material purchasing rate could be decreased using this scenario since the recycled materials meet part of the required raw materials. Remanufactured components also play an essential role in reducing the raw material purchasing because they can satisfy final product demand, same as new products.

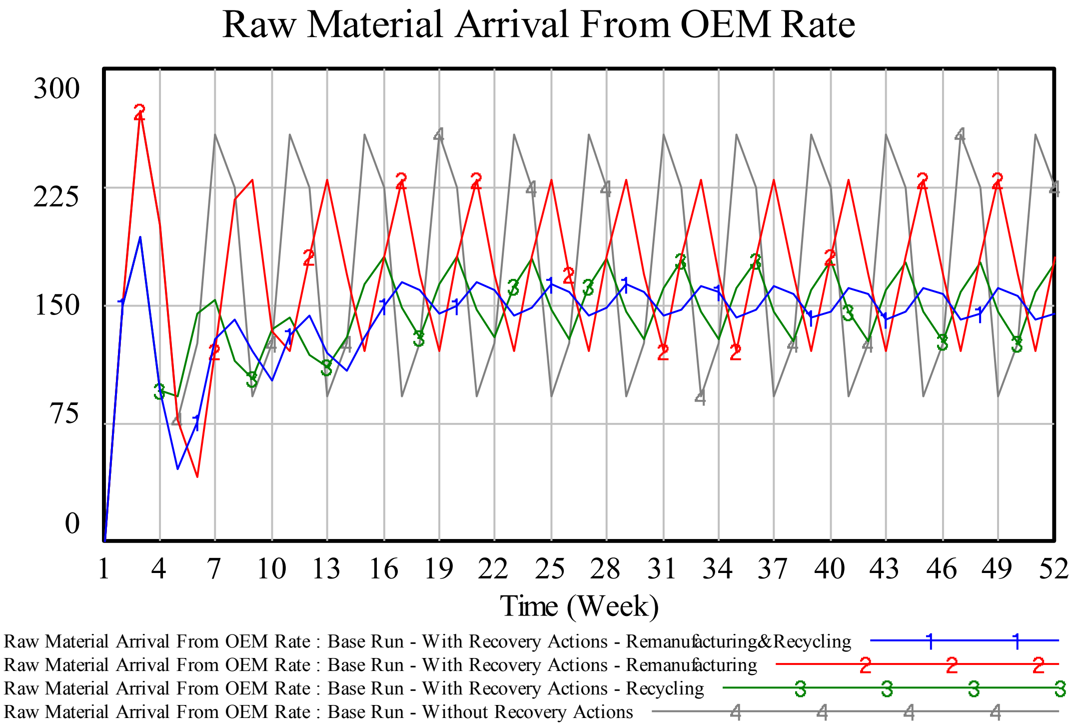

Figure 4.6 Comparison of raw material arrival in different production scenarios

As figure 4.7 presents, the production cost associated with one unit of a laptop is more steady for "remanufacturing and recycling" scenarios than the others. The graph illustrates that when there is no recovery action, the high cost of purchasing original raw material is possible. This cost affects the associated cost for manufacturing the laptop.

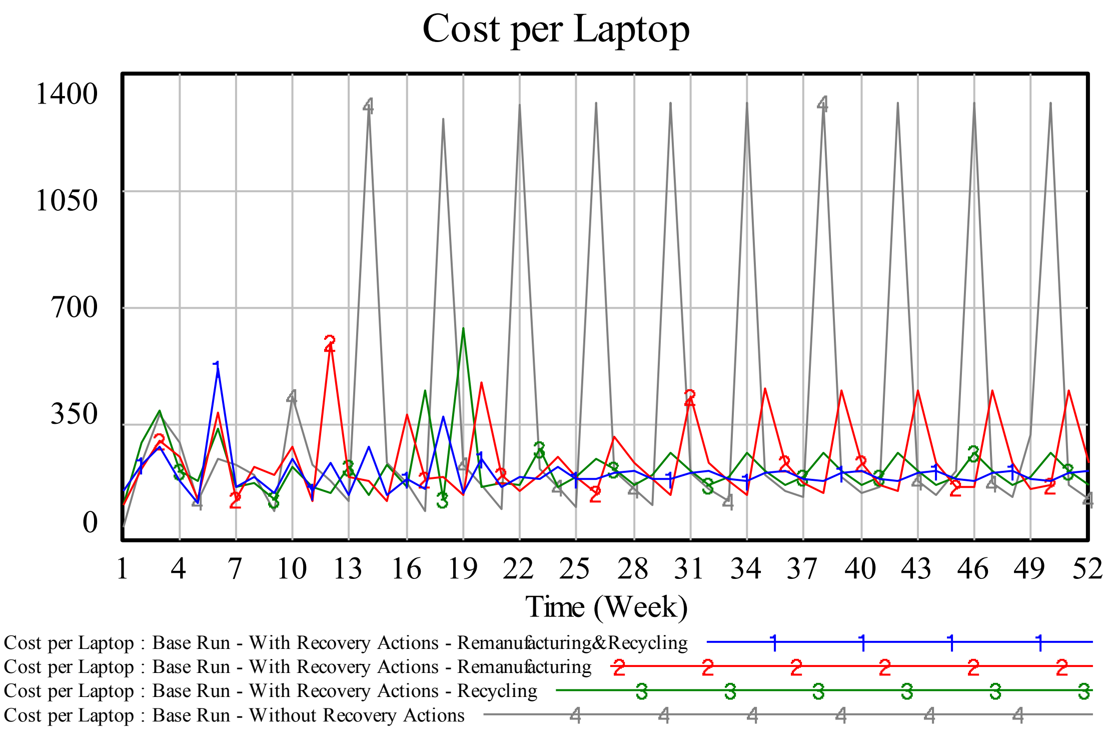

Figure 4.7 Comparison of cost per laptop for different production scenarios

Since this research aims to evaluate the production system in terms of profit and cost per unit, we calculate the average cost per laptop in 52 weeks for all scenarios from the following formula:

$$Cost\ per\ laptop = Total\ Cost/Shipment\ Rate \tag{4.4}$$

Table 4.2 The average cost per laptop in different production scenarios

Scenario	**Remanufacturing and Recycling**	**Remanufacturing**	**Recycling**	**Without a recovery action**
Average cost per laptop (USD)	200.06	238.68	214.74	396.59

Comparing the average cost between the scenarios presents that the lowest cost is related to when the OEM uses both remanufacturing and recycling. Moreover, due to what we mentioned, the most profit can be generated in this case.

