2-1-2015

Modeling and optimization of remanufacturing operations of spent products for sustainability

Eman Heikal

THE AMERICAN UNIVERSITY IN CAIRO

SCHOOL OF SCIENCES AND ENGINEERING

Modeling and Optimization of Remanufacturing Operations of Spent Products for Sustainability

BY

Eman Alaa Heikal

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

Under the supervision of:

Dr. Salah El-Haggar

Chairman of Department of Mechanical Engineering

The American University in Cairo

Dr. Tamer Abdelmaguid

Associate Professor of Industrial Engineering, Production and Mechanical design Department, Cairo University

July 2015

Abstract

In last century, the world has witnessed a great deal of technological and industrial progress. Branded products manufacturers have been competing in introducing new versions of their products frequently. Retailers and banks have been developing relaxed paying systems to fund the purchase of these new products. Exchanging strategies have been initiated by companies for customers to exchange their old version product for the latest versions. Such exchanging strategies are famous for vehicles, mobiles, and electrical appliances. Hence, a huge amount of unused or spent products are generated every day.

Many researchers have been developing different models for dealing with the decisions related to remanufacturing operations. However, there is no decision making system the manufacturers could use for cost / benefit assessment of disassembling and recovering these products that considers the following points: (1) evaluating the value of recovering the whole product versus value associated with recovering its disassembled items , (2) using Multi-Objective Mixed Integer Linear Programming (MILP) to assign spent products and their items to various recovery alternatives considering their received physical conditions, (3) selection of operations for items is not limited by a fixed regular production-hour capacity for each operation, (4) model assumptions, constraints, and formulation that satisfy the three aspects of sustainability, which are economic, social responsibility, and environmental aspects in one step model , (5) considering other vital dimensions which are the quality of recovered products and the minimum batch size for vending recycled materials, (6) utilizing the recycling operation in the optimum way that increases revenue from vending isolated materials. The thesis addresses these points using mathematical modeling and optimization for the remanufacturing operations of spent products.

The aim of this study is achieved through modeling the problem using a multi-objective mixed integer linear programming technique with two objective functions considering net profit maximization and total disposal weight minimization. Maximizing the net profit over specified planning periods satisfies the economic aspect of sustainability. Minimizing the total weight at all items assigned to disposal over specified planning periods satisfies the environmental aspect of sustainability. Initiating fair refunding system for spent products satisfies social responsibility aspect of sustainability. The optimum solutions of the model provides: optimal disassembly sequence of items, number of each item assigned to various recovery operations of the

remanufacturing unit, specification of the required total regular production hours, total needed number of workers, and specification of the number of workers hired and fired.

For verifying the proposed model and its LINGO code, the data of a simplified version of the trailer case study was used to display the model and tracking the displayed model to assure that the generated code exactly matches the model formulation, and to discover and correct any logical error. Then, the model was run several times to assure the accuracy of the model and to test the functionality of all the model mathematical equations. Its target was to assure that the integration of the model constraints exactly matched the logic of solving the problem, and the mathematical equation succeeded in expressing the model goals.

A case study that involves a numerical real- life critical problem in Egypt is solved considering only the first objective function, which is targeting feasible solutions for the collected trailers that are prohibited to move on the Egyptian roads. The results show that the remanufacturing of semi-trailers from the collected trailers is the most profitable solution for the good-condition trailers, while applying the cannibalization operation on the bad conditions trailers is the most profitable solution for the case. The remanufacture unit would make a net profit of L.E 8,878,800 for applying this solution at the end of the three planning periods. In case the remanufacture unit decided to restrict its recovery activities to the good condition trailers, the net profit of scenario 2 is L.E 20,499,100 at the end of the three planning periods, which is associated with an increase of L.E 11,620,300 in profit compared to recovering different conditions trailers.

A professional sensitivity analysis is implemented using the factorial design to accurately decide the significant input parameters that impact the net profit and total disposal weight at the end of the three planning periods for the trailers numerical problem. This factorial sensitivity analysis is designed to test 3 factors for 5 levels. Therefore, $5^3 = 125$ runs are conducted of all possible combination of these factors (input parameters), and the determination of output responses corresponding to each combination. Hence, the significant input parameters that impact the decisions were concluded. The input parameters that were selected are: selling prices, refund costs, and direct labor processing costs. The output responses that were selected are the net profit and the total disposal weight. It was discovered that changing the selling prices of the output products from the recovery operations which are refurbishing, repairing, remanufacturing, and cannibalization, and the selling prices of the recycled materials has the most influential impact on the net profit , and has the only significant impact on the total disposal weight at the end of the three planning periods. The refund costs paid to the end users for compensating them of getting their products is the second significant factor on the net profit at the end of the three planning periods. Hence, it is crucial to specify these selling prices and refund costs wisely.

Two approaches are used to solve the multiple objectives of the modified trailer case study, and to create a set of non-dominating solutions for the referred case which are: Minimax weighting method and constrained method. The most profitable and worst environmental non-dominated solution happened when the referred case was solved using the constrained method at bounding the disposal to 14870.3 kg, where the net profit value reaches its maximum of L.E 8,183,012, when the total weight of the items assigned to disposal reaches its peak of 14835.3 kg. This first best environmental non-dominating solution happened when the case was solved using the constrained method at bounding the disposal to 0 kg, where the net profit value reaches its minimum of L.E 7, 425,400. Solving the referred case using Minimax weighting methods is resulted in balancing solution of two competing objectives. The generated set of non-dominated solutions demonstrated the multi-objective nature of the proposed model.

Acknowledgements

I would like to express my sincere gratitude to Dr. Salah El-Haggar for his valuable support, guidance, and advice during each stage of my graduate study.

I would like to express my sincere gratitude to, Dr. Tamer Abdelmaguid for his valuable help, guidance, and suggestions. I have learned a lot of his knowledge and experience.

I would like to express my thanks to, Dr. Abdelghani Elimam for his valuable help and suggestions.

I would like to express my sincere and profound thanks to my dissertation committee members, Dr Mervat Badr, Dr Hatem Elayat, Dr Mustafa Arafa, for their insightful comments and suggestions. It was a great honor and pleasure to have them in my committee.

I am very thankful to Engineering Automotive Manufacturer Company (EAMCO) in Wadi Hof and Dr Taha Goma and Eng Said Nasser for their support and help in applying the proposed model to the real life trailer problem.

I am very thankful for the Canadian International College (CIC), Dr Mahmoud Mohamed Ahmed El-Sayed for permitting me the enough time to conduct this research.

Table of Contents

List of Tables

List of Figures

Chapter One

Introduction

1.1 Foreword

If we look around us, we find many spent products that exist at their end users and need disposal. These products are electric appliances such as fans and Vacuum Cleaners, electronics such as personal computers and mobiles, and vehicles including trailers. Landfill spaces are mostly full and the safe disposal process requires a great deal of time and money. Furthermore, the non -renewable energy sources consumed by factories producing these products are declining; therefore the prices of these energy sources are increasing. Moreover, the amount of materials required for the manufacture of these products is declining. Therefore, the acquisition prices for these products are also increasing. For all of the above reasons, companies have been exploiting the above facts for initiation of new business ventures for value recovery from these spent products in what is known as reverse logistics, which helps to achieve sustainability.

Researchers have developed various definitions for reverse logistics, the most inclusive of which is offered by Rahmatian(2008); which defines reverse logistics as "the process of planning, implementing, and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain direction for the purpose of recovering value or proper disposal."

Researchers have been discussing this problem from multiple perspectives. These perspectives are strategic, operational, or a mix of both. The strategic perspective is concerned with the specification of locations and capacities for opening inspection centers, remanufacturing facilities, and /or recycling plants that overhaul these spent products. Alumur et al (2012); R. Cruz- Rivera (2009); Schultmann (2006); and Zhou Yongsheng et al, (2008) studied the problem from the strategic perspective. The operational perspective is usually concerned with the disassembly sequence of these products, the optimum selection of recovery operations for them, and the production planning for these recovering facilities. Simic and Dimitrijevic (2012), A. Xanthopoulos,

E. Lakovo (2009) , K. Kim et al, 2006, Y. Shimizu et al (2007);and Kongar and Gupta (2006) studied the problem from the operational perspective. N.A. Harraz and N.M. Galal (2011), Das and Chowdhury (2011); and M. Chouinard et al, (2008) studied the problem from both strategic and operational perspectives. However, there are still many new features related to the problem that needs to be covered. Section1.4 shows some of these features that are considered by this research.

In this work, it is assumed that the spent products are overhauled by the manufacture facilities for three main reasons. The first one is to protect the intellectual property and technical know-how of the manufacturer's spent products from leaking valuable trade secrets to its competitors (Rahmatian, 2008). The second is to increase the value of the recovered products by using these reprocessed products and its recycled materials in the forward manufacturing path of new ones, and in the remanufacturing of similar products. The third is to save the huge startup cost required for opening recovery facilities. Therefore, this work is not concerned with the strategic perspective decisions of reverse logistics.

To maximize the value from these spent products, this thesis proposes a new model that aims to optimize the recovery operations for spent products for higher sustainability. The model considers new perspectives of the problem that has not been considered before. These perspectives are highlighted in section 1.4 and the literature review chapter. The model combines a multilevel disassembly tree, a multi-objective mixed integer linear programing (MILP) technique, economic viability, and technical feasibility targeting to achieve higher sustainability. Spent products like retired mobiles, fans, vacuum cleaners and televisions are typical examples of items that are used in reverse logistics activities, but other applications of the referred activities are needed to better fit different manufacturing processes and products—such as truck trailers. Truck trailers applications have particular importance in Egypt owing to the latest transportation law that penalizes their move on the Egyptian roads.

Although the area of forward supply chain management has been widely covered in recent decades, reverse supply chain is considered relatively new. The problem of reverse supply chain modeling is considered too complex and that it involves multiple perspectives that lead to unclear decision-making. These perspectives are strategic, operational, or a mix of both.

According to Chouinard et al. (2008)" Some models in the literature deal with reverse logistics only. Spent Products flows are thus directed toward different recovery alternatives primarily according to the site capacities, without considering the states of recovered product and needs for valorized products"

According to Chouinard et al. (2008)" Other models integrate reverse logistics into current supply chains. They generally consider one or two processing alternatives. When more than two processing alternatives are considered, the proportions of product flows directed toward different processing alternatives are generally fixed as a priori. Proportions are established notably according to expected states of recovered products. The product flows are directed toward one or many processing centers according to these proportions and to site capacities"

1.2 Problem context and proposed model definition

The generation of various spent products is sprouting due to several reasons. In most of the developing countries, these spent products remain as wastes in their initiation places for the lack of recovery companies. In the developed companies, these spent products are either transferred to the manufacturers or to other recovery companies to overhaul them. These manufactures or the recovery companies should decide the most sustainable strategy for dealing with spent products. Therefore, it is required to optimize the decisions related to assigning these spent products to the various recovery operations in the way that results in achieving maximum net profit, and minimum total disposal weight, as well as compensating the owners of these spent products with fair refunds. However, there is no decision making tool for remanufacturers to optimize the disassembly and recovery of these repurposes products that consider the following vital considerations:

- The disassembly of a whole spent product isn't considered *a priori*, yet decisions are evaluated using cost / benefit analysis of value based, on the value of the whole product versus value associated with its disassembled items.

- How to assign the whole spent product / its assemblies and parts (items) toward recovery operations is based on the physical condition of these items. The physical conditions corresponding to each spent product determine the technical feasibility portion of total received amount toward recovery operations.
- The assignment of the whole spent product / its assemblies and parts toward any recovery operation is not limited by available fixed regular production hour available for each operation in each period.
- The model assumptions, constraints, and formulation satisfy the three dimensions of sustainability, which are economic, social responsibility, and environmental dimensions in one step model.
- The consideration of other vital aspects, which are the quality of recovered products and the minimum batch size for vending recycled materials.
- The optimum utilization of the recycling operation.

The formulation of the proposed model integrates all the previous stated crucial considerations to be efficient enough to assess and analyze cost and profit of disassembling and recovering repurposed products. The multi-objective nature of this thesis model yields a set of non-dominated solutions, where the decision makers would select the solution that mostly fits their case. The proposed model ensures that the decisions associated with the set of non-dominated solutions achieve the highest net profit as well as the lowest total disposal weight from dealing with the spent products. The proposed model ensures that the social responsibility dimension is satisfied through its refunding system. This refunding system ensures that fair refund is paid to the owners of spent products according to their products physical conditions.

Despite the objective function of many recovery models are formulated to minimize the total recovery costs, the first objective function of the proposed model is formulated to maximize the net profit as maximizing the difference between revenue and costs is more practical to be targeted. The second objective function considered in the proposed model is formulated to minimize the total weight of items assigned to disposal.

Since, the three goals of sustainability are economic, social responsibility, and environmental goals as shown in fig1 (www.google.com); therefore, the formulation of the model targeted satisfying these three goals of sustainability. Maximizing the net profit satisfies the economic goal. Minimizing the disposal weight satisfies the environmental goal (Harraz and Galal, 2011). Initiating a fair refund system for spent product owners satisfies the social responsibility goal. Therefore, the proposed model could be considered a supportive optimization tool for the manufacturer who overhauls its spent products in the developed countries. Moreover, it could motivate manufacturers in the developing countries to initiate recovery activities within their main facilities.

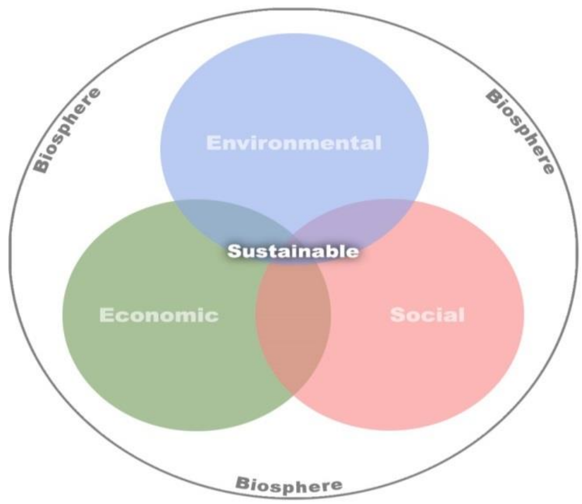

Fig 1.1: Three dimensions of sustainability
(http://globalfoodsystemanalysis.weebly.com/biofuels.html)

1.3 Scope and Objectives

This thesis proposes a mathematical modeling for the optimization of remanufacturing operations for managing the reverse supply chain of spent products aiming at achieving sustainability. The goals of this model are satisfying the three aspects of sustainability. The goals of this study is accomplished through the development of a Multi-Objective mixed integer linear Programing (MILP) optimization model.

The model formulation considers and satisfies other significant aspects, these are the quality of recovered products, and the minimum batch size for vending recycled materials. Multiple constraints are presented in the model to assure that the quality of the output products from recovery operations retain good quality. For instance, the remanufacturing operation is only assigned for spent products characterized by good physical conditions in order to assure that remanufactured products maintain good quality. The minimum batch size for vending recycled materials is satisfied through initiating some restrictions in this model, which ensure that the recycling operation is only considered for any material type if the recycled output of the considered material type exceeds the minimum amount that could be acquired by the merchant for this material type. The optimum solutions of the model provide the following:

1. The optimum disassembly sequence of items (spent products).
2. The number of each item assigned to various recovery operations (alternatives) of the remanufacturing unit in each planning period. In other words, the determination of portion from total number of items toward various recovery operations.
3. The specification of the total production hours required for the remanufacture unit in each planning period
4. The specification of the total number of workers needed for executing the recovery operations in each period.
5. The specification of the number of workers hired and fired in each period.

1.4 Contributions

This research considers important elements in the decision-making models used for remanufacturing operations of spent products that were not considered. These elements are summarized as follow:

- Assess the tradeoffs between the value of dealing with the whole spent product versus the value from its disassembly and dealing with the dissembled items separately. In other words, the consideration of the assignment of the whole spent product to various recovery operations.
- Restrict the assignment of items (spent products and/or its assemblies and parts) to various recovery operations based on their technical feasibility portion and economic viability toward these operations.

- Expand the assignment (usability) of spent products and/or its assemblies &parts to various recovery operations to the upper limit of the total available labors for all operations in regular production hours. This means that, selection of operations for items is not limited by a fixed regular production hour capacity for each operation.
- Satisfy the three dimensions of sustainability, which are economic, social responsibility, and environmental dimensions in one step model.
- Consider other vital aspects, which are the quality of recovered products and the minimum batch size for vending recycled materials.
- Utilize of the recycling operation in the optimum way through disassembling and grouping the parts belonging to the same material group; hence, increasing the income from selling recycled isolated materials.

1.5 Organization of the thesis

This thesis is organized into eight chapters. Chapter1 is the introduction. Chapter 2 provides a background of reverse logistics and remanufacturing operations. Chapter 3 provides a review of the literature of reverse logistics and modeling of remanufacturing operations. In Chapter 4, problem description and model formulation as well as the verification are presented. A Summary to the real trailer case study and its numerical example solution is presented in Chapter 5. Sensitivity analysis is presented for the real trailer case study in Chapter 6. Chapter 7 presents the solution technique for the multi-objective model. Finally, Chapter 8 provides the conclusion with suggestions for future research.

Chapter Two

Background on Reverse Logistics and Remanufacturing Operations

2.1 Background on Spent Products Creation

The world has witnessed a great deal of technological and industrial progress in the last century. New versions of the same branded products are introduced in the market every year. Moreover, different brands for the same product are competing to introduce new features and categories of their products to attract different marketing segment. Entrepreneurial advertising and marketing techniques are designed to initiate a need for the latest versions products, which motivates customers to acquire these new versions even though they don't need them. Banks have been developing different lending systems to fund the purchase of these new products, especially the expensive ones such as vehicles. Specialized purchasing debit cards have been introduced to bank customers to facilitate the acquisitions of new products. Exchanging strategies have been initiated by companies for customers to exchange their old version product for the latest versions. Such exchanging strategies are famous for vehicles, mobiles, electrical appliances. For example, an individual could exchange an old laptop or a mobile with new ones using certain debit cards. For instance, B-tech shop for electrical appliances offers the exchange of old television for a new Samsung television plus extra money suitable for the exchange. Some companies offer the exchange of any old car with a new one for relaxed installments of the difference. Therefore, it is obvious that the creation of unused products has been sprouting everywhere. That is why there is a need for optimization models that sustainably deal with these spent products.

2.2 Reverse Logistics Characteristics

Various characteristics of reverse logistics are demonstrated in this section. These characteristics are categorized into four main categories, which are spent-products categories, products and material recovery motivations, recovery operations purposes, and parties involved.

2.2.1 Spent-products categories

There are five categories of Spent-products: End-of-use returns, Warranty returns, Commercial returns, Production scrap and by-products and Packaging materials. The nature of these spent product categories impact the design of the reverse logistics recovery network (Rahmatian, 2008).

i. End-of-use returns:

This category includes products in which their use has been completed, products that have reached the end of their lives, and rented product returns that cannot be used any more. Companies are concerned about these returns due to many reasons. First, they contain elements and materials to recover that are valuable. Second, environmental regulations in some developed countries require the manufacture with the collection, recover, and recycle these products. Third, intellectual property and asset protection reasons may derive manufacturer to recover their own returns.

ii. Warranty returns:

This category contains faulty products including recalls, or products that have been destroyed during their delivery. They are returned to their producer for refund or repair. The producer is either maintaining the returns or disposing them.

iii. Commercial returns:

This category includes products that are sold from first to second users or to other seller for a reduced price. These products can be sold again since they are not used or they retain acceptable conditions.

iv. Production scrap and by-products:

Generally speaking, production processes usually yield various production scraps and by-products. Both the economic concerns and the environmental regulations are the main drivers for recycling these scraps.

v. Packaging materials:

This category of returns is considered the most attractive returns for manufacturers due to the minor processing they need such as cleaning for other direct uses. Examples for these returns are refillable bottles, and reusable boxes.

2.2.2 Products and material recovery motivations

Many motivations encourage companies toward reverse logistic activities of spent products. The most significant reasons for these activities are asset protection, economic, environmental regulations, transportation regulations and marketing potential.

i. Asset protection:

The manufacturers of the spent products may need to gather their own products from their customers and recover them to prevent the leakage of sensitive components to their competitors or to secondary markets.

ii. Economic:

The manufacturers of the spent products are attracted for the recovery of their spent products to exploit the cheap material sources required for their processes from these spent products. Hence, they avoid buying the equivalent virgin resources with their sprouting prices.

iii. Environmental regulations:

The manufacturers are in some cases obliged with the responsibility of recovering their products at the end of its life cycle. Consequently, they require collecting their products from end users to assign them to the suitable recovery operations. This was the case in the most developed countries.

iv. Transportation regulations:

Sometimes, transportation regulations banned the travel of old vehicles due to their harmful emissions that affect the atmosphere. Also, they banned the travel of some heavy transport types such as trailers due to their associated accidents. In these cases the manufactures of these vehicles are attracted to recover these products.

v. Marketing potential:

The manufacturers of the spent products are motivated to recover their spent products by many marketing polices. First, they introduce a relaxed polices for their customers to return their spent products for refund in order to build strong links with their customers. Second, manufactures of spent products are concerned to have sustainable profile for their companies. This means they have to be responsible for collecting and recovering

2.2.3 Purposes of Recovery Operations

The main goal of the recovery operations is to efficiently benefit from all remaining value in these spent products. Remaining values in these products varies according to the physical conditions of these products. It is required to assess the physical condition of each spent product. To assess the values of spent products, manufactures must test and inspect the received spent products to know their physical condition. The physical conditions determine their technical feasibility portion and/or economic viability from the total received return type toward proposed recovery operations. There are seven recovery operations used in this thesis: disassembly, refurbishment, repairing, remanufacturing, cannibalization, recycling, and disposal. The purposes and definitions are explained below.

i. Disassembly purpose

The two main disassembly operations are: partial disassembly and full disassembly. Partial disassembly requires refurbishment/repair/remanufacture/cannibalization/ recycling for final reassembly of the whole spent product; full disassembly requires the total breakdown of the spent product components. Refurbishment and/or repair of whole spent product require partial disassembly to get out the targeted assembly/part to be target reconditioned, and then reassemble them. For example, to refurbish a whole trailer, rim and tire assemblies are disassembled via the refurbishing operation then they are reassembled as a whole trailer, ready for resale.

At what level a spent product is disassembled is a critical decision especially for the complex structures of the returns. This decision is optimized on two factors. The first is the physical condition of the spent product. This condition determines the technical feasibility portion of the spent items as they relate to each recovery operation. The second is the economic viability of the spent products as they relate to each recovery operation. The proposed model considers the major trade-off between the consumed costs of disassembly and recovery operations versus the value of the output products from these disassembly and recovery operations.

ii. Refurbishment

The main purpose of refurbishment is reconditioning spent products to a higher quality. This operation involves cleaning and/ or doing minor repairs and/or replacing a small number of components in the spent assemblies or its subassemblies. This might require partial disassembly to get out the target assembly/part to do target reconditioning, and then reassemble them. For instance, cleaning a car, replacing tires, changing the interior of the car are typical examples of refurbishment.

iii. Repair

The main purpose of repairing failed products is bringing them back to a full functionality. This could be done through repairing or/and replacing unreliable subassemblies, parts or components. Doing repairs, dismantling of the unreliable elements then assembling them again are required. For example, filling the holes in the tire, batteries, maintaining the car engine are illustrative examples of repairing.

vi. Remanufacture

The main purpose of remanufacture is to take spent products and rebuild them in newly manufactured products. This proposed recovery operation is considered the most complex operation among other recovery operations. It is complex because it requires detailed inspection for all the assemblies and parts decided to enter in the manufacture flow of the equivalent new products. The manufactured products sold as brand new products or manufactured ones. For instance, axles and wheels are disassembled from the collected trailer, and then these axles and wheels are refurbished. After that, the refurbished axles and wheels are used in the manufacture of semi-trailers.

vii. Cannibalization

The main purpose of cannibalization is to remove assemblies and / or parts that maintain value from a product with bad physical condition product. The goal of this process is to create a supply of parts for the forward manufacture chain of such full products and for input products or materials required by other operations such as refurbishing, repairing or recycling. It is assumed in the proposed model, that the removed assemblies and / or parts that maintain value from the bad physical condition products would be a supply of parts for other purposes outside the manufacture unit.

viii. Recycling

The purpose of recycling is to transform the assemblies and/or parts of spent products to raw materials. Such recycled materials could be used in the manufacture of similar parts and products. This transformation takes place through melting, grinding, shredding, etc.

ix. Disposal

The purpose of disposal is to safely deal with the items that are non-reusable due to technical and / or economic reasons. These products are usually sent to a landfill or incinerated.

2.2.4 Entities involved in reverse logistics activities

There are various entities involved in the recovery of spent products. They collect and transport, inspect and test, dissemble and recover spent products.

i. Collection and transportation

These entities are specialized in the collection and transportation of the spent products, and moving the products from collection centers to testing centers. These companies would be made obsolete by the proposed model, which streamlines these functions, transferring the responsibility of the transportation of spent products to the owners of those products.

ii. Testing and inspection centers

After the spent products are collected, they are transported to the testing and inspection centers. In these centers the physical conditions of these spent products are specified. If these centers use manual labor, the spent products may require slight disassembly to determine the physical conditions of the spent products. If these centers are automated and use high-end technological testing devices, the spent products could be inspected without disassembly. The testing and inspection centers categorize the spent products according to their physical condition. A certain refund is paid to the product owner according to the categorized physical condition. The whole spent products are then assigned to recovery operations according to the proposed methodology.

iii. Recovery companies

If the manufacturers are not responsible for the recovery operation, then specialized recover parties such as specialized remanufacturing companies will play this role. In some scenarios, only one recover party is responsible for all recovery operations.

iv. Manufacturer

The manufacturers have the central role in most scenarios of reverse logistics if they are responsible for the recovery operations for these products. In such cases, the role of the recovery companies would be minimized. The role of the main manufacturer is to recover the spent products by the proposed recovery operations according to the physical conditions of the spent products as well as other considerations.

Chapter Three

Literature Review

3.1 Introduction

This chapter discusses relevant literature of reverse logistics and modeling of remanufacturing operations. The rising concerns about the sustainable alternatives for spent products have driven researchers to model and design reverse supply chain. Although the area of forward supply chain management has been widely covered in recent decades, reverse supply chain and recovery network is considered relatively new, which is why there are many new point of views in the research that should be considered. The problem of reverse supply chain modeling is considered a complex one that involves multi-perspectives decision-making. These perspectives are strategic, operational, or a mix of both.

The network and facility planning models of the reverse logistics are typical models that represent strategic decisions. These models involve specification of: the optimum locations for opening inspection centers, remanufacturing facilities, and /or recycling plants. These models also involve determination of: the optimum capacities for opening each type of such facilities to accommodate these spent products or wastes Alumur et al (2012). Moreover, these models involve deciding the remanufacturing facilities that are highly required to be opened for processing the spent products or the waste.

The operational decision-making models can be categorized into decision-making and production planning for remanufacturer facilities, and the optimal disassembly sequence of spent products models. The decision-making and production planning for remanufacturer facilities models involve the specification of: the amount of spent product assemblies and parts to be assigned to different remanufacturing operations, the number of labors required for each remanufacturer facilities, the number of labors to be hired and fired at each period, the number of overtime hours needed, and other decisions related to the production. The optimal disassembly sequence of spent products models basically involve the specification of items to be dissembled in each product versus the item to leave intact.

3.2 Strategic planning models

A Multi-period reverse logistics network design was developed by Alumur et al (2012). They formulated the problem using mixed-integer linear programming addressing several features of practical relevance which are: a multi-period setting, modular capacities, capacity expansion of the facilities, reverse bill of materials, minimum throughput at the facilities, variable operational costs, finite demands in the secondary market, and a profit-oriented objective function. Their model is useful for allocating the inspection centers as well as the remanufacturing facilities; also their model helps in deciding the initial capacities of new facilities as well as the required expansion for the existing facilities. Their model specifies the holding inventory and components requiring to be purchased at the remanufacturing plants and the network flows.

An End-of-Life-Vehicle (ELV) management system to be implemented in Mexico was designed by Rivera et al (2009) which addressed three features of the Mexican case. These features are the unknown number of ELV, the determination of the optimum location for the facilities' various types, and the financing system for applying the recovery system. The collection network for ELV is modeled as an Incapacitated Facility Location Problem. They modeled the ELV collection facility location problem disregarding the capacity limitation. The model outputs specified the optimum locations for collection centers, shredders, recyclers, and disposals.

