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Performance Evaluation of a Reverse Logistics Enterprise - An Agent-Based Modelling Approach

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Performance Evaluation of a Reverse Logistics Enterprise – An Agent-Based Modelling Approach

By

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ABSTRACT

Reverse Logistics (RL) has been applied in many industries and sectors ever since its conception. Unlike Forward Logistics retracing consumer goods from the point of consumption to the point of inception is not a well-studied process. It involves many uncertainties such as time, quality and quantity of return. It is important to address these uncertainties to meet the economic, ecological and social challenges. The returned products can be remanufactured, can have parts harvested, or can be disposed safely. It is important to implement these activities in a cost-effective manner. The aim of this research is to measure the performance of the RL enterprise with the help of an Agent-based Modeling technique. The major entities in the RL network are considered as Agents that can act independently. There are several different agents: Collector Agent, Sorting-Cum-Reuse Agent, Remanufacturing Agent, Recycler Agent, Supplier Agent, and Distributor Agent. The individual performances of each agent are measured and recommendations are given to improve their performance, leading to the enhancement of the total performance of the RL enterprise. The solution approach is applied to a case study involving cell-phone remanufacturing.

DEDICATION

Dedicated to my late Grandmother, Jothi, who always taught me to be brave at heart and never give up on any life’s ventures.

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LIST OF ABBREVIATIONS/ ACRONYMS/ INITIALISMS

5R1P (Recovery operations) – Reuse, Remanufacture/ Refurbish, Repair, Recondition, Recycle, and Parts Harvest

AHP- Analytical Hierarchy Process

ANP- Analytical Network Process

APRA- Automotive Parts Remanufacturers Association

BSC- Balance Score Card

CA- Collector Agent

CWTA – Canadian Wireless Telecommunication Association

DA- Distributor Agent

DEMATEL- Decision-Making Trial and Evaluation Laboratory

EES – Ecology, Economy and Social

GPS- Global Positioning System

IR- Independent Recyclers

IDS- Interconnected Database System

LAN- Local Area Network

LPP- Linear Physical Programming

OEM- Original Equipment Manufacturer

OES- Ontario Electronics Stewardship

PET - Polyethylene terephthalate

PDA- Personal Digital Assistant

QFD- Quality Function Deployment

RCA- Recycling Agent

RI- Remanufactured Inventory

RMA- Remanufacturing Agent

RMC – Recycle My Cell,

SA- Supplier Agent

SCRA- Sorting-Cum-Reuse Agent

SMS- Short Message Service

USEPA- The United States Environment Protection Agency

WDA- Waste Diversion Ontario

WEEE- Waste Electrical and Electronic Equipment Directive

WIP- Work-in-process

CHAPTER 1

INTRODUCTION

1.1 Research Preface:

The evolution of electronic products has been constantly transforming people's lives. Over the years, systems have become less cumbersome and processes have become much more simple and effective. From the first communication device, the papyrus, to the latest cell phone, technology and electronic products have played an important role in revolutionizing people's way of living. In the year 2012, the computer and electronics manufacturing sector contributed nearly $6.8 billion to Canada's GDP (Government of Canada, 2013). The revenue generated from home electronics, computer and camera sales in the same year was nearly $6.8 billion in Canada (Government of Canada, 2014). The numbers show the significance of computer and electronic products.

Electronic products are being used extensively as integral devices in day-to-day life. They are looked after carefully when in use, they should receive the same care once they become obsolete. Old electronic products can be reused or recycled instead of being disposed of in landfills. There are interesting recovery options: resale, remanufacturing or refurbishing, repair, reconditioning, parts harvesting and recycling (Kara et al., 2007). In addition, a used electronic product consists of precious minerals and parts that can be reused in new parts or products manufacturing. According to the Automotive Parts Remanufacturers Association (APRA), all the recovered materials around the globe can fill up to 155,000 railroad cars annually (Rogers and Tibben-Lembke, 1999). The various recovery options have noteworthy benefits for nature as well. First, a used product can be kept away from a landfill and, second, the materials from a used product can be reused, and valuable virgin materials (fresh raw materials) can be preserved for the future generations. Therefore, a used product can generate profit from various recovery options and, at the same time, save the planet earth from toxic waste.

The process of handling, managing and moving a used product from the customer to a recovery stage is a challenge. Reverse Logistics (RL) studies the movement of products from the point of consumption to the point of origin. RL focuses on planning, controlling and implementing an efficient and cost-effective process to recapture the residual value from a used product or dispose of a used product safely without affecting the environment. Concisely put, Forward Logistics (FL) focuses on the movement of goods from a point of origin to a point of consumption, whereas RL focuses on the movement of used goods from a point of consumption to a point of origin with the purpose to reuse or recycle the used goods (Rogers and Tibben-Lembke, 1999).

Normally, in an RL system, there are many departments or sub-systems that work together to control the outcome of the company or system. Some of the major departments or sub-systems commonly present in an RL system are the collectors, sorters, remanufacturers or refurbishers, recyclers, suppliers, and distributors. Used products flow through each one of these departments, undergo the required operation and are either sold back in the market by the process of remanufacturing or reduced to their material level by the process of recycling.

There are three major reasons for a remanufacturer or manufacturer to collect used electronic products for reuse or recycle: (i) the product take-back laws imposed by governmental or environmental organizations like Waste Electrical and Electronic Equipment (WEEE) directive on the Original Equipment Manufacturers (OEM), so they take responsibility to collect used products and keep the environment clean; (ii) the profit that can be generated by reusing or recovering material; and (iii) the importance of falling under the banner of an environmentally conscious company (Rajagopalan and Yellepeddi, 2007; Xiong and Li, 2010; Zhang et al., 2013). These motives encompass the necessity for a company to include RL activities in its profile to seize the ecological, economic and social advantage from reusing or recycling a used product. The three advantages, ecological, economical and social will be termed as "EES" throughout this research.

The other grounds to return a product are these: (i) 14-day return policy; (ii) defective part or product; (iii) warranty requirements; (iv) shipment of the wrong item; and (v) product recalls (Meade and Sarkis, 2002; Xiong and Li, 2010). In Canada and the U.S., remanufacturing industries are active in 125 different product categories at least (Lund, 2012). The most common devices returned are these: laptops, computers, cell phones, toner cartridges, televisions, network devices, and single-use cameras.

Electronic goods are present in almost every North American household in the 21st century, with the cell phone becoming one of the most revolutionary, and new models coming at a more frequent pace than they were a few years ago. The total number of cell phone subscribers in Canada is 27.6 million (CWTA, 2013a), with a total population of 35.2 million as of December 2013 (S. C. Government of Canada, 2013). The number of phones is estimated to be even more since some of the older phones are kept in storage and are not currently in use. In Canada, the average life span of a cell phone in the year 2012 was 22 months, which decreased from 25 months in 2010 (CWTA, 2013b). As the number of new model cell phones arriving in the market increases and as the life span of cell phones is starting to decrease, the number of cell phones becoming obsolete every day increases. In the year 2013, Recycle My Cell (RMC), with other recycling initiatives, recovered 1,067,266 cell phones for either remanufacturing or recycling in Canada (CWTA, 2014). It is important to collect these phones in an efficient manner, and remanufacture for profit or recycle to keep the environment clean.