To summarize, remanufacturing and recycling scenario has been identified as the best production scenario for the hybrid production system. As per the presented graphs, there are some fluctuations throughout the time horizon regarding shipment rate, raw material arrival from OEM rate, and cost per laptop figures. To study the causes of the oscillations, we need to focus on the relationships among the different elements of the system. According to formula 4.4, rising and falls concerning shipment rate can directly affect the cost per laptop. From the systemic view used in system dynamics methodology, the reason behind the shipment rate fluctuations must be found in the system's elements before it. Table 4.3 shows figures concerning the system elements that are related to each other.

Available finished goods in the inventory for each period are equivalent to the summation of manufactured products and remanufactured products related. According to the table, 188 units can be shipped on week 5 due to the available products in the finished goods inventory, but the production rate is equal to 0. The delay in production rate *(pr)*, which is considered in formula 4.5, might be the reason for that. Raw material consumption rate is shown in the formula by *rmcr:*

$$pr = \min\Big(WIP, \max\big(0, DELAY3(rmcr, Cycle\ time)\big)\Big) \tag{4.5}$$

Table 4.3 Data related to each week

Time (week)	Demand	FGI	Shipment rate	Production rate	Remanufactured rate	WIP
1	202	200	200	124	80	200
2	204	204	204	124	80	200
3	205	204	204	124	64	153
4	207	188	188	124	64	192
5	209	188	188	0	64	227
6	211	64	64	379	64	379
7	213	444	213	0	20	138
8	215	251	215	298	13	298
9	217	346	217	0	13	165
10	219	142	142	370	13	370
11	221	383	221	0	13	164

Table 4.3 Data related to each week (continued)

Time (week)	Demand	FGI	Shipment rate	Production rate	Remanufactured rate	WIP
12	222	175	175	321	13	321
13	224	334	224	0	13	180
14	225	123	123	374	13	374
15	227	388	227	40	13	166
16	229	214	214	290	13	290
17	231	303	231	17	14	165
18	233	102	102	292	14	318
19	236	306	236	69	14	211
20	238	152	152	250	14	323
21	240	264	240	162	14	238
22	242	199	199	170	14	247
23	244	184	184	150	14	262
24	246	164	164	201	14	292
25	248	216	216	189	14	256
26	250	203	203	155	15	237
27	254	169	169	157	15	267
28	256	172	172	198	15	290
29	258	213	213	190	15	257
30	261	205	205	154	15	236
31	263	169	169	158	15	267
32	265	173	173	197	15	290
33	268	212	212	191	15	258
34	270	206	206	154	15	236
35	272	169	169	158	15	267
36	276	173	173	197	15	290
37	279	212	212	192	15	258
38	282	207	207	154	16	236
39	285	169	169	158	16	267
40	289	174	174	196	16	290
41	292	212	212	192	16	258
42	296	208	208	154	16	236
43	299	170	170	158	16	267
44	303	174	174	196	16	289
45	306	212	212	192	16	259
46	310	208	208	154	16	236
47	313	170	170	158	16	267
48	317	174	174	196	16	289
49	321	212	212	192	16	259
50	327	209	209	154	17	236
51	333	171	171	158	17	266
52	338	174	174	196	17	289

We change the type of delay used in the software to find if it can reduce the observed fluctuations in shipment rate. The shipment rate is studied in figure 4.8 to observe the effects of this reduction on the system's fluctuations. As shown, fewer fluctuations are observed in all scenarios; however, our primary focus is on the best production scenario, "remanufacturing and recycling".

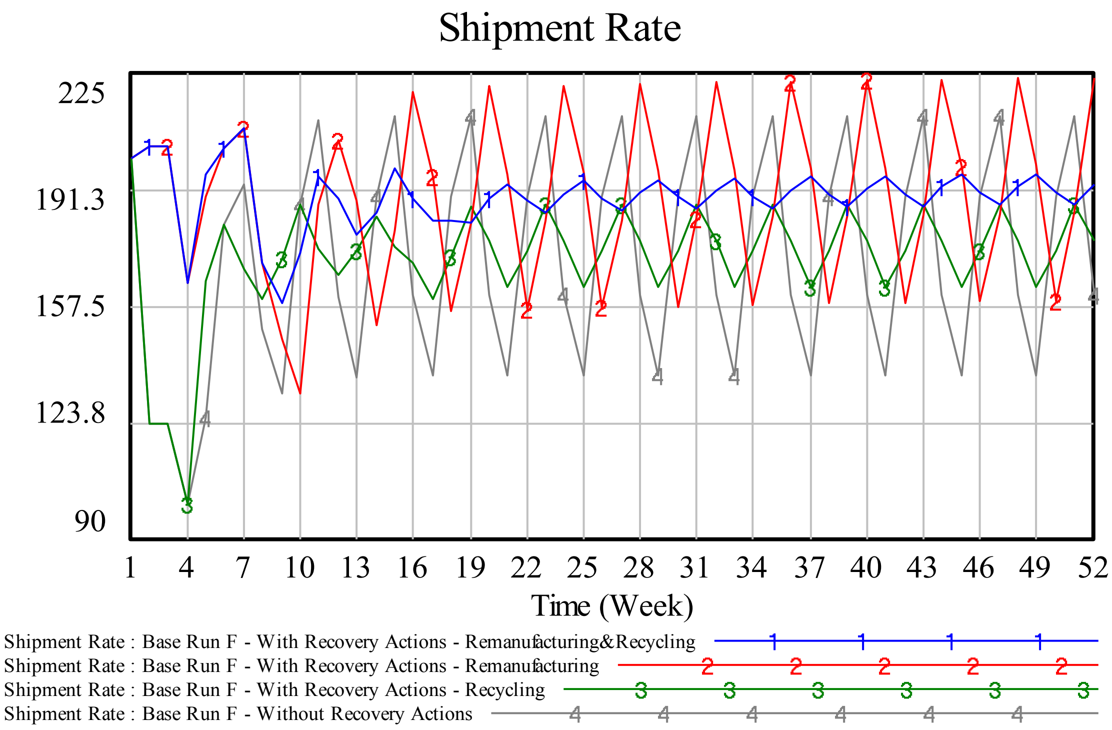

Figure 4.8 Comparison of shipment rate in different production scenarios after delay reduction

According to figure 4.9, cumulative profit is the same for graphs 1 and 2 at the first weeks of production. Although both graphs have an increasing trend, graph 1 gets ahead of graph 2 after week 13 compared to graph 2.