Generic Model of Reverse Logistics Network Design was developed by Yongsheng and Shouyang (2008). They integrated both the repairing and remanufacturing options simultaneously. They formulated the problem using mixed integer formulation, and solved it using standard branch and bound techniques. They conducted the numerical example of the case study copy magic for the demonstration of the model's efficiency and practicability. The results showed that the consideration of both repairing and remanufacturing cut down the costs if compared to considering only remanufacturing facility.

3.3 Operational planning models

3.3.1 Decision-making and production planning models

Simic and Dimitrijevic (2012) formulated a decision making model to decide if the investment required for the full transformation of the vehicle recycling platform of the current equipment to modern sorting equipment is considered a profitable business and is attainable. They modeled the production planning processes in a vehicle recycling plant using linear programming to solve this problem. The result showed that the modern sorting equipment is a profitable business because the income from the sales of the isolated materials that output from modern sorting equipment are many times exceed the total consumed costs in delivering those materials. Also, the sensitivity analysis showed that even if the prices of those materials decreased to 50 %, this transformation remains profitable investment and should be attainable.

Kim et al. (2006) discussed the process of the remanufacture of reusable parts. In this process, the manufacturer has to choose between two options for supplying parts. The first is to assign spent products to the remanufacture facility and bring them back to a new condition to use them in this remanufacturing process. The second is to acquire parts from subcontractor for use in this remanufacturing process. The authors proposed a mathematical model that maximizes the cost savings associated with the described tradeoffs for supplying parts alternatives.

Jayaraman (2006) introduced a linear programming model for the Aggregate production planning model for closed- loop supply chains with product recovery and reuse. They formulated the objective function to minimize the total cost per remanufactured unit given the incoming distribution of nominal quality. The output of the model contained the estimation of the material recovery rates (MRR), set of replacement parts and materials, and the corresponding associated costs of the replacement parts and materials, as well as the workloads at resource centers.

3.3.2 Disassembly sequence models

Xanthopoulos and Iakovo (2009) formulated a model to address the optimal design of the disassembly and recovery processes. They dealt with the optimal design of the recovery processes of the end-of-life (EOL) electric and electronic products problem. They focused on the disassembly issues. They targeted to maximize the recovery of economic and ecological value as well as reducing the total wastes. They presented a two-phased algorithm for solving the problem. The first phase includes a multi-criteria/goal-programming analysis used for the selection and determination of the most desirable subassemblies and components to be disassembled for recovery from a set of different types of EOL products. The second phase includes mixed-integer linear programming (MILP) for optimizing the recovery processes for the multi-product, multi-period problem. The authors applied their model on a case study.

Kongar and Gupta (2006) formulated the problem of disassembly-to-order (DTO) system under uncertainty as multi-criteria decision-making optimization model. The goal of the proposed model was the determination of the best combination of the number of each product type to be taken back from the end user and/or collectors. These products are dissembled for the purpose of removing the functioning components and recycled materials to be sold. The sold products must meet certain demands while satisfying other financial, physical, and environmental boundaries. Fuzzy goal programming technique was employed to solve the problem. The model solution provided the decision maker with the optimum number of spent products to be taken back as well as the number of items to be recycled, reused, stored and disposed. The model generated the performance measures, total profit, items and materials sales revenues, total costs. The authors presented a case example to explain the model's implementation.

Meacham et al. (1999) formulated disassembly configurations to decide the optimal disassembly sequence for single and multiple Products. These configurations specified which assemblies and subassemblies should be dismantled and which should not. They used a hierarchical product tree representation to decide optimal disassembly that maximizes revenue for a single product. A linear time algorithm is developed to solve the problem. An extension to that algorithm is developed which assumed the association of fixed costs with the disassembly of certain nodes in the product tree. The problem was further developed and formulated as an optimization problem including three assumptions. The first one assumed the existence demand for the recovered products that should be satisfied. The second assumed limited disassembly capacity. The third assumed the existence of common components upon the disassembly of different products. They solved the problem by a using column-generation algorithm, which proved capability of solving reasonably sized problems in a few seconds of CPU time on average.

3.4 Mixed Strategic operational planning models

Harraz and Galal (2011) formulated a model to address the design of sustainable end-of-life vehicle recovery network in Egypt. They modeled the problem using a lexicographic mixed integer goal programming approach. The goals of the model were economic, environmental, and social. These goals were achieved by maximization of the profit, minimization of the disposal amount and maximization the recycled amount, and increasing the refund given to the vehicle owner. The deliverables of the model were the optimum locations of different processing facilities that supposed to process EOL vehicles as well as the amount of EOL vehicle assemblies and parts to be allocated to different EOL options.

Das and Chowdhury (2011) proposed an integrated reverse logistics supply chain planning process with modular product design that produces and markets products at different quality levels. They used mixed integer programming for the formulation of the entire planning process. They targeted to maximize the profit raised from collecting the returns and specifying the recovery modules for them as well as deciding the product mix proportion at different quality levels. Their model is useful in allowing the market selection between various quality levels of each product. They used the entire view of a supply chain, which considered the production, transportation and distribution of products to customers. They illustrated the applicability of the model using a numerical problem.

Chouinard et al. (2008) formulated a stochastic programming approach for designing supply loops. The authors used a two-step stochastic programming model to consider randomness related to the design decisions for a single period. The first step of the model determined the service and processing center, warehouse locations and the assignment of user zones to service centers for the collection. The second step specified the function of each site and the number of products that assigned to proposed processing alternatives. The authors tackled the randomness in the quality of the returned products by including five quality states for the returns. This involved two processing alternatives assigned to each product state according to its costs in a single planning horizon.

3.5 Summary of considerations that were not considered before

This section concludes and summarizes some of the important attentions that were not considered before for the defined problem. These considerations are summarized as follow:

- In previous works, the disassembly of the spent products is a priori. They consider the disassembly is the basic step for dealing with its assemblies and parts. No one assesses tradeoffs between the value of recovering the whole spent product versus the value from its disassembly and recovering the dissembled items separately.
- In many of the previous works, the concern of limiting the assignment of the received spent products to various recovery operations according to their specified physical conditions was neglected. Even though, the few research that considered such important factor, used it in the model based on expectation. Only Chouinarda et al (2008) used Stochastic Programming to tackle the randomness in the quality of the returned products by including five quality levels for the returns. Chouinarda model involved two processing alternatives assigned to each product state according to its costs in a single planning horizon. In Chouinarda model, repairing and disassembly alternatives are assigned to good state. No one used Multi-objective mixed integer liner programming technique to restrict the assignments of spent

products toward various operations according to their received physical conditions that determined from the testing and inspection center.

- In previous works, the fixed available workers for each operation always limit the assignment of spent products toward recovery operations by the fixed labor processing capacity. No one expand the assignment of spent products and/or its assemblies and parts to various recovery operations to the upper limit of the total available labors for all operations in regular production hours.
- In many of previous works, the recycling operation involves the melting of a group of different parts dissembled from the spent product that may belong to a material family such as metals. No one considered maximizing value of the recycling operation through disassembling and grouping the parts belonging to the similar material alloy.
- In many of previous works, they consider a maximum bound for the recycling operation. Yet, they did not consider the constriction of the minimum batch size for vending recycled materials. In other words, no one concerned that the recycling alternative should only considered if the recycled weight of each material satisfy the minimum weight that could be accepted by the market.
- Most of the works were concerned with the disassembly and recovering issues of electronics and electric appliances. None of these models applied on large spent products such as trailers. None of the researches proposed a mathematical formulation that model and optimize a numerical real life trailer problem with its practical importance in Egypt nowadays.

Chapter Four

Problem description and Mathematical Model and Verification

4.1 Problem Context

The studied problem considers a situation in which a manufacturer is planning for necessary recovery operations for its own spent end products or components that are returned from end customers. The manufacturer owns a remanufacturing facility that can handle various types of remanufacturing operations. It is required to determine the necessary workforce needed in the remanufacturing facility along with selecting remanufacturing operations on spent end products and their constituent subassemblies and parts with the objectives of achieving higher sustainability.

In the studied problem, there is a set of spent end products that are received from outside sources to be processed by the remanufacturing facility. In addition, the remanufacturing facility can receive spent subassemblies and components that are disassembled externally. Let $\boldsymbol{\mathcal{F}}$ denote the set of all spent items that are received from external sources. One of the operations that can be conducted by the remanufacturing facility on the received end products and components is disassembling them into their constituent subassemblies and parts. Let $\boldsymbol{\mathcal{P}}$ denote the set of subassemblies or parts that can be obtained by disassembling parent items in $\boldsymbol{\mathcal{F}}$, and let $\boldsymbol{\mathcal{I}} = \boldsymbol{\mathcal{F}} \cup \boldsymbol{\mathcal{P}}$.

Received items are inspected upon arrival and they are classified into three categories based on their physical or operating condition. Let $\boldsymbol{\mathcal{S}}$= {1, 2, 3} denote the set of physical conditions of received items, where 1 refers to good condition, 2 refers to intermediate condition and 3 refers to bad condition.

The product structure tree or bill of material (BOM) defines the quantities of each part/subassembly that are needed to assemble their parent assembly/subassembly. Such quantities are represented here using the integer parameters $\alpha_{ij} \geq 0 \ \forall i, j \in \boldsymbol{\mathcal{I}}$. Here, α_{ij} equals the quantity of item j obtained by disassembling one unit of its direct parent assembly/subassembly i. By setting $\alpha_{i,j} = 0$, it is meant that item i is not a direct parent of item j. It is important to note here that some parts or subassemblies can be common items in more than one assembly/subassembly, and therefore have multiple parents.

4.2 Model Formulation

4.2.1Operations Selection Constraints

There are seven types of operations that can be conducted on any item $i \in \mathcal{I}$. These operations and their assigned numbers between brackets are: (1) disassemble, (2) refurbish, (3) remanufacture, (4) repair, (5) cannibalize, (6) recycle and (7) dispose. The definition and description of these processes are presented earlier in section 2.2.3. Let $\mathcal{O}$ = {1, 2, 3, 4, 5, 6, 7} denote the set of the types of operations that can be applied on any disassembled item in the remanufacturing facility. Based on the physical state of a received item, only a subset of operations is applicable. In this research, and based on recommendations from industry experts, the assigned operations based on the physical state of received items are summarized in table 4.1.

Table 4.1: Operations assigned to each physical condition of received spent products

Physical condition	Assigned possible operations
1 (good)	1 (disassemble) 2 (refurbish) 3 (remanufacture)
2 (intermediate)	4 (repair)
3 (bad)	5 (cannibalize) 6 (recycle)

The studied problem involves the selection of the operations that are going to be applied on each item in each period throughout a planning horizon of T periods. We denote the set of planning periods as $\mathcal{T} = \{1,2, \dots T\}$.

Let $n_{i,s,t}$ be the quantity received of a spent item $i \in \mathcal{F}$ with condition $s \in \mathcal{S}$ in period $t \in \mathcal{T}$. The total quantity received from a spent item $i \in \mathcal{F}$ in period $t \in \mathcal{T}$, denoted $Q_{i,t}$, is then defined as.

$$Q_{i,t} = \sum_{s \in \mathcal{S}} n_{i,s,t} \qquad \forall\, i \in \mathcal{F} \qquad (1)$$

It is required to determine the number of units for each item $i \in \mathcal{F}$ that are going to be processed by operation $o \in \mathcal{O}$ in period t, which is denoted $X_{i,o,t}$. For received spent items $i \in \mathcal{F}$, and based on the relationships presented in table 4.1, the following equations are formulated.

$$X_{i,1,t} + X_{i,2,t} + X_{i,3,t} = n_{i,1,t} \qquad \forall\, i \in \mathcal{F}, t \in \mathcal{T} \tag{2}$$

$$X_{i,4,t} = n_{i,2,t} \qquad \forall\, i \in \mathcal{F}, t \in \mathcal{T} \tag{3}$$

$$X_{i,5,t} + X_{i,6,t} = n_{i,3,t} \qquad \forall\, i \in \mathcal{F}, t \in \mathcal{T} \tag{4}$$

For each item $j \in \mathcal{P}$, the quantity available in each period, denoted $Q_{j,t}$, is determined based on the disassembled parent items in that period. The following equation represents this relationship.

$$Q_{j,t} = \sum_{i \in \mathcal{I}} \alpha_{ij} X_{i,1,t} \qquad \forall\, j \in \mathcal{P}, t \in \mathcal{T} \tag{5}$$

In a given period, it is possible to have more than one operation applied to different quantities of the same item $j \in \mathcal{P}$. However, this is governed by some technical restrictions. Such restrictions are represented here using a pre-specified proportion of the total number of item j in period t that is technically feasible to be processed by operation $o \in \mathcal{O}$, denoted $p_{j,o,t}$. The following constraints represent this condition.

$$X_{j,o,t} \le p_{j,o,t}\, Q_{j,t} \qquad \forall\, j \in \mathcal{P}, o \in \mathcal{O}, t \in \mathcal{T} \tag{6}$$

Where,

$$Q_{j,t} = \sum_{o \in \mathcal{O}} X_{j,o,t} \qquad \forall\, j \in \mathcal{P}, t \in \mathcal{T} \tag{7}$$

4.2.2Workforce planning Constraints

An important part of the planning for remanufacturing operations is the distribution and control of the workforce that is going to be used to execute the required operations. In the current study, it is assumed that all workers will have the same skill level and they can be allocated to any type of operation as needed. A flexible and dynamic workforce control policy is also assumed which permits hiring/firing decisions as needed to match dynamic variations in the workloads from one period to another.

To represent the workforce planning part of the problem, let $l_{i,o}$ denote the man-hours needed to conduct operation $o \in \mathcal{O}$ on one unit of item $i \in \mathcal{I}$. Therefore, load (L_t) or the total number of man-hours needed in period t is evaluated as follows.

$$L_t = \sum_{i\in\mathcal{I}} \sum_{o\in\mathcal{O}} l_{i,o} X_{i,o,t} \qquad \forall\, t \in \mathcal{T} \qquad (8)$$

Workers are assumed to have the same skill level and the skills needed by the types of operations conducted could be acquired in negligible time. Therefore, workers can be allocated to any type of operation as needed. Let h_t denote the number of working hours available in period t. Accordingly, the total number of workers needed in period t, denoted W_t should satisfy the load requirement as represented by the following inequality.

$$W_t \geq L_t / h_t \qquad \forall\, t \in \mathcal{T} \qquad (9)$$

Let W_t^+ and W_t^- denote the number of workers hired and fired respectively at the beginning of period t. Hence, the workforce level change equation is provided as follows.

$$W_t = W_{t-1} + W_t^+ - W_t^- \qquad \forall\, t \in \mathcal{T} \qquad (10)$$

4.2.3Inconsumable resources constraints

Operations may share inconsumable resources such as tools and equipment. Let $\mathcal{R}$ denote the set of inconsumable resources shared by operations, and let $U_{r,t}$ denote the quantity of resource $r \in \mathcal{R}$ that is available in period t. If operation $o \in \mathcal{O}$ requires $u_{i,o,r}$ units of resource $r \in \mathcal{R}$ to process one unit of item $i \in \mathcal{I}$ for a total time of $\tau_{i,o,r}$, the following inequality represents a constraint on the number of resources used.

$$\sum_{o\in\mathcal{O}} \sum_{i\in\mathcal{I}} u_{i,o,r} \tau_{i,o,r} X_{iot} \leq h_t U_{r,t} \qquad \forall\, r \in \mathcal{R}, t \in \mathcal{T} \qquad (11)$$

4.2.4 Disposal

Disposal for unneeded parts may be associated with recovering the spent products. For applying the second objective function of this model, the total weight of items assigned to the disposal operation should be mathematical expressed. Let g_i denote the weight of item $i \in \mathcal{I}$.The total weight of items assigned to disposal at the end of the planning periods denoted K, is then defined as.

$$\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}} g_i X_{i,7,t} = K \qquad (12)$$

4.2.5 Recycled material minimum weight constraints

For recycling operation (6), the recycled material has to satisfy a minimum weight that is acceptable by merchants. We define set $\mathcal{M}$ as the set of major material types that can be sold to merchants.. If G_m^{SELL} defines the minimum weight of material m that can be sold to a merchant in one period, the following constraints need to be satisfied.

$$\sum_{i\in\mathcal{I}} g_i \pi_{i,m} X_{i,6,t} \geq G_m^{SELL} Z_{m,t} \qquad \forall\, m \in \mathcal{M},\ t \in \mathcal{T} \qquad (13)$$

Where $Z_{m,t}$ is a binary variable that equals 1 if the recycling operation is to be applied on any item in period $t \in \mathcal{T}$ with the objective of obtaining material $m \in \mathcal{M}$ and equals 0 otherwise. If $Y_{i,t}$ is another binary variable that equals 1 if the recycling operation is to be applied on item $i \in \mathcal{I}$ in period $t \in \mathcal{T}$ and equals 0 otherwise, the following constraints are necessary to represent logical relationships between $X_{i,6,t}$ and $Z_{m,t}$ variables.

$$X_{i,6,t} \leq M Y_{i,t} \qquad \forall\, i \in \mathcal{I},\ t \in \mathcal{T} \qquad (14)$$

$$X_{i,6,t} \geq e Y_{i,t} \qquad \forall\, i \in \mathcal{I},\ t \in \mathcal{T} \qquad (15)$$

Where, M is a sufficiently large number, and e is a sufficiently small number. The above two constraints define the logical condition that $Y_{i,t}$ equals 1 if $X_{i,6,t}$ has a positive value and 0 otherwise. Let $\beta_{i,m}$ define an input parameter that equals 1 if material m constituting item i and equals 0 otherwise. Now, the following constraints represent the relationships between $Z_{m,t}$ and $Y_{i,t}$, they define the logical condition that $Z_{m,t}$ equals 1 if the recycling operation is applied on one or more of item $i \in \mathcal{I}$ that partially or fully made from material m .

$$\sum_{i\in\mathcal{I}} \beta_{i,m} Y_{i,t} \geq Z_{m,t} \qquad \forall\, m \in \mathcal{M}, t \in \mathcal{T} \qquad (16)$$

$$\sum_{i\in\mathcal{I}} \beta_{i,m} Y_{i,t} \leq M Z_{m,t} \qquad \forall\, m \in \mathcal{M}, t \in \mathcal{T} \qquad (17)$$

4.2.6 Integer Constraints

$X_{i,o,t}, L_t, W_t, W_t^+, W_t^-$ *are* integer (18)

4.2.7 Binary Constraints

$$Z_{o,t},\ Y_{i,t} \in \{0,1\} \tag{19}$$

4.2.8 Non- negativity Constraints

$$X_{i,o,t}, L_t, W_t, W_t^+, W_t^-, Q_{j,t} \geq 0 \tag{20}$$

4.2.9 Costs

The decisions involved in the remanufacturing facility are associated with different types of costs. The first type is related to the workforce level which includes both direct labor and overhead costs and the costs of hiring and firing. Let c_t^{DL} denote the Direct labor and overhead costs for having one labor working h_t hours in period t, and let c^H and c^F denote the costs associated with hiring and firing one labor.

In addition, each operation is associated with operating costs. Let $c_{i,o}^{OP}$ denote the additional operating costs associated with conducting operation o on one unit of item i. The spent end products and components are purchased from outside sources and there is a refund paid to those sources. Here, $c_{i,s,t}^{REF}$ denotes the refund paid for item i received in period t with condition $s \in \boldsymbol{\mathcal{S}}$. Accordingly, the total cost is evaluated as follows.

$$\text{Total cost (TC)} = \sum_{t\in\boldsymbol{\mathcal{T}}}(c_t^{DL}W_t + c^H W_t^+ + c^F W_t^-) + \sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{o\in\boldsymbol{\mathcal{O}}}\sum_{i\in\boldsymbol{\mathcal{I}}} c_{i,o}^{OP} X_{i,o,t} + \sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{i\in\boldsymbol{\mathcal{F}}}\sum_{s\in\boldsymbol{\mathcal{S}}} c_{i,s,t}^{REF} n_{i,s,t} \tag{21}$$

4.2.10 Revenues

Revenues come from selling refurbished, remanufactured, repaired, cannibalized, and recycled items. For refurbished, remanufactured, repaired, and cannibalized items, let $v_{i,o,t}^{SELL}$ denote the revenue that is received from selling one unit of item $i \in \boldsymbol{\mathcal{I}}$ for which operation $o \in \{2,3,4,5\}$ is conducted in period $t \in \boldsymbol{\mathcal{T}}$. For recycled items, let $v_{m,t}^{REC}$ denote the revenue that can be received by selling one unit weight of material $m \in \boldsymbol{\mathcal{M}}$ in period $t \in \boldsymbol{\mathcal{T}}$. Accordingly, the total revenue is evaluated as follows.

$$\text{Total revenue (TR)} = \sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{o\in\{2,3,4,5\}}\sum_{i\in\boldsymbol{\mathcal{I}}} v_{i,o,t}^{SELL} X_{i,o,t} + \sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{m\in\boldsymbol{\mathcal{M}}} v_{m,t}^{REC} \sum_{i\in\boldsymbol{\mathcal{I}}} g_i\, \pi_{i,m} X_{i,6,t} \tag{22}$$

4.2.11 First Objective Function

Maximize Profit = $\sum_{t\in\mathcal{T}}\sum_{o\in\{2,3,4,5\}}\sum_{i\in\mathcal{I}} v_{i,o,t}^{SELL} X_{i,o,t} + \sum_{t\in\mathcal{T}}\sum_{m\in\mathcal{M}} v_{m,t}^{REC} \sum_{i\in\mathcal{I}} g_i \pi_{i,m} X_{i,6,t}$

$$-\sum_{t\in\mathcal{T}}(c_t^{DL}W_t + c^H W_t^+ + c^F W_t^-) - \sum_{t\in\mathcal{T}}\sum_{o\in\mathcal{O}}\sum_{i\in\mathcal{I}} c_{i,o}^{OP} X_{i,o,t} - \sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{F}}\sum_{s\in\mathcal{S}} c_{i,s,t}^{REF} n_{i,s,t} \quad (23)$$

4.2.12 Second Objective Function

Minimize Disposal= $\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}} g_i X_{i,7,t}$ (24)

4.3 Summary of the model

Sets

$\mathcal{F}$	Set of all spent items that are received from external sources.
$\mathcal{P}$	Set of subassemblies or parts that can be obtained by disassembling parent items in $\mathcal{F}$
$\mathcal{I}$	$= \mathcal{F} \cup \mathcal{P}$.
$\mathcal{S}$	Set of physical conditions of received items = {1,2,3} 1 = good condition, 2 = intermediate condition, 3 = bad condition
$\mathcal{O}$	set of the types of operations that can be applied on any item in the remanufacturing facility = {1, 2, 3, 4, 5, 6, 7}. 1 = disassemble, 2 = refurbish, 3 = repair, 4 = remanufacture, 5 = cannibalize, 6 = recycle, 7 = dispose.
$\mathcal{T}$	Set of planning periods = $\{1,2, \dots T\}$
$\mathcal{R}$	Set of inconsumable resources shared by operations
$\mathcal{M}$	Set of material types that can be sold to merchants

Parameters

α_{ij}	The quantity of item j obtained by disassembling one unit of its direct parent assembly/subassembly i
$n_{i,s,t}$	The quantity received of a spent item $i \in \mathcal{F}$ with condition $s \in \mathcal{S}$ in period $t \in \mathcal{T}$
$Q_{i,t}$	The total quantity received from a spent item $i \in \mathcal{F}$ in period $t \in \mathcal{T}$

$p_{j,o,t}$	A pre-specified proportion of the total number of item $j \in \boldsymbol{\mathcal{P}}$ in period $t \in \boldsymbol{\mathcal{T}}$ that is technically feasible to be processed by operation $o \in \boldsymbol{\mathcal{O}}$
$l_{i,o}$	The man-hours needed to conduct operation $o \in \boldsymbol{\mathcal{O}}$ on one unit of item $i \in \boldsymbol{\mathcal{I}}$
h_t	The number of working hours available in period t
$U_{r,t}$	The quantity of resource $r \in \boldsymbol{\mathcal{R}}$ that is available in period t
$u_{i,o,r}$	Units of resource $r \in \boldsymbol{\mathcal{R}}$ needed to process one unit of item $i \in \boldsymbol{\mathcal{I}}$ by operation $o \in \boldsymbol{\mathcal{O}}$
$\tau_{i,o,r}$	Time needed for using one unit of resource $r \in \boldsymbol{\mathcal{R}}$ to process one unit of item $i \in \boldsymbol{\mathcal{I}}$ by operation $o \in \boldsymbol{\mathcal{O}}$
g_i	Total weight of item $i \in \boldsymbol{\mathcal{I}}$
G^{DISP}	Maximum disposal weight allowed in a given period
$\pi_{i,m}$	Percentage of material $m \in \boldsymbol{\mathcal{M}}$ constituting item $i \in \boldsymbol{\mathcal{I}}$
$\beta_{i,m}$	Input parameter that equal 1 if material $m \in \boldsymbol{\mathcal{M}}$ constituting item $i \in \boldsymbol{\mathcal{I}},$ 0 otherwise
G_m^{SELL}	Minimum weight of material $m \in \boldsymbol{\mathcal{M}}$ that can be sold to a merchant in one period

Decision variables

$X_{i,o,t}$	The number of units for each item $i \in \boldsymbol{\mathcal{I}}$ that are going to be processed by operation $o \in \boldsymbol{\mathcal{O}}$ in period t
$Q_{j,t}$	The quantity obtained via disassembly operations for parents of item $j \in \boldsymbol{\mathcal{P}}$ in period $t \in \boldsymbol{\mathcal{T}}$
L_t	Total load (number of workers) needed in period $t \in \boldsymbol{\mathcal{T}}$
W_t	The total number of workers needed in period $t \in \boldsymbol{\mathcal{T}}$
W_t^+	The number of workers hired at the beginning of period $t \in \boldsymbol{\mathcal{T}}$
W_t^-	The number of workers fired at the beginning of period $t \in \boldsymbol{\mathcal{T}}$
$Z_{m,t}$	Binary variable that equals 1 if the recycling operation is to be applied on any item in period $t \in \boldsymbol{\mathcal{T}}$ to obtain material $m \in \boldsymbol{\mathcal{M}}$ and equals 0 otherwise.
$Y_{i,t}$	Binary variable that equals 1 if the recycling operation is to be applied on any item $i \in \boldsymbol{\mathcal{I}}$ in period $t \in \boldsymbol{\mathcal{T}}$ and equals 0 otherwise

Costs

c_t^{DL}	Direct labor and overhead costs for having one labor working h_t hours in period t
c^H	Cost of hiring one worker
c^F	Cost of firing one worker
$c_{i,o}^{OP}$	Additional operating costs associated with conducting operation $o \in \boldsymbol{\mathcal{O}}$ on one unit of item $i \in \boldsymbol{\mathcal{P}}$
$c_{i,s,t}^{REF}$	Refund paid for item $i \in \boldsymbol{\mathcal{P}}$ received in period $t \in \boldsymbol{\mathcal{T}}$ with condition $s \in \boldsymbol{\mathcal{S}}$

Revenues

$v_{i,o,t}^{SELL}$	Revenue that is received from selling one unit of item $i \in \boldsymbol{\mathcal{I}}$ for which operation $o \in \{2,3,4\}$ is conducted in period $t \in \boldsymbol{\mathcal{T}}$
$v_{m,t}^{REC}$	Revenue that can be received by selling one unit weight of material $m \in \boldsymbol{\mathcal{M}}$ in period $t \in \boldsymbol{\mathcal{T}}$

First Objective function

Maximize Profit = $\sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{o\in\{2,3,4,5\}}\sum_{i\in\boldsymbol{\mathcal{I}}} v_{i,o,t}^{SELL} X_{i,o,t} + \sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{m\in\boldsymbol{\mathcal{M}}} v_{m,t}^{REC} \sum_{i\in\boldsymbol{\mathcal{I}}} g_i \pi_{i,m} X_{i,6,t}$

$-\sum_{t\in\boldsymbol{\mathcal{T}}}(c_t^{DL}W_t + c^H W_t^+ + c^F W_t^-) - \sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{o\in\boldsymbol{\mathcal{O}}}\sum_{i\in\boldsymbol{\mathcal{I}}} c_{i,o}^{OP} X_{i,o,t}$