First challenge involved in the return process is to collect a retired electronic product as quickly as possible, since it can become obsolete very soon because of a diminishing market demand for the used product or out-of-date material or technology (Yellepeddi, 2007). In order to thwart a product from becoming obsolete, recyclers need to collect a used product promptly and make sure it does not sit idly in storage after becoming old (Rajagopalan and Yellepeddi, 2007). The second is to collect a product through the correct channel and not let it slip away in a landfill (Olugu et al., 2011). It is vital that the co-operation and communication between the customers, collectors, and recyclers increase to overcome some of the challenges in the reverse flow of products.

In addition, the returned products depend on a customer's preferences. For example, a customer may have a different time of return or different quality of return or different quantity of return when compared to other customers. Unknown information about time, quality and quantity of return can affect the remanufacturing process, since remanufacturers may take varying time to remanufacture a product depending on the level of damage (quality), number of returns (quantity) and the time of return. Therefore, RL, unlike its counterpart, has been faced with many uncertainties over the last few years (Yellepeddi, 2007). Many scholars and researchers have shared their views in remedying the losses caused by these uncertainties. The problem has a high stack in the literature since the outcome of not addressing the uncertainties is unimaginable in terms of cost and time.

In order to surmount the challenges, the uncertainty problems, and the EES advantages pertaining to RL, the RL group should understand how the system operates and performs. A system needs to perform to its expectations (Yellepeddi, 2007) and have an efficient process (Xiong and Li, 2010). To achieve the above requisites RL managers must measure the performance of the system.

This research is aimed at measuring the performance of an RL enterprise. The method used to measure the performance is called an agent-based modeling technique. Generally, remanufacturing or refurbishing an electronic product involves six entities: collector, sorter, refurbisher, recycler, supplier and distributor. Each of these is considered a separate agent with a unique behavior and objective. The performance of each agent is measured, and recommendations for improvement are provided for each of them. This leads to the total performance improvement of the RL system. The measurement of performance of each individual agent also provides recommendations to mitigate the problems regarding uncertainty, to overcome the common challenges, and to help to achieve the EES advantages.

The main reason to consider the agent-based modelling technique over other modelling techniques is the ability to model each company in the RL system independently with a unique behaviour and objective. This would help companies to take actions and make decisions on their own, work together with the other companies, and contribute to the goals of the total RL system successfully. The second major reason is the possibility to measure the performance of each company separately and the total system performance at one time collectively. Other techniques would be able to measure the performance of the entire system or each company's performance. With the advantage of the agent-based modelling technique, the shortcomings of each individual company can be easily identified and improved. By improving the performance of each individual company, the total RL system ultimately could be improved.

1.2 Research Objective:

The objectives of this thesis are to measure successfully the performance of a reverse logistics enterprise using the agent-based modelling technique at an operational level, to develop a generic agent-based decision-making model for the electronics remanufacturing industry, to provide recommendations to pacify the problems related to uncertainty, to overcome the common challenges, and to achieve the EES advantages in RL.

The objectives will be achieved by:

1. developing a generic:
    - (i) decision-making model that includes the actions, decisions and objectives of each agent in an RL system, and
    - (ii) RL process flow for electronic products;
2. measuring the performance of an RL enterprise using the agent-based modeling technique, and providing recommendations for each agent to improve its performance, ultimately leading to the improvement of the total RL performance;
3. using cell phone remanufacturing industry as an example;
4. using agent-based simulation model;
5. providing recommendations

(i) to solve the three problems related to uncertainty:

   a. Quality of return,

   b. Quantity of return and

   c. Time of return,

(ii) to overcome the common challenges in RL, and

(iii) to achieve the ecological, economical and social advantages in RL.

The research will also help to:

1. achieve a cost-effective RL process;
2. measure the profit generated from
   (i) remanufacturing or refurbishing an electronic product,
   (ii) parts harvesting and
   (iii) material recovery;
3. show the environmental benefits of remanufacturing or refurbishing an electronic product with focus on
   (i) pollution controlled,
   (ii) energy saved,
   (iii) virgin material saved, and
   (iv) tons/number of used products saved and kept away from landfill.

1.3 Research Scope:

Logistics and Supply Chain Management (SCM) is a huge umbrella; there are many fields enclosed in it. First, logistics can be divided into Forward Logistics (FL) and Reverse Logistics (RL). Similarly, SCM encompasses Forward Supply Chain (FSC), Reverse Supply Chain (RSC), and Closed-Loop Supply Chain (CLSC). In this research, concepts and literature from RSC and CLSC are included to support RL, but the main focus is on RL as depicted in Figure 1.

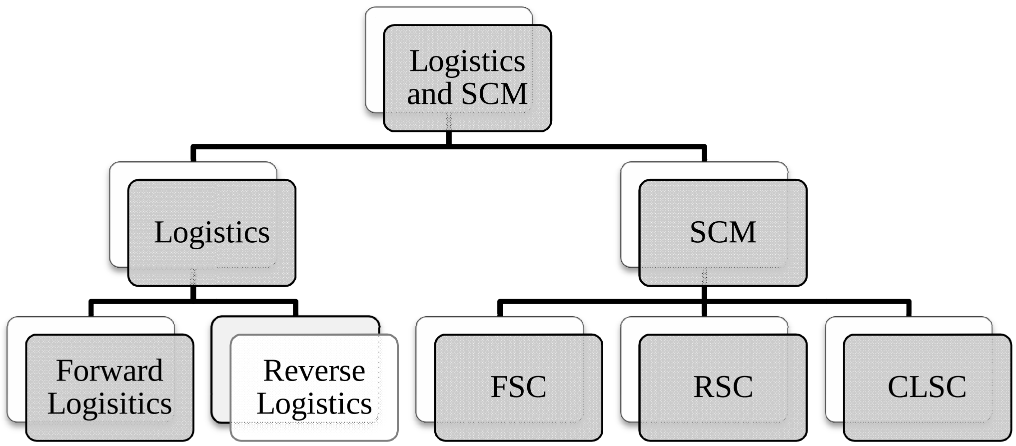


Figure 1: Scope of research

In general, decision making process takes place at three levels of management: strategic, tactical and operational. The performance of a system can be measured at all the three levels. In this research, the performance measurement will be focused at the operational level of management. Tactical and strategic level performance measures are not covered. The prime reason is the necessity to find solutions to the three uncertainties in reverse logistics. By focusing and measuring the performance at the operational level, recommendations for improvement and ways to address the three uncertainties can be provided more concisely since the time, quantity and quality can be reasonably studied easily at the operational level.

A product can have several recovery options, among them: reuse, remanufacturing or refurbishing, repair, refilling, reconditioning, part harvesting and recycling are only considered in this research. The focus of this research is mainly on the Canadian market. Input data from published articles are used, and the output results are studied with focus on Canada. The datum in the model is within the years ranging from 2000 to 2013. In Canada, there may be several companies practising remanufacturing, but in the simulation model, the performance is measured only for one company. Also, the input parameter, the total number of products returned in a year is for the entire nation but the results are based on only one company.