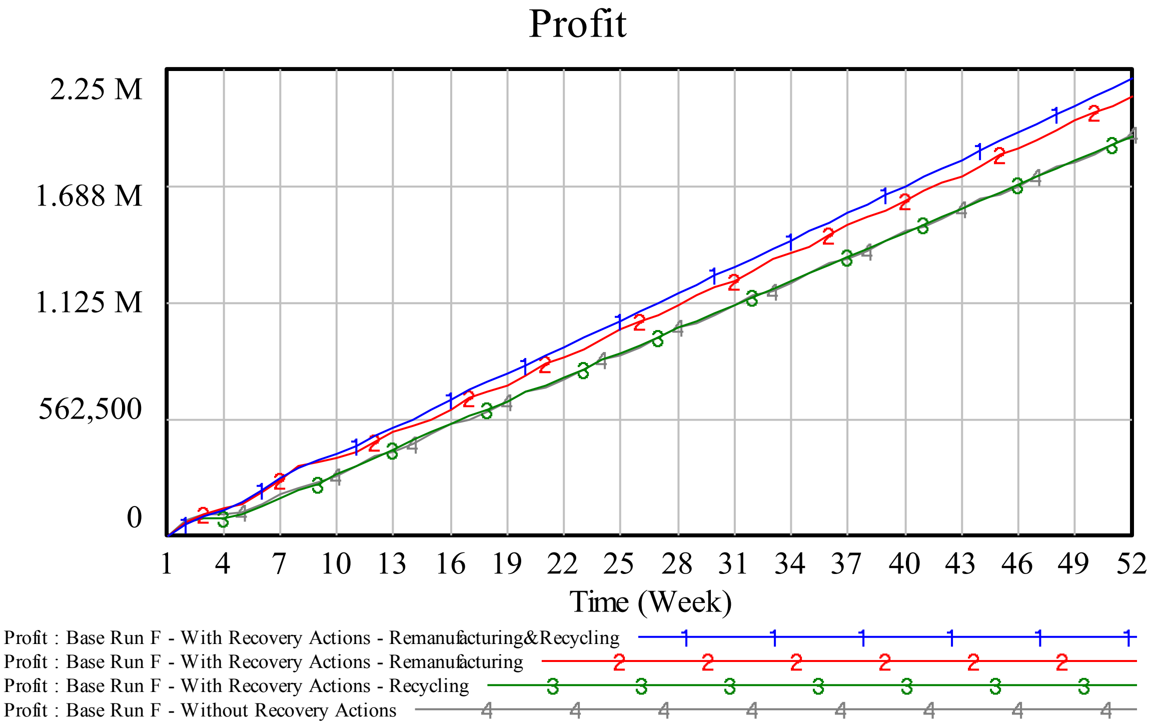

Figure 4.9 Comparison of cumulative profit in production scenarios after delay reduction

To examine more about generated profit, we add a new variable to the model, weekly profit. Although cumulative profit in figure 4.9 shows that the most profit could be generated by using "remanufacturing and recycling" over 52 weeks, weekly profit (figure 4.10) in some periods is less for this scenario than the others. Even in some weeks, such as week 13, weekly profit in the "without a recovery action" scenario is more than "remanufacturing and recycling". This point shows that how is essential for decision-makers to study cumulative profit over time to make a correct decision on selecting the best production scenario.

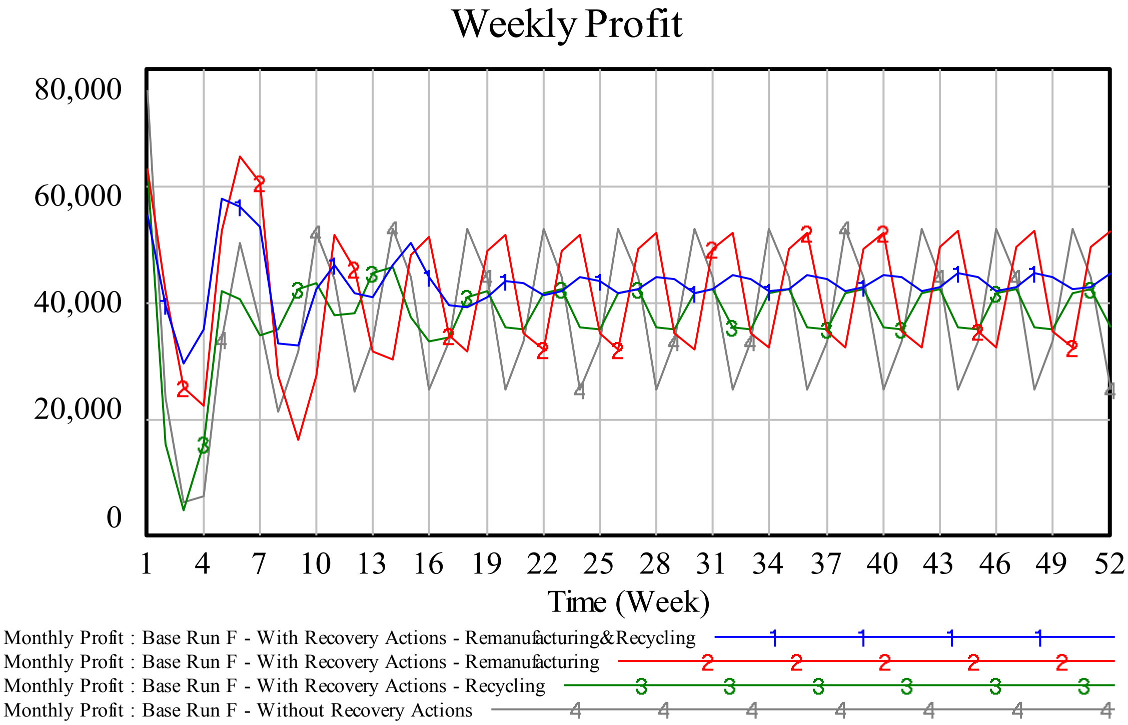

Figure 4.10 Comparison of weekly profit in production scenarios after delay reduction

Table 4.4 shows that delay reduction in production rate can also decrease the cost per laptop of each scenario.

Table 4.4 Comparison of cost per laptop in different scenarios after delay reduction

Scenario	**Remanufacturing and Recycling**	**Remanufacturing**	**Recycling**	**Without a recovery action**
Average cost per laptop (USD)	191.59	199.65	202.20	202.89

4.4 Improvement strategy

After running the model and comparing different production scenarios, we detected the best scenario regarding profit and cost per laptop. We attempted to decrease fluctuations in shipment rate by reducing the delay in production rate. In the current step, three parameters are selected that changing them may improve the production system. First, the parameters are changed within the possible ranges, and then their impacts on critical variables are investigated. Finally, an improvement production strategy is presented accordingly. The main emphasis of these strategies is on modifying the internal elements under the OEM control.