$-\sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{i\in\boldsymbol{\mathcal{F}}}\sum_{s\in\boldsymbol{\mathcal{S}}} c_{i,s,t}^{REF} n_{i,s,t}$

Second Objective function

Minimize K= $\sum_{t\in\boldsymbol{\mathcal{T}}}\sum_{i\in\boldsymbol{\mathcal{I}}} g_i X_{i,7,t}$

Constraints

$Q_{i,t} = \sum_{s \in \mathcal{S}} n_{i,s,t}$	$\forall\, i \in \mathcal{F}$	(1)
$X_{i,1,t} + X_{i,2,t} + X_{i,3,t} = n_{i,1,t}$	$\forall\, i \in \mathcal{F}, t \in \mathcal{T}$	(2)
$X_{i,4,t} = n_{i,2,t}$	$\forall\, i \in \mathcal{F}, t \in \mathcal{T}$	(3)
$X_{i,5,t} + X_{i,6,t} = n_{i,3,t}$	$\forall\, i \in \mathcal{F}, t \in \mathcal{T}$	(4)
$Q_{j,t} = \sum_{i \in \mathcal{I}} \alpha_{ij} X_{i,1,t}$	$\forall\, j \in \mathcal{P}, t \in \mathcal{T}$	(5)
$X_{j,o,t} \le p_{j,o,t}\, Q_{j,t}$	$\forall\, j \in \mathcal{P}, o \in \mathcal{O}, t \in \mathcal{T}$	(6)
$Q_{j,t} = \sum_{o \in \mathcal{O}} X_{j,o,t}$	$\forall\, j \in \mathcal{P}, t \in \mathcal{T}$	(7)
$L_t = \sum_{i \in \mathcal{I}} \sum_{o \in \mathcal{O}} l_{i,o}\, X_{i,o,t}$	$\forall\, t \in \mathcal{T}$	(8)
$W_t \ge L_t / h_t$	$\forall\, t \in \mathcal{T}$	(9)
$W_t = W_{t-1} + W_t^{+} - W_t^{-}$	$\forall\, t \in \mathcal{T}$	(10)
$\sum_{o \in \mathcal{O}} \sum_{i \in \mathcal{I}} u_{i,o,r} \tau_{i,o,r} X_{iot} \le h_t U_{r,t}$	$\forall\, r \in \mathcal{R}, t \in \mathcal{T}$	(11)
$\sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} g_i X_{i,7,t} = K$		(12)
$\sum_{i \in \mathcal{I}} g_i\, \pi_{i,m} X_{i,6,t} \ge G_m^{SELL}\, Z_{m,t}$	$\forall\, m \in \mathcal{M},\ t \in \mathcal{T}$	(13)
$X_{i,6,t} \le M Y_{i,t}$	$\forall\, i \in \mathcal{I},\ t \in \mathcal{T}$	(14)
$X_{i,6,t} \ge e Y_{i,t}$	$\forall\, i \in \mathcal{I},\ t \in \mathcal{T}$	(15)
$\sum_{i \in \mathcal{I}} \beta_{i,m}\, Y_{i,t} \ge Z_{m,t}$	$\forall\, m \in \mathcal{M}, t \in \mathcal{T}$	(16)
$\sum_{i \in \mathcal{I}} \beta_{i,m}\, Y_{i,t} \le M Z_{m,t}$	$\forall\, m \in \mathcal{M}, t \in \mathcal{T}$	(17)
$X_{i,o,t}, L_t, W_t, W_t^{+}, W_t^{-} \ge 0$ and integer		(18)
$Q_{j,t}, \ge 0$		(19)
$Z_{o,t},\ Y_{i,t} \in \{0,1\}$		(20)

4.4 Summary of the remanufacture unit recovery scenario

The recovery scenario of spent products is shown in fig 2. The end users have the responsibility of transferring their spent products to the testing and inspection center of the remanufacture unit. It is assumed that the testing and inspection center receives, inspects and categorizes the spent products according to their physical conditions in a time before the start of each planning period. Hence, this center generates detailed reports that specify the total number of spent products that would be overhauled by the remanufacture unit at the beginning of each planning period as well as the number of each physical condition products. These physical conditions determine the refund paid to the owners, and determines the proposed recovery operations that would be applied. The remanufacturing facility optimizes the most sustainable strategy for dealing with the total number of these spent products through; assigning these products to the recovery operations, allotting the total available workers toward these operations, and hiring and firing extra workers if needed. In order to recover these spent products, the remanufacture unit spends money in the direct and overhead costs, hire & fire costs, additional operating costs, as well as refund costs paid upon inspecting the received spent products. This remanufacture unit makes revenues through selling the output products resulted from the refurbishing, remanufacturing, repairing, cannibalization, and the recycling operations.

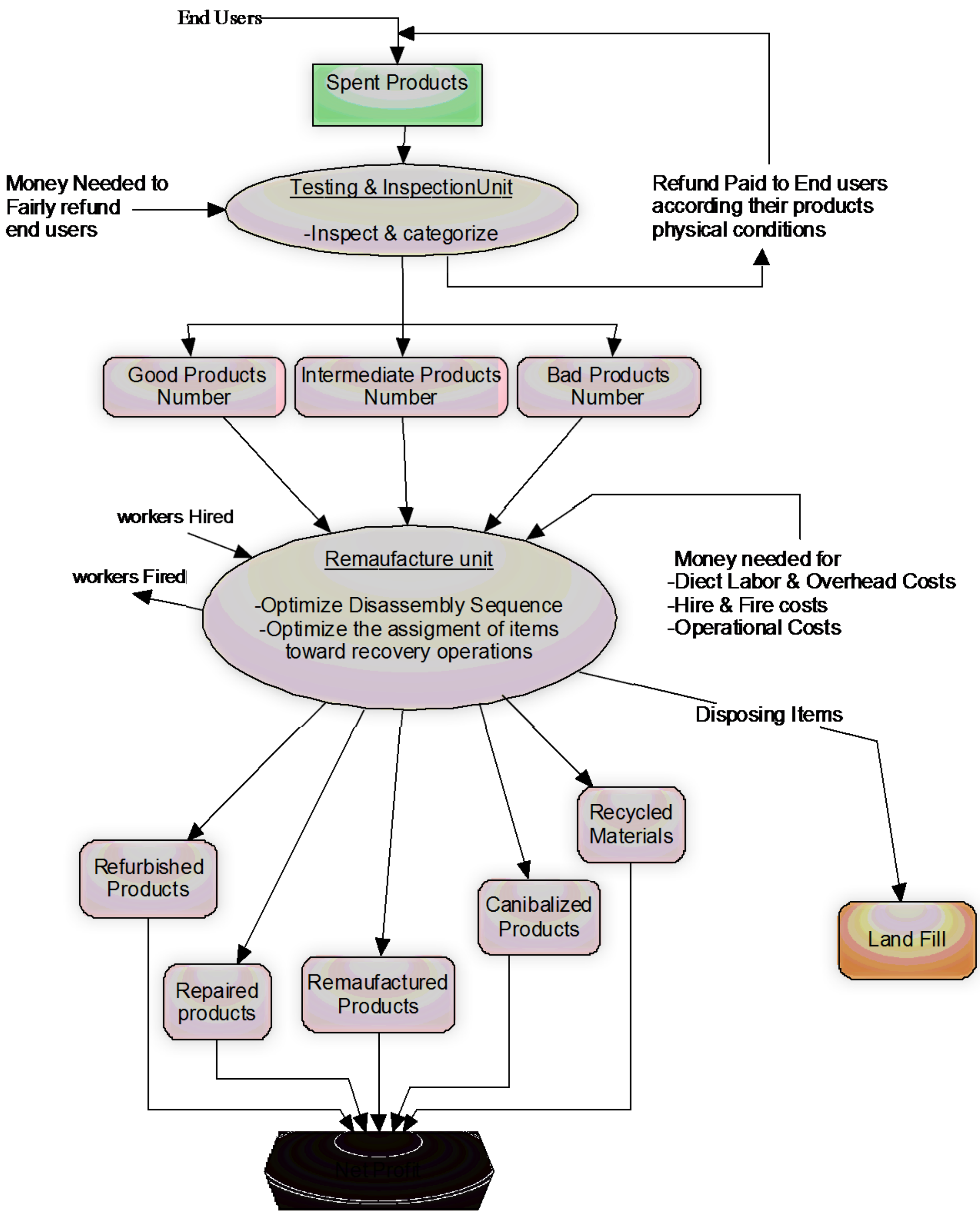

Fig 4.1: Recovery scenario of spent products

4.5 Summary of the new points considered in the proposed work

This section summarizes the new points that are considered in this thesis model. It elaborates how this thesis model can successfully consider these points. Also, it illustrates the advantage of considering each of these points.

i. **Assess tradeoffs between the value of recovering the whole spent product versus the value from its disassembly and recovering the dissembled items separately.**

In previous work, the disassembly of the spent products is given a priori. They consider the disassembly is the basic step for dealing with its assemblies and parts. On the other hand, this thesis model does not consider the disassembly of spent products as given a priori; it takes into account the assignment of the whole spent products to various recovery operations. They are assigned to various recovery operations considering their physical conditions that are specified according to the testing and inspection stage (received quality of spent product). This point considers that the net profit associated from assigning spent products to the suitable proposed operations may be more profitable than the traditional disassembly and dealing with its assemblies/ subassemblies/ parts separately.

ii. **Quality of received items is a main factor that restricts the assignment of items (spent products and/or its assemblies &parts) to various recovery operations.**

In many of the previous works, limiting the assignment of the received spent products to various recovery operations according to their quality was neglected. Even though, the few works that considered such important factor, used it in the model based on expectation. Only Chouinarda et al (2008) used Stochastic Programming to tackle the randomness in the quality of the returned products by including five quality levels for the returns. Their model involved two processing alternatives assigned to each product state according to its costs in a single planning horizon. In their model, Repairing and disassembly alternatives are assigned to good state. On the other hand, this thesis develops a MILP model to restrict the assignments of spent products toward various operations according to theirs quality that determined from the testing and inspection center. The proposed model tackles the variation in the quality of the spent products by including three quality levels for received spent products. The spent product would be tested and inspected to determine its quality level (physical condition). Good condition spent products could be assigned to disassembly, refurbish, remanufacture operations. Intermediate condition is only assigned to repairing. Bad state could be assigned to cannibalization, recycling operations. Disassembled items are characterized by good condition, which could be assigned to all the proposed seven operations.

iii. **Expand the assignment of spent products and/or its assemblies and parts to various recovery operations to the upper limit of the total available labors for all operations in regular production hours. In other words, selection of operations for items is not limited by a fixed number of workers available for each operation**

In previous work, the assignment of spent products toward recovery operations is always limited to the fixed available workers for each operation. Previous work did not pay attention to the fact that the strategy of fixing a number of workers for each operation may be the main cause of decreasing the net recovery revenue. This strategy could decrease the net revenue because it limits the maximum number of products and/or its assemblies and parts to various recovery operations according to the workers processing capacity for each operation. The proposed model has considered not limiting the selection of operations for items by fixed available workers for each operation. It is designed to allow all available labors in any period to rotate between different operations. This thesis model is designed to firstly assign labors toward high production operations. Moreover, it has considered hiring and firing options. The consideration of this point tackles the limitation of the strategy that involves fixing a number of workers for each operation. Therefore, the production capacity related to available workers for each recovery operation is not the dominant factor for the optimized decisions.

iv. **Introducing parameters and constraints that maximize the value of the recycling operation. By other words, utilizing the recycling operation in the optimum way**

In many of previous work, the recycling operation involves the melting of a group of different parts dissembled from the spent product and assigned to that operation that belongs to the family material group. Such recycling operation yield low grade recycled materials due to the various parts mixed for the recycling. Thus the selling value of such recycled material is corresponding to such low-grade material. The proposed model is formulated to assure that only elements within similar material alloys are melted with each other. It introduced a parameter that identifies the proportion of the total weight from each item that is made of each material alloy. It included a constraint that ensures maximizing the value of the recycling alternative. Revenue result from selling the recycled materials is maximized because each material is sold according to the actual selling value of its grade in the market instead selling them according to the lowest grade value of them.

v. **Study optimal disassembly sequence on applications such as trailers**

Most of the works were concerned with the disassembly and recovery issues of electronics and electric appliances. None of these models applied on large spent products such as trailers. This research is considered a pioneering one that try to investigate different solutions for the truck-trailer problem in Egypt.

4.6 Verification and Validation process demonstration

4.6.1Code Verification

The LINGO code was written all the model equations as shown in the Appendix D. Data for a simplified version of the trailer case study were used to display the model. This displayed model was printed, tracked, and revised to assure that the generated code exactly matches the model formulation. It was assured that the matrices of the input parameters were entered in the exact, right way. Also, tracking the generated model easily helped in discovering any logical error that may be associated with the model. If a logical error was discovered, the model was corrected. Then, the code was corrected and generated again.

4.6.2 Model Verification

Several runs were performed to assure the accuracy of the model. To prove the model verification, we referred to two runs that use deviated data for the simplified version of the trailer case study. This deviated data is slightly changed in each run to test the right functionality of all the model mathematical equations. Its target was to assure that the integration of the constraints exactly matched the logic of solving the problem, and the mathematical equation succeeded in expressing the model goals.

4.6.3 Model results Validation

At the same time of executing the model verification through the described runs, the accuracy of the output values of the decisions variables, as well as the objective function value, were tested. This was done through the manual computation of the values of decision variables according to the optimized situation and comparing these computed values within that output from the LINGO. The organized sequence for verifying the model is demonstrated in fig 3.

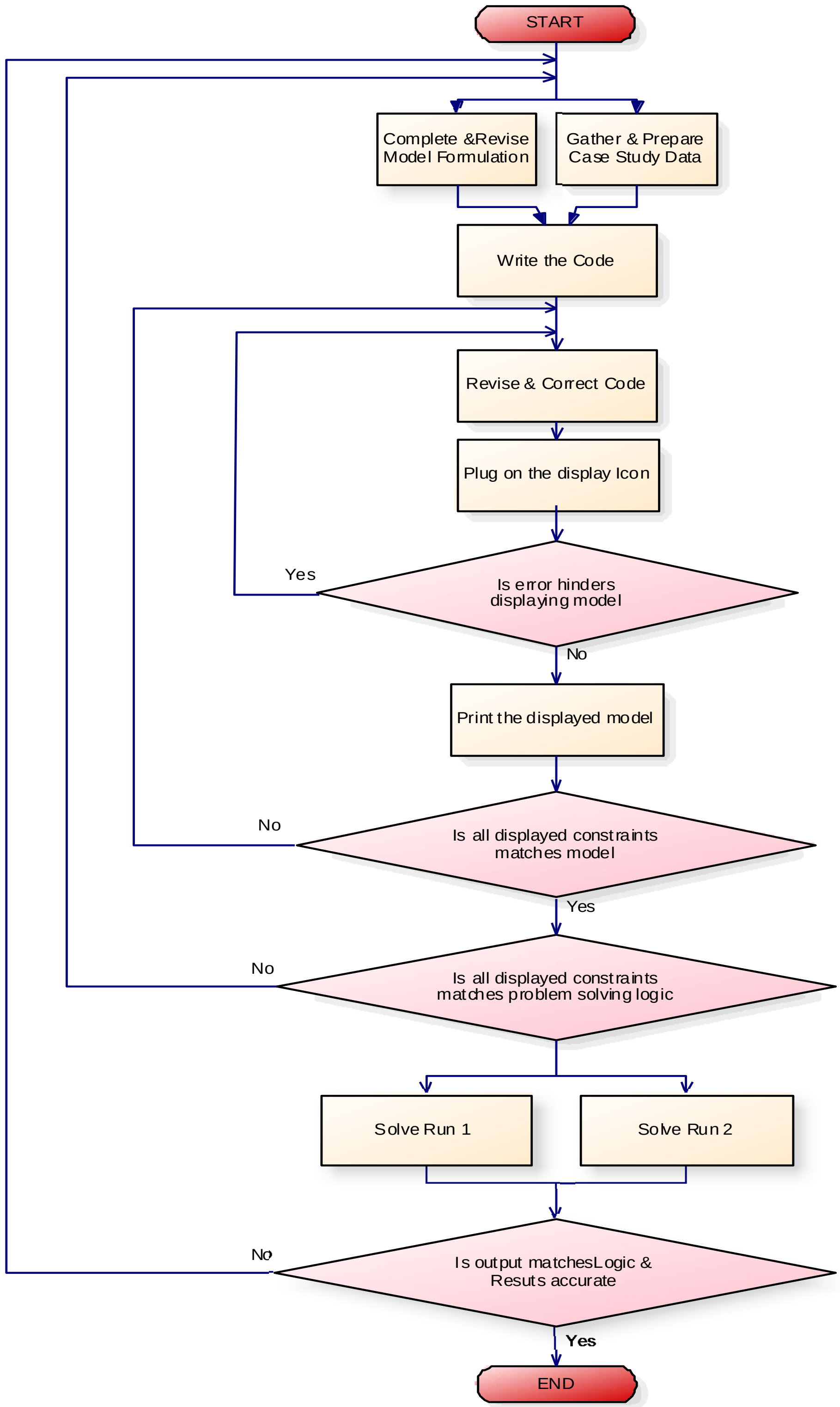

Fig 4.2: Sequence for verifying the model

4.7 Summary of the case study used in verifying the model

A simplified version of the trailer case study is used to verify the model. The simplified product structure tree or bill of material (BOM) of a spent trailer $i \in \mathcal{F}$ yields seven items$j \in \mathcal{P}$ as shown in fig 4.Table 4.2 summarizes the disassembly level for each item $i \in \mathcal{I}$, its referred number that is used in the LINGO code, and the amount of each item that is present upon its parent disassembly (α_{ij}). This scenario assumes the following: received trailers would vary in their physical conditions ($n_{i,s,t}$), assignment of the eight items $\mathcal{I}$ = {1, 2, 3, ….. 8} to seven recovery operations $\mathcal{O}$ = {1, 2, 3, 4, 5, 6, 7}, and the planning over three periods $\mathcal{T} = \{1,2,3\}$. This scenario considers the presence of only one objective function 1 which is maximizing the net profit at the end of 3 periods , while the objective function 2, which is minimizing the disposal weight, is dealt with as a constraint bounded by a value that exceed the maximum weigh that could be disposed. Note that the verification of the accuracy of each objective function and the tradeoffs accuracy between the two objective functions are already verified through countless runs used in the following chapter. The model is solved by LINGO 11 optimization software. All the input data tables used for solving this simplified case study, as well as the written code itself, are attached in the Appendix B.

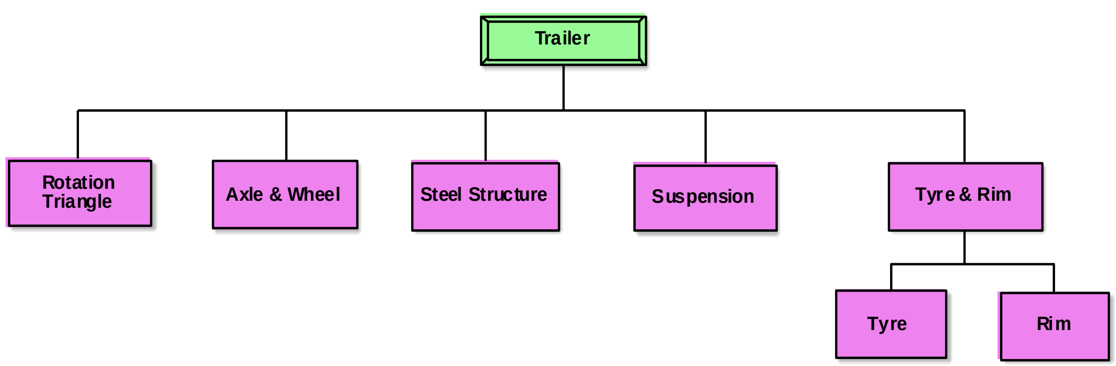

Fig 4.3: Simplified product structure tree of the spent trailer

Table 4.2: Details for simplified product structure tree of the spent trailer

Disassembly Level	item i ∈ I	Referred number for item i ∈ I	α_{ij}
0	Trailer	1	-
1	Triangle of Rotation	2	1
1	Axle & Wheel Assembly	3	3
1	Steel Structure	4	1
1	Suspension Assembly	5	4
1	Tyre & Rim Assembly	6	13
2	Tyre	12	1
2	Rim	13	1

4.8 Goals of the runs used in verifying the model

The main goal of the first run was to check that the model constraints succeeded in assigning each spent product characterized by a certain physical condition to the most profitable operation proposed for each physical condition. The main goal of the second run was to check whether the model constraints succeeded in optimizing the spent product disassembly sequence according to the model objectives. This was done through ensuring that the quantity of each dissembled item was correctly computed according to the quantity of its parents assigned to the disassembly operation in each period. Moreover, it was ensured that item disassembly only took place in case its disassembly was more sustainable than leaving it intact and dealing with it as a whole.

It was targeted to check in both runs the right allocation of the available workers toward various operations, and the proper execution of hire and fire strategy among the three periods. It was also targeted to assure that the function of the recycling constraints exactly matched within the problem solving logic. Furthermore, it was objected to check in both runs the proper function of all the integers as well as binary decision variables, and that the optimized decisions and model output were exactly matching the problem solving logic and the output was free of any errors. It was aimed to assure the linearity of the model and the optimized decisions were satisfying the model objectives. The demonstration for data adjustment that used in the refereed verification runs as well as their output and their results investigation and were attached in Appendix G.

Chapter Five

Application to spent Trailers in Egypt

5.1 Background on the 2010 Egyptian law of prohibiting the move of truck trailers on the Egyptian roads

In 2010, the Egyptian government passed a traffic law banning the movement of truck trailers on the Egyptian roads. Truck owners and drivers can face strict penalties for breaking the law. However, the law has not been enforced yet to avoid negative reactions of the drivers and owners, and the limited financial budget of the enforcement agency, especially after the 2011 riots.

5.1.1. The new law was enacted for the following reasons:

1 According to the Central Authority for Public Mobilization and Statistics (CAPMAS), road accidents resulted in the death of more than 7000 persons in Egypt in 2010, with a rise of 7.9% from the previous year. Trucks were involved in 40% of vehicle accidents in 2010, making them the primary cause of car accidents on the highway.

2 According to the reports issued by the ministry of interior in 2008, two out of every three accidents were caused by big trucks, which are resulting in more than three deaths per accident.

3 The total number of truck trailers on Egyptian roads has reached more than 34,000.

The Egyptian government proposed a conversion solution of truck-trailer to semi-trailer through lengthening the chassis of the trailer. Yet, many arguments held around the infeasibility of that solution. Also, up to 14,000 trailers cannot be feasibly converted. Additionally, truck owners or drivers cannot afford the conversion from the truck- trailers to semi-trailer. Many drivers / owners have protested the implementation of the new law because of the increased costs.

5.2 Objectives of applying the proposed model on trailers

The developed model is applied on the reverse supply chain of trailers for various reasons. The first is to validate the constructed model, and the second is to support the Egyptian government in prohibiting these trailers on the Egyptian roads. Such support would help in preventing accidents that are accompanied with severe damage. The owners of these trailers as well as their drivers have protested such decisions. They protest for two main reasons; the first is that they could not acquire the legal semi-trailers, and the second is that they claim that the carrying loads of the semi-trailers are much less than the carrying loads of truck trailers. Therefore, designing and applying such a model may be considered as an attempt to solve such critical issues.

The proposed model is considered a decision making tool that helps the manufacturer to investigate if dealing with these trailers in reverse order associated with profit after deducting the compensation given for their owners. In order to motivate the decision makers to go on recovery business for these trailers, the following questions should be answered. Is remanufacturing semi-trailers from trailers profitable? If it considered profitable business, does this remanufacturing operation is considered the most profitable operations among other proposed recovery operations? To what extent, changing the selling value of the remanufactured semi -trailer is associated with good profit to the factory? It also helps the Egyptian government to know the consequences from applying such a law. Moreover, it helps the public understand the law.

5.3 Trailers remanufacturing and cannibalization recovery operations

As demonstrated in section 2.2.3, the remanufacture and the Cannibalization operation are the most complex recovery operations in their planning. These operations are greatly varied from one product to another. Therefore this section summarizes the procedures of such complex recovery operations. Note that these procedures are executed under the umbrella of remanufacturing operation, and the level of planning of the proposed model does not integrate the remanufacturing operation with the remaining operations. Note that all the data used for illustrating both the remanufacturing and the cannibalization operations were based on the consultation of the engineering automotive manufacturer company (EAMCO) in Wadi Hof.

5.3.1 Remanufacture of Semi-trailers from Spent Trailers

5.3.1.1 Semi-trailers Remanufacture process summary

In order to demonstrate the procedure of remanufacturing a semi-trailer it is crucial to highlight the main differences between a semi-trailer and a trailer. Fig 5 shows the simplified product structure tree of a typical semitrailer while Fig 6 Show the simplified product structure tree of a spent trailer. Therefore, the main difference between semi-trailers and trailers are the following:

1. The semi-trailer must include landing gears, while the trailer does not.
2. The semi-trailer must include Kingpin assembly, while the trailer does not.
3. The trailer must include Rotation Triangle, while the semi-trailer does not.

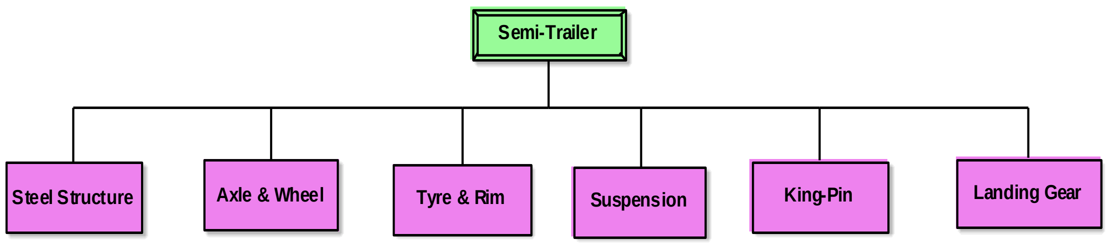

Fig 5.1: Simplified product structure tree of a typical semitrailer

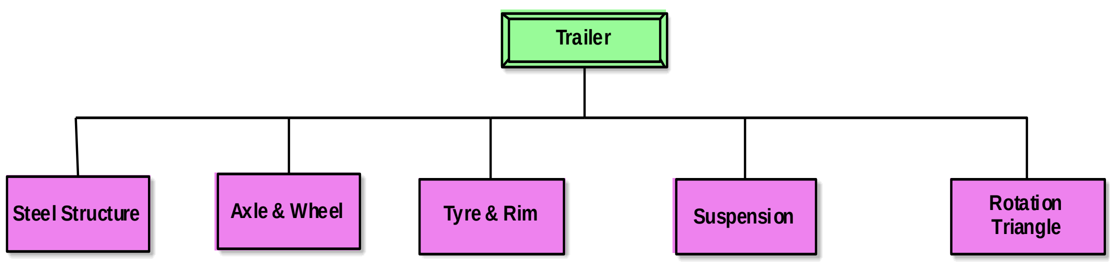

Fig 5.2: Simplified product structure tree of a spent trailer

Summarizing the remanufacturing process from a trailer to a semi- trailer in the following points:

1 Dismantle the axle and wheel assembly, suspension assemblies, and the tire and rim subassemblies from the collected trailers.
2 Refurbish the dismantled assemblies and subassemblies and do the needed repairs.
3 Manufacture the semi-trailer chassis.
4 Select and purchase the required brake air circuits, kingpin, and landing gears.
5 Assemble of the semi-trailer.
6 Coat the semi-trailer.

5.3.1.2 Rough estimate of Semi-trailers remanufacture process costs & revenues

Since the needed hours for remanufacturing the semi-trailer is 48 hours, it's required additional operating cost is 76,000 L.E, and it's selling value is 140,000 L.E. These hours, costs, and prices are the highest if compared by other proposed recovery operations. Therefore, it is important to demonstrate how these high numbers are estimated. Table 5.1 summarizes the processes involved in a semi-trailer remanufacturing operation and their corresponding processing hours. Table 5.2 present rough estimates of the additional costs required for remanufacturing a semi-trailer. Table 5.3 summarizes the expected sources of revenues result from applying the remanufacture operation on the collected trailers; hence, it highlights how the remanufacture semitrailer-selling price is estimated.