The industry sector tackled in this research is the electronics remanufacturing industry. First reason is, in consumer electronics sector of all the products sold, 4-5% of the products are retuned (Rogers and Tibben-Lembke, 1999). Second, the revenue that can be generated from remanufacturing or recycling electronic products is enormous. Third, the after-effect of disposing electronic devices in a landfill is dangerous. And finally, electronic products become obsolete very soon due to rapid growth in technology. It is therefore imperative to give attention to the electronics industry, collect the products effectively, remanufacture or recycle them and protect the planet earth from unnecessary wastes.

1.4 Research Approach:

The approach adapted for this research is a general research approach. In the beginning, the topic to work on is narrowed down to performance evaluation of a RL system at the operational level. Then a deep review of the literature on the topic is done to familiarize with the concepts, and to gain knowledge about previously published works. In the next step, the research is set forth to identify a gap or problem in the field. By a detailed study, the gap and problem in the literature are identified. Later, a method to solve the problem is recognised. Agent-based modelling approach is chosen as the appropriate method. The methodology is thoroughly studied to solve the problem at hand.

Interviews were then conducted with remanufacturing industry experts, to mould the model to a real world situation. A simulation model is then created using the agent-based modelling technique and with the help of the simulation software package ProModel 7.5. In the next stage, the important performance measures are selected. The model is then analysed and the output results are calculated. Based on the results, recommendations are provided to improve the system. This research approach helps to fill the gap, achieve the required research objective indicated earlier, and contribute to the RL field successfully.

A brief summary of the approach, method and tool used for this research are provided in Table 1. Also, the research steps are depicted in Figure 2.

Table 1: Summary of research approach

Criteria	**Present Research**
Performance measurement approach	Agent-based modelling technique
Decision making process approach	Agent-based decision-making model
Tool	Simulation
Simulation approach	Agent-based simulation
Software	ProModel version 7.5
Level of Management	Operational level

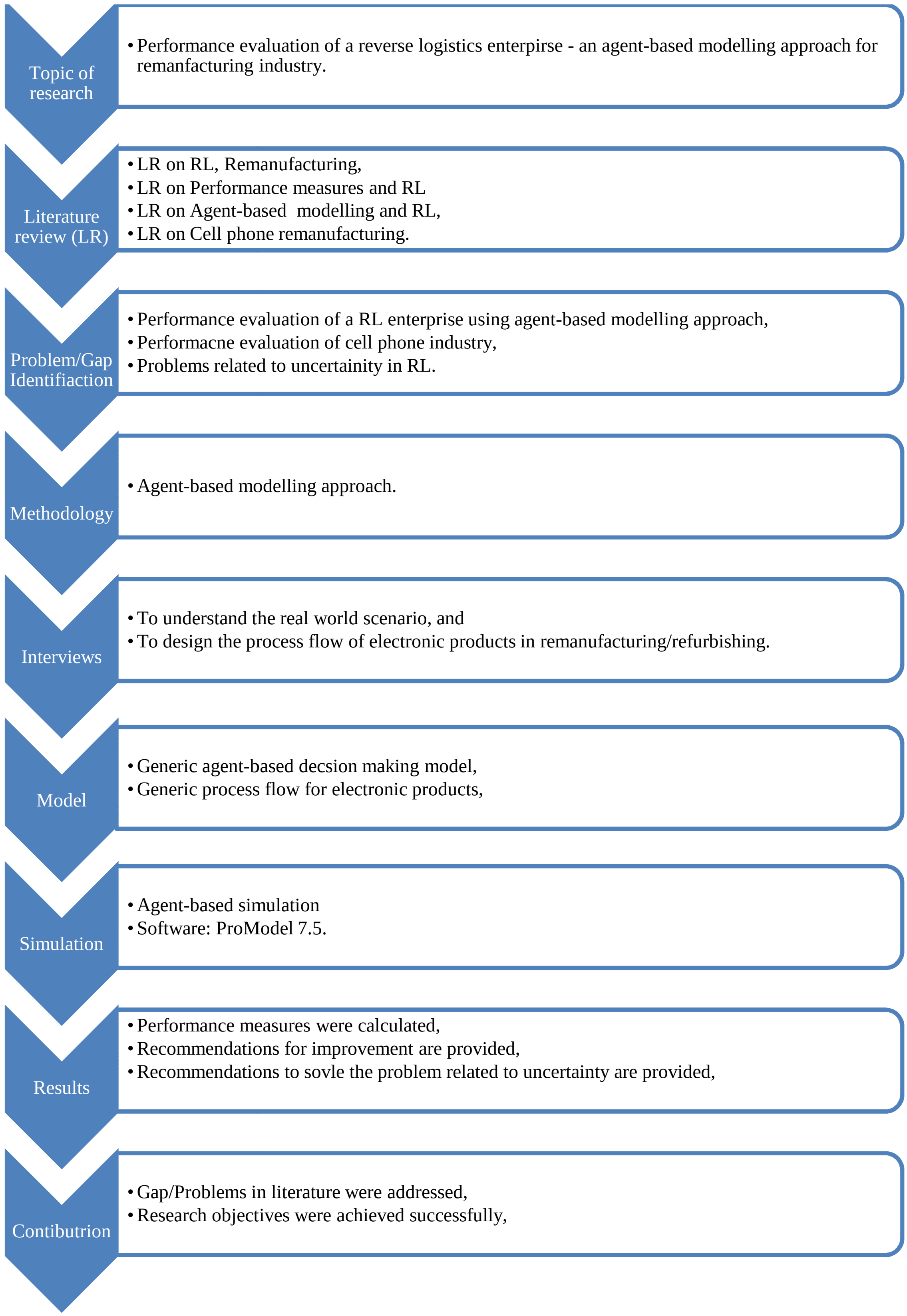


Figure 2: Research Approach

1.5 Research Organisation:

The remainder of the thesis begins with the research background in chapter 2. Background information about RL and the different recovery operations are provided. Chapter 3 presents a review of the RL literature and previously published methods for evaluating the performance of an RL enterprise. Chapter 4 provides the problem statement of this research. Chapter 5 presents the research methodology and the method used in this research along with the generic RL process flow and decision making process. Chapter 6 outlines the case study on cell phone remanufacturing process with the help of product structure, remanufacturing process, RL process flow, decision making process, experiments and experiment analysis. Based on the case study results and discussion an interconnected database system for RL system improvement is presented in chapter 7. Chapter 8 presents the conclusion and future work of this research.

CHAPTER 2

RESEARCH BACKGROUND

This chapter will throw some light on Reverse Logistics and the practices that are involved in RL. Background information pertaining to this research will be covered in this section. The topics will include: RL and the different types of recovery options.

2.1 Reverse Logistics:

RL, as previously enlightened in the introductory section, is a field of logistics that focuses on the movement of goods in the reverse direction. Rogers and Tibben-Lembke, (1999) coined the definition of RL as, *"the process of planning, implementing, and controlling the efficient, cost effective flow of materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal"*.

The starting period of RL is quite unclear, but the RL activities have been in practice ever since the inception of the Industrial Revolution (circa 1760). Though the name of practice was not widespread at the beginning, it gradually became an epoch-making activity. In the starting stages, metallic parts were collected and melted to recover material from it (Dyckhoff et al., 2004). Later, during the era of World War II, the concept of remanufacturing had stepped in, countries at war had dedicated all their automobile manufacturing floors to manufacture military equipments, this left the public with no option but to remanufacture existing automobiles and reuse them (Ilgin and Gupta, 2012).