4.4.1 Disposal ratio

Disposal ratio (DR) is defined in the model to compare EOL laptops quantity that is either kept or disposed of by the consumers and the number of returned laptops that are considered for disassembly. According to the model, DR affects the disposal rate *(dr)* and disassembly rate (α). The disposal rate is calculated as follows:

$$dr = DR \times EOL\ Inventory \tag{4.6}$$

Moreover, the disassembly rate can be calculated according to formula 4.7. Shipment Rate and EOL inventory are shown sr and $EOLI$ respectively in the formula:

$$\alpha = min\Big(\big((1 - DR) \times EOLI\big), SMOOTHI\ (sr, Average\ time, sr(t_0)\ )\Big) \tag{4.7}$$

We decrease the DR from 0.6 (initial value) to 0.4 as a possible improvement. It could occur when consumers are more willing to return the EOL(s). The OEM can inform consumers of collection centers and encourage them to return instead of keeping or disposing of the laptops. Once DR decreases, the disassembly rate increases as a result and intensifies the recovery feedback loops. Therefore, more components will be forwarded for the remanufacturing and recycling flows.

4.4.2. Recycling ratio

As we defined the recycling ratio in section 4.2.2, it determines the ratio of accepted components for recycling to the accepted components for remanufacturing. The higher recycling ratio shows that the quality of most of the disassembled parts is lower than what is required for the remanufacturing process. We changed the parameter value from 0.6 to 0.4. This change means more inspected components are proper for the remanufacturing flow. To that end, more returned laptops should be re-manufacturable, or operational activities including disassembly and inspection should be improved to be able to retrieve more components through the remanufacturing process. Soh et al. (2016) believed that developing standards and regulations regarding product design is essential to manufacture products that can be used in their second life cycle. Therefore, product design in the first life cycle must be highlighted for the OEM to produce re-manufacturable products to be used again at the end of their early life cycle. Disassembly and reassembly are among the most critical steps in remanufacturing process. According to the experts' comments, disassembly of some laptop models is time-consuming or even impossible. This fact must be considered by the OEM technical team to be taken into account in product design.

4.4.3. Recycled raw material ratio

Recycled raw material ratio (RRMR) is defined in the model to demonstrate the amount of recycled material that is allowed to be used instead of the original raw material. RRMR cannot be more than a limitation defined by the technical team; otherwise, it affects the final product quality. RRMR is increased from 0.3 to 0.5 in this section by considering similar studies and based on what the experts in this field believe is possible. This change can occur when the quality of recycled materials improved. In this case, the technical team permits using more recycled materials in the manufacturing process. Generally, recycled material has lower quality compared to virgin material, but many factors affect this fact. In other words, the type of material and kind of recycling approach can make a difference in the output of the recycling process.

The changes are regarded in the model to observe their impacts and find whether they can positively affect the critical variables. The simulation results show that applying the changes leads to profit enhancement from 2,203,956 USD to 2,385,731 USD. As a result of the improvements, 8% enhancement can be achieved for profit at the end of the time horizon (52 weeks).

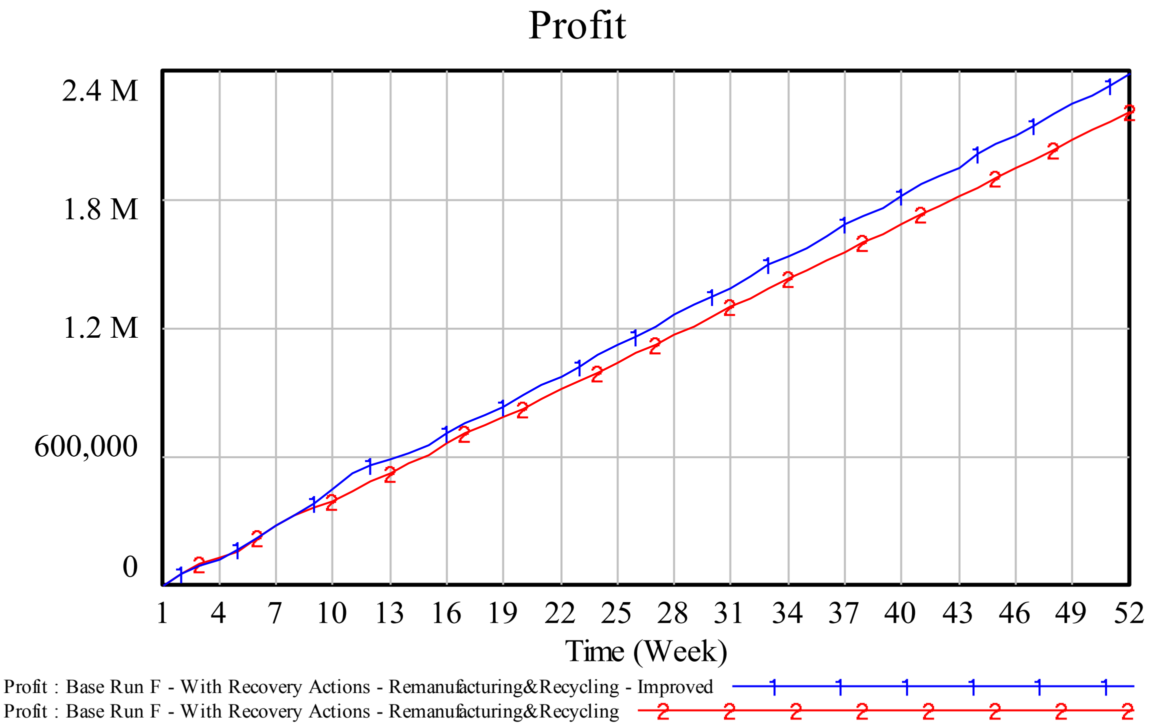

Figure 4.11 Comparison of profit for before and after improvement strategy

As illustrated in figure 4.12, there are notable fluctuations after using the improvement strategy in weekly profit. It is necessary to compare weekly profit and cumulative profit to make appropriate strategic decisions. This point validates that how is essential to have a systematic view in making decisions throughout time. Over time more profit will be generated after using the improvement strategy. It means that the manufacturer should not decide only based on weekly profits.