5.3.1.3 Economic feasibility of remanufactured Semi-trailers

The total cost by the remanufacture unit to fix up one semi -trailer from a used trailer is 116,000 L.E. This is the summation of the remanufacture additional cost, which is 76,000 L.E as shown in table 5.2, and the spent trailer refund cost which equal to 40,000 L.E plus the processing cost, around 600 L.E . The total revenue associated from applying the remanufacture operation on one spent trailer is equal to 140,000 L.E/trailer. This 140,000 L.E / trailer equals the summation of the semi-trailer selling value (L.E 120,000), and the spent trailer steel scrap selling value (L.E20,000 L.E). Therefore, the total profit for the remanufacture of one semitrailer equals 140,000 – 116,000 = 24,000 L.E / unit.

Table 5.1Estimating the working hours needed by semi-trailer remanufacturing operation

Process required	**Corresponding time / unit**
Dismantle tires from axle	= 0.5 *2 sides * 3 axles = 3 hours / Trailer
Remove the fixation of suspension	= 0.5 * 4 assemblies = 2 hours / Trailer
Remove the balancers	= 0.5 * 4 =2 hours / trailer
Dismantle the leaf spring	= 0.5 * 4 =2 hours / trailer
Dismantle the torque rods	= 0.5 * 6 =3 hours / trailer
Remove and handle the axle out	= 1 *3 = 3 hours / trailer
Refurbish dismantled items	= 8 hours
Assemble remanufactured semi-trailer	=25 h / semi-trailer
Total remanufacture hours	**= 48 hours per unit**

Table 5.2: Estimating the additional operating costs required for remanufacturing a semi-trailer

Process required	**Corresponding cost / unit**
Manufacture a semitrailer chassis	= 65,000 L.E / semi-trailer
Purchase king-pin	= 2000 L.E / semi-trailer
Purchase brake air circuit	= 6000 L.E / semi-trailer
Purchase landing gears	= 1000 L.E / semi-trailer
Coat the remanufactured semi-trailer	= 2000 L.E / semi-trailer
Total remanufacture costs	**= 76,000L.E / semi-trailer**

Table 5.3: Estimating the suitable selling price for the remanufactured semi-trailer

Revenue sources	**L.E / unit**
Selling remanufactured Semitrailer	= 120,000 L.E
Selling old trailer chassis steel material	= 6000 * 1 ton = 6000 L.E / unit
Selling old trailer remaining steel material	= 3500 * 4 ton = 14,000 L.E / unit
Total selling values	**= 140, 000 L.E / unit**

5.3.2 Summary on the cannibalization operation

According to the proposed model, the cannibalization operation is only applied on bad physical condition products. The cannibalization operation involves disassembly of the trailers into assemblies and parts then sorting and grouping the elements with value from the remaining non value elements without value. It is assumed in the proposed model, that the removed assemblies and / or parts that maintain value from the bad physical condition products would be a supply of parts for other purposes outside the manufacture unit. Note that the level of planning of the proposed model does not integrate the cannibalization operation with the remaining operations. Since this operation is only applicable on the trailers characterized as in bad physical condition. Therefore, the selling values of the removed assemblies and parts will have much lower selling values if compared to those of good conditions. Table 5.4 summarizes the sources of revenue associated from applying cannibalization operation on one spent trailer.

Table 5.4: Estimating the suitable selling prices for the cannibalized items

Process required	**Corresponding Revenue / cost**
Selling trailer dismantled steel structure	= 15,000 L.E / trailer
Selling trailer axle & wheel	= 1000 * 3 = 3000 L.E / trailer
Selling trailer suspension	= 400 * 4 = 1600 L.E / trailer
Selling trailer tires	= 100 * 13 = 1300 L.E / trailer
Selling trailer rims	= 150 * 13 = 1950 L.E / trailer
Total Selling values	**= 22850 L.E**

5.4 Applying the proposed model on spent trailers

A full real version of the trailer case study is solved using the proposed model. As shown in fig 7, the intricate product structure tree or bill of material (BOM) of a spent trailer $i \in \mathcal{F}$ yields 33 items $j \in \mathcal{P}$ = { 2, 3, 4,….. 34}. Table 5.5 summarizes the disassembly level for each item $i \in \mathcal{I}$, its referred number that is used in the LINGO code, and the amount of each item that is present upon its parent disassembly (α_{ij}). Such complex level of disassembly yields a total of thirty-four items. Scenario 1 assumes the following: received trailers would vary in their physical conditions $where\ \mathcal{S} = \{1,2,3\}$, assignment of the 34 items $\mathcal{I}$ = {1, 2, 3, ….. 34} to seven recovery operations $\mathcal{O}$ = {1, 2, 3, 4, 5, 6, 7}, and the planning over three periods $\mathcal{T} = \{1,2,3\}$. It is assumed that the trailer is composed from main eight material groups $\mathcal{M} = \{1,2,3 \ldots 8\}$.

Scenario 1 is solved considering the presence of only one objective function 1 which is maximizing the net profit at the end of 3 periods , while the objective function 2, which is minimizing the disposal weight, is dealt with as a constraint bounded by a value that exceed the maximum weigh that could be disposed. The second objective function is dropped while solving Scenario1 for two main reasons: First, this real case study with its particular importance in Egypt is a profit oriented, and minimizing the disposal weight is not the main target of this real case study; second, such real input data is not good enough to generate a set of non-dominated solutions as demonstrated in chapter 7. The input parameters for scenario 1 are attached in Appendix A. LINGO code used in solving Scenario 1 is attached in Appendix F

Scenario 2 is same as Scenario 1 with all input data and assumption; expect that Scenario 2 assumes that the remanufacture unit receives the entire 300 trailers characterized by good physical condition $\mathcal{S} = \{1\}$. In Scenario 2; it is assumed that the entire 300 trailers could to be recovered by all the seven recovery operations proposed for whole spent trailers. Hence, equations 3 and 4 of the proposed model are dropped; Equation 2 is modified to allow the entire good trailers to be assigned to any of the seven operations. The main target from Scenario 2 is to investigate if the proposed model could successfully work if the remanufacture unit decided to only accept good physical condition trailers. Also, it is targeted to investigate the net profit at the end of the three planning periods in such case and comparing it with Scenario 1 LINGO code modification of Scenario 2 is attached in Appendix F

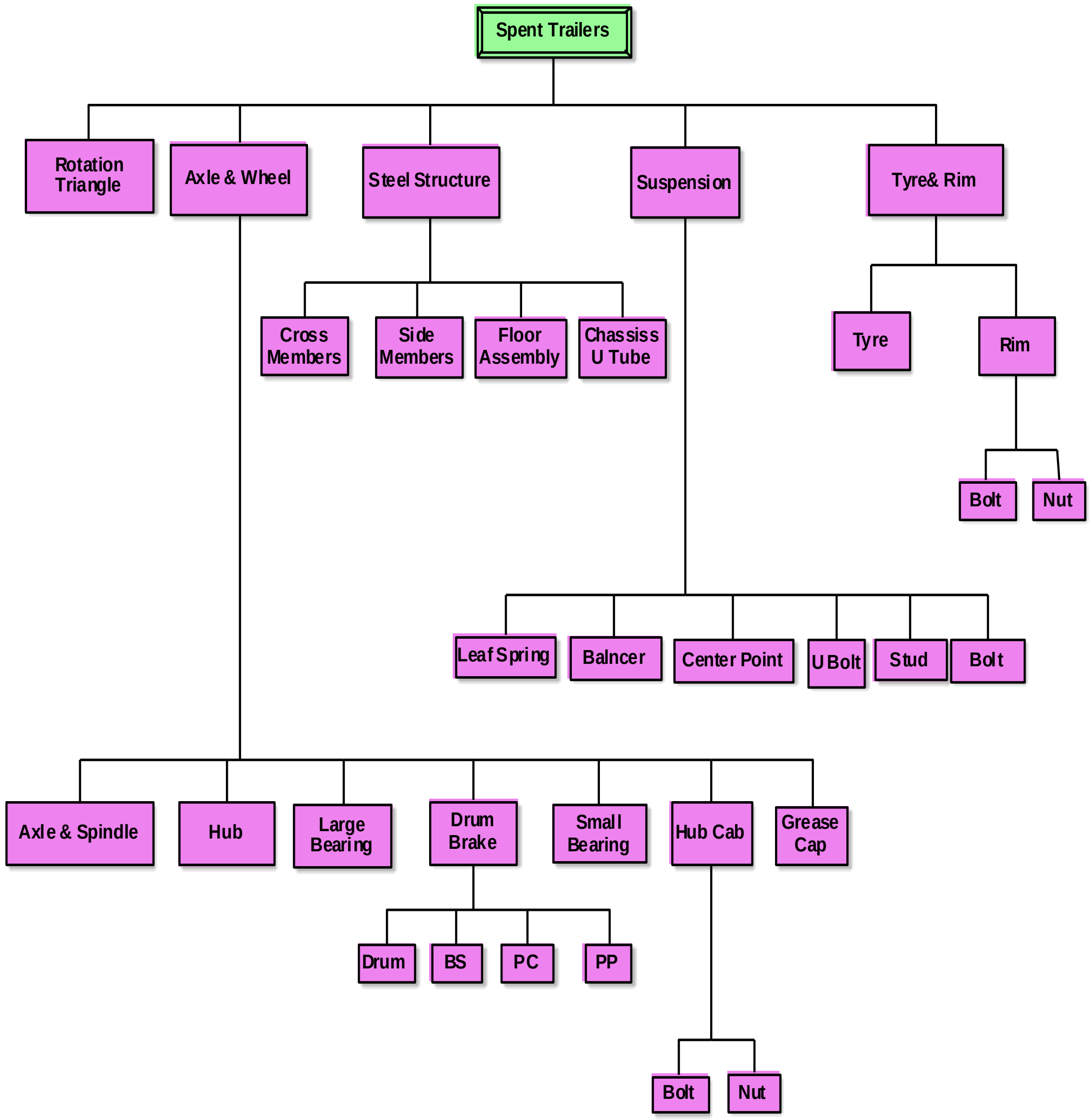

Fig 5.3: Intricate product structure tree of a spent trailer

Table 5.5: Details for intricate product structure tree of the spent trailer

Disassembly Level	item $i \in I$	Referred number for item $i \in I$	α_{ij}
0	Trailer	1	-
1	Triangle of Rotation	2	1
1	Axle & Wheel Assembly	3	3
1	Steel Structure	4	1
1	Suspension Assembly	5	4
1	Tyre & Rim Assembly	6	13
2	Cross Member	7	1
2	Side Member	8	1
2	Floor Assembly	9	1
2	Chassis U Tube	10	1
2	Tyre	12	1
2	Rim	13	1
2	Axle & Spindle	14	1
2	Hub	15	1
2	Large Bearing	16	1
2	Drum Brake	17	1
2	Small Bearing	18	1
2	Hub Cab	19	1
2	Grease Cap	20	1
2	Leaf Spring	21	1
2	Balancer	22	1
2	Center Point	23	1
2	U Bolt	24	1
2	Stud	25	1
2	Bolt	26	1
3	Drum	27	1
3	Brake shoe	28	1
3	Piston Cylinder (PC)	29	1
3	Piston Pin (PP)	30	1
3	Bolt	31	10
3	Nut	32	10
3	Bolt	33	6
3	Nut	34	6

5.4.1 LINGO output Summary of Scenario 1

Table 5.6: Details of Scenario 1

Model class	ILP
Generator Memory used	446 K
State	Global Optimum
Objective Value	8878800
Objective Bound	8878800
Solver Type	Branch and Bound
Infeasibility	0
Iterations	678
Total Variables	962
Integers	849
Constraints	1190

Table 5.7: Summary of non-zeros decision variables values of senario1

Decision Variable	**Value**
TC	0.5197620E+08
TR	0.6085500E+08
Q (1, 1) = Q (1, 2) = Q(1, 3) =	300
X (1, 3, 1) = X (1, 3, 2) = X (1, 3, 3) =	100
X (1, 4, 1) = X (1, 4, 2) = X (1, 4, 3) =	100
X (1, 5, 1) = X (1, 5, 2) = X (1, 5, 3) =	100
LL (1) = LL (2) = LL (3) =	8900
W(1) = W(2) = W(3) =	51
W_HIRE(1)=	6
W_HIRE(2)= W_HIRE(3)=	0
W_FIRE (1)= W_FIRE (2)= W_FIRE (3)=	0
All Y (i, t) =	0
All Z (M, t) =	0

The results of table 5.7 show that:

- All the 100 trailers characterized by good physical condition are assigned to the remanufactured operation in the three planning periods. This means that the remanufacture operation is the most profitable operation between the refurbishing and disassembly in the three planning periods.
- All the 100 trailers characterized by bad physical condition assigned to the cannibalization operation in the three planning periods. This means that the cannibalization operation is more profitable than recycling.

- The remanufacture unit requires 8900 hours to recover the received 300 trailers; hence, it needs 51 workers in each period.
- Since, there are 45 workers available at the beginning of period 1; therefore, extra six workers would be hired.
- The 51 workers exactly match the needs in period 2, and 3; therefore, no workers are either hired or fired in period 2 and 3.
- All the binary decision variables equal zero because no item assigned to recycling operation.
- The disposed weight at the end of 3 planning periods equal zero

5.4.2 Basic sensitivity analysis of Scenario 1

The results of this scenario require conducting such basic sensitivity analysis. Since most of the trailers characterized by good functioning condition are assigned to the remanufacture operation (alternative) due to the high profitability associated from selling the remanufactured semitrailer. Therefore, it is critical to evaluate the impact of the gradual decrease of the selling price of the remanufactured semitrailer on the net profit. It is also important to define the effect of changing selling price on the values of certain decision variables. Hence, the impact of the sequential decrease of the selling price of the remanufactured semitrailer is evaluated every L.E 1000 L.E from L.E 140,000 to L.E120, 000.

The described sensitivity analysis is conducted, and the results are tabulated in Table 5.8 and demonstrated by fig 8. Table 5.8 show the impact of decreasing the selling values of remanufacture semi-trailer on the net profit and total disposal weight at the end of the three planning periods. It also shows the impact of decreasing the selling values of remanufacture semi-trailer on directing the decision of dealing with the received good physical conditions trailers.

Table 5.8: Impact of decreasing Remanufactured Semi-Trailer selling price on selected responses in Scenario 1

Remanufactured Semi-Trailer SV L.E	Net Profit * 10^5 L.E	Disposal Weight Kg	Number of Trailers Assigned to Disassembly in 3 periods	Number of Trailers Assigned to Refurbishing in 3 periods	Number of Trailers Assigned to Remanufacturing in 3 periods
140000	88.788	0	0	0	300
139000	85.788	0	0	0	300
138000	82.788	0	0	0	300
137000	79.788	0	0	0	300
136000	76.788	0	0	0	300
135000	73.788	0	0	0	300
134000	73.62175	458	299	0	1
133000	73.6155	462.6	298	0	2
132000	73.6125	450	300	0	0
131000	73.6125	450	300	0	0
130000	73.6125	450	300	0	0

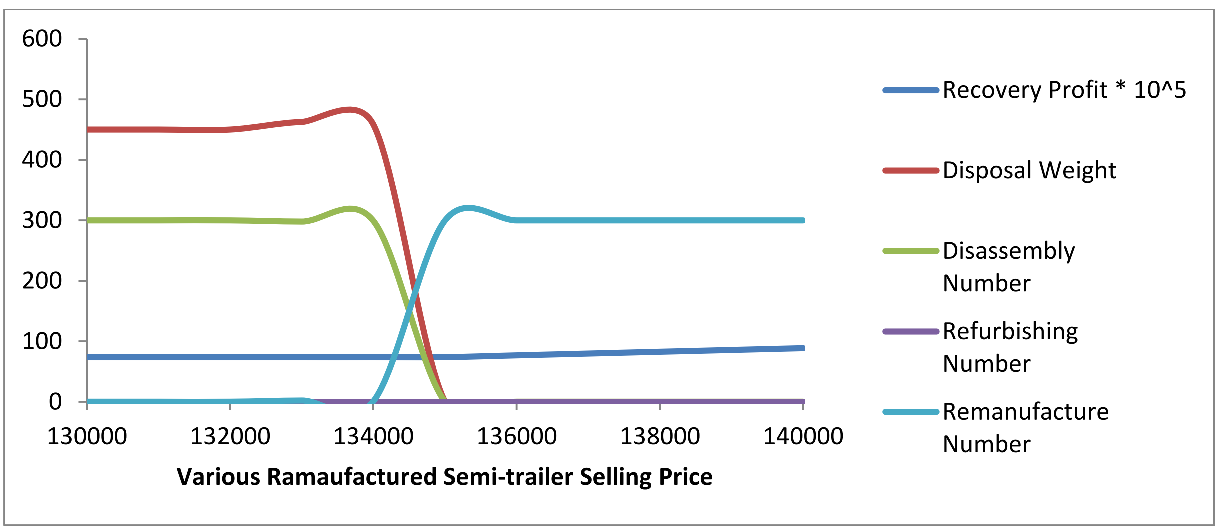

Fig 5.4: Impact of the variation of SV of remanufactured semi-trailer on the on the selected responses in Senario1

From table 5.8 and figure 8, it could be seen that:

- Changing the selling price of the remanufactured semi-trailer from 140,000 L.E to 135,000 L.E. shows a gradual decrease of the objective function value from 8.8788 million to 8.5788 million while all remaining output decision variables unchanged.
- Dropping the selling price of the remanufactured semi-trailer to 134,000 L.E is considered a turning point in the critical decisions variables. At this SV= 134,000, 1 trailers only are assigned to be remanufactured while 299 is assigned to disassembly as shown in the table.
- At selling price of the remanufactured semi-trailer is 134,000 L.E , the total weight assigned to disposal is 458 kg

5.5.1 LINGO output Summary of Scenario 2

Table 5.9: Details of Scenario 2

Model class	ILP
Generator Memory used	421 K
State	Global Optimum
Objective Value	20499100
Objective Bound	20499100
Solver Type	Branch and Bound
Infeasibility	0
Iterations	614
Total Variables	962
Integers	852
Constraints	1161

Table 5.10: Summary of non-zeros decision variables values of scenario 2

Decision Variable	**Value**
TC	0.5197620E+08
TR	0.6085500E+08
Q(1, 1) = Q(1, 2) = Q(1, 3) =	300
X (1, 3, 1) = X (1, 3, 2) = X (1, 3, 3) =	300
LL (1) = LL (2) = LL (3) =	14400
W(1) = W(2) = W(3) =	82
W_HIRE(1)=	37
W_HIRE(2)= W_HIRE(3)=	0
W_FIRE (1)= W_FIRE (2)= W_FIRE (3)=	0
All Y (i, t) =	0
All Z (M, t) =	0

The results in table 5.10 show that:

- The entire 300 trailers characterized by good physical condition assigned to the remanufactured operation in the three planning periods. This means that the remanufacture operation is the most profitable operation among the disassembly refurbishing, repairing, cannibalization, and recycling in the three planning periods.
- The remanufacture unit requires 14400 hours to recover the received 300 trailers; hence, it needs 82 workers in each period.

- Since, there are 45 workers available at the beginning of period 1; therefore, extra 37 workers would be hired.
- The 82 (45+37) workers exactly match the needs in period 2, and 3; therefore, no workers are either hired or fired in period 2 and 3.
- All the binary decision variables equal zero because no item assigned to recycling operation.
- The disposed weight at the end of 3 planning periods equal zero

5.5.2 Basic sensitivity analysis of Scenario 2

Since the entire trailers characterized by good physical conditions are assigned to the remanufacture operation (alternative) due to the high profitability associated from selling the remanufactured semitrailer. Therefore, it is critical to evaluate the impact of the gradual decrease of the selling value of the remanufactured semitrailer on the net profit. It is also vital to know to which extent changing this selling value would affect the values of certain decision variables. Hence, the impact of the sequential decrease of the selling value of the remanufactured semitrailer is evaluated every L.E 1000 L.E from L.E 140,000 to L.E120, 000.

The results of the described sensitivity analysis tabulated in Table 5.11 and illustrated by fig 9. Table 5.11 Show the impact of decreasing the selling values of remanufacture semi-trailer on the net profit and total disposal weight at the end of the three planning periods. It also shows the impact of decreasing the selling values of remanufacture semi-trailer on directing the decision of dealing with the received good trailers.

Table 5.11: Impact of decreasing Remanufactured Semi-Trailer SV on the selected responses in Scenario 2

Input	Number of Trailer Assigned the following operations in the 3 planning periods							
Remanufactured Semi-Trailer SV L.E	Recovery Profit * 10^5 L.E	Disposal Weight Kg	Disassembly	Refurbishing	Remanufacturing	Repairing	Cannibalization	Recycling
140000	205	0	0	0	300	0	0	0
139000	196	0	0	0	300	0	0	0
138000	187	0	0	0	300	0	0	0
137000	178	0	0	0	300	0	0	0
136000	169	0	0	0	300	0	0	0
135000	160	0	0	0	300	0	0	0
134000	160	1350	300	0	0	0	0	0
133000	160	1350	300	0	0	0	0	0
132000	160	1350	300	0	0	0	0	0
131000	160	1350	300	0	0	0	0	0
130000	160	1350	300	0	0	0	0	0

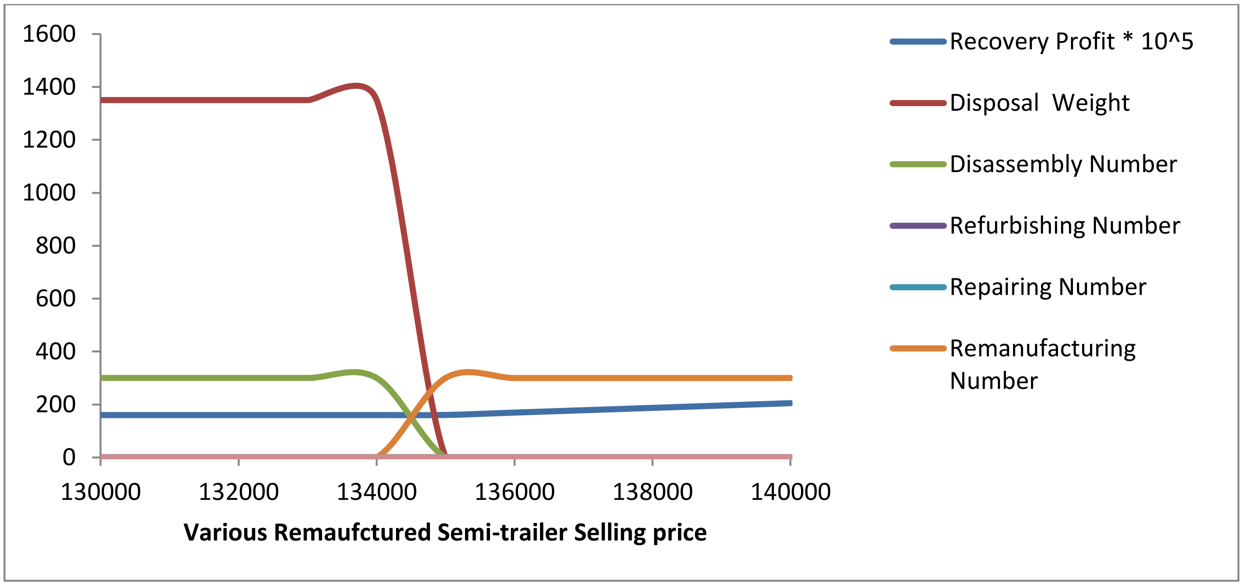

Fig 5.5: shows the impact of the variation of SV of remanufactured semi-trailer on the on the selected responses in Scenario 2

From table 5.11 and figure 9, it could be seen that:

- Changing the selling price of the remanufactured semi-trailer from 140,000 L.E to 135,000 L.E. shows a gradual decrease of the objective function value from 20 million to 16million while the remaining all of the output decision variables unchanged.

- Dropping the selling price of the remanufactured semi-trailer to 134,000 L.E is considered a turning point in the critical decisions variables. At this SV= 134,000, the entire 300 trailers would be assigned to disassembly as shown in the table.

- At selling price of the remanufactured semi-trailer is 134,000 L.E , the total weight assigned to disposal is 1350 kg

5.6 Trailer case study concluding remarks

The net profit of scenario 1 is L.E 8,878,800, at the end of the three periods which involves the recovery of various physical conditions of trailers. While the net profit of scenario 2 is L.E 20,499,100 at the net of the three planning periods which involves the recovery of only good trailers. Hence, scenario 2 is associated with an increase of L.E 11,620,300 in profit if compared to the profit of scenario 1. This means that if the remanufacture unit restricted its recovery activities to the good condition trailers, this is associated with a sprouting profit.

The proposed model is succeeded in playing the role of decision-making tool for EAMCO through optimizing the most profitable solution to deal with the collected trailers. The results proved that collecting the trailers and remanufacturing them into semitrailers is a feasible business for EAMCO. This thesis model results are considered a strong support to the Egyptian government for enforcing the law of prohibiting the trailers on the Egyptian roads. Consequently, the work executed in this thesis would save severe trailers accidents and save the lives of tons of Egyptian individuals.

Chapter Six

Sensitivity Analysis

A professional sensitivity analysis is implemented using the factorial design to accurately decide the significant input parameters that impact the net profit and total disposal weight at the end of the three planning periods. Hence, factorial sensitivity analysis is designed for the real trailer case study to generate runs of all possible combination of the dominant input parameters, and to show the output responses corresponding to these combinations. It also indicates the significant input parameters that influence the selected responses. The following are the procedures for implementing a factorial sensitivity analysis:

1. Specification of the objective of the analysis
2. Selection of response variables
3. Choice of input parameters (factors) and levels
4. Computation of the factors levels
5. Data analysis
6. Runs results
7. Conclusion and recommendations

6.1Objective of the analysis

The objective from designing a factorial sensitivity analysis and conducting it is to discover which one of the selected input parameters that are the most influential on the responses. This could be achieved through performing a series of runs of all combinations of the selected input parameters (factors) in order to observe the corresponding changes in output responses. Consequently, the most significant input parameter that highly impacts these responses are observed from the remaining parameters.

6.2 Selection of the response variable

Runs are conducted to test the impact of changing input parameters on the target responses that are the values of the first and the second objective functions. The value of the first objective function is the net profit from dealing with the spent products at the end of the three planning periods. Net profit is considered as the most important motivator that encourages the businessmen to initiate reverse logistics business opportunities.

Hence, it is important to define the significant input parameters that impact this response to try adjusting it for getting the maximum profit. The value of the second objective function is the total weight of items assigned to disposal the end of the three planning periods. Minimizing the total disposal weight is important for satisfying the environmental aspect of the sustainability.

6.3 Choice of input parameters (factors) and levels

6.3.1 Factors (F)

The input parameters (Factors) that are selected for conducting the factorial sensitivity analysis are the following three factors:

1. The refund cost ($c_{i,s,t}^{REF}$)
2. The direct labor cost and overhead cost (c_t^{DL})
3. The selling values of output products and materials ($v_{i,o,t}^{SELL}/v_{m,t}^{REC}$)

Therefore, the factors $F \in \{\mathrm{c}_{\mathrm{i,s,t}}^{\mathrm{REF}}, \mathrm{c}_{\mathrm{t}}^{\mathrm{DL}}, \mathrm{v}_{\mathrm{i,o,t}}^{\mathrm{SELL}}/\mathrm{v}_{\mathrm{m,t}}^{\mathrm{REC}}\}$

6. 3.2 Levels

Five levels are selected in order to examine the impact of the variation of each factor within each of these levels. The values of these levels are determined according to the following criteria:

- Level 3 is the mean value of any of these input parameters (factors)
- Level 2 is decreasing from the mean value by 10 %.
- Level 1 is decreasing from the mean value by 15%.
- Level 4 is increasing by the mean value by 10 %.
- Level 5 is increasing by the mean by 15 %.