The field soon gained a firm grip during the 1980's and 90's, when strict environment legislations came into place. These legislations enforced OEM to collect and dispose used products safely without affecting the environment (Dyckhoff et al., 2004). It was the verge of this stage when the RL became famous and renowned. Soon scholars began to contribute to the field and study about RL which led to the establishment of Reverse

Logistics literature. RL has now become an integral part of study in engineering and management that focuses on applying techniques and methods to achieve an effective and cost-efficient RL process flow.

A typical RL process flow of a product would involve the activities of collection, sorting, remanufacturing or refurbishing, recycling and distributing. A comprehensive process flow diagram enveloping all components involved in the FSC or FL, the RSC or RL and the CLSC, are depicted in Figure 3 below. The continuous lines denote the products flow in the FL, the dotted lines depict the products flow in the RL, and a combination of dashed & dotted lines along with continuous and dotted lines denote the products flow in a CLSC.

In FL, at the first step, materials are extracted from the resources present in the earth's crust. The extracted materials are then processed and taken to part manufacturing stage. From this stage, the manufactured parts move either to the product manufacturing stage or sold in the spare parts market depending on the requirement. The parts that arrive at the product manufacturing stage are assembled together to form the product. The product once assembled moves to the product inventory stage and later to the distribution centre. The products are then sold to the customers and the product begins its life in the utilisation phase.

Once a product becomes old or is returned due to any of the major reasons as mentioned in the introductory section, it is collected for either reprocessing or recycling. The product is then sorted based on its quality and inspected for basic operating conditions. Based on the quality, they are classified into good, moderate and bad categories. The good products are sent to the reuse stage, and can be reused as it is or with minimal repair operations. The product is labelled as a refurbished product and sent to the remanufactured products inventory. The moderate products are disassembled for detailed inspection and then remanufactured or parts harvested based on the condition (detail explanation of the remanufacturing operation will be provided in the next section: *2.2 Recovery Options*). The product once remanufactured is labelled as a remanufactured product and is forwarded to the remanufactured inventory stage. The remanufactured or refurbished products from this stage are later sent to the distribution centres and sold to the customers to begin its life again in the utilization phase.

Similarly the bad products (products that cannot be reused) are sent to the material recovery stage. The recovered materials are sold to the raw material extractors or the parts manufacturing companies. In the case of closing the supply chain, there are three ways. The first way is at the disassembly stage in the RSC, where the partly disassembled product can be sent to the final assembly stage in the FSC. The partly disassembled product still undergoes the remanufacturing operations but in the FSC. They are then sold as new or remanufactured product, this process can be found especially in the automobile parts manufacturing sector. The second way of closing the loop is from the parts harvesting stage in the RSC; the parts that are good and can be used in a new product assembly with minimal cleaning operation are harvested and sent to the final assembly stage of the FSC. The manufactures are not constrained to assemble the product with these parts but at times of shortage or negligible quality difference between the new and harvested part, the harvested parts can be handy.

The third way to close the chain is by sending the recovered material in the RSC to the parts manufacturing stage in the FSC. Since the recovered material is almost same in quality with a new material, recycled material can be combined with the new material to manufacture a part. This saves a lot of energy that would otherwise be used for material extraction and also saves virgin materials from being exploited. Thus, in these three ways the supply chain can be closed, this is termed as closed loop supply chain. The three ways are depicted with dashed & dotted lines in Figure 3.

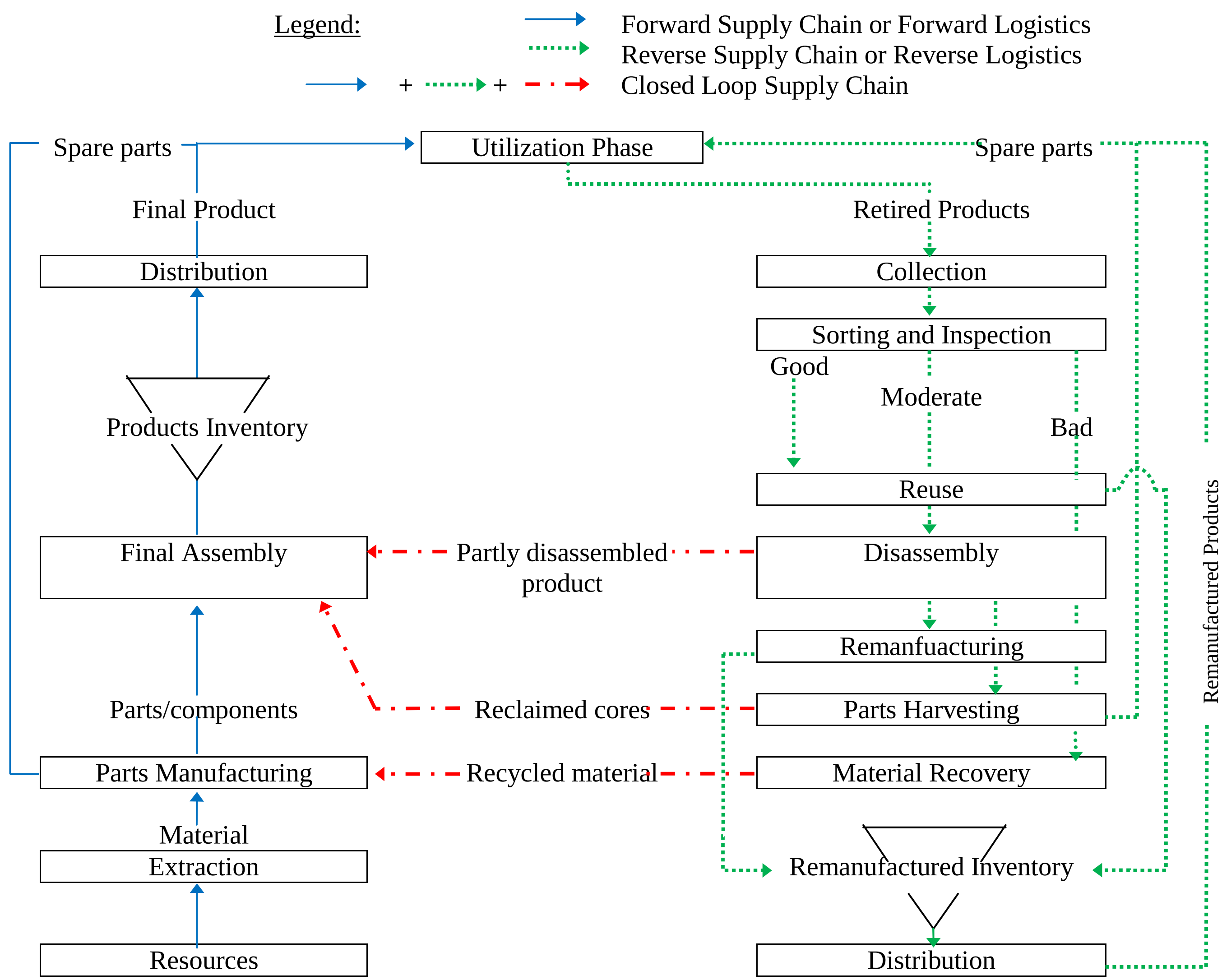


Figure 3: Process flow of a product in a FL, RL and CLSC (Adapted from Lebreton, 2007).