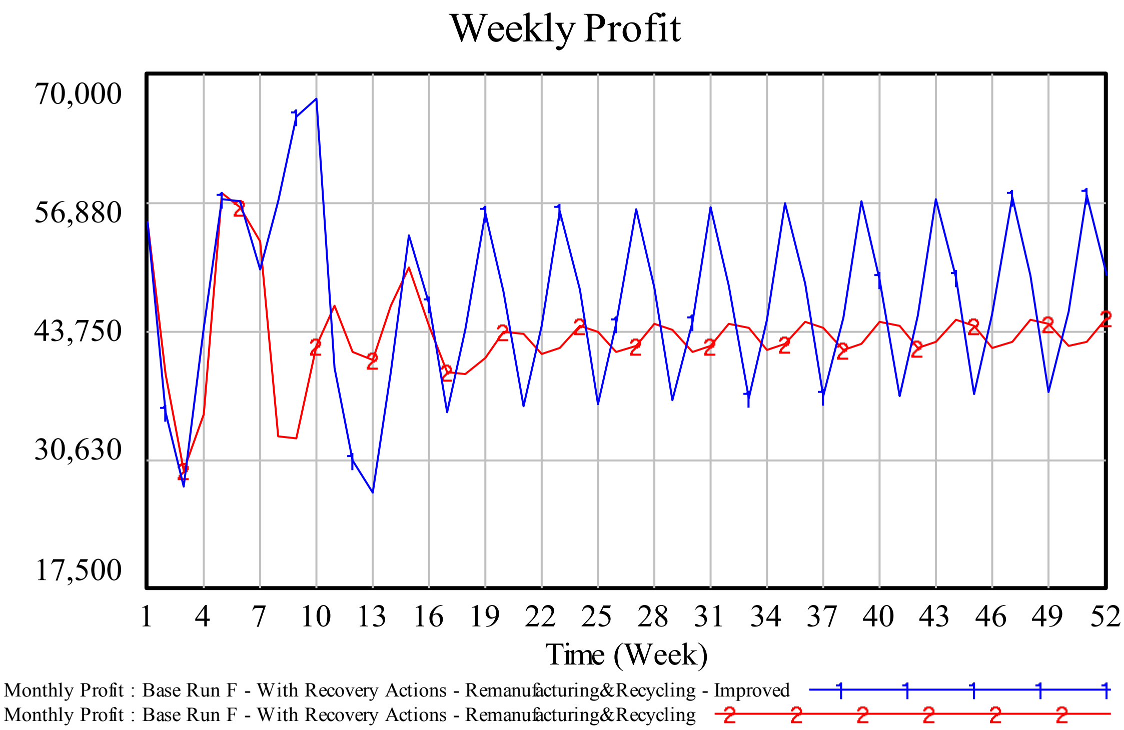

Figure 4.12 Comparison of weekly profit after and before improvement strategy

The average cost per laptop can be decreased from 191.59 USD to 189.69 USD by using the improvement strategy. By considering this assumption that there are 270 units for average weekly sales, the estimated savings resulting from the improvement strategy over the time horizon (52 weeks) can be calculated as follows:

$$52\ (time\ horizon) \times 270 (average\ weekly\ sales) \times 1.9 (saving\ in\ cost\ per\ laptop)$$

$$= 26{,}676\ USD$$

According to what was mentioned, the manufacturer can change three selected parameters and achieve profit enhancement and cost per unit reduction. For this purpose, the manufacturer must design a strategy aligned with the mentioned changes. Firstly, it must encourage consumers to return EOL(s) more. It is required to inform consumers about the collection centers and attempt to attract consumers' attention to the environmental benefits of recovery actions., It can be performed through different channels, such as social media platforms.

Moreover, the OEM must consider re-manufacturability in designing products that aim to be retrieved after the end of their first life cycle. Educating works regarding operational activities such as appropriate disassembly and inspection must be considered. The components can lose their re-manufacturability specifications during wrong disassembly operations. Also, it might be possible that some components are forwarded to the recycling flow incorrectly due to the lack of workers' knowledge and skills. Furthermore, the OEM must improve recycling technologies to increase the quality of recycled materials and using them in the manufacturing process more than before.

4.5 Strategy Optimization

This section attempts to find the optimized value for the parameters discussed in the improvement strategy. The aim of optimizing the parameters is to propose an optimized strategy that considers cumulative profit as a payoff variable. For this purpose, first, it is required to define possible ranges for the parameters:

$$0.2 \leq RRMR \leq 0.6$$

$$0.3 \leq Disposal\, ratio \leq 0.7$$

$$0.35 \leq Recycling\, ratio \leq 0.60$$

Vensim optimization engine can search within the possible ranges for each parameter and find the optimal value that gives the best payoff value. Optimized values are detected through the Powell heuristic algorithm used in the software:

RRMR = 0.372345

Disposal Ratio = 0.3

Recycling Ratio = 0.35

We can define an optimized strategy by considering the optimized values of three discussed parameters. Indeed, the optimized strategy refers to using the best production scenario (remanufacturing and recycling) by considering the optimized values for three parameters (DR, recycling ratio, and RRMR).

Figure 4.13 demonstrates how profit changes over the period given for both optimized and non-optimized strategies. The increasing trend of profit in the two mentioned cases is evident in the figure. The line graph related to the optimized strategy has surpassed the other line over the time horizon. The estimated profit resulting from the optimized improvement strategy is 2,576,825 USD. The percentage increase in profit after the optimized improvement strategy is about 8.25%.

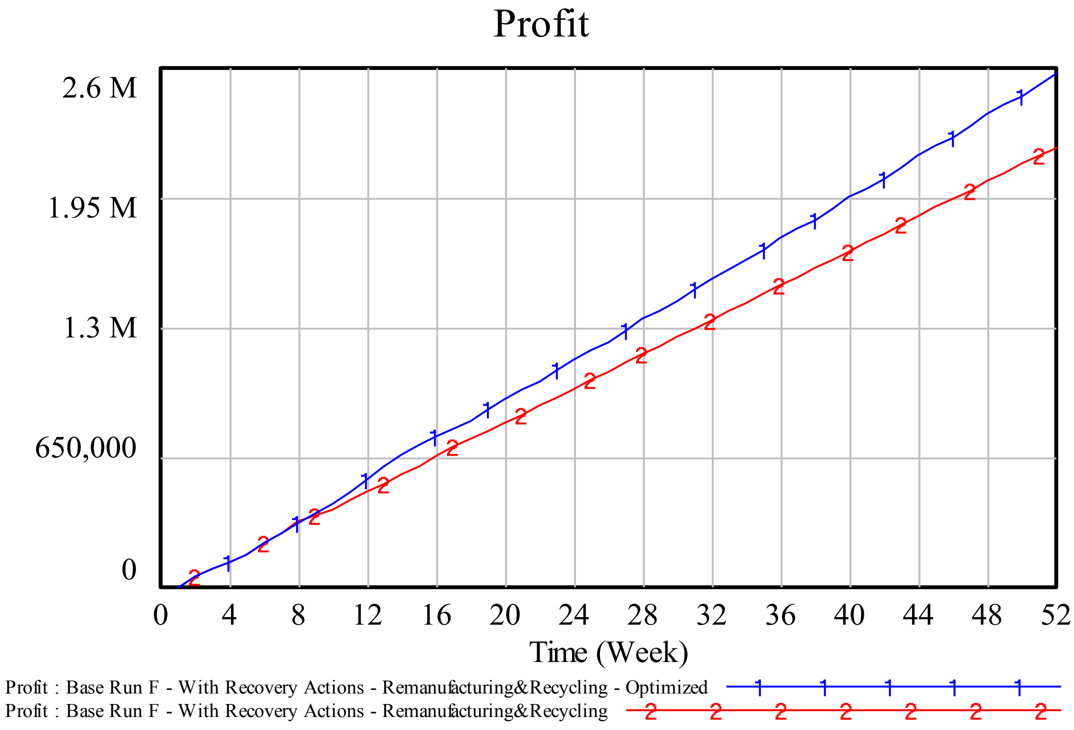

Figure 4.13 Comparison of profit in optimized strategy and non-optimized strategy