Level 3 values are the mean values of these parameters. For instance, the selling values of the recovered products are determined according to the market selling values of the equivalent of these products. Therefore, the levels $\mathrm{L} \in \{1, 2, 3, 4, 5\}$

6.4 Computation of the factors levels

The computation of the factors levels is modeled in this section, stating that $\boldsymbol{F_L}$ represent the value of factor $F \in \{c^{REF}_{i,s,t}, c^{DL}_{t}, v^{SELL}_{i,o,t}/v^{REC}_{m,t}\}$ at level $L \in \{1, 2, 3, 4, 5\}$. It is assumed that Level 3 values for factors are known. Therefore, equations I, II, III, and IV show how to compute the values of each factor of other unknown levels.

$$F_1 = F_3 - (F_3 * 15/100) = F_3 - 0.15F_3 = 0.85F_3 \quad \text{(I)}$$

$$F_2 = F_3 - (F_3 * 10/100) = F_3 - 0.10F_3 = 0.9F_3 \quad \text{(II)}$$

$$F_4 = F_3 + (F_3 * 10/100) = F_3 + 0.10F_3 = 1.1F_3 \quad \text{(III)}$$

$$F_5 = F_3 + (F_3 * 15/100) = F_3 + 0.15F_3 = 1.15F_3 \quad \text{(IV)}$$

Therefore, $5^3 = 125$ runs are conducted. Since the manual specification of 125 run is complicated, very time consuming, and associated with a high probability of error. Therefore, Minitab 17 software is used in the proposed work to generate all possible combination required for the 125 runs. The 125 possible combinations that were generated by the Minitab17 software are numbered and organized. A LINGO file is created according to each combination .The responses corresponding to each combination run was documented. Random samples from each group of runs are revised to assure that they are error free. Finally, all the tabulated parameters combinations and their corresponding responses are tested and analyzed.

6. 5 Data analysis

The results of the conducted runs are analyzed using Anova analysis tool that is built in the Minitab17 software. The analysis involves concluding the general impact associated with changing the levels of the input parameters (factors) on the net profit and the disposal weight (responses). This analysis also specifies the combination of input parameters levels that are associated with the maximum and minimum net profit as well as disposal weight at the end of three periods.

6.5.1 Impact of the input parameters on net profit

As shown in fig 10, changing the selling values of the output products from the recovery operations has the first significant impact on the net profit as expected. Changing the refund paid to the spent product owners has the second important influence on the net profit. On the other hand, changing the direct and overhead cost has the least impact on the net profit. It is concluded that the net profit value is directly proportional to the selling values. The highest net profit occurs when the selling values are increased by 15% of the mean selling prices. The lowest net profit happens when the selling values are decreased by 15% of the mean selling prices. The net profit value is inversely proportional to the refund cost. The highest net profit occurs when the refund costs are decreased by 15% less than the mean selling prices. The lowest net profit occurs when the refund costs are increased by 15% more than the mean selling prices. Since the net profit equals total revenues minus total costs. Therefore, increasing the selling prices, which are the main source of revenue, increases the net profit. Also, that decreasing the refund costs, which are the highest costs involves in recovering trailers, increases the net profit. Since the value of direct and overhead costs are very low if compared to the value of refund costs or selling prices. Hence, the impact of the refund cost is very low.

6.5.2 Impact of the input parameters on total disposal weight

As shown in fig 11, changing the selling values of the output products from the recovery operations has the only significant impact on the total disposal weight. Increasing the selling prices of output products or leaving it at its mean values directs the decision toward the remanufacture of trailers into semi-trailers, which results into zero disposals. Yet, decreasing these selling values directs the decision toward the disassembly of trailers, which is associated with items the needed to be disposed.

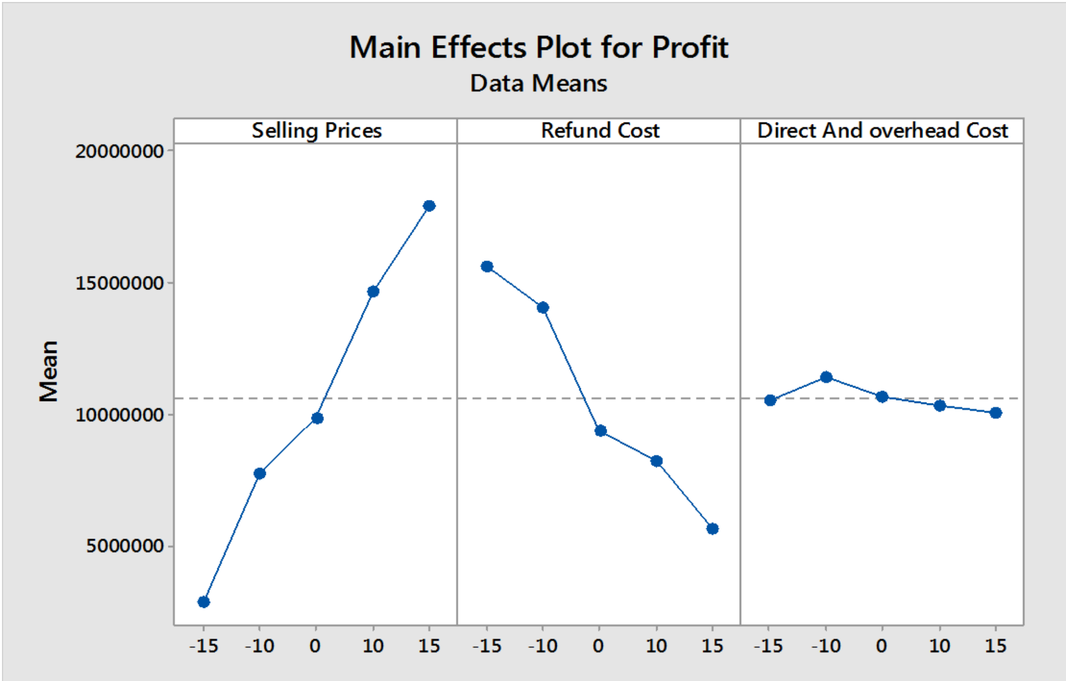

Fig 6.1: Impact of the input parameters on the net profit

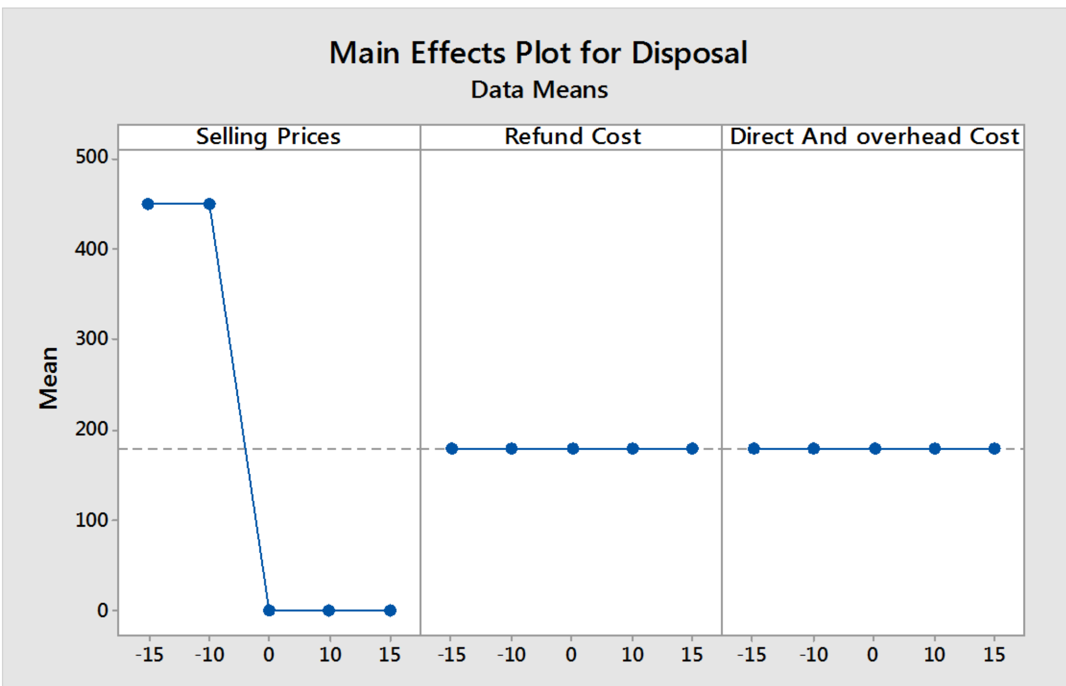

Fig 6.2: Impact of the input parameters on the total disposal weight

6.6 Results of the conducted runs

In order to easily present the results of $5^3 = 125$ runs, they are organized and tabulated in five tables. Since, it is clearly demonstrated from fig 10 that the selling prices has the significant effect on the response among other input parameters. Therefore, the following tables involve the fixation of certain level of selling values at each table versus the variation of other input parameters. Table 6.1 Show the impact of increasing selling values of output products by 15 % of the mean with all other Combinations of refund costs & Direct and overhead costs on the profit and disposal. Table 6.2 Show the impact of increasing selling values of output products by 10 % of the mean with all other Combinations of refund costs & Direct and overhead costs on the profit and disposal. Table 6.3 Show the impact of setting selling values of output products at its mean with all other Combinations of refund costs & Direct and overhead costs on the profit and disposal. Table 6.4 Show the impact of decreasing selling values of output products by 10 % of the mean with all other Combinations of refund costs & Direct and overhead costs on the profit and disposal. Table 6.5 Show the impact of decreasing selling values of output products by 15 % of the mean with all other Combinations of refund costs & Direct and overhead costs on the profit and disposal. .

Table 6.1: Profit and disposal at increasing selling prices by 15 % of the mean versus different refund, direct and overhead costs

Exp	Input Parameters (factors Levels)			Output effect	
	Refund Cost	Direct & Overhead Cost	Selling Prices	Profit * 10^6	Disposal
22	-15	-15	15	22.15818	0
117	-15	-10	15	22.12452	0
49	-15	0	15	22.0572	0
76	-15	10	15	21.98988	0
31	-15	15	15	21.95622	0
23	-10	-15	15	20.80818	0
104	-10	-10	15	20.77452	0
109	-10	0	15	20.7072	0
86	-10	10	15	20.63988	0
10	-10	15	15	20.77452	0
57	0	-15	15	18.10818	0
78	0	-10	15	18.07452	0
48	0	0	15	18.0072	0
8	0	10	15	17.93988	0
100	0	15	15	17.90622	0
72	10	-15	15	12.33162	0
122	10	-10	15	15.37452	0
46	10	0	15	15.3072	0
18	10	10	15	15.23988	0
52	10	15	15	15.20622	0
70	15	-15	15	14.05818	0
115	15	-10	15	14.05818	0
92	15	0	15	13.9572	0
88	15	10	15	13.88988	0
17	15	15	15	13.85622	0

Table 6.2: Profit and disposal at increasing selling prices by 10 % of the mean versus different refund, direct and overhead costs

Exp	Input Parameters (factors Levels)			Output effect	
	Refund Cost	Direct & Overhead Cost	Selling Prices	Profit * 10^6	Disposal
53	-15	-15	10	19.11528	0
105	-15	-10	10	19.08162	0
110	-15	0	10	19.0143	0
95	-15	10	10	18.94698	0
62	-15	15	10	18.91332	0
28	-10	-15	10	16.26528	0
13	-10	-10	10	16.23162	0
27	-10	0	10	16.1643	0
15	-10	10	10	16.09698	0
42	-10	15	10	16.06332	0
35	0	-15	10	15.06528	0
112	0	-10	10	15.03162	0
29	0	0	10	14.9643	0
64	0	10	10	14.89698	0
58	0	15	10	14.86332	0
113	10	-15	10	12.36528	0
71	10	-10	10	12.33162	0
120	10	0	10	12.2643	0
80	10	10	10	12.19698	0
96	10	15	10	12.16332	0
34	15	-15	10	11.01528	0
119	15	-10	10	10.98162	0
114	15	0	10	10.9143	0
38	15	10	10	10.84698	0
11	15	15	10	10.81332	0

Table 6.3: Profit and disposal at selling prices equal the mean values versus different refund, direct and overhead costs

Exp	Input Parameters (factors Levels)			Output effect	
	Refund Cost	Direct & Overhead Cost	Selling Prices	Profit * 10^6	Disposal
97	-15	-15	0	13.02978	0
33	-15	-10	0	12.99612	0
69	-15	0	0	17.5188	0
40	-15	10	0	17.45148	0
103	-15	15	0	12.82782	0
37	-10	-15	0	11.67978	0
81	-10	-10	0	11.64612	0
116	-10	0	0	11.5788	0
124	-10	10	0	11.51148	0
50	-10	15	0	11.47782	0
89	0	-15	0	8.97978	0
55	0	-10	0	8.94612	0
54	0	0	0	8.8788	0
82	0	10	0	8.81148	0
102	0	15	0	8.77782	0
83	10	-15	0	6.27978	0
87	10	-10	0	12.16332	0
4	10	0	0	6.1788	0
3	10	10	0	6.11148	0
107	10	15	0	6.24612	0
101	15	-15	0	13.32978	0
118	15	-10	0	4.89612	0
41	15	0	0	4.8288	0
30	15	10	0	4.76148	0
44	15	15	0	4.8288	0

Table 6.4: Profit and disposal at decreasing selling prices by 10 % of the mean versus different refund, direct and overhead costs

Exp	Input Parameters (factors Levels)			Output effect	
	Refund Cost	Direct & Overhead Cost	Selling Prices	Profit * 10^6	Disposal
121	-15	-15	-10	7.69	450
123	-15	-10	-10	7.649	450
6	-15	0	-10	7.55	450
5	-15	10	-10	7.45	450
56	-15	15	-10	7.40	450
108	-10	-15	-10	6.34	450
66	-10	-10	-10	6.29	450
2	-10	0	-10	6.20	450
125	-10	10	-10	6.10	450
43	-10	15	-10	6.05	450
111	0	-15	-10	3.648868	450
9	0	-10	-10	3.599368	450
79	0	0	-10	3.500368	450
47	0	10	-10	3.401368	450
75	0	15	-10	3.351868	450
60	10	-15	-10	0.9488679	450
45	10	-10	-10	12.19698	450
14	10	0	-10	0.8003679	450
12	10	10	-10	0.7013679	450
67	10	15	-10	0.6518679	450
84	15	-15	-10	-0.4011321	450
7	15	-10	-10	-0.4506321	450
51	15	0	-10	-0.5496321	450
21	15	10	-10	-0.6486321	450
19	15	15	-10	-0.6981321	450

Table 6.5: Profit and disposal at decreasing selling prices by 15 % of the mean versus different refund, direct and overhead costs

Exp	Input Parameters (factors Levels)			Output effect	
	Refund Cost	Direct & Overhead Cost	Selling Prices	Profit * 10^6	Disposal
98	-15	-15	-15	5.809378	450
94	-15	-10	-15	5.759878	450
16	-15	0	-15	5.660878	450
20	-15	10	-15	5.561878	450
91	-15	15	-15	5.512378	450
106	-10	-15	-15	4.459378	450
63	-10	-10	-15	4.409878	450
26	-10	0	-15	12.41088	450
74	-10	10	-15	4.211878	450
1	-10	15	-15	4.162378	450
32	0	-15	-15	1.759378	450
68	0	-10	-15	1.709878	450
73	0	0	-15	1.610878	450
24	0	10	-15	1.511878	450
77	0	15	-15	1.462378	450
90	10	-15	-15	1.759378	450
25	10	-10	-15	12.2643	450
59	10	0	-15	1.610878	450
85	10	10	-15	1.511878	450
39	10	15	-15	1.462378	450
99	15	-15	-15	-2.290742	450
36	15	-10	-15	-2.340122	450
61	15	0	-15	-2.439122	450
65	15	10	-15	-2.538348	450
93	15	15	-15	-2.587622	450

Table 6.6: Tabulates the runs associated with the worst responses

Exp	Input Parameters (factors Levels)			Output effect	
	Refund Cost	Direct & Overhead Cost	Selling Prices	Profit * 10^6	Disposal
84	15	-15	-10	-0.4011321	450
7	15	-10	-10	-0.4506321	450
51	15	0	-10	-0.5496321	450
21	15	10	-10	-0.6486321	450
19	15	15	-10	-0.6981321	450
99	15	-15	-15	-2.290742	450
36	15	-10	-15	-2.340122	450
61	15	0	-15	-2.439122	450
65	15	10	-15	-2.538348	450
93	15	15	-15	-2.587622	450

The results in the above mentioned tables are discussed in the following points

1 Run associated with maximum profit and minimum disposal:

The value of the net profit reaches its maximum of 22.15818 million, and the total weight of items assigned to disposal reaches its minimum of 0 kg in run 22. The combination of the factors levels at this run involves setting the selling value at its highest level and setting the refund cost as well as the direct and overhead costs at its lowest levels. This combination increases the revenue and decreases the costs to yield the highest profit as it directs the decision toward remanufacturing the entire good condition trailers. Therefore, there is no trailer assigned to disassembly that always yields items that need disposing.

2 Zero disposal

According to table 6.1, 6.2, and 6.3 as well as fig 11, the total weight assigned to disposal becomes equal zero when the selling prices are at levels 3, 4 and 5. This is because medium and high levels of selling prices direct the decision toward remanufacturing semi-trailers from trailers, which results into zero disposals.

3 Fixed amount of disposal

According to table 6.4 and 6.5 as well as fig 11, the total weight assigned to disposal is a fixed amount which is 450 kg which occurs at the selling prices of levels 1and 2. This is because low selling prices direct the decision toward disassembling the good trailers. This disassembly operation is associated with items that could be assigned to disposal. Yet, in this trailer case study, decreasing the selling prices of the reprocessed disassembled items remains higher than the costs consumed in recovering them. Hence, most of the items are always assigned to other recovery operations other than disposal. The 450 kg comes from bottom-disassembled items that are not proposed to any recovery operations other than disposal, this is the reason behind the fixed disposal limit. If the target is to reach disposal limit less than the 450 kg, then the tradeoffs are between dissembling its parent assembly for high net profit and 450 kg disposal or leaving this assembly intact for a lower net profit and zero disposal.

4 Negative net profit

The net profit reaches a negative value in 10 runs; these runs are sorted and tabulated in a separate table for clarifying them. As shown in table 6.6, the combination involves increasing the refund costs by 15 % of the mean, decreasing the selling values either 10 % or 15 % of the mean and any level of direct and overhead costs results in a negative net profit. We conclude that such combinations would result in total recovery costs higher than total recovery revenue. Also, these combinations are associated with 450 kg disposal. Therefore, setting the refund cost at level 5 cannot work with the selling prices either level 1 or 2.

6.7 Conclusions and recommendations

Changing the selling prices of the output products from the recovery operations which are refurbishing, repairing, remanufacturing, and cannibalization, and the selling prices of the recycled materials has the most significant impact on the net profit , and has the only significant impact on the total disposal weight at the end of the three planning periods. Hence, it is crucial to specify these selling prices wisely in order to maximize the net profit and to minimize the total disposal weight. The refund costs paid to the end users for compensating them of getting their products is the second significant factor on the net profit at the end of the three planning periods. Hence, it is vital to determine its value wisely way in order to maximize the net profit.

Chapter Seven

Solution Technique

7.1 Single objective versus Multi-objective optimization

The main aim of single objective optimization is to discover the optimum solution of the situation required to be solved. This optimal solution represents the highest or lowest value for a single objective function, such as maximizing profit and minimizing pollution. Single objective optimization is only beneficial for problems that do not involve conflict tradeoff, where the decision maker is searching for one optimal solution for his objective. In many real cases, the decision maker might need to tradeoff between maximizing the profit and minimizing the disposal weight. In such cases, there is no optimal solution. However, the integration between multiple objectives generates a set of tradeoffs called, non-dominated solutions or Pareto-optimal solutions. According to Cohon (1978), the consideration of multiple objectives offers three major advantages for the decision making process, which are; the generation of wide range of alternatives, more involvement of the role of planners or decision makers, and more importantly, the multi-objective optimization model yields more realistic results.

7.2 Multi-objective optimization

The Multi-objective optimization model requires the decision maker to first define the objectives of the studied problem. The decision maker then has to create the optimal zone for the multi-objective optimization model through the creation of Pareto front. Since the going from one solution to another leads to the improvement of one objective on the sake of the other, any solution included in the set of Pareto front cannot be dominated by another solution. On the other hand, the generation of more solutions is highly required to help the decision maker to select the most suitable solution in his case. It also helps him in making more balanced decisions considering various vital factors in the studied situation, Cohon (1978).

7.3 Solution Approaches for multi-objectives problem

Generating a set of non-dominated solutions, in order to solve multiple objective problems could be done through various approaches. The most common methods are; Goal Programming approach, Weighting method, and Constraint method, Rahmitman (2008).

Goal programming approach is a well-known solution method in solving multiple objective problems. Goal Programming basically works by specifying goal values for all objectives being considered, where those goals are to be achieved with minimum deviation from them. This method needs specific targeted goals from the decision makers. In general, this method gives a definite solution for each specified goal, rather than a set of non-dominated solutions, Rahmitman (2008).

According to Rahmitman (2008), "In weighting method, conflicting objective functions in a multi-objective problem are transformed into a single-objective. To do so, a single objective function is obtained by combining the original objective functions and assigning a weight to each of them. By varying the weights and applying a conventional solution approach to solve the single objective problem, a set of non-dominating solutions for the multi-objective problem can be obtained."

Constraint method basically works by solving the problem for one objective function while the other objective functions are treated as constraints that are bounded by target values. Varying the bounds of the constrained objective functions in each run would create a set of non-dominating solutions, Rahmitman (2008).

In this thesis, the model is solved using both; The Weighting method, and the Constraint method. The results from those two methods yield a set of various solutions, where the decision maker has to make the trade off and select the most suited solution to his case. In this thesis, the weighting method is implemented using Weighting minimx formulation. Weighting Minimx formulation helps in achieving a better objective; it allows the decision maker to explore non-corner point solutions of the feasible region Elimam (2012).

7.4 Application of the Multi-Objective model using Trailer case study

To demonstrate the nature of the studied multi-objective model, a set of deviated data was used to create a set of non-dominated solutions for the Trailer case study. Spent trailers are made from large percentages of valuable metals as shown in table A.10 in the Appendix A; this would hinder the real life data from verifying the nature of the multi-objective model, since up to 99% of trailer components, could be sustainably assigned to other recovery operations other than disposal. Also in recycling, positive revenues are obtained when recycling the most consumed products like fasteners. Hence, in some runs the maximum profit could be associated with zero disposals. Therefore, the real data of the trailer case is not good enough to generate a set of non-dominated solutions that allow the decision maker to tradeoff between maximizing the profit and minimizing the disposal weight. That is why a data that deviates from the real one is generated to create non-dominated solutions of the multiple objectives model. This deviated data is concluded after conducting the factorial sensitivity analysis that is presented in the previous chapter. This deviated data is based on the combination of increasing the selling prices 10 % of the mean and decreasing the refund costs 10 % of the mean with other minute deviations. The deviations of this data from the real ones, is attached in the Appendix C. LINGO code used for solving the problem using the two multi-objective approaches is attached in Appendix E.

7.5 Using the Minimx Weighting method

7.5.1 Solving Steps of trailer multi-objective case using Minimx Weighting method

Step 1:

I. Solve the model with the first objective function, which is maximizing the net profit while relaxing the second objective function, which is minimizing the disposal weight.

II. Find the optimal solution of the first objective function, as well as the corresponding value of the total weight assigned to disposal.

III. Solve the model with the second objective function, which is minimizing the total weight assigned to disposal while relaxing the first objective function.

IV. Find the optimal solution of the second objective function, as well as the corresponding value of the net profit.

V. Construct the objective function trade-offs table, in order to find the ranges of the objective functions values in the non-dominating set.

Table 7.1: Objective function tradeoffs

Solving the model as the prescribed criteria in	Optimum solution for the solved objective function	Corresponding Value of relaxed objective
STEP 1. I	L.E 8,183,006	14870.3 KG
STEP 1. III	0 KG	L.E 7,425,400

It is clear from table 7.1 that the two objective functions are not correlated. When solving the model with the first objective function, which is maximizing the profit, the profit obtained is L.E 8183006, but a high disposal weight of 14870 Kg is also obtained. Solving the model with the second objective function, which is minimizing the disposal weight, gives the lowest disposal, which is 0, but at the same time it yields the lowest profit which is L.E 7425400. Therefore, it is clear that minimizing the disposal is associated with reducing the net profit, and maximizing the profit is associated with maximizing the disposal. Hence, it is demonstrated that the two objective functions are not correlated.

Step Two:

I. Specify the simplified equations of the two objectives functions

Objective function 1: Maximize R = TR - TC

Objective function 2: Minimize K= $\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}} g_i X_{i,7,t}$

II. Convert the multi-objective model to its corresponding MiniMax weighted model

Minimize D (1M)

S.t

W_1 * (V_1- R) / $V_1 \leq$ D (2M)

W_2*(K - V_2) / $V_2 \leq$ D (3M)

W_1 + W_2 = 1 (4M)

Where

R: Optimized Value of actual profit produced in each iteration. Referring to iterations that are associated with different weights combinations.

K: Optimized Value of actual disposal weight produced in each iteration. Referring to iterations that are associated with different weights combinations.

D: Deviation from the targets.

V_1: Target value of profit.

V_2: Target value of Disposal.

W_1: Weight assigned to objective 1.

W_2: Weight assigned to objective 2.

Step Three:

I. Specify the parameters values of the weighted model.

V_1 is selected according to its maximum limit which is equal to 8,183,006 L.E .

V_2 is selected to be equal to 300 kg for one run series, and 150 kg for another run series . *Selection of V_2 values are demonstrated at the end of this page*

Therefore, Two Pareto optimal diagrams would be drawn. One for using V_1= 8,183,006 L.E verses V_2= 300 kg. The other one using V_1= 8,183,006 L.E verses V_2= 150 kg.

II. Choose the weights

25 combinations of W_1 and W_2 are determined to generate a set of 25 non-dominated solutions in order to draw the stated Pareto Front for the two series of runs. This large set of solutions allows the decision maker to easily select the satisfying solution.

III. Solve the weighted model using each weight combination for the two series of runs.

Step Four:

I. Generate the corresponding tradeoffs tables, which are the set of solutions corresponding to each combination of W_1 and W_2 for each run series.
II. Draw the Pareto corresponding optimal for each run series.

Note: In many cases, the decision maker need to select a solution among the set of non-dominated solution concerning the values of certain decision variables, which are associated with the objective function tradeoffs values. To demonstrate the associated impact of two objective function tradeoffs on the vital decision variables, which are the number of trailers assigned to disassembly versus number of trailers assigned to refurbishing, V_2 is selected to be greater than 50 Kg and less than 450 Kg. After conducting preliminary runs to investigate the sufficient disposal weight to direct the assignment of trailers toward disassembly and refurbishing, V_2 is selected to be greater than 50 kg and less than 450 kg. 450 kg is a sufficient disposal limit to direct the assignment of most of 100 trailers toward disassembly. 50 kg is considered an insufficient disposal limit to direct the assignment of most of 100 trailers toward disassembly; hence, this insufficient disposal limits direct most of the trailers toward refurbishing.

7.5.2 Set of non-dominated solutions produced by Minimx weighting method

7.5.2.1 Solutions associated with setting disposal target (V_2) at 300kg

Table 7.2 Shows the set of non-dominated solutions produced upon solving the trailer case study using the Minimx Weighting method at $\boldsymbol{V_1}$= 8,183,006 L.E and $\boldsymbol{V_2}$= 300 kg and their trade-offs (Run 1 series trade-offs). It also shows the associated impact of two objective function tradeoffs on the vital decision variables, which are the number of whole trailer assigned to disassembly versus number whole trailer assigned to refurbishing in each planning period.