RL is not quite an easy process, it involves 12 times more transactions than FL (Rajagopalan and Yellepeddi, 2007). Across all industries, return percentages varies from 5-50% (Li and Olorunniwo, 2008). The cost of returns is also high, in the year 2001, the cost for returns were 2 or 3 times more than the product value (Li and Olorunniwo, 2008). Having a challenging scenario with increased returns, high cost involved and precious value in the returns, it is important to have an efficient and cost effective process. RL takes the sole responsibility in setting up the platform for a successful practice.

To summarize the important features of RL, a dimensional framework of RL adapted from Dyckhoff et al., (2004) will be used as shown in Figure 4. The dimensions that will be included are these: motivation for RL, reasons for returns, types of returns, challenges in RL, problems related to uncertainty in RL, types of recovery options, level of recovery, and actors in RL.

2.2 Recovery Options:

In general, a product is composed of several parts. If a product is returned due to any of the aforesaid reasons in the introduction section (see page 3), the entire product cannot be considered as obsolete; only according to the user, the product has elapsed its time period or has become non-functional, but from the engineering perspective, the parts inside the product and the material in it are not outmoded; they may be still alive functionally or might have material value. Of all the returned products, 75% of them are not defective (Li and Olorunniwo, 2008). The product can be diagnosed with simple repair operations to bring it back to life. Even if basic diagnosis is not possible, the useful parts can be salvaged and the product can be recycled to recover material from it. One step higher is remanufacturing, that involves complete disassembly of the product, followed by remanufacturing operations, and reassembly of the product. Thus a retired product can be reused at part level, material level and product level. The recovery options and operations will be enlightened in this section.

Motivation for RL	✓ Environment Protection (Ecology), ✓ Profit (Economy), and ✓ Good Image (Society)
Reasons for return	- 14 Day return policy, - Defective parts/ products, - Warranty requirements, - Wrong shipments, and - Product recalls
Type of return	• Used products (old products), • Packaging material, • Warranty requirements, • Wrong shipments, and • Product recalls,
Challenges in RL	❖ Quick residual value, and ❖ Proper return channel
Problems related to uncertainty	➢ Time of return, ➢ Quality of return, ➢ Quantity of return, ➢ Process route of a product during recovery operations, and ➢ Process time of a product in a recovery operation.
Different types of recovery operations	o Reuse, o Remanufacture/ Refurbish, o Repair, o Recondition, o Recycle, o Parts Harvest
Level of recovery	Product level, Part level, and Material Level,
Actors in RL	Collector, Sorter, Remanufacturer/ Refurbisher, Recycler, Supplier, and Distributor

Figure 4: Dimensions of RL (Adapted from Dyckhoff et al., 2004).

Returns have become inevitable, and common recovery options for a returned product are these: remanufacture, repair, recycle, and reconditioning (repainting or surface polishing) (Ilgin and Gupta, 2012). After going through many related literatures it was found that the residual value from a retired product can be recovered in six different ways: reuse the product as it is, repair the product, recondition the product, remanufacture the product, recycle the product, and harvest parts from the product (Kara et al., 2007; Rajagopalan and Yellepeddi, 2007). The operations that will be involved for the above six recovery operations are these:

1. Reuse,
2. Repair,
3. Recondition,
4. Remanufacturing/ Refurbishing,
5. Recycle and
6. Parts Harvesting.

These six operations can be termed as 5R1P. The rudiments of these operations will be explained in the following section. A retired product can be recovered in one of the six ways as shown in Figure 5.

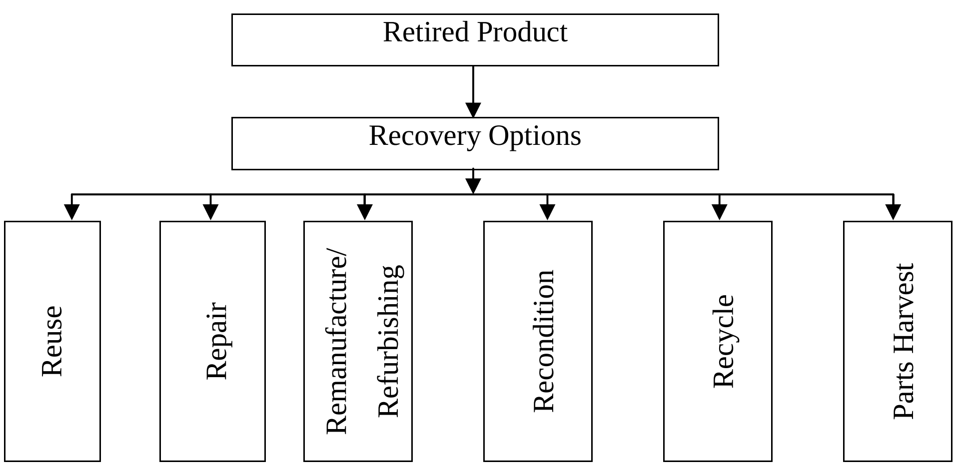


Figure 5: Six recovery options

2.2.1 Reuse:

A returned product can be reused as it is, provided it is good and satisfies all working conditions. The operations that might be involved for reuse are not many but pertain to simple testing, cleaning and repacking. Products that usually come under 14 day return policy undergo this process, other products that have been used exhaustively for few years may undergo remanufacturing process. The products that undergo this process are labelled as 'refurbished products' when sold in the market and the price tends to be lower than the original new product.

2.2.2 Repair:

Repair operations are specific operations, if a product is returned due to a specific fault, only that parts is repaired, the rest of the parts undergo minimal checking. Most of the products that fall under this category are the ones that return during the warranty period of the product. The customer may receive the same retuned product after repair or sometimes a refurbished product may be compensated. These products may also undergo remanufacturing operations in addition to repair based on the company's policy.

2.2.3 Reconditioning:

Sometimes a repaired product may require additional work like painting or surface polishing. At instances like this, the product undergoes reconditioning operations in addition to repair operations. Reconditioning generally involves operations like repainting and surface polishing (Ilgin and Gupta, 2012). The painting and surface polishing operations may be only at the surface level. Products that undergo reuse operations may also include these reconditioning operations.

2.2.4 Remanufacture:

The most important recovery operation in terms of time and process among all the others operations is the remanufacturing operation. Remanufacturing is the process of giving a retired product a total new life in terms of functionality and appearance. Remanufacturing is defined as *"the process of restoring a non-functional, discarded, or traded-in product to like-new condition"* (Lund, 2012). The first prototype of a remanufacturing model dates back to the year 1861 when a steam frigate was converted into an ironclad ship (Ilgin and Gupta, 2012). A typical remanufacturing process involves complete disassembly of a product to the part level, inspection of each part, cleaning the parts, reassembling the product, and quality test of the reassembled product. A remanufactured product is equal or superior in quality to a new product, this sets remanufacturing process position far ahead of other recovery operations.