The average cost per laptop can be decreased by 4.29 USD through the optimized strategy compared to the "remanufacturing and recycling" scenario with no changing three parameters. The average cost per laptop can be reduced from 189.69 USD to 187.30 USD after optimizing the improvement strategy.

4.6 Government subsidy

Although results illustrate that implementing the optimized improvement strategy can lead to profit enhancement and cost per unit reduction, the generated profit is not notably significant compared to the required efforts to make the changes. Therefore, the external supports could help the OEM(s) be more willing to engage in the recovery activities. Government subsidy was mentioned by Wan and Hong (2019) as a motivating power to support the recycling and remanufacturing activities. Allocation of subsidy for the OEM's recovery actions can motivate them to continue the activities and respect environmental concerns and material utilization. To that end, we add the subsidy to the model as an auxiliary variable that directly affects total revenue. It is assumed that the allocated amount of government recycling subsidy for each set of recycled equivalents to a laptop is \$20 ($\mathrm{a}_1 = 20$), and the corresponding amount for a remanufactured product is \$10 ($\mathrm{a}_2 = 10$). These amounts are defined to compensate for the expenses of recovery actions for the OEM. Formula 4.8 presents how subsidy *(s)* is defined in the model by considering raw material arrival from recycled rate *(rrm)* and remanufactured rate *(rr)*:

$$s = a_1.rrm + a_2.rr \tag{4.8}$$

Total revenue *(tr)* can be calculated after considering subsidy as follows. Product price and profit margin are shown in the formula by *pp* and *pm*, respectively:

$$tr = pp.st.pm + s \tag{4.9}$$

Figure 4.14 shows the developed model by considering the government subsidy. The model is run to observe the impacts of using the government subsidy on the critical variables.