Table 7.2: Tradeoffs Solutions

#	Disposal Weight / Kg	Profit Value L.E	Number of trailers assigned to Disassembly in each planning periods			Number of trailers assigned to Refurbishing in each planning periods		
			X(1, 1, 1)	X(1, 1, 2)	X(1, 1, 3)	X(1, 2, 1)	X(1, 2, 2)	X(1, 2, 3)
1	300.3	7983150	66	66	68	34	34	32
2	300.3	7983150	66	66	68	34	34	32
3	301.8	7984793	66	66	69	34	34	31
4	303.3	7987256	66	68	68	34	32	32
5	304.8	7989015	66	69	68	34	31	32
6	307.8	7993120	68	69	68	32	31	32
7	312.3	7999110	68	70	70	32	30	30
8	315.3	8003235	70	70	70	30	30	30
9	318.3	8006850	70	70	72	30	30	28
10	324.3	8015080	72	72	72	28	28	28
11	331.8	8024729	74	74	73	26	26	27
12	336.3	8031184	75	77	78	25	23	22
13	339.3	8035290	82	83	83	18	17	17
14	345.3	8043029	75	77	78	25	23	22
15	349.6	8049029	75	79	79	25	21	21
16	354	8054893	78	79	79	22	21	21
17	358.8	8060874	79	79	81	21	21	19
18	364.8	8069085	81	81	81	19	19	19
19	372.3	8078593	82	83	83	18	17	17

There are various points in table 7.2 that needs to be pointed out. The net profit value reaches its maximum of L.E 8,075,593, when the number of trailers assigned to the disassembly operation reaches its peak, while the number of trailers assigned to refurbishing reaches its minimum values for the 3 planning periods as shown in iteration 19. Yet, this maximum profit is associated with the highest total weight of items being disposed, which is 372.3 kg. This accounts to; the increase in the number of trailers assigned to disassembly is associated with increasing the items that needs disposal, the net profit values decreases gradually with the gradual decrease of assigning trailers to disassembly operation and the gradual increase of assigning trailers to refurbishing operation. Therefore, the total weight of items being disposed is decreasing as trailer refurbishing doesn't yield any items assigned to disposal. The net profit value reaches its minimum of L.E 7,983,150, when the number of trailers assigned to disassembly operation reaches its minimum value. And the number assigned to refurbishing reaches its peak in the 3 planning periods as shown in iteration 1. This minimum profit value is associated with the minimum disposal weight, which is 300.3 kg. In Fig 12, the x- axis represents different disposal weights. The y- axis represents the corresponding net profit values. The top point represents the maximum net profit corresponding to the highest total disposal weight. The bottom point represents the minimum net profit corresponding to the lowest disposal weights.

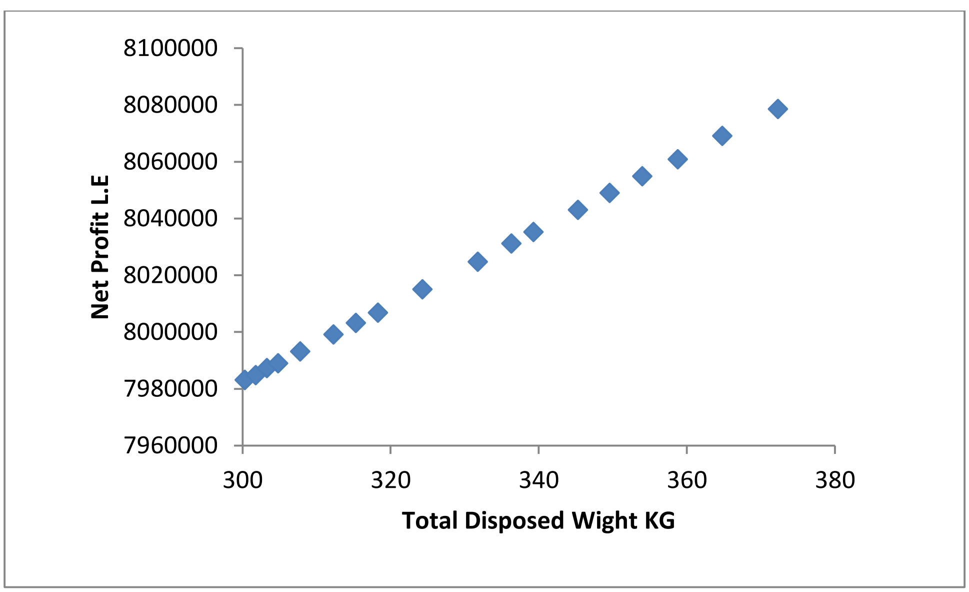

Fig 7.1: Relationship of two objectives

7.5.2.2 Solutions associated with setting disposal target (V_2) at 150kg

Table 7.3 Shows the set of non-dominating solutions produced upon solving the trailer case study using Minimx Weighting method using $\boldsymbol{V_1}$= 8,183,006 L.E and $\boldsymbol{V_2}$= 150 kg and their trade-offs (Run 2 series trade-offs). It also shows the associated impact of two objective function tradeoffs on the vital decision variables, which are the number of whole trailer assigned to disassembly versus number whole trailer assigned to refurbishing in each planning period.

Table 7.3: Tradeoffs Solutions

#	Disposal Weight / Kg	Profit Value L.E	Number of trailers assigned to Disassembly in each planning periods			Number of trailers assigned to Refurbishing in each planning periods		
			X(1, 1, 1)	X(1, 1, 2)	X(1, 1, 3)	X(1, 2, 1)	X(1, 2, 2)	X(1, 2, 3)
1	150.3	7783136	33	33	34	67	67	66
2	150.3	7783146	33	33	34	67	67	66
3	151.8	7785152	34	34	33	66	66	67
4	153.1	7787283	32	35	35	68	65	65
5	153.3	7787283	32	35	35	68	65	65
6	154.8	7789402	33	35	35	67	65	65
7	156.3	7791408	34	35	35	66	65	65
8	157.8	7793783	35	35	35	65	65	65
9	160.6	7797388	35	35	37	65	65	63
10	162.3	7799147	35	35	38	65	65	62
11	165.3	7803253	35	38	37	65	62	63
12	169.8	7809243	35	39	39	65	61	61
13	175.8	7817473	39	39	39	61	61	61
14	186.3	7831067	41	42	41	59	58	59
15	192.2	7838881	43	43	42	57	57	58
16	195.3	7842979	42	44	44	58	56	56
17	204	7855451	44	46	46	56	54	54
18	208.8	7861281	46	47	46	54	53	54
19	216	7869972	48	48	48	52	52	52
20	223.5	7880976	48	51	50	52	49	50
21	232.8	7892831	51	52	52	49	48	48
22	244.8	7909162	53	54	54	47	46	46

There are various points in table 7.3 that needs to be pointed out. The net profit value reaches its maximum of L.E 7,909,162, when the number of trailers assigned to disassembly operation reaches its peak, while the number of trailers assigned to refurbishing reaches its bottom for the 3 planning periods as shown in iteration 23. Yet, this maximum profit is associated with the highest total weight of items being disposed which is 244.8kg. This accounts to; the increase in the number of trailers assigned to disassembly is associated with increasing the items that needs disposal, the net profit values decreases gradually with the gradual decrease of assigning trailers to disassembly operation and the gradual increase of assigning trailers to refurbishing operation. Therefore, the total weight of the items being disposed is decreasing, as trailer refurbishing does not yield any items assigned to disposal. The net profit value reaches its minimum of L.E 7,783,136, when the number of trailers assigned to disassembly operation reaches its bottom, and the number assigned to refurbishing reaches its peak in the 3 planning periods as shown in iteration 1. This minimum profit value is associated with the minimum disposal weight which is 150.3 kg. In, Fig 13 the x- axis represents different disposal weights. The y- axis represents the corresponding net profit values. The top point represents the maximum net profit corresponding to the highest total disposal weight. The bottom point represents the minimum net profit corresponding to the lowest disposal weights.

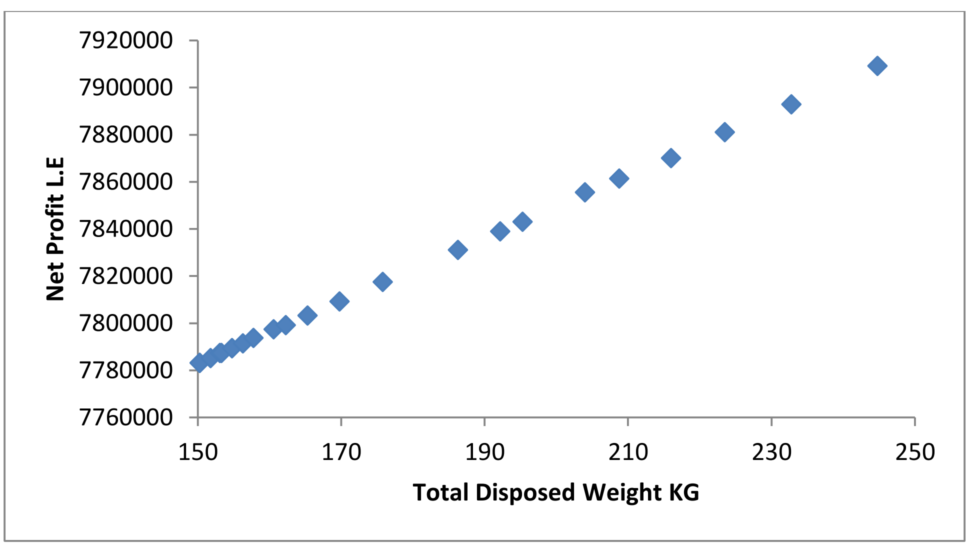

Fig 7.2: Relationship of two objectives

7.6 Using the constrained method

7.6.1 Solving Steps of trailer multi-objective case using the constrained method

Step One:

Same as stated before for the Minimx weighted method.

Step Two:

I. Specifiy the simplified equations of the two objective functions

Objective function 1: Maximize R = TR - TC

Objective function 2: Minimize K = $\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}} g_i X_{i,7,t}$

II. Convert the multi-objective model to its corresponding constrained model, where one of the objectives is selected to be the main objective function in the constrained model, while the other objective function is relaxed and limited to certain bounds, where these bounds are changed in each iteration .

III. The constrained model would be

Maximize R (1C)

S.t

$K \leq B_U$ (2C)

$B_U = 14870 - 14870\alpha$ (3C)

Where

R: is the optimized value of the actual profit produced in each iteration. Referring to the iterations that are associated with different disposal upper bounds.

K: is the optimized value of actual disposal weight produced in each iteration. Referring to the iterations that are associated with different disposal upper bounds.

14870: is the actual disposal weight obtained from solving the model by only considering the first objective function, which is maximizing the net profit at the end of the three planning periods.

B_U: The upper bound allowed for disposal.

α: Reduction portion value for disposal.

Step Three:

I. Specify the upper bounds that limits the disposal
Assume that we need to generate 20 non-dominating solution, so the selected α values are as follows: $\alpha \in \{0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . . 0.95\}$.

II. Substitute in equation (3C) using different α values to generate a set of disposal upper bounds (B_U).

III. Solve the constraint model for each disposal upper bound.

Step Four:

I. Generate the corresponding tradeoffs table which is the set of solutions corresponding to each (B_U) value.

II. Draw the corresponding Pareto optimal.

7.6.2 Set of non-dominating solutions produced by the constrained method

7.6.2.1 Solutions associated with setting disposal bound (B_U) between 14870kg and 594.8kg

Table 7.4 shows the set of non-dominating solutions produced upon solving the trailer case study using the constrained method at setting disposal bounds from its maximum of 14870.3 kg till 594.8 kg . It also shows the associated impact of two objective function tradeoffs on the vital decision variables, which are the number of whole trailer assigned to disassembly versus number whole trailer assigned to refurbishing in each planning period. Note that the disposal bounds in each iteration rose from substituting with different values of α in equation 3C.

Table 7.4: Tradeoffs Solutions

#	Disposal Bound Kg	Actual Disposal Weight / Kg	Profit Value L.E	Number of trailers assigned to Disassembly in each planning periods			Number of trailers assigned to Refurbishing in each planning periods		
				X(1, 1, 1)	X(1, 1, 2)	X(1, 1, 3)	X(1, 2, 1)	X(1, 2, 2)	X(1, 2, 3)
1	14870.3	14835.3	8183012	100	100	100	0	0	0
2	14126.785	14100.3	8182996	100	100	100	0	0	0
3	13383.27	13190.3	8182962	100	100	100	0	0	0
4	12639.755	12630.3	8182934	100	100	100	0	0	0
5	11896.24	11825.3	8182892	100	100	100	0	0	0
6	11152.725	11125.3	8182877	100	100	100	0	0	0
7	10409.21	10215.3	8182835	100	100	100	0	0	0
8	9665.695	9655.3	8182808	100	100	100	0	0	0
9	8922.18	8920.3	8182772	100	100	100	0	0	0
10	8178.665	8150.3	8182743	100	100	100	0	0	0
11	7435.15	7415.3	8182707	100	100	100	0	0	0
12	6691.635	6680.3	8182681	100	100	100	0	0	0
13	5948.12	5945.3	8182646	100	100	100	0	0	0
14	5204.605	5175.3	8182616	100	100	100	0	0	0
15	4461.09	4440.3	8182581	100	100	100	0	0	0
16	3717.575	3705.3	8182555	100	100	100	0	0	0
17	2974.06	2970.3	8182519	100	100	100	0	0	0
18	2230.545	2095.3	8182479	100	100	100	0	0	0
19	1487.03	1430.3	8182451	100	100	100	0	0	0
20	743.515	730	8182409	100	100	100	0	0	0
21	594.812	555.3	8182411	100	100	100	0	0	0

There are various points in table 7.4 that needs to be pointed out. The net profit value reaches its maximum of L.E 8,183,012, when the total weight of the items being disposed reaches the peak limit of 14870.3kg. The net profit values decreases gradually with the gradual decrease of the total weight of the items being disposed. The net profit value reaches its minimum of L.E 8,182,411, when the total weight of the items being disposed reaches its bottom of 555.3 kg. In this constrained approach, changing the disposal bound from 14870.3 kg to 594.812 kg is high enough to assign all the trailers characterized by good physical condition to disassembly operation. That is why the tradeoffs table 7.5 is made with lower bounds for the disposal limit, to show its effect on directing the decisions of assigning the whole trailer toward certain operation. In, Fig 14 the x- axis represents different disposal weights. The y- axis represents the corresponding net profit values. The top point represents the maximum net profit corresponding to the highest total disposal weight. The bottom point represents the minimum net profit corresponding to the lowest disposal weights

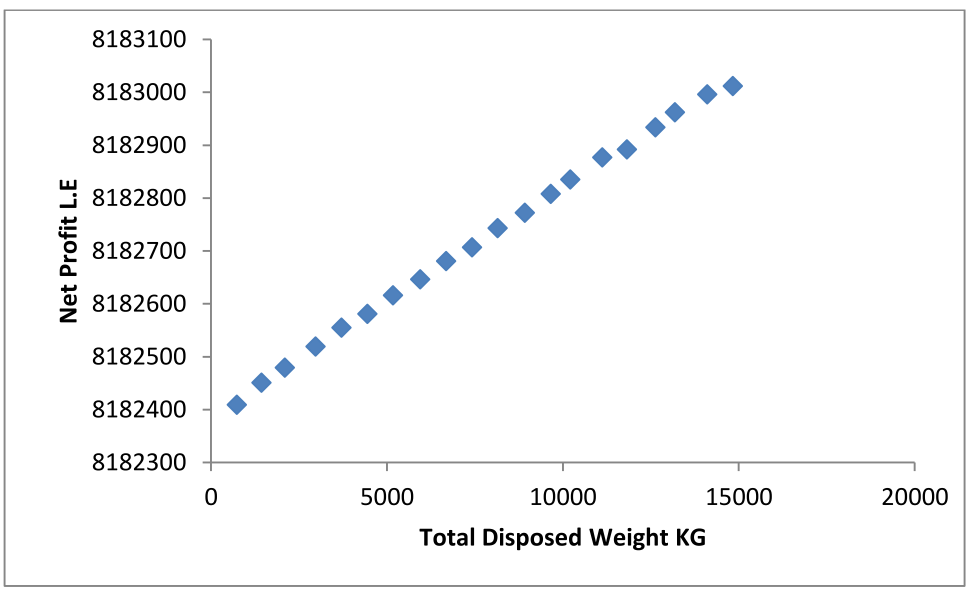

Fig7.3: Relationship of two objectives

.

7.6.2.2 Solutions associated with setting disposal bound (B_U) between 1000kg and 0 kg

Table 7.5 shows the set of non-dominating solutions produced upon solving the trailer case study using the constrained method by setting the disposal bounds from 0 kg to 660 kg. It also shows the associated impact of two objective function tradeoffs on the vital decision variables, which are the number of whole trailer assigned to disassembly versus number whole trailer assigned to refurbishing in each planning period.

Table 7.5: Tradeoffs Solutions

#	Disposal Bound Kg	Actual Disposal Weight / Kg	Profit Value L.E	Number of trailers assigned to Disassembly in each planning periods			Number of trailers assigned to Refurbishing in each planning periods		
				X(1, 1, 1)	X(1, 1, 2)	X(1, 1, 3)	X(1, 2, 1)	X(1, 2, 2)	X(1, 2, 3)
1	0	0	7425400	0	0	0	100	100	100
2	50	49.8	7616092	25	4	4	75	96	96
3	100	99.3	7706524	32	17	17	68	83	83
4	150	150	7783146	33	34	33	67	66	67
5	200	199.8	7849395	45	44	44	55	66	66
6	250	249	7915397	55	55	56	45	45	44
7	300	300	7983150	66	66	68	34	34	32
8	350	349.8	8049029	75	79	79	25	21	21
9	400	399.3	8114888	88	88	90	12	12	10
10	450	450	8182400	100	100	100	0	0	0
11	500	485.3	8182404	100	100	100	0	0	0
12	550	520.3	8182407	100	100	100	0	0	0
13	600	590.3	8182414	100	100	100	0	0	0

There are various points in table 7.5 that needs to be pointed out. The net profit value reaches its maximum of L.E 8,182,414, when all 100 trailers characterized by good physical conditions are assigned to the disassembly operation, and no trailer is assigned to the refurbishing operation for the 3 planning periods as shown in iteration 13. This maximum profit is associated with the highest total weight of items being disposed which is 590 kg. The net profit values decreases gradually with the gradual decrease of assigning trailers to the disassembly operation at and the gradual increase of assigning trailers to the refurbishing operation. The net profit value reaches its minimum of L.E 7,425,400, when all 100 trailers characterized by good physical conditions are assigned to the refurbishing operation, and no trailer is assigned to the disassembly operation for the 3 planning periods as shown in iteration 1.This is associated with zero disposal weight.

7.7 Evaluations of solutions obtained from solving the multi-objective model using the two solution approaches

Table 7.6 shows the comparison of some of the selected non-dominated solutions produced upon solving the trailer case study using two solution methods.

Table 7.6: Two objectives tradeoffs for the used solution methods

Sol Point	Solution Approach	Disposal Target / Disposal bound Kg	Actual Disposal Value Kg	Actual Profit Value L.E	Number of Trailers Assigned to Disassembly in 3 periods	Number of Trailers Assigned to Refurbishing in 3 periods
1	Constraint	0	0	7425400	0	0
2	Weighting	150	150.3	7783136	100	200
3	Weighting	150	244.8	7909162	161	139
4	Weighting	300	300.3	7983150	200	100
5	Weighting	300	372.3	8078593	248	52
6	Constraint	594.812	555.3	8182411	300	0
7	Constraint	600	590.3	8182414	300	0
8	Constraint	14870.3	14835.3	8183012	300	0

Note that the solution points 4 & 5 obtained upon solving the model using the Weighting method at setting the disposal target to 300 kg with different weights. Also, the solution points 2 & 3 obtained upon solving the model using the Weighting method at setting the disposal target to 150 kg with different weights.

There are various points in table 7.6 that needs to be pointed out. The net profit value reaches its maximum of L.E 8,183,012, when the total weight of the items assigned to disposal reaches its peak of 14835.3 kg. This is the most profitable and worst environmental non-dominated solution happened when the case was solved using the constrained method at bounding the disposal to 14870.3 kg. This solution direct the assignment of all trailers characterized with good physical conditions towards the disassembly operation for the three planning periods. The second most profitable non-dominating solution happened when the case was solved using the constrained method at bounding the disposal to 1000 kg. At this point the profit value is L.E 8,182,430, while the disposal value is 940 kg. The total weight of items assigned to disposal reaches its minimum of 0 kg, when all trailers characterized with good physical conditions are assigned towards the refurbishing operation for the three planning periods. The corresponding profit value reaches its minimum of L.E 7,425,400. This first best environmental non-dominated solution happened when the case was solved using the Constrained method at bounding the disposal to 0 kg. The second best environmental non-dominating solution happened when the case was solved using the Weighting method by setting the disposal target to 150 kg. The corresponding profit value reaches L.E 7,783,136. The decision maker has to choose the non-dominated solution point that best suits his objectives. From my point of view, I would select the non-dominated solution of either point 5 or 6 shown in table 7.6, because it fits best with the two objectives.

Chapter Eight

Conclusion and future work

A summary of the conducted research in the proposed work is presented in this chapter. Moreover, it includes the concluding comments based on the problem modeling. The recommendations for future research are also debated.

8.1 Conclusion

This research is developed for the aim of deciding the most sustainable way to deal with the spent products. The aim of this study is achieved through modeling the problem using a multi-objective mixed integer linear programming technique with two objective functions considering net profit maximization and total disposal weight minimization. Maximizing the net profit at the end of all planning periods satisfies the economic aspect of sustainability. Minimizing the total weight at all items assigned to disposal at the end of all planning periods satisfies the environmental aspect of sustainability. Initiating fair refunding system for spent products satisfies social responsibility aspect of sustainability. The deliverables of the model are the specification of the following in each planning period: optimal disassembly sequence of items, number of each item assigned to various recovery operations of the remanufacturing unit, specification of the required total regular production hours, specification of the total needed number of workers, and specification of the number of workers hired and fired.

The developed multi-objective mixed integer linear programming model is flexible enough that allow new constrictions addition for different assumptions and applications. The formulation of the developed model is associated with some limitations. The first is the deterministic nature of the model that does not capture any uncertainties may be associated with dealing with the received spent products. The second is the categorization of the received spent products into three physical conditions only. The third is the consideration of only one place to receive the spent products by their end users at the remanufacture unit location, which may demotivate them especially if the refund prices of the returns are low to get their spent products to the testing and inspection center of the remanufacture unit.

The main contribution of this research is considering new features in modeling the problem: Assessing the tradeoffs between the value of recovering the whole spent product versus the value from its disassembly and recovering the dissembled items separately, Using MILP technique to restrict the assignment of items to various recovery operations based on their technical feasibility portion and economic viability toward these operations, Expanding the assignment of items to various recovery operations to the upper limit of the total available labors for all operations in regular production hours , utilizing the recycling operation in the optimum way that increases the income from selling recycled isolated materials , considering new vital aspects which are the quality of recovered products and the minimum batch size for vending recycled materials, Studying optimal disassembly sequence on applications such as trailers . Moreover, proposing sustainable solutions for the collected trailers that are prohibited to move on Egyptian roads is from the main contribution for this thesis work.

8.2 Future work

The following points are worth consideration to be addressed in the future research:

- Consider the planning of the testing and inspection stage
- Consider the planning for the remanufacture and the cannibalization operations
- Considering various physical conditions of items to be assigned to disassembly operation; hence, considering the variation in the dissembled items quality from single type parent.
- Inventory control issues for received products, and recovered products. This thesis model has not considered Inventory costs based on the assumption that the storing time of the received products and volatized is very low and negligible. Yet, in case this assumption is violated, it is crucial to consider inventory issues.

References

1 Meacham,A. Uzso ,R. Venkatadri,U Optimal disassembly configurations for single and multiple products", J. Manufacturing Systems 18(5) (1999)

2 Amelia, L., Wahab, D. A., Che Haron, C. H., Muhamad, N., & Azhari, C. H. (2009). Initiating automotive component reuse in malaysia. Journal of Cleaner Production, 17(17), 1572-1579. doi:10.1016/j.jclepro.2009.06.011

3 Alumur, S. A., Nickel, S., Saldanha-da-Gama, F., & Verter, V. (2012). Multi-period reverse logistics network design. European Journal of Operational Research, 220(1), 67-78. doi:10.1016/j.ejor.2011.12.045

4 Chouinard, M., D'Amours, S., & Aït-Kadi, D. (2008). A stochastic programming approach for designing supply loops. International Journal of Production Economics, 113(2), 657-677. doi:10.1016/j.ijpe.2007.10.023

5 Cruz-Rivera, R., & Ertel, J. (2009; 2008). Reverse logistics network design for the collection of end-of-life vehicles in mexico. European Journal of Operational Research, 196(3), 930-939. doi:10.1016/j.ejor.2008.04.041

6 Cohon, J.L., (1978). Multiobjective programming and planning, Mathematics in Science and Engineering, Vol. 140, Academic Press, Inc

7 Das, K., & Chowdhury, A. H. (2011; 2012). Designing a reverse logistics network for optimal collection, recovery and quality-based product-mix planning. International Journal of Production Economics, 135(1), 209-221. doi:10.1016/j.ijpe.2011.07.010

8 Elimam A. A. 2012, Goal Programming and Multiple objective optimization, Lecture power point slides of system modeling and optimization course, Mechanical department, American university in Cairo

9 Fandel, G., & Stammen, M. (2004). A general model for extended strategic supply chain management with emphasis on product life cycles including development and recycling. International Journal of Production Economics, 89(3), 293-308. doi:10.1016/S0925-5273(03)00198-1

10 Farahani, R. Z., SteadieSeifi, M., & Asgari, N. (2010). Multiple criteria facility location problems: A survey. Applied Mathematical Modelling, 34(7), 1689-1709. doi:10.1016/j.apm.2009.10.005

11 Jayaraman, V. (2006). Production planning for closed-loop supply chains with product recovery and reuse: An analytical approach. International Journal of Production Research, 44(5), 981-998. doi:10.1080/00207540500250507

12 Kim, J., Kim, K., Song, I., & Jeong, B. (2006). Supply planning model for remanufacturing system in reverse logistics environment. Computers & Industrial Engineering, 51(2), 279-287. doi:10.1016/j.cie.2006.02.008

13 Kongar, E., & Gupta, S. M. (2006). Disassembly to order system under uncertainty. Omega, 34(6), 550-561. doi:10.1016/j.omega.2005.01.006

14 Lambert, A. J. D. (2003). Disassembly sequencing: A survey. International Journal of Production Research, 41(16), 3721-3759. doi:10.1080/0020754031000120078

15 Lambert, A. J. D. (2006). Exact methods in optimum disassembly sequence search for problems subject to sequence dependent costs. Omega, 34(6), 538-549. doi:10.1016/j.omega.2005.01.005

16 Li, S., Wang, N., He, Z., Che, A., & Ma, Y. (2012). Design of a multiobjective reverse logistics network considering the cost and service level. Mathematical Problems in Engineering, 2012 doi:10.1155/2012/928620

17 Mansour, S., & Zarei, M. (2008). A multi-period reverse logistics optimisation model for end-of-life vehicles recovery based on EU directive. International Journal of Computer Integrated Manufacturing, 21(7), 764-777. doi:10.1080/09511920701685325

18 McGovern, S. M., & Gupta, S. M. (2006). Ant colony optimization for disassembly sequencing with multiple objectives. The International Journal of Advanced Manufacturing Technology, 30(5), 481-496. doi:10.1007/s00170-005-0037-6

19 Harraz, N.A. Galal, N.., Design of Sustainable End-of-life Vehicle recovery network in Egypt, Ain Shams Eng J (2011), doi:10.1016/j.asej.2011.09.006

20 Montgomery, D. (2005). Factorial and Fractional Experiments for Process Design and Improvement. In Introduction to Statistical quality control (Fifth ed., pp. 550-556). John Wiley & Sons.

21 Ondemir .O. (2012).End of Life Decision Making Models For Sensors Embedded Products. Phd thesis in the Industrial Engineering department at Northeastern University Boston, Massachusetts. 2012.04.

22 Schultmann, F., Zumkeller, M., & Rentz, O. (2006). Modeling reverse logistic tasks within closed-loop supply chains: An example from the automotive industry. European Journal of Operational Research, 171(3), 1033-1050. doi:10.1016/j.ejor.2005.01.016

23 Schuur, P. C., van Harten, A., & Krikke, H. R. (1998). On a medium term product recovery and disposal strategy for durable assembly products. International Journal of Production Research, 36(1), 111-140. doi:10.1080/002075498193967

24 Shimizu, Y., Tsuji, K., & Nomura, M. (2007). Optimal disassembly sequence generation using a genetic programming. International Journal of Production Research, 45(18), 4537-4554. doi:10.1080/00207540701440261

25 Simic, V., & Dimitrijevic, B. (2012). Modeling production processes in a vehicle recycling plant. Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA, 30(9), 940.