The feature of rejuvenating the product alone does not draw attention to remanufacturing but there are other beneficial outcomes also by remanufacturing a product. Remanufacturing old products helps to save energy, virgin materials, labour, waste, and pollution, which leads to savings in cost from not producing a new product (Kerr and Ryan, 2001). The potential of remanufacturing are increased profit, sales and reduction in cost (Ilgin and Gupta, 2012).

In the U.S., over the years, remanufacturing industry has grown up to a $50 billion industry (Gutowski et al., 2011). As of 2012, in Canada and the U.S., there are approximately 7000 remanufacturing firms present. Remanufacturing firms are present in every province in Canada and in every state in the U.S. These 7000 companies remanufacture nearly 125 different kind of products (Lund, 2012). Some of the famous products that can be remanufactured in addition to Sundin's list, (2004) are given in Table 2. Automobile sector is by far the highest contributor to the remanufacturing field (Ilgin and Gupta, 2012).

Table 2: Remanufactured products along with their industry sector (Sundin, 2004).

Industry Sector	Product/Components
Automotive	Alternators, Starters, Motors, Clutches, and Engines.
Tires	Truck, automobile and airplane tires
Compressors and Refrigeration	Air conditioner and Refrigerator compressors
Electrical apparatus	Transformers, Electrical motors, and Switch gears
Electronic products	Cell phones, laptops, single-use cameras, televisions, vacuum cleaners, and network devices
Printer Cartridges	Laser toner cartridge and Ink jet cartridges

Remanufacturing can be taken up by independent remanufacturing companies or OEM. Some of the reasons that encourage OEM to set up RL activities are these: strong government legislations, economic profit from recovery, product or material is reused and conserved, environment awareness about recycling and impacts of wrong disposal (Zhang et al., 2013). All companies that remanufacture can be considered as green companies. Green companies produce remanufactured products with only a fraction of new materials and energy when compared to a new product manufacturing (Lund, 2012). For instance, 85% of energy spent on manufacturing a new product can be preserved by remanufacturing a used product (Gregory et al., 2009). The next section will outline the remanufacturing process in detail steps.

2.2.4.1 Remanufacturing Process:

The product that is returned for remanufacturing is called a “core” (Gutowski et al., 2011). Remanufacturing is done to return a core to its normal functioning before the wear out phase begins (Lebreton, 2007). The remanufacturing process requires considerably less amount of labours, cost and resources required when compared to the traditional manufacturing. In general, the remanufacturing process involves 6 stages: disassembly, cleaning, inspection, repair, reassembly, and final testing. The stages are depicted in Figure 6. Each of these operations will be explained briefly in the following section.

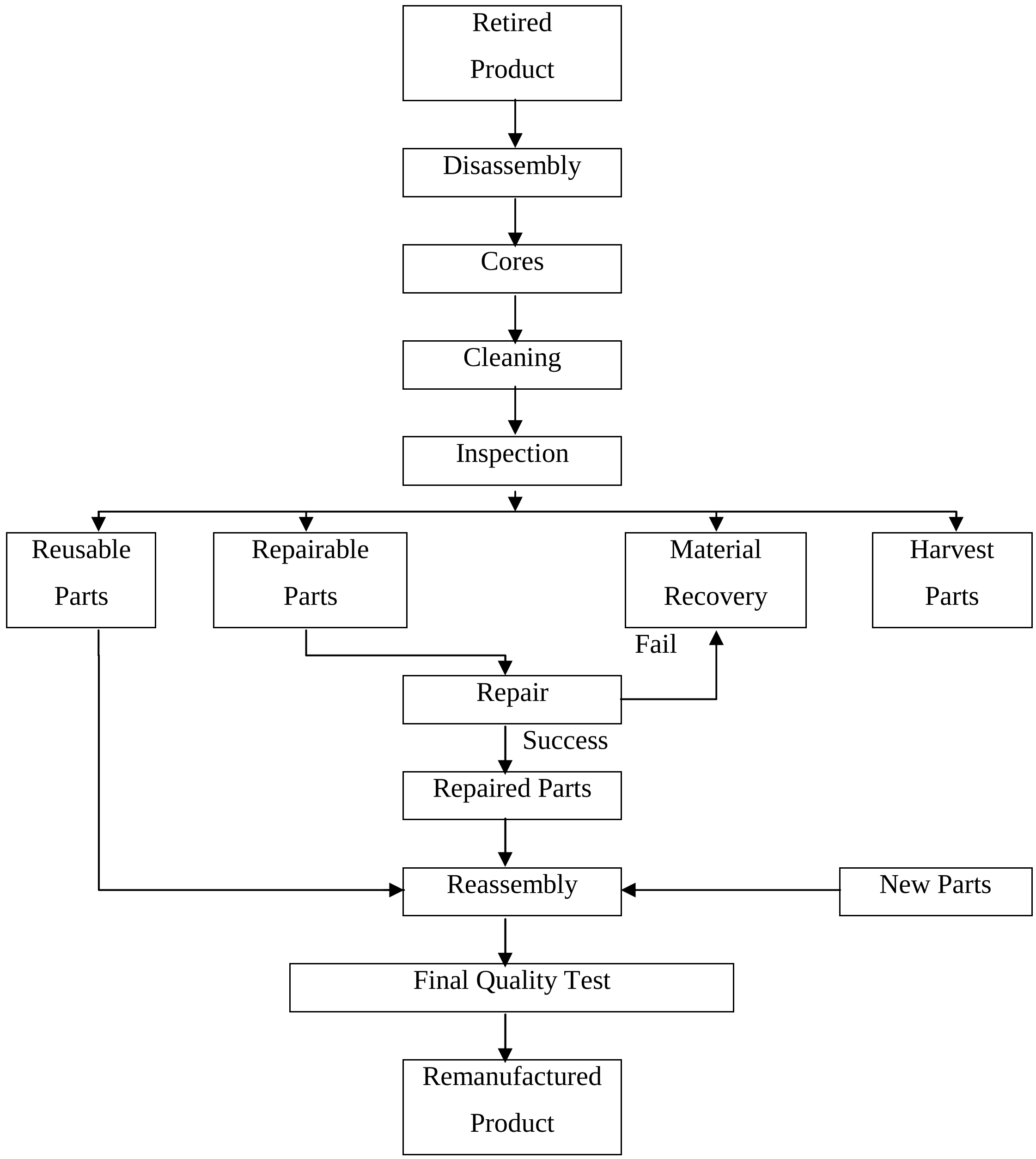


Figure 6: Remanufacturing Process Flow (Adapted from Li et al., 2013).

2.2.4.1.1 Disassembly:

Of all the recovery operations, disassembly operation is the most challenging process. It requires more manpower and time (Gungor and Gupta, 1999). When the core arrives at the remanufacturing station, the identity (number or name) is first erased. Then, the core is completely disassembled to its part level. The disassembly process can either be done automatically or manually.

2.2.4.1.2 Cleaning:

The cleaning operation involves removing dirt and dust from the disassembled parts (Ilgin and Gupta, 2012). There are several cleaning techniques to clean a part or a product: thermal, solvent-based, biological and abrasive cleaning techniques. The different processes involve treatment according to their name and it may also involve general water, detergent or chemical treatment. The cleaning process not only helps to remove dirt and dust but also to remove other oil, grease, rust and paint stains either inside or outside the surface of the part or product (Ilgin and Gupta, 2012).