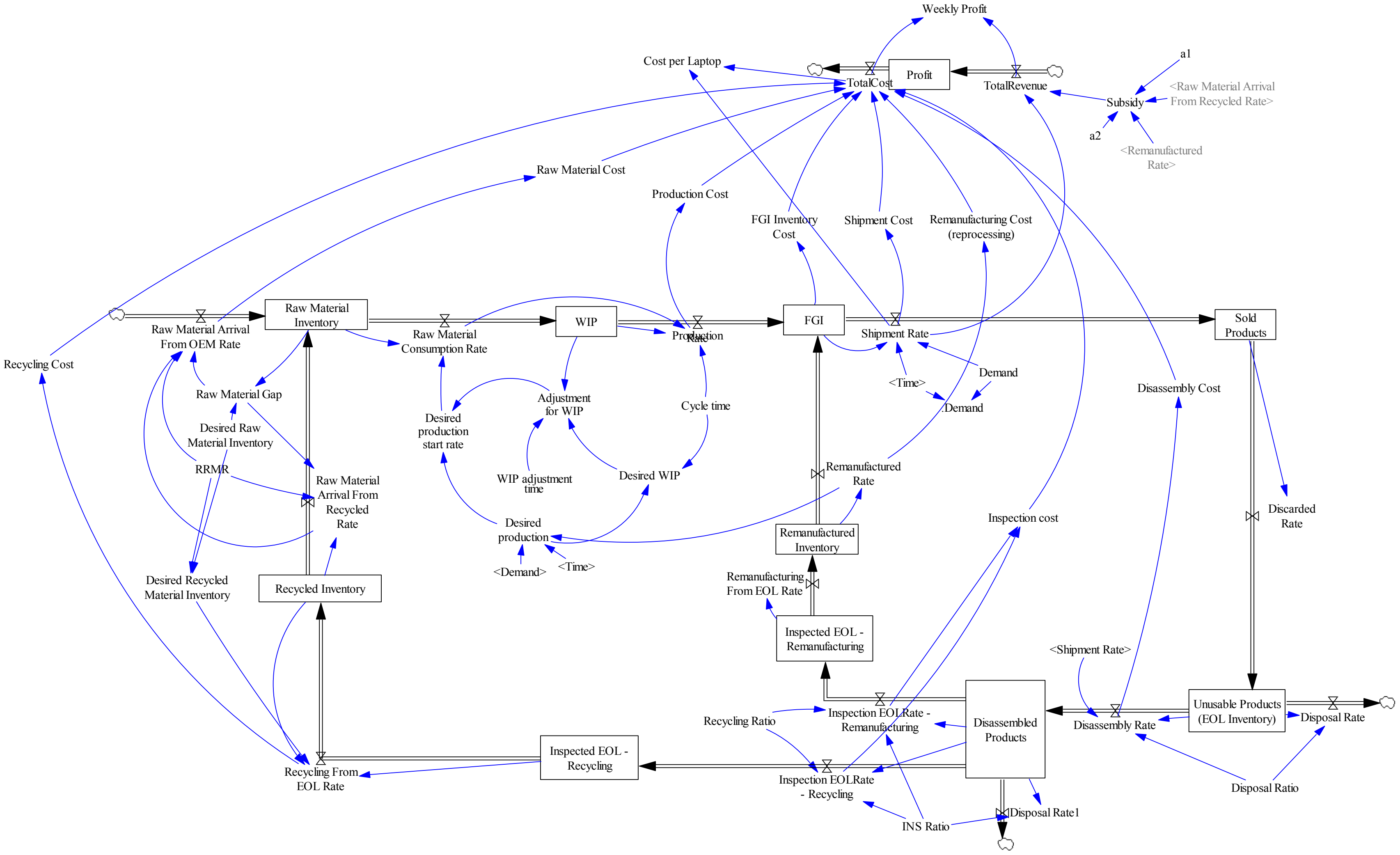

Figure 4.14 Improvement model after considering the government subsidy

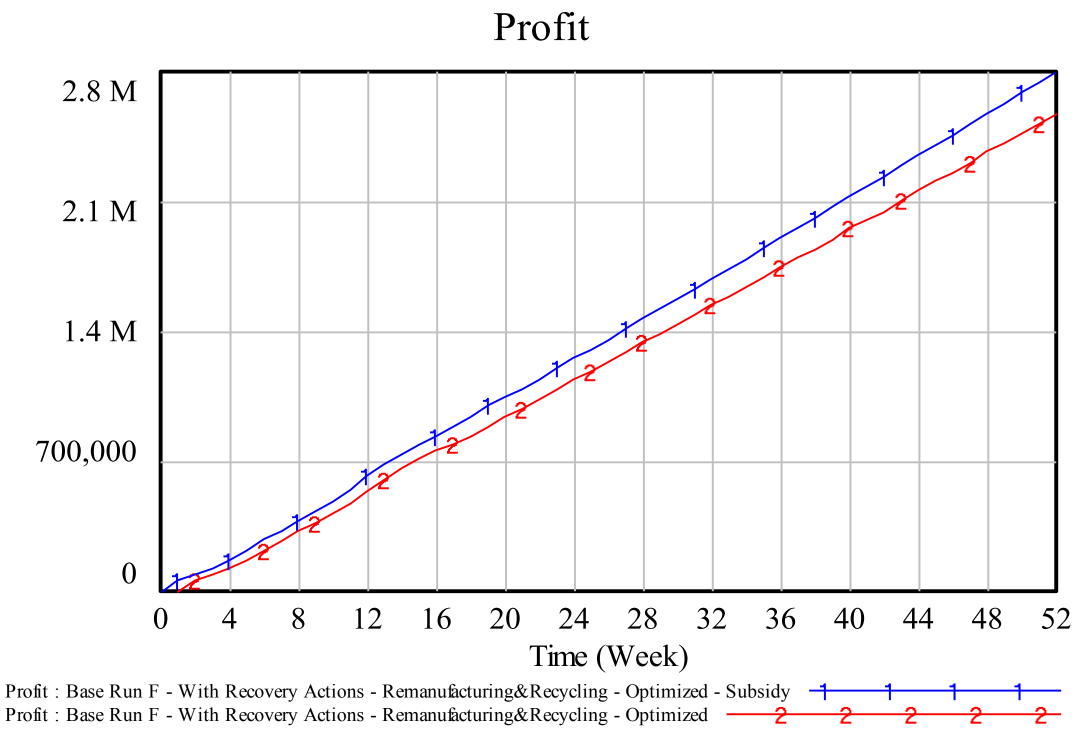

Figure 4.15 Comparison of profit before and after allocation of the subsidy

The cumulative profit in figure 4.15 is fairly similar to the graphs concerning cumulative profit in previous cases. An increasing trend is observed for both lines, blue and red. The subsidy could positively affect cumulative profit as the blue line gradually surpass the red line after week 13. Profit resulted from allocation of the subsidy is 2,761,477 USD by the end of the time horizon, which increased by 7.17 % compared to employing the optimized improvement strategy without the subsidy. Moreover, profit could be improved by 25.30% using the improvement strategy and receiving the subsidy compared to the base run.

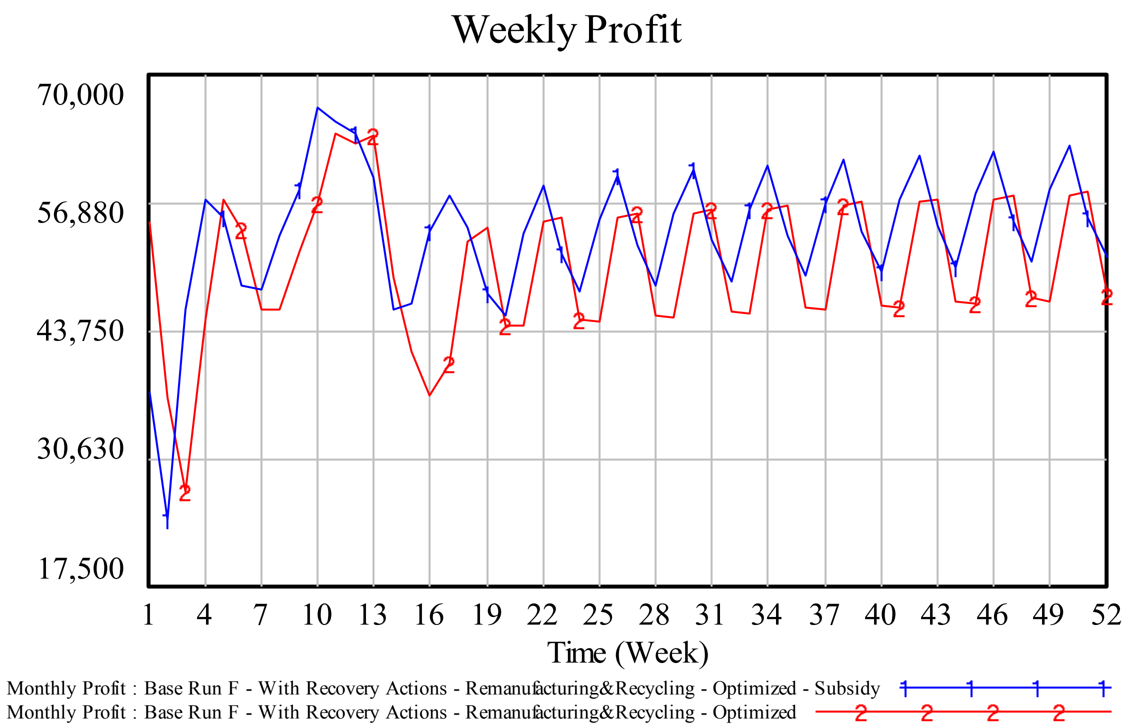

Figure 4.16 Comparison of weekly profit before and after the subsidy

Although there are still continual fluctuations in weekly profit as per figure 4.16, weekly profit in the presence of the subsidy is almost more in all weeks than in the absence of it.