26 Simic, V., & Dimitrijevic, B. (2012). Production planning for vehicle recycling factories in the EU legislative and global business environments. Resources, Conservation & Recycling, 60, 78-88. doi:10.1016/j.resconrec.2011.11.012

27 Srivastava, S. K. (2008). Network design for reverse logistics. Omega, 36(4), 535-548. doi:10.1016/j.omega.2006.11.012

28 Rahmatian, M. (2008). Multi-objective Reverse Logistics Network Design and Analysis. Master Thesis in the Mechanical and Industrial Engineering department at Concordia University Montreal, Quebec, Canada. 2008.07.

29 Wang, Z., & Bai, H. (2010). Reverse logistics network: A review. Paper presented at the 1139-1143. doi:10.1109/IEEM.2010.5674319

30 Xanthopoulos, A., & Iakovou, E. (2009). On the optimal design of the disassembly and recovery processes. Waste Management, 29(5), 1702-1711. doi:10.1016/j.wasman.2008.11.009

31 Yang, J., & Li, D. (2002). Normal vector identification and interactive tradeoff analysis using minimax formulation in multiobjective optimization. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, 32(3), 305-319. doi:10.1109/TSMCA.2002.802806

32 Zarei, M., Mansour, S., Kashan, A. H., & Karimi, B. (2010). Designing a reverse logistics network for end-of-life vehicles recovery. Mathematical Problems in Engineering, 2010, 1-17. doi:10.1155/2010/649028

33 Zhang, X. M., Chen, Y. Q., Ansari, N., & Shi, Y. Q. (2004). Mini-max initialization for function approximation. Neurocomputing, 57, 389-409. doi:10.1016/j.neucom.2003.10.014

34 http://globalfoodsystemanalysis.weebly.com/biofuels.html

Appendix A

Input data for the Real Trailer Case Study

Table A.1: Number of items present in each set as well as the given number for components of set members and their identification

Sets	Members of sets	Members range	Identification of set members
$\boldsymbol{\mathcal{F}}$	1	F=1	One Spent trailer
$\boldsymbol{\mathcal{P}}$	33	P=2, 3, 4, 5, 6, 7, ……34	33 disassembled items
$\boldsymbol{\mathcal{I}}$	34	I=1, 2, 3, 4, 5, 6, 7,….34	34 items
$\boldsymbol{\mathcal{O}}$	7	O= 1, 2, 3, 4, 5 , 6, 7	7 Operations
$\boldsymbol{\mathcal{S}}$	3	S= 1, 2, 3	3 Physical Conditions
$\boldsymbol{\mathcal{T}}$	3	T= 1, 2, 3	3 Periods
$\boldsymbol{\mathcal{M}}$	8	M=1, 2, 3, 4, 5, 6, 7, 8	8 Material group

Table A.2: Number of received trailers in all planning periods corresponding to various physical conditions

$\boldsymbol{n_{i,s,t}}$	**Number**
$n_{1,1,t}$	100
$n_{1,2,t}$	100
$n_{1,3,t}$	100

Table A.3: Refund paid for one trailer corresponding to its physical conditions

$\boldsymbol{c_{i,s,t}^{REF}}$	**L.E / Trailer**
$c_{1,1,t}^{REF}$	40,000
$c_{1,2,t}^{REF}$	30,000
$c_{1,3,t}^{REF}$	20,000

Table A.4: Technical feasibility portion of item I to the proposed recovery operation o

	O= 1	O= 2	O= 3	O= 4	O= 5	O= 6	O= 7
I=1	-	-	-	-	-	-	-
I=2	0	0	0	0	0	1	0
I=3	1	1	0	1	0	0	0
I=4	1	1	0	1	0	1	0
I=5	1	1	0	1	0	1	0
I=6	1	1	0	1	0	0	0
I=7	0	0	0	0	0	1	1
I=8	0	0	0	0	0	1	1
I=9	0	0	0	0	0	1	1
I=10	0	1	0	1	0	1	1
I=11	0	0	0	0	0	0	0
I=12	0	0	0	1	0	1	1
I=13	1	0	0	1	0	1	1
I=14	0	0	0	1	0	1	1
I=15	1	0	0	1	0	1	1
I=16	0	1	0	0	0	1	1
I=17	1	0	0	1	0	1	1
I=18	0	1	0	0	0	1	1
I=19	1	1	0	0	0	1	1
I=20	0	0	0	0	0	0	1
I=21	0	0	0	1	0	1	1
I=22	0	0	0	0	0	1	1
I=23	0	0	0	0	0	1	1
I=24	0	0	0	0	0	1	1
I=25	0	1	0	1	0	1	1
I=26	0	0	0	0	0	1	1
I=27	0	0	0	0	0	1	1
I=28	0	0	0	0	0	1	1
I=29	0	0	0	0	0	1	1
I=30	0	0	0	0	0	1	1
I=31	0	0	0	0	0	1	1
I=32	0	0	0	0	0	1	1
I=33	0	0	0	0	0	1	1
I=34	0	0	0	0	0	1	1

Table A.5: Needed labor hours to process item I by operation O

	O= 1	O= 2	O= 3	O= 4	O= 5	O= 6	O= 7
I=1	20	8	48	16	25	25	0
I=2	0	0	0	0	0	0.05	0
I=3	5	2	0	12	0	0	0
I=4	3	4	0	12	0	5	0
I=5	3	4	0	11	0	0.05365	0
I=6	1	1	0	1.5	0	0	0
I=7	0	0	0	0	0	1	2
I=8	0	0	0	0	0	1	2
I=9	0	0	0	0	0	2	4
I=10	0	1	0	8	0	1	2
I=11	0	0	0	0	0	0	0
I=12	0	0	0	1	0	0.035	0.07
I=13	1	0	0	1	0	0.02	0.04
I=14	0	0	0	8	0	0.1	0.2
I=15	1	0	0	1	0	0.03	0.06
I=16	0	0.5	0	0	0	0.003	0.006
I=17	2	0	0	2	0	0.03	0.06
I=18	0	0.5	0	0	0	0.002	0.004
I=19	0.25	0.5	0	0	0	0.0005	0.001
I=20	0	0	0	0	0	0	0.0005
I=21	0	0	0	2	0	0.025	0.05
I=22	0	0	0	0	0	0.003	0.006
I=23	0	0	0	0	0	0.001	0.002
I=24	0	0	0	0	0	0.001	0.002
I=25	0	4	0	11	0	0.035	0.07
I=26	0	0	0	0	0	0.015	0.03
I=27	0	0	0	0	0	0.00025	0.0005
I=28	0	0	0	0	0	0.00025	0.0005
I=29	0	0	0	0	0	0.0001	0.0002
I=30	0	0	0	0	0	0.0002	0.0004
I=31	0	0	0	0	0	0.00025	0.0005
I=32	0	0	0	0	0	0.0001	0.0002
I=33	0	0	0	0	0	0.00025	0.0005
I=34	0	0	0	0	0	0.0001	0.0002

Table A.6: Selling value of the output product result from processing item I by operation o

	O =1	O =2	O=3	O=4	O=5	O=6	O=7
I=1	-	45,000	140, 000	40,000	222850	-	-
I=2	-	0	0	0	0	-	-
I=3	-	4000	0	6000	0	-	-
I=4	-	22000	0	23,000	0	-	-
I=5	-	1000	0		0	-	-
I=6	-	1000	0	1000	0	-	-
I=7	-	0	0	0	0	-	-
I=8	-	0	0	0	0	-	-
I=9	-	0	0	0	0	-	-
I=10	-	7000	0	7000	0	-	-
I=11	-	0	0	0	0	-	-
I=12	-	0	0	500	0	-	-
I=13	-	0	0	500	0	-	-
I=14	-	0	0	3000	0	-	-
I=15	-	0	0	1000	0	-	-
I=16	-	600	0	0	0	-	-
I=17	-	0	0	1500	0	-	-
I=18	-	400	0	0	0	-	-
I=19	-	200	0	0	0	-	-
I=20	-	0	0	0	0	-	-
I=21	-	0	0	1000	0	-	-
I=22	-	0	0	0	0	-	-
I=23	-	0	0	0	0	-	-
I=24	-	0	0	0	0	-	-
I=25	-	0	0	0	0	-	-
I=26	-	0	0	0	0	-	-
I=27	-	0	0	0	0	-	-
I=28	-	0	0	0	0	-	-
I=29	-	0	0	0	0	-	-
I=30	-	0	0	0	0	-	-
I=31	-	0	0	0	0	-	-
I=32	-	0	0	0	0	-	-
I=33	-	0	0	0	0	-	-
I=34	-	0	0	0	0	-	-

Table A.7: Additional operating costs required to process item I by operation o

	O =1	O =2	O=3	O=4	O=5	O=6	O=7
I=1	0	1000	76000	5000	0	0	0
I=2	0	2000	0	5000	0	0	0
I=3	0	500	0	2000	0	0	0
I=4	0	500	0	2000	0	0	0
I=5	0	150	0	400	0	0	0
I=6	0	100	0	600	0	0	0
I=7	0	0	0	0	0	0	0
I=8	0	0	0	0	0	0	0
I=9	0	0	0	0	0	0	0
I=10	0	200	0	1000	0	0	0
I=11	0	0	0	0	0	0	0
I=12	0	0	0	100	0	0	1
I=13	0	0	0	50	0	0	0
I=14	0	0	0	3000	0	0	0
I=15	0	0	0	100	0	0	0
I=16	0	50	0	0	0	0	0
I=17	0	0	0	200	0	0	0
I=18	0	50	0	0	0	0	0
I=19	0	50	0	0	0	0	0
I=20	0	0	0	0	0	0	0
I=21	0	0	0	300	0	0	0
I=22	0	0	0	0	0	0	0
I=23	0	0	0	0	0	0	0
I=24	0	0	0	0	0	0	0
I=25	0	0	0	0	0	0	0
I=26	0	0	0	0	0	0	0
I=27	0	0	0	0	0	0	0
I=28	0	0	0	0	0	0	0
I=29	0	0	0	0	0	0	0
I=30	0	0	0	0	0	0	0
I=31	0	0	0	0	0	0	0
I=32	0	0	0	0	0	0	0
I=33	0	0	0	0	0	0	0
I=34	0	0	0	0	0	0	0

Table A.8: Proportion of the total weight of item i that is made from material type m

	M=1	M=2	M=3	M=4	M=5	M=6	M=7	M=8
I=1	0.0075	0.1428	0.586	0.049	0.026	0.004	0.005	0.00428
I=2	0	0	1	0	0	0	0	0
I=3	0	0	0	0	0	0	0	0
I=4	0	0.2	0.8	0	0	0	0	0
I=5	0	0	0	1	0	0	0	0
I=6	0	0	0	0	0	0	0	0
I=7	0	0	1	0	0	0	0	0
I=8	0	0	1	0	0	0	0	0
I=9	0	0	1	0	0	0	0	0
I=10	0	1	0	0	0	0	0	0
I=11	0	0	0	0	0	0	0	0
I=12	0	0	0	0	0	0	0	1
I=13	0	0	0	0	0	0	1	0
I=14	0	0	0	1	0	0	0	0
I=15	0	0	0	0	1	0	0	0
I=16	0	0	0	0	0	1	0	0
I=17	0	0	0	0	1	0	0	0
I=18	0	0	0	0	0	1	0	0
I=19	0	0	0	0	0	0	0	0
I=20	0	0	0	0	0	0	0	0
I=21	0	0	0	0	1	0	0	0
I=22	0	0	1	0	0	0	0	0
I=23	0	0	1	0	0	0	0	0
I=24	0	0	1	0	0	0	0	0
I=25	0	0	0	1	0	0	0	0
I=26	0	0	0	1	0	0	0	0
I=27	0	0	0	1	0	0	0	0
I=28	1	0	0	0	0	0	0	0
I=29	1	0	0	0	0	0	0	0
I=30	1	0	0	0	0	0	0	0
I=31	1	0	0	0	0	0	0	0
I=32	1	0	0	0	0	0	0	0
I=33	1	0	0	0	0	0	0	0
I=34	1	0	0	0	0	0	0	0

Table A.9: Input matrix for the input parameter$\beta_{i,m}$, where $\beta_{i,m}$ =1 if material $m \in \boldsymbol{\mathcal{M}}$ constituting item $i \in \boldsymbol{\mathcal{I}}$ **,** 0 otherwise. Ex, Since all materials groups constitute item 1, which is the whole trailer. Therefore, $\beta_{1,1} = \beta_{1,2} = \beta_{1,3} = \beta_{1,4} = \beta_{1,5} = \beta_{1,6} = \beta_{1,7} = \beta_{1,8}$

	M=1	**M=2**	**M=3**	**M=4**	**M=5**	**M=6**	**M=7**	**M=8**
I=1	1	1	1	1	1	1	1	1
I=2	0	0	1	0	0	0	0	0
I=3	0	0	0	0	0	0	0	0
I=4	0	1	1	0	0	0	0	0
I=5	0	0	0	1	0	0	0	0
I=6	0	0	0	0	0	0	0	0
I=7	0	0	1	0	0	0	0	0
I=8	0	0	1	0	0	0	0	0
I=9	0	0	1	0	0	0	0	0
I=10	0	1	0	0	0	0	0	0
I=11	0	0	0	0	0	0	0	0
I=12	0	0	0	0	0	0	0	1
I=13	0	0	0	0	0	0	1	0
I=14	0	0	0	1	0	0	0	0
I=15	0	0	0	0	1	0	0	0
I=16	0	0	0	0	0	1	0	0
I=17	0	0	0	0	1	0	0	0
I=18	0	0	0	0	0	1	0	0
I=19	0	0	0	0	0	0	0	0
I=20	0	0	0	0	0	0	0	0
I=21	0	0	0	0	1	0	0	0
I=22	0	0	1	0	0	0	0	0
I=23	0	0	1	0	0	0	0	0
I=24	0	0	1	0	0	0	0	0
I=25	0	0	0	1	0	0	0	0
I=26	0	0	0	1	0	0	0	0
I=27	0	0	0	1	0	0	0	0
I=28	1	0	0	0	0	0	0	0
I=29	1	0	0	0	0	0	0	0
I=30	1	0	0	0	0	0	0	0
I=31	1	0	0	0	0	0	0	0
I=32	1	0	0	0	0	0	0	0
I=33	1	0	0	0	0	0	0	0
I=34	1	0	0	0	0	0	0	0

Table A.10: Identify the material belonging to each material group material $m \in M$

Material group number	Material Identification	Example of items belonging to the material group
1	Steel SAENO 1035	Fasteners
2	High Steel	Chassis
3	Mild Steel	Triangle of Rotation , remaining steel structure
4	Steel SAENO 4063 / 4140	Axles , Suspensions
5	GS 60	Hub , Drum Brake
6	Steel SAENO 52100	Bearings
7	Cast Aluminum	Rim
8	Rubber	Tyre

Table A.11: Selling value of recycled material $m \in M$ in all planning periods

Material	Selling Price / ton	Selling Price / kg
1	1500	1.5
2	6000	6
3	3500	3.5
4	4000	4
5	6000	6
6	4000	4
7	8000	8
8	1000	1

Appendix B

Input data for the simplified Trailer Case Study

Table B.1: Number of items present in each set as well as the given number for components of set members and their identification

Sets	Members of sets	Members range	Identification of set members
$\mathcal{F}$	1	F=1	One Spent trailer
$\mathcal{P}$	33	P=2, 3, 4, 5, 6,12, 13	7 disassembled items
$\mathcal{I}$	34	I=1, 2, 3, 4, 5, 6, 12, 13	8 items
$\mathcal{O}$	7	O= 1, 2, 3, 4, 5 , 6, 7	7 Operations
$\mathcal{S}$	3	S= 1, 2, 3	3 Physical Conditions
$\mathcal{T}$	3	T= 1, 2, 3	3 Periods
$\mathcal{M}$	8	M=1, 2, 3, 4, 5, 6, 7, 8	8 Material group

Table B.2: Number of received trailers in all planning periods corresponding to various physical conditions

$\boldsymbol{n_{i,s,t}}$	**Number**
$n_{1,1,t}$	100
$n_{1,2,t}$	100
$n_{1,3,t}$	100

Table B.3: Refund paid for one trailer corresponding to its physical conditions

$\boldsymbol{c_{i,s,t}^{REF}}$	**L.E / Trailer**
$c_{1,1,t}^{REF}$	40,000
$c_{1,2,t}^{REF}$	30,000
$c_{1,3,t}^{REF}$	20,000

Table B.4: Technical feasibility portion of item I to the proposed recovery operation o

	O= 1	O= 2	O= 3	O= 4	O= 5	O= 6	O= 7
I=1	-	-	-	-	-	-	-
I=2	0	0	0	0	0	1	0
I=3	0	1	0	1	0	0	0
I=4	0	1	0	1	0	1	0
I=5	0	1	0	1	0	1	0
I=6	1	1	0	1	0	0	0
I=12	0	0	0	1	0	1	1
I=13	1	0	0	1	0	1	1

Note: In this simplified version of the case study, the disassembly of trailer doesn't involve the disassembly of items 3, 4, 5, and 13. That is why the product structure tree is simple.

Table B.5: Needed labor hours to process item I by operation O

	O= 1	**O= 2**	**O= 3**	**O= 4**	**O= 5**	**O= 6**	**O= 7**
I=1	20	8	48	16	25	25	0
I=2	0	0	0	0	0	0.05	0
I=3	5	2	0	12	0	0	0
I=4	3	4	0	12	0	5	0
I=5	3	4	0	11	0	0.05365	0
I=6	1	1	0	1.5	0	0	0
I=12	0	0	0	1	0	0.035	0.07
I=13	1	0	0	1	0	0.02	0.04

Table B.6: Selling value of the output product result from processing item I by operation o

	O =1	**O =2**	**O=3**	**O=4**	**O=5**	**O=6**	**O=7**
I=1	-	45,000	140, 000	40,000	222850	-	-
I=2	-	0	0	0	0	-	-
I=3	-	4000	0	6000	0	-	-
I=4	-	22000	0	23,000	0	-	-
I=5	-	1000	0		0	-	-
I=6	-	1000	0	1000	0	-	-
I=12	-	0	0	500	0	-	-
I=13	-	0	0	500	0	-	-

Table B.7: Additional operating costs required to process item I by operation o

	O =1	O =2	O=3	O=4	O=5	O=6	O=7
I=1	0	1000	76000	5000	0	0	0
I=2	0	2000	0	5000	0	0	0
I=3	0	500	0	2000	0	0	0
I=4	0	500	0	2000	0	0	0
I=5	0	150	0	400	0	0	0
I=6	0	100	0	600	0	0	0
I=12	0	0	0	100	0	0	1
I=13	0	0	0	50	0	0	0

Table B.8: Proportion of the total weight of item i that is made from material type m

	M=1	M=2	M=3	M=4	M=5	M=6	M=7	M=8
I=1	0.0075	0.1428	0.586	0.049	0.026	0.004	0.005	0.00428
I=2	0	0	1	0	0	0	0	0
I=3	0	0	0	0	0	0	0	0
I=4	0	0.2	0.8	0	0	0	0	0
I=5	0	0	0	1	0	0	0	0
I=6	0	0	0	0	0	0	0	0
I=12	0	0	0	0	0	0	0	1
I=13	0	0	0	0	0	0	1	0

Table B.9: Input matrix for the input parameter$\beta_{i,m}$, where $\beta_{i,m}$ =1 if material $m \in \mathcal{M}$ constituting item $i \in \mathcal{I}$, 0 otherwise. Ex, Since all materials groups constitute item 1, which is the whole trailer. Therefore, $\beta_{1,1} = \beta_{1,2} = \beta_{1,3} = \beta_{1,4} = \beta_{1,5} = \beta_{1,6} = \beta_{1,7} = \beta_{1,8}$

	M=1	M=2	M=3	M=4	M=5	M=6	M=7	M=8
I=1	1	1	1	1	1	1	1	1
I=2	0	0	1	0	0	0	0	0
I=3	0	0	0	0	0	0	0	0
I=4	0	1	1	0	0	0	0	0
I=5	0	0	0	1	0	0	0	0
I=6	0	0	0	0	0	0	0	0
I=12	0	0	0	0	0	0	0	1
I=13	0	0	0	0	0	0	1	0

Table B.10: Identify the material belonging to each material group material $m \in M$

Material group number	Material Identification	Example of items belonging to the material group
1	Steel SAENO 1035	Fasteners
2	High Steel	Chassis
3	Mild Steel	Triangle of Rotation , remaining steel structure
4	Steel SAENO 4063 / 4140	Axles , Suspensions
5	GS 60	Hub , Drum Brake
6	Steel SAENO 52100	Bearings
7	Cast Aluminum	Rim
8	Rubber	Tyre

Table B.11: Selling value of recycled material $m \in M$ in all planning periods

Material	Selling Price / ton	Selling Price / kg
1	1500	1.5
2	6000	6
3	3500	3.5
4	4000	4
5	6000	6
6	4000	4
7	8000	8
8	1000	1

Appendix C

Deviated input data of the trailer case study

Compare the Real input data for the Trailer Case Study to the deviates one that used for verifying the multi-objective nature of the problem

Table C.1: The table on the left show the Refund paid per trailer corresponding to its physical conditions while the table on the right shows the deviated refunds for these physical condition trailers

$c_{i,s,t}^{REF}$	L.E / Trailer
$c_{1,1,t}^{REF}$	40,000
$c_{1,2,t}^{REF}$	30,000
$c_{1,3,t}^{REF}$	20,000

Real Trailer Case Data

$c_{i,s,t}^{REF}$	L.E / Trailer
$c_{1,1,t}^{REF}$	44000
$c_{1,2,t}^{REF}$	33000
$c_{1,3,t}^{REF}$	22000

Deviated Trailer Case Data

Table C.2: The second row show the real selling value of after processing the whole trailer by operation o while the third row show the deviated selling value of after processing the whole trailer by operation o

		O =2	O=3	O=4	O=5
I=1	Real	45,000	140, 000	40,000	222850
I=1	Deviated	38,250	119000	34,000	19,428

Table C.3: The second row show the real additional operating costs required to process the whole trailer by operation o while the third row show the deviated additional costs required to process the whole trailer by operation o

		O =2	O=3	O=4	O=5
I=1	Real	1000	76000	5000	0
I=1	Deviated	1000	86000	5000	0

Table C.4: The table on the left show of the selling prices of output product results from processing item I by operation O = 2, 4 , While the table on the right show the deviated selling prices for the same items

	O = 2	O = 4
I = 3	4000	6000
I = 4	22000	23,000
I = 5	1000	
I = 6	1000	1000
I = 7	0	0
I = 8	0	0
I = 9	0	0
I = 10	7000	7000
I = 11	0	0
I = 12	0	500
I = 13	0	500
I = 14	0	3000
I = 15	0	1000
I = 16	600	0
I = 17	0	1500
I = 18	400	0
I = 19	200	0
I = 20	0	0
I = 21	0	1000
I = 22	0	0
I = 23	0	0
I = 24	0	0
I = 25	0	0
I = 26	0	0
I = 27	0	0
I = 28	0	0
I = 29	0	0
I = 30	0	0
I = 31	0	0
I = 32	0	0
I = 33	0	0
I = 34	0	0

Real Trailer Case Data

	O = 2	O = 4
I = 3	3400	5100
I = 4	18700	19550
I = 5	850	0
I = 6	850	850
I = 7	0	0
I = 8	0	0
I = 9	0	0
I = 10	5950	5950
I = 11	0	0
I = 12	0	425
I = 13	0	425
I = 14	0	2550
I = 15	0	850
I = 16	510	0
I = 17	0	1275
I = 18	340	0
I = 19	170	0
I = 20	0	0
I = 21	0	850
I = 22	0	0
I = 23	0	0
I = 24	0	0
I = 25	0	0
I = 26	0	0
I = 27	0	0
I = 28	0	0
I = 29	0	0
I = 30	0	0
I = 31	0	0
I = 32	0	0
I = 33	0	0
I = 34	0	0

Deviated Trailer Case Data

Table C.5: The table on the left show of the selling prices of output materials results from the recycling operation, while the table on the right shows the deviated selling prices for these materials

Material	Selling Price / kg
1	1.5
2	6
3	3.5
4	4
5	6
6	4
7	8
8	1

Real Trailer Case Data

Material	Selling Price / kg
1	1.35
2	5.4
3	3.15
4	3.6
5	5.4
6	3.6
7	7.2
8	0.9

Deviated Trailer Case Data

Appendix D

LINGO code used for simplified version of Trailer Case Study

```
Model:
! A 1 Parent with 3 _S 8 _I 7 _O 3 _T problem;

SETS:
	! Set members;

	_I / 1, 2, 3, 4, 5, 6, 12, 13/: g;

	_F( _I) / 1/;

	_P( _I) / 2, 3, 4, 5, 6, 12, 13/;

	_O / 1, 2, 3, 4, 5, 6, 7/;

	_T / 1, 2, 3/: LL, W, W_HIRE, W_FIRE, h, C_DL, C_HIRE, C_FIRE;

	_M / 1, 2, 3, 4, 5, 6, 7, 8/: G_SELL;

	_S / 1, 2, 3/;

	_R;

	_FST( _F, _S, _T): N, c_REF;

	_IT( _I, _T): Q, Y  ;

	_IOT ( _I, _O, _T): X ;

	_II( _I, _I): alpha  ;

	_PO ( _P, _O): p;

	_IO ( _I, _O): v_SELL, c_OP, l;

	_IM ( _I, _M): pi, B;

	_MT ( _M, _T): Z, v_REC;

ENDSETS
```

! Constraints;

! Operation selection Constraints;

```
! 1;
@FOR( _T(t) :
  @FOR( _F(i) :
    Q(i,t) = @SUM( _S(s): N(i,s,t))
  )
);

! 2;
@FOR( _T(t) :
  @FOR( _F(i) : X(i, 1, t) + X(i, 2, t) + X(i, 3, t) = N(i, 1, t)
  )
);

! 3;
@FOR( _T(t) :
  @FOR( _F(i) : X(i, 4, t) = N(i, 2, t)
  )
);

! 4;
@FOR( _T(t) :
  @FOR( _F(i) : X(i, 5, t) + X(i, 6, t) = N(i, 3, t)
  )
);

! 5;
@FOR(_T( t):
  @FOR(_P( j):
    Q( j, t) = @SUM(_I( i): alpha( i, j) * X(i, 1, t))
  )
);

! 6;
@FOR(_T( t):
  @FOR(_P( j):
    @FOR(_O( o): X( j, o, t) <= p( j, o) * Q( j, t)
    )
  )
);

!7;
@FOR(_T( t):
  @FOR(_P( j):
    Q( j, t) = @SUM(_O( o): X( j, o, t))
  )
);
```

! Workforce planning Constraints;

```
!8;
@FOR(_T( t):
  LL( t) = @SUM(_I( i): @SUM(_O( o): l( i, o) * X( i, o, t)))
);

!9;
@FOR(_T( t):
  W(t) >= LL( t )/ h( t)
);

!10;
W(1)= 45 + W_HIRE (1 )+ W_FIRE (1 );

@FOR(_T( t) | t #GT# 1:
  W( t)= W( t-1 )+ W_HIRE (t )- W_FIRE (t )
);
```

! Disposal;

```
!12;
@FOR(_T( t):
  @SUM (_I( i): g( i) * X(i, 7, t)) <= 10000000
);
```

! Inconsumable resources constraints;

```
!13;
@FOR(_T( t):
  @FOR(_M( m):
    @SUM(_I( i):  X( i, 6, t) * g( i) * pi( i, m)) >= G_SELL (m) * Z( m, t)
  )
);
```

! Recycled material minimum weight constraints;

```
!14;
@FOR(_T( t):
  @FOR (_I( i):
    X( i, 6, t) <= 10000.0 * Y( i, t)
  )
);

!15;
@FOR(_T( t):
  @FOR (_I( i):
    X( i, 6, t) >= 0.0001 * Y( i, t)
  )
);
```

```
!16;
@FOR(_T( t):
  @FOR(_M( m):
    @SUM(_I( i):  Y( i, t)* B( i, m)) >=  Z( m, t)
  )
);


!17;
@FOR(_T( t):
  @FOR(_M( m):
    @SUM(_I( i):  Y( i, t)* B( i, m)) <= 100000000 * Z( m, t)
  )
);
```

! Integer & binary constraints;

```
@FOR (_MT ( m, t ):@BIN (Z ( m, t)));

@FOR (_IT ( i, t ):@BIN (Y ( i, t)));

@FOR (_IOT ( i, o, t ):@GIN (X ( i, o, t)));

@FOR( _T(t):
  @GIN (LL (t));
  @GIN( W(t));
  @GIN( W_HIRE(t));
  @GIN( W_FIRE(t));
);
```

! Total cost;

```
TC = @SUM(_T( t): 4400 * W(t) +  500 * W_HIRE(t) + 800 * W_FIRE(t))
     + @SUM(_T( t): @SUM (_O( o): @SUM (_I( i): c_OP ( i, o) * X( i, o, t))))
     + @SUM(_T( t):@SUM (_F( i):@SUM (_S( s): c_REF ( i, s, t) * N ( i, s, t)
)));
```

! Total Revenue;

```
TR =  @SUM(_T( t): @SUM(_O( o) | o #EQ# 2 #OR# o #EQ# 3 #OR# o #EQ# 4 #OR# o
#EQ# 5: @SUM( _I(i): v_SELL(i, o) * X(i,o,t))))
    + @SUM(_T( t): @SUM(_M( m) : v_REC(m, t) * @SUM(_I( i):  X( i, 6, t) * g(
i) * pi( i, m))));
```

! First Objective Function which is maximizing net profit at the end of three planning periods;

```
MAX = TR - TC;
```

END

Appendix E

LINGO code of solving the problem using the two multi-objective approaches

```
Model:
! A 1 Parent with 3 _S 34 _I 7 _O 3 _T problem;

SETS:

! Set members;

    _I / 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,
20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34/: g;

    _F( _I) / 1/;

    _P( _I) / 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,
20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34/;

    _O / 1, 2, 3, 4, 5, 6, 7/;

    _T / 1, 2, 3/: LL, W, W_HIRE, W_FIRE, h, C_DL, C_HIRE, C_FIRE;

    _M / 1, 2, 3, 4, 5, 6, 7, 8/: G_SELL;

    _S / 1, 2, 3/;

    _R;

    _FST( _F, _S, _T): N, c_REF;

    _IT( _I, _T): Q, Y  ;

    _IOT ( _I, _O, _T): X ;

    _II( _I, _I): alpha  ;

    _PO ( _P, _O): p;

    _IO ( _I, _O): v_SELL, c_OP, l;

    _IM ( _I, _M): pi, B ;

    _MT ( _M, _T): Z, v_REC;


ENDSETS
```

! **Constraints in case of solving with Minimax weighting Method;**

All constraints are written as shown in Appendix D except the following modification:

- Constraint 12 is modified as follow :

```
@SUM (_T (t):@SUM (_I (i): g (i) * X (i, 7, t))) = k;
```

- The first objective function is dropped

The following equations codes are added for solving run series 1:

```
MIN = D;

W1 *(8183006 – R) / 8183006 <= D;

W2 (K - 300)/300 <= D;
```

`W1 and W2 are` changed in each iteration to generate a set of non-dominated solution.