2.2.4.1.3 Inspection:

The inspection stage involves activities to test the working condition of each part in the product. The parts again may be either manually tested or automatically tested. This stage mainly focuses on checking if a part meets the original factory functionality requirements or not. The parts should be able to perform its respective functions and operations that a normal part is expected to perform. Most of the parts usually are reusable, the success rate of the reusable parts is 70-80% (Gregory et al., 2009). If there is a malfunction, the part is repaired. If it is repaired successfully, then the part is reused, if not, the part is recycled to recover material from it. At the time of recycling a part, a new part is replaced in its position.

2.2.4.1.3 Repair:

The parts that are inspected as bad undergo repair operation. The repair process might involve few steps or far-reaching steps depending on the level of damage. The repair process aims at bringing a part that is damaged back to its working condition (Ilgin and Gupta, 2012). The part is thoroughly inspected and repaired such that it matches its original factory standards. In addition, it is made sure that a repaired part is equal in performance and quality with a new part.

2.2.4.1.4 Reassembly:

Once all the parts are cleaned, inspected and repaired or replaced, they arrive at the reassembly station for reassembly. During reassembly process, the parts are reassembled as per the original configuration of the product. At first, the assembler makes sure all parts are present before starting to reassemble. Then, when all parts are present, the assembler puts together the parts to form the final remanufactured product. The product is then etched a new serial number or name and labelled as remanufactured product. The labelling operation may also be done with the help of RFID tags. The tags would contain the date of remanufacturing, operations performed, and other details. This would help the remanufacturing company to maintain a record of the product and also have an idea about the product's history when it arrives for remanufacturing the next time (Ferrer et al., 2011).

2.2.4.1.5 Final Quality Test:

The remanufactured product is then tested to make sure all the parts are functioning up to the standard requirements. It is also tested to make sure it meets all the quality requirements of an original new product. A remanufactured product performs like a new product and has a new lifetime (Lund, 2012).

Remanufacturing process is mostly successful; it meets the customer's requirements and satisfies the quality standards. To attain highest market share, a remanufactured product must have better specification and lower selling price than other products (Kwak and Kim, 2013). The demand for remanufactured product usually depends on generation difference, selling price, and product status (New or Remanufactured) (Kwak and Kim, 2013). Satisfying the above needs sets the remanufactured product in a good position in the market.

2.2.4.2 Part Upgrades:

Remanufacturing may also include upgrades to match the present technology and science (Ilgin and Gupta, 2012; Lund, 2012). In the remanufacturing process, during reassembly, all parts are inspected before assembly, at that time certain parts have the capability or adaptability to include additional new parts or upgrade older parts to present technology parts, this process is called part upgrade. Also, Gutowski et al., (2011) suggested that products should be designed with a modular platform to incorporate new parts or update technology when returned for remanufacturing. Remanufacturing with optimal part upgrades was studied by Kwak and Kim, (2010). Potential applications for part upgrades are big machineries or electronic products with quick residual value.

2.2.4.3 Remanufacturing and other related terms:

Many industries involve in remanufacturing process but all industries do not use the same name. Different industries use different names for remanufacturing according to their industry sector, a summary of the different names for remanufacturing are given in Table 3 below. Commonly used terms are refurbishing and remanufacturing which will be explained in the following section.

Table 3: Equivalent remanufacturing terms (Lund, 2012)

Industry/ Product	Term
Aircraft Engines	Overhaul
Automotive Parts	Rebuild
Tires	Retread
Laser Toner Cartridges	Recharge/ Refill
Wrestling Mats	Recondition
Industrial Valves	Repair
Motor Oil	Re-refine
Furniture/ Musical Instruments	Restore
Military Equipment	Reset
Electronic Products	Refurbishing
Generic Term	Remanufacturing

2.2.4.4 Remanufacturing and Refurbishing:

Remanufacturing and Refurbishing terms have been used interchangeably in literature and industries. Both terms represent the same recovery process; however there is a subtle difference between them. Refurbishing process just like remanufacturing involves operations like disassembly, cleaning, inspection, repair, and reassembly that would only make the product look better like a new product but does not give a new lifetime (Lund, 2012). This does not mean all refurbished products do not have a new life time. Few products still undergo refurbishing process and have a new lifetime, but for the reason they fall under different industry category they attain that name (refurbishing). In general, refurbishing pertains to and is favored for electronic products that have quick returns due to damage, short lifespan, wrong shipment, and return policy of the company (Lund, 2012). A detailed difference between remanufacturing and refurbishing is given in Table 4.

Table 4: Comparison between Refurbishing and Remanufacturing.
(Based on Interviews; Kerr and Ryan, 2001; Lebreton, 2007; Lund, 2012)

Process	Remanufacturing	Refurbishing
Inspection	Yes	Yes
Disassembly	Yes	Yes
Parts Reuse/Repair/Replace	Yes	Yes
Cleaning	Yes	Yes
Reassembly	Yes	Yes
Quality Inspection	Yes	No
Polishing and Packing	Yes	Yes
New Life	Yes	No
Disassembly Level	Completely	Partly
Products	Mechanical Products e.g. Automobile Parts, tires, Aircraft Engines, Laser Toner Cartridges etc.	Electronic Products e.g. Cell Phones, Televisions, Hard Disks, Laptops/Personal Computers etc.

2.2.4.5 Benefits of Remanufacturing

This section will outline the benefits of remanufacturing. Some of the benefits as highlighted by Ilgin and Gupta, (2012) are as follows,

1) Remanufacturing is a profitable business when compared to traditional manufacturing,
2) Remanufacturing involves dynamic work unlike traditional manufacturing that involves monotonous work. This flexibility in work leads to workers skill development,
3) During disassembly, the failure reason can be found correctly. This information can be sent to the new product’s design department for future design improvements,

4) One can buy a remanufactured product that is high in quality at a reasonably low price; this can be very much useful when buying large number of products.
5) Less energy is used for the remanufacturing process:
    a. To remanufacture a product, only 15% of a new product manufacturing energy is required,
    b. Instead of manufacturing new products, if products are remanufactured, then 400 trillion BTU of energy is estimated to be saved worldwide annually,
    c. Greenhouse gases are reduced as a result of energy savings,
    d. Natural resources are conserved by extracting only a fraction from the earth's crust, since the materials are already available from the product,
6) Penalty for OEM from the environment legislations are reduced by remanufacturing a used product, and
7) By remanufacturing, the ultimate disposal time of a product is extended,

2.2.5 Recycling:

Recycling is the process of reducing a product to its material level and obtaining value form it. Products disposed as waste can either be material recovered or safely disposed by recycling. Most products contain materials like metals, plastics, and other valuable resources that have precious value. By recycling, one can not only make profit from extracting these valuable materials but can also preserve the raw materials present in the earth's crust. Usually retired products that are classified as bad, based on appearance and working condition are recycled. These products do not have any functional value but has material value that can be reused by recycling. Common recycling methods include shredding, chemical processing and material separation. The separated materials are processed into pellets and sold to the raw material extractors or part manufacturers. The important benefits of recycling are these: profit can be made from selling precious recovered material, virgin raw materials can be preserved, and the planet can be kept free from toxic waste and landfills.

2.2.6 Parts Harvesting

Parts harvesting is the last recovery option. Normally when a product is unfit to be remanufactured, the next option is to recycle, but one should also remember that a product might contain valuable parts. Parts harvesting is done to those products that cannot be remanufactured but at the same time contain valuable parts and cannot be recycled directly. During remanufacturing, after disassembly, if a majority of the parts are found to be in bad condition, and if it is not economical to remanufacture, then at that instance the good parts alone are salvaged and the product along with the bad parts are recycled, this practice is called as parts harvesting.

These harvested parts can be used in other products or in a new product manufacturing stage. Parts harvesting involves selective disassembly; only valuable parts are harvested whereas bad parts remain in the product itself and are sent for material recovery (Kerr and Ryan, 2001; Lebreton, 2007). This process is also termed as cannibalisation (Lebreton, 2007).

The difference between the important recovery operations: remanufacture, repair, recondition and recycle are tabulated in Table 5. The table also includes important highlights of the four operations.

Table 5: The difference between remanufacture, repair, recondition and recycle operations (Based on Gregory et al., 2009; Ilgin and Gupta, 2012)

Characteristics	**Remanufacturing**	**Repair**	**Recondition**	**Recycle**
Aim	To give the product a new lifetime	To extend the lifetime of a product	To extend the lifetime of a product	To recover material from the product

Characteristics	Remanufacturing	Repair	Recondition	Recycle
Warranty	For all parts	Only repaired parts	Major wearing parts	-
Level of Disassembly	Completely	Partially	No	Crushed to material level
Level of Recovery	Product Level and Part Level	Product Level	Surface Level	Material Level
Inspection/ Testing	All parts are cleaned, repaired or replaced and the product is recalibrated	Only certain parts are cleaned, repaired, adjusted.	The product is only cleaned	-
Loss of Identity	Yes	No	No	Yes
Upgrades	Yes, one or more	No	No	-
Quality Level	Same as a new product	Not as good as a new product	Not as good as a new product except for the physical appearance	-

Characteristics	Remanufacturing	Repair	Recondition	Recycle
New Life	Yes	No	No	Yes
Performance	Higher	Lower	Lower	-
Resources Conserved	Materials, Energy, Labour	-	-	Material, Energy
Profit	Higher	-	-	Sometimes low due to quality conformance
Other objectives	To give a product like new condition	To restore a product to working order	To extend the physical appearance of an old product	To keep the earth clean and preserve virgin raw materials

This section provided a brief overview about RL and the different recovery operations. The background information pertaining to these two subjects: RL and the different recovery operations serve as a backbone for this research. The next section will present the review of literature.

CHAPTER 3

LITERATURE REVIEW

This chapter will delineate the literature and concepts circumscribed in this research. A deep review of existing literature and concepts is conducted in order to have a profound knowledge of the literature and to find a gap or problem in literature. The review of literature covered for this research includes:

1. Reverse Logistics,
2. Performance Measurement and Reverse Logistics,
3. Agent-based Modelling and Reverse Logistics,
4. Remanufacturing, and
5. Cell Phone Remanufacturing

The published works of scholars related to the research was studied to understand the concepts, their methods and drawbacks if any. The literature pertaining to each of these sections will be provided below under their respective title.

3.1 Literature Review on Reverse Logistics:

RL has achieved tremendous significance over the past few years. This has been primarily due to the imperative need for an efficient and cost-effective process. Other reasons are to overcome the uncertainties, to trounce the common challenges, and to address the EES issues. In any company, RL contributes to 4.5% of logistics cost (Rajagopalan and Yellepeddi, 2007). The main parameter in the RL is the money, which is stored in the form of assets in returned products. The foremost motive of any company in RL is to recapture the asset value from a used product or dispose the used product correctly and have a good name in the society (Rajagopalan and Yellepeddi, 2007).

RL is relatively a new field when compared to other practices in Industrial Engineering. The inception of the field dates back to the year 1993. Over the years, RL has achieved tremendous growth and importance. Many scholars and researches have contributed significantly to the field. The current literature bank has abundance of research in various fields of RL in categories like production planning & control, inventory management, network design, economic lot sizing, quality management, pricing approach for returned products, and many more. The graph below (Figure 7) depicts the number of Journal articles published in RL over the past 21 years as of April 1, 2014.

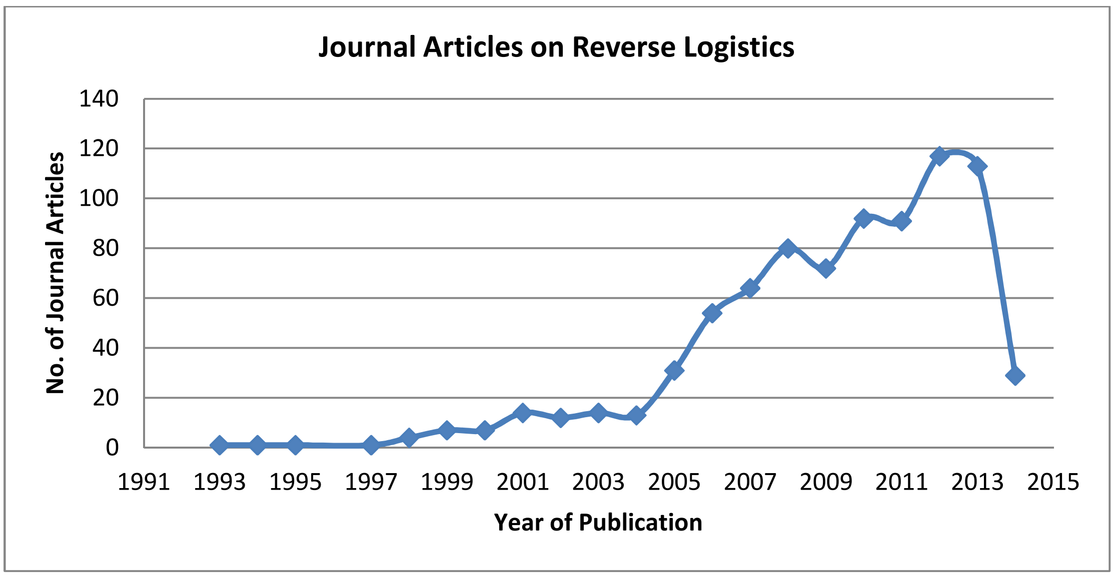


Figure 7: Number of journal articles published on reverse logistics (Adapted from SCOPUS website).

3.2 Literature Review on Reverse Logistics and Performance Measurements:

RL has taken a firm seat in most companies as returns have become inevitable. Whether it is product recalls, returns or disposal, a stable RL set up is required. To establish a stable RL system, evaluating the systems performance is a promising option. By evaluating the systems performance, one can understand the current performance and investigate ways to improve inept processes if any. Performance evaluation of RL has become a real necessity over the past decade.

3.2.1 Definition:

Performance measurement is defined as "*The process of quantifying the efficiency and effectiveness of past actions*" (Neely et al., 2002). Going by definition, it is important to measure the performance of a system so as to coordinate all the operations. There are several methods to evaluate