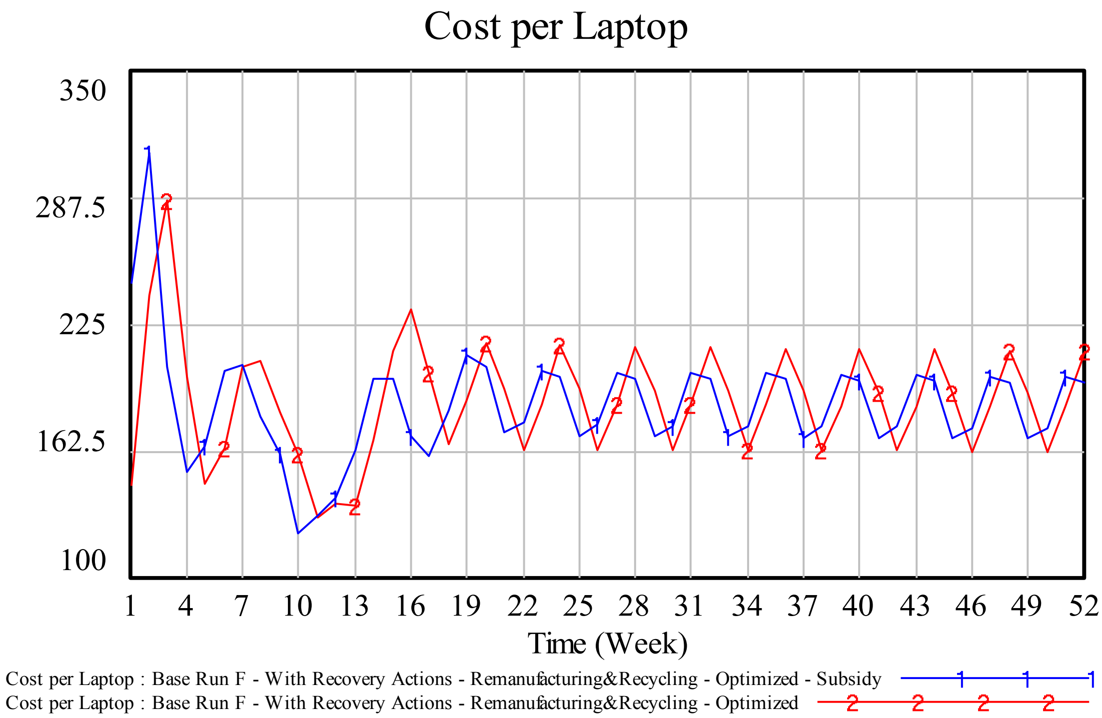

Figure 4.17 Comparison of cost per laptop before and after the subsidy

As shown in figure 4.17, the cost has not changed much after considering the subsidy. In order to find more details regarding the cost per laptop in two different cases, it is required to compare the average cost per laptop. It can be reduced from 187.30 USD to 184.39 USD if the subsidy is allocated to the OEM.

4.7 Summary

In this chapter, the system dynamics model was run for 52 weeks. Different production scenarios were simulated to find the best case in terms of profit and cost per laptop. The results indicated that the manufacturer must select the "remanufacturing and recycling" production scenario to make a hybrid production system. In the next step, the fluctuations in shipment rate were studied to find the causes behind that. The delay in production was detected as the primary cause of the fluctuations. The delay in production was reduced in the model to observe if the fluctuations can be decreased.

Three parameters were selected to modify them as a possible improvement. Modifications were considered in the model, and the results showed that they could affect the critical variables positively. Therefore, the improvement strategy was proposed accordingly.

In the next step, the Vensim optimizer was applied to optimize the three discussed parameters to enhance cumulative profit. As a result, the optimized strategy was offered. Simulation results presented that the optimized strategy leads to save more money and generate more profit. The results indicated that the profit enhancement and cost per unit reduction resulted from using the optimized improvement strategy. The results are in line with the manufacturer's goals and environmental considerations; however, they are not notable compared to the required efforts for changing the three parameters discussed in the improvement strategy.

Finally, government subsidy concerning recycling and remanufacturing was regarded in the model due to the necessity of external supports. The results presented that the government subsidy could positively affect the critical variables on the system.

CHAPTER 5: CONCLUSION AND FUTURE WORK

In this chapter, a summary of the research performed in this thesis is presented. Also, several suggestions are included for future works.

5.1 Conclusion

In this thesis, remanufacturing and recycling as promising recovery strategies in the closed-loop supply chain were reviewed. A system dynamics model for a hybrid production system relating to electronics industries was developed using the definitions and concepts introduced in chapter 3. Interrelationships among the system elements and delays in the production process were considered in the model through the respective equations. The main objective of the model was to study the behavior of the production system over time, detect the best production scenario from the manufacturer's perspective, and propose an improvement strategy to generate more profit and reduce cost per product.

Information and parameters related to a laptop manufacturing company as an example of electronics industries applied to the model. The model was run for a specific time horizon and time step using Vensim PLE 8.2.1. Four different production scenarios, including remanufacturing as a single recovery strategy, recycling as a single recovery strategy, remanufacturing and recycling, and without recovery actions, were defined to detect the best scenario in terms of meeting the manufacturer's goals (profit enhancement and reduction of cost per unit). The best production scenario, remanufacturing and recycling, was found through system dynamics simulation. Continual fluctuations resulted from delays in the production process were observed in the behavior of several system elements, such as shipment rate. To reduce the observed fluctuations, the delay in the production process was decreased. In the next step, three model parameters were selected to develop an improvement strategy through changing them. After providing the improvement strategy, Vensim optimizer optimized the discussed parameters and offered optimized values for them. The results presented that more profit, as well as less cost per unit, could be achieved by using the optimized improvement strategy. Although the improvement suggestions regarding the production system were aligned with the manufacturer's goals, the generated profit was not notably significant compared to the required efforts to change the values of the three discussed parameters. Therefore, the government subsidy was considered in the model as external support for remanufacturing and recycling activities. Considering the subsidy in the model led to profit enhancement and cost per unit reduction.

The main contribution of this study is the analysis of the hybrid production system through the system dynamics approach to perceive the interrelationships of system elements and how they can generate system behavior over time. The systematic view from the manufacturer's perspective by emphasizing on profit generation goal could be considered a distinctive feather of this study. Most work performed in this area was about using mathematical models or discrete simulations. The continuous change in variables resulting from the dynamic production environment was not considered in those studies. Although some research was conducted using system dynamics, most of them focused on the environmental impacts of recovery strategies. They did not concentrate on the financial variables such as profitability of manufactures.

5.2. Future work

There are several suggestions to extend the research presented in this thesis. Future work could be performed according to the following recommendations:

- The system boundary in the model can be extended to include what was excluded in our system boundary, such as different product models, marketing strategies, or human resource training.
- The exogenous variables could be changed to endogenous variables due to different research objectives. For example, demand, cycle time, or recycling ratio could be considered endogenous variables for future work to determine their values inside the model.
- Other electronic waste recovery strategies can be added to remanufacturing and recycling to detect the best combination of them in the hybrid production system aligned with generating more profit.
- Uncertainties in EOL arrival could be considered in the system to simulate a model which is more similar to the real world.

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