The following equations codes are added for solving run series 2:

```
MIN = D;

W1 *(8183006 – R) / 8183006 <= D;

W2 (K - 150)/150 <= D;
```

`W1 and W2 are` changed in each iteration to generate a set of non-dominated solution.

! **Constraints in case of solving with Constrained Method;**

All constraints are written as shown in Appendix D except the following modification:

- Constraint 12 is modified as follow :

```
@SUM (_T (t):@SUM (_I (i): g (i) * X (i, 7, t))) = k;
```

$K \leq B_U$

B_U: The upper bound allowed for disposal that is changed in each iteration to generate a set of non-dominated solution.

Appendix F

LINGO code used for Real Trailer Case Study

Model:
! A 1 Parent with 3 _S 34 _I 7 _O 3 _T problem;

SETS:

! Set members;

```
    _I / 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,
20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34/: g;

    _F( _I) / 1/;

    _P( _I) / 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,
20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34/;

    _O / 1, 2, 3, 4, 5, 6, 7/;

    _T / 1, 2, 3/: LL, W, W_HIRE, W_FIRE, h, C_DL, C_HIRE, C_FIRE;

    _M / 1, 2, 3, 4, 5, 6, 7, 8/: G_SELL;

    _S / 1, 2, 3/;

    _R;

    _FST( _F, _S, _T): N, c_REF;

    _IT( _I, _T): Q, Y  ;

    _IOT ( _I, _O, _T): X ;

    _II( _I, _I): alpha  ;

    _PO ( _P, _O): p;

    _IO ( _I, _O): v_SELL, c_OP, l;

    _IM ( _I, _M): pi, B ;

    _MT ( _M, _T): Z, v_REC;
```

ENDSETS

! Constraints;
! Operation selection Constraints for Scenario 1 ;

```
! 1;
@FOR( _T(t) :
  @FOR( _F(i) :
    Q(i,t) = @SUM( _S(s): N(i,s,t))
  )
);

! 2;
@FOR( _T(t) :
  @FOR( _F(i) : X(i, 1, t) + X(i, 2, t) + X(i, 3, t) = N(i, 1, t)
  )
);

! 3;
@FOR( _T(t) :
  @FOR( _F(i) : X(i, 4, t) = N(i, 2, t)
  )
);

! 4;
@FOR( _T(t) :
  @FOR( _F(i) : X(i, 5, t) + X(i, 6, t) = N(i, 3, t)
  )
);

! 5;
@FOR(_T( t):
  @FOR(_P( j):
    Q( j, t) = @SUM(_I( i): alpha( i, j) * X(i, 1, t))
  )
);

! 6;
@FOR(_T( t):
  @FOR(_P( j):
    @FOR(_O( o): X( j, o, t) <= p( j, o) * Q( j, t)
    )
  )
);

!7;
@FOR(_T( t):
  @FOR(_P( j):
    Q( j, t) = @SUM(_O( o): X( j, o, t))
  )
);
```

```
! Workforce planning Constraints;

!8;
@FOR(_T( t):
  LL( t) = @SUM(_I( i): @SUM(_O( o): l( i, o) * X( i, o, t)))
);

!9;
@FOR(_T( t):
  W(t) >= LL( t )/ h( t)
);


!10;
W(1)= 45 + W_HIRE (1 )+ W_FIRE (1 );

@FOR(_T( t) | t #GT# 1:
  W( t)= W( t-1 )+ W_HIRE (t )- W_FIRE (t )
);

! Disposal;

!12;
@FOR(_T( t):
  @SUM (_I( i): g( i) * X(i, 7, t)) <= 1000
);

! Inconsumable resources constraints;

!13;
@FOR(_T( t):
  @FOR(_M( m):
    @SUM(_I( i):  X( i, 6, t) * g( i) * pi( i, m)) >= G_SELL (m) * Z( m, t)
  )
);

! Recycled material minimum weight constraints;

!14;
@FOR(_T( t):
  @FOR (_I( i):
    X( i, 6, t) <= 10000.0 * Y( i, t)
  )
);

!15;
@FOR(_T( t):
  @FOR (_I( i):
    X( i, 6, t) >= 0.0001 * Y( i, t)
  )
);
```

```
!16;
@FOR(_T( t):
  @FOR(_M( m):
    @SUM(_I( i):  Y( i, t)* B( i, m)) >=  Z( m, t)
  )
);



!17;
@FOR(_T( t):
  @FOR(_M( m):
    @SUM(_I( i):  Y( i, t)* B( i, m)) <= 100000000 * Z( m, t)
  )
);
```

! Integer & binary constraints;

```
@FOR (_MT ( m, t ):@BIN (Z ( m, t)));

@FOR (_IT ( i, t ):@BIN (Y ( i, t)));

@FOR (_IOT ( i, o, t ):@GIN (X ( i, o, t)));

@FOR( _T(t):
  @GIN (LL (t));
  @GIN( W(t));
  @GIN( W_HIRE(t));
  @GIN( W_FIRE(t));
);
```

! Total cost;

```
TC = @SUM(_T( t): 4400 * W(t) +  500 * W_HIRE(t) + 800 * W_FIRE(t))
     + @SUM(_T( t): @SUM (_O( o): @SUM (_I( i): c_OP ( i, o) * X( i, o, t))))
     + @SUM(_T( t):@SUM (_F( i):@SUM (_S( s): c_REF ( i, s, t) * N ( i, s, t)
)));
```

! Total Revenue;

```
TR =  @SUM(_T( t): @SUM(_O( o) | o #EQ# 2 #OR# o #EQ# 3 #OR# o #EQ# 4 #OR# o
#EQ# 5: @SUM( _I(i): v_SELL(i, o) * X(i,o,t))))
    + @SUM(_T( t): @SUM(_M( m) : v_REC(m, t) * @SUM(_I( i):  X( i, 6, t) * g(
i) * pi( i, m))));
```

! First Objective Function which is maximizing net profit at the end of three planning periods;

```
MAX = TR - TC;
```

END

Deviation in LINGO code for Scenario 2

! Constraints in case of solving Scenario 2;

All constraints are written as shown in for Scenario 1 except the following modification:

- Constraint 3 and 4 are dropped:

```
@SUM (_T (t):@SUM (_I (i): g (i) * X (i, 7, t))) = k;
```

- Constraint 2 is modified as follow :

```
! 2;
@FOR( _T(t) :
  @FOR( _F(i) : X(i, 1, t) + X(i, 2, t) + X(i, 3, t)+ X(i, 4, t)
              + X(i, 5, t) + X(i, 6, t)  = N(i, 1, t)
  )
);
```

Appendix G

Verification Runs

G.1 Summary of the Verification Run1

G.1.1 Experimental data adjustment for verification Run 1

For the 'good' physical condition trailer, the difference between the revenue resulting from selling the remanufactured semi-trailer and the costs consumed in the remanufacturing operation was settled to be higher than such a difference in the case of both refurbishing and disassembly operations. For the 'bad' physical condition trailer, the difference between the revenue results from cannibalizing the trailer and costs consumed in the cannibalizing operation was settled to be higher than such a difference in the case of recycling operations.

These settled data were used to assure that all the trailers in good physical conditions were assigned to the most profitable operation, which is remanufacturing for such data. It is also used to assure that all the trailers in bad physical conditions were assigned to the most profitable operation, which is cannibalization for such data. The values of the other decision variables would be checked according to this situation.

G.1.2 LINGO output summary of Run1

Run 1 details summary is shown in table G.1, while the nonzero decisions variables are summarized in table G.2

Table G.1 Details of run 1

Model class	ILP
Generator Memory used	114 K
State	Global Optimum
Objective Value	0.1187880E+08
Solver Type	Branch and Bound
Iterations	2263
Total Variables	257
Integers	225
Constraints	330

G.1.3 Non-zeros decision variables output summary of Run 1

Table G.2 Summary of non-zeros decision variables values of run 1

Decision Variable	Value
Q(1, 1) = Q(1, 2) = Q(1, 3) =	300
X (1, 3, 1) = X (1, 3, 2) = X (1, 3, 3) =	100

X (1, 4, 1) = X (1, 4, 2) = X (1, 4, 3) =	100
X (1, 5, 1) = X (1, 5, 2) = X (1, 5, 3) =	100
LL (1) = LL (2) = LL (3) =	8900
W(1) = W(2) = W(3) =	51
W_HIRE(1)=	6
W_HIRE(2)= W_HIRE(3)=	0
W_FIRE (1)= W_FIRE (2)= W_FIRE (3)=	0
All Y (i, t) =	0
All Z (M, t) =	0

G.1.4 Run 1 results and verification

The non-zero decision variables of Run1were analyzed in the following points to verify and validate the formulated model

1. **Verification of constraint 1**

According to LINGO output, Q (1, 1) = Q (1, 2) = Q (1, 3) = 300. Since 100 Good trailers + 100 Intermediate trailers + 100 Bad trailers = 300, then the logic of computing the decision variable Q (i, t), which is represented by equation 1, matches the number computed by LINGO in the 3 planning periods. Therefore, equation 1 is verified.

2. **Verification of constraint 2**

According to LINGO output, X (1, 3, 1) = X (1, 3, 2) = X (1, 3, 3) = 100. This shows that all good trailers are assigned to remanufacturing operation. No trailer was assigned to refurbishing or disassembly because remanufacturing was shown to be more profitable than refurbishing and disassembly in the three periods.

3. **Verification of constraint 3**

According to LINGO output, X (1, 4, 1) = X (1, 4, 2) = X (1, 4, 3) = 100.This shows that all intermediate trailers are assigned to repairing operation in the three periods.

4. **Verification of constraint 4**

According to LINGO output, X (1, 5, 1) = X (1, 5, 2) = X (1, 5, 3) = 100. This shows that all bad trailers are assigned to cannibalization operation. No trailer is assigned to recycling in the three periods because cannibalization is more profitable than recycling.

Operations selection constraints concluding remark

According to 1, 2, 3, and 4, the operation selection constraints are verified and it was proven that their logic supports the target of maximizing the profit through assigning items to the most proposed profitable operations.

5. **Verification of constraint 8**

According to LINGO output, LL (1) = LL (2) = LL (3) = 8900. Since the refurbishing operation of one trailer consumes 48 hours, the repairing operation of one trailer consumes 16 hours, and the cannibalizing operation of one trailer consumes 25 hours. Therefore, the total recovery hours needed by the remanufacturing unit = (48 * 100) + (16*100) + (25*100) = 8900. This exactly matches the total working hours needed for each period as computed by lingo. Therefore, the logic of equation 8 is verified and its corresponding output is validated.

6. **Verification of constraint 9 and constraint 18**

According to LINGO output, W (1) = W (2) = W (3) = 51. Since the total number of working hours needed by the remanufacturing unit in each period = 8900, and the number of working hours available in each period = 176, the total number of workers needed per period is >= 8900/176 >=50.56 = 51 labor. This exactly matched the number computed by lingo. Therefore, the logic of equation 9 is verified and its corresponding output is validated. Also, rounding up the number from 50.56 to 51 satisfies the integrity constraint of equation 18.

7. **Verification of constraint 10**

According to LINGO output, W_HIRE (1)= 6, while W_HIRE (2)= W_HIRE (3)= 0. According to LINGO output, W_FIRE (1) = W_FIRE (2) = W_FIRE (3) = 0. Since the total number of workers needed per period = 51 labor, while the available in period 1 = 45, then the number of labors needed to be hired in period 1 = 51 needed - 45 available = 6 workers. Thus, there is no need for extra hire or fire in either period 2 or 3. This exactly matches the number computed by LINGO. Therefore, the logic of equation 10 is verified and its corresponding output is validated.

Work force planning constraints concluding remark

According to 5, 6, and 7, the Work force planning constraints are verified.

8. **Verification of constraint 14, 15, 16, and 17**

According to LINGO output, All Y (i, t) = 0, and All Z (M, t) = 0. Some or all of the binary variables Y(i, t) , Z(M, t) would be equal to 1 only if the recycling operation is assigned to any item. Since there is no item assigned to recycling operation in that run. Therefore, part of the binary variables functions is verified. The other part of this function would be verified in run 2, which involves the assignment of recycling operation to many items.

G.2 Summary of the Verification Run 2

G.2.1 Experimental data adjustment for verification Run2

For the good physical condition trailer, the difference between the revenue results from selling the remanufactured semi-trailer and the costs consumed in such remanufacturing operation was settled to be a negative value. Also, make this difference a negative value for refurbishing. This is done to direct the decision toward assigning the entire 100 good condition trailers toward disassembly operation. For the bad physical condition trailer, the difference between the revenue results from cannibalizing the trailer and costs consumed in the cannibalizing operation was settled to be higher than such difference in case of recycling operations.

The settled data were used to assure that all the trailers in good condition were assigned to the most profitable operation, which is disassembly for such data. It is used also to assure that all the trailers in bad condition assigned to the most profitable operation, which, is cannibalization for such data. The settled data were also used to test the accuracy of equations 5, 6, and 7. The settled data were aimed of allowing the assignment of items to recycling operation; hence, the right functionality of recycling constraints could be tested.

G2.2 LINGO output summary of Run2

Run 2 details summary is shown in table G.3, while the nonzero decisions variables are summarized in table G.4

Table G.3 shows the details of run 2

Model class	ILP
Generator Memory used	114 K
State	Global Optimum
Objective Value	4234520
Solver Type	Branch and Bound
Iterations	11631061
Total Variables	257
Integers	225
Constraints	330

G.2.3 Non-zeros decision variables output summary of Run 2

Table G.4 shows the summary of non-zeros decision variables values of run 2

Decision Variable	Value
Q(1, 1) = Q(1, 2) = Q(1, 3) =	300
X (1, 1, 1) = X (1, 1, 2) = X (1, 1, 3) =	100
X (1, 4, 1) = X (1, 4, 2) = X (1, 4, 3) =	100
X (1, 5, 1) = X (1, 5, 2) = X (1, 5, 3) =	100
X(2, 6, 1) = X(2, 6, 2) = X(2, 6, 3) =	100
X(3, 2, 1) = X(3, 2, 2) = X(3, 2, 3) =	6
X(3, 4, 1) = X(3, 4, 2) = X(3, 4, 3) =	294
X(4, 2, 1) = X(4, 2, 2) = X(4, 2, 3) =	100
X(5, 2, 1) = X(5, 2, 2) = X(5, 2, 3) =	400
X(6, 1, 1) =	1296
X(6, 2, 1) =	4
X(6, 1, 2) = X(6, 1, 3) =	1300
X(12, 6, 1) = X(12, 6, 2) = X(12, 6, 3) =	1288
X(12, 7, 1) =	8
X(12, 7, 2) = X(12, 7, 3) =	12
X(13, 6, 1) = X(13, 6, 2) = X(13, 6, 3) =	1296
X(13, 7, 2) = X(13, 7, 3) =	4
LL (1) = LL (2) = LL (3) =	13016
W(1) = W(2) = W(3) =	74
W_HIRE(1)=	29
W_HIRE(2)= W_HIRE(3)=	0
W_FIRE (1)= W_FIRE (2)= W_FIRE (3)=	0
Y (2, 1) = Y (2, 2) = Y (2, 3) =	1
Y (12, 1) = Y (12, 2) = Y (12, 3) =	1
Y (13, 1) = Y (13, 2) = Y (13, 3) =	1
Z(3, 1) = Z(3, 2) = Z(3, 3) =	1
Z(7, 1) = Z(7, 2) = Z(7, 3) =	1
Z(8, 1) = Z(8, 2) = Z(8, 3) =	1

G.2.4 Run 2 results and verification

The non-zero decision variables of Run2 were analyzed in the following points to verify and validate the formulated model

1. **Verification of constraint 1**

According to LINGO output, Q (1, 1) = Q (1, 2) = Q (1, 3) = 300. Since 100 Good trailers + 100 Intermediate trailers + 100 Bad trailers = 300, then the logic of computing the decision variable Q (i, t), which is represented by equation 1, matches the number computed by LINGO in the 3 planning periods. Therefore, equation 1 is verified and validated.

2. **Verification of constraint 2**

According to LINGO output, X (1, 1, 1) = X (1, 1, 2) = X (1, 1, 3) = 100. This shows that all good trailers are assigned to disassembly operation. No trailer was assigned to refurbishing or remanufacturing because disassembly was shown to be more profitable than refurbishing and remanufacturing in the three periods.

3. **Verification of constraint 3**

According to LINGO output, X (1, 4, 1) = X (1, 4, 2) = X (1, 4, 3) = 100.This shows that all intermediate trailers are assigned to repairing operation in the three periods.

4. **Verification of constraint 4**

According to LINGO output, X (1, 5, 1) = X (1, 5, 2) = X (1, 5, 3) = 100. This shows that all bad trailers are assigned to cannibalization operation. No trailer is assigned to recycling in the three periods because cannibalization is more profitable than recycling.

5. **Verification of constraint 5 and constraint 6**

According to LINGO output, X (2, 6, 1) = X (2, 6, 2) = X (2, 6, 3) = 100. Since there is one triangle of rotation present in each trailer, the disassembly of 100 trailer must yield one triangle of rotation * 100 trailers = 100 triangles of rotation. All the 100 triangles of rotation are assigned to operation 6, which is recycling in the 3 planning periods, because they are technically feasible to process by recycling. Therefore the logic of equations 5 and 6 are verified.

6. **Verification of constraints 5, 6, and 7**

According to LINGO output, X (3, 4, 1) = X (3, 4, 2) = X (3, 4, 3) = 294, and X (3, 2, 1) = X (3, 2, 2) = X (3, 2, 3) = 6. This implies that the summation of X (3, 4, 1) and X (3, 2, 1) = 300, the same for period 2 and 3. Since there are 3 Axle & Wheel assemblies present in each trailer, the disassembly of 100 trailers must yield 3 Axle & Wheel assemblies * 100 trailers = 300 Axles & Wheel assemblies. 294 Axle & Wheel assemblies are assigned to operation 4, which is repairing, while the remaining 6 Axle & Wheel assemblies are assigned to operation 2, which is refurbishing in the 3 planning periods. They are assigned to refurbishing as well as repairing because they are technically feasible to be processed by these operations. Most of these Axle & Wheel assemblies are assigned to repairing because it is more profitable than refurbishing. Therefore, the logic of equations 5, 6, and 7 are verified. Moreover, the first objective function logic of maximizing the profit through assigning items to the most proposed profitable operations is verified.

7. **Verification of constraint 5 and 6**

According to LINGO output, X (4, 2, 1) = X (4, 2, 2) = X (4, 2, 3) = 100. Since there is 1 Steel Structure present in each trailer, the disassembly of 100 trailer must yields 1 Steel Structure * 100 trailer = 100 Steel Structures. All the 100 Steel Structure are assigned to operation 2 which is refurbishing in the 3 planning periods because they are technically feasible to process by refurbishing and more profitable to be assigned to this operation than any other proposed operation. Therefore, the logic of equations 5 and 6 are verified.

8. Verification of constraint 5 and 6

According to LINGO output, X (5, 2, 1) = X (5, 2, 2) = X (5, 2, 3) = 400. Since there are 4 Suspension assemblies present in each trailer, the disassembly of 100 trailer must yields 4 Suspension * 100 trailer = 400 Suspension assemblies. All the 400 suspension assemblies are assigned to operation 2 which is refurbishing in the 3 planning periods because they are technically feasible to process by refurbishing and more profitable to be refurbished than being assigned to any other operation. Therefore the logic of equations 5 and 6 are verified

9. Verification of constraint 5 , 6, and 7

According to LINGO output, X (6, 1, 1) = X (6, 1, 3) = 1300. While X (6, 1, 2) = 1296, and X (6, 2, 2) = 4. Since there are 13 Tyre and Rim assemblies present in each trailer, the disassembly of 100 trailer must yields 13 Tyre and Rim * 100 trailer = 1300 Tyre and Rim assemblies. 1296 Tyre and Rim assemblies are assigned to operation 1, which is disassembly, while the remaining 4 are assigned to operation 2, which is refurbishing in period 2. They are assigned to disassembly as well as refurbishing because they are technically feasible to be processes by these operations. Most of these Tyre and Rim are assigned to disassembly because it is more profitable than refurbishing. The 1300 Tyre and Rim are assigned to disassembly in period 1 and 3 because it is the most profitable operation. None of these Tyre and Rim is assigned to repairing because it is the least profitable operation. Therefore the logic of equations 5, 6, and 7 are verified. Moreover, the first objective function logic of maximizing the profit through assigning Tyre and Rim assembly to the most proposed profitable operations is verified.

10. Verification of constraint 5, 6, and 7

According to LINGO output, X (12, 6, 1) =1288, and X (12, 7, 1) =12. This implies that the summation of X (12, 6, 1) and X (12, 7, 1) = 1300, since there are 1 tyre present in each Tyre and rim assembly. Hence, the disassembly of 1300 Tyre and rim assemblies must yields 1 tyre *

1300 Tyre and rim assemblies = 1300 tyre. 1288 Tyre are assigned to recycling while the remaining 12 are assigned to disposal. Therefore the logic of equations 5, 6, and 7 are verified.

11. Verification of constraint 5, 6, and 7

According to LINGO output, X (13, 6, 1) =1296, and X (13, 7, 1) =12. This implies that the summation of X (13, 6, 1) and X (13, 7, 1) = 1300. Since there is 1 rim present in each Tyre and rim assembly, the disassembly of 1300 Tyre and rim assemblies must yields 1 Rim * 1300 Tyre and rim assemblies = 1300 rims. 1288 rims are assigned to recycling while the remaining 12 are assigned to disposal. Therefore the logic of equations 5, 6, and 7 are verified.

Operations selection constraints concluding remark

According to 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 , all the operation selection constraints are verified and it was proven that their logic supports the target of maximizing the profit through assigning items to the most proposed profitable operations.

12. Verification of constraint 8

According to LINGO output, LL (1) = 13016. Since disassembling one trailer consumes 20 hours, repairing one trailer consumes 16 hours, and cannibalizing one trailer consumes 25 hours. Since, recycling one triangle of rotation consumes 0.05 hour, refurbishing one Axle & wheel consume 2 hours, and repairing one Axle & wheel consume 12 hours. Since, refurbishing one steel structure or one suspension consumes 4 hours. Since, dissembling one tyre and rim assembly consumes 1 hour. Since, recycling 1 tyre consumes 0.035 hours, and recycling 1 rim consumes 0.02 hours. Therefore, the total recovery hours needed by the remanufacturing unit =

$$(20 * 100) + (16*100) + (25*100) + (0.05 * 100) + (2* 6) + (12 * 294) + (4* 100) + (4 * 400) + (1 * 1300) + (0.035 * 1288) + (0.02 * 1296) =$$

2000 + 1600 + 2500 + 5 + 12 + 3528 + 400 + 1600 + 1300 + 45.08 + 25.9 = 13016. This is exactly matched the total working hours needed for period 1 as computed by LINGO. Therefore, equation 8 is verified and its corresponding output is validated.

13. Verification of constraint 9 and constraint 18

According to LINGO output, W(1) = W(2) = W(3) = 74 . Since the total number of hours needed by the remanufacturing unit in each period = 13016, and the number of working hours available in each period = 176. Therefore, the total number of workers needed per period is >= 13016/176 >=73.95 = 74 labor. This matches the number computed by LINGO. Therefore, equation 9 is verified and validated. Also, rounding up the number from 73.95 to 74 this satisfies the integrity constraint related equation 18

14. Verification of constraint 10

According to LINGO output, W_HIRE(1)= 29 , while W_HIRE(2)= W_HIRE(3)= 0 . W_FIRE (1) = W_FIRE (2) = W_FIRE (3) = 0 . Since, the total number of workers needed per period = 74 labor, While the available in period 1 = 45, then the number of labors needed to be hired in period 1 = 74 needed - 45 available = 29. Thus, there is no need for extra hire or fire in either period 2 or 3. This exactly matches the number computed by LINGO. Therefore, the logic of equation 10 is verified, and its corresponding output is validated.

Work force planning constraints concluding remark

According to 12, 13, and 14, the Work force planning constraints are verified.

15. Verification of constraint 14 and constraint 15

According to LINGO output, Y (2, 1) = Y (2, 2) = Y (2, 3) = 1, Y (12, 1) = Y (12, 2) = Y (12, 3) = 1, and Y (13, 1) = Y (13, 2) = Y (13, 3) = 1. Since the binary variable Y (i, t) equal 1 if item I assigned to recycling operation, 0 otherwise. Since item 2, 12, and 13 are assigned to recycling operation in period 1, 2, and 3. Therefore, the logic of equations 14, and 15 is verified.

16. Verification of constraint 16 and constraint 17

According to LINGO output, Z (3, 1) = Z (3, 2) = Z (3, 3) = 1, Z(7, 1) = Z(7, 2) = Z(7, 3) =1 , and Z(8, 1) = Z(8, 2) = Z(8, 3) =1. Since the binary variable Z (m, t) equal 1 if the recycling operation is applied on any item to obtain material m, 0 otherwise. Since item 2 is made from material 3 and assigned to recycling operation. Since, item 12 is made from material 8 and assigned to recycling operation. Since, item 13 is made from material 7 and assigned to recycling operation. Therefore, the logic of equations 16 , and 17 is verified.

17. Verification of constraint 13

Since the unit weight of triangle of rotation is 50 kg, the unit weight of tyre is 35kg, and the unit weight of rim is 20 kg. Therefore, the total weight of 100 triangle of rotation is 5000 kg which exceed the minimum weight of material 3 that could be acquired by the merchant. This the main reason beyond the assignment of all triangle of rotation to recycling operation. Consequently, tyres and rims are assigned to recycling for the same reason. Therefore, the logic of equation 13 is verified.

Recycled material minimum weight constraints concluding remark According to 15, 16, and 17 the Recycled material minimum weight constraints are proved its accuracy and are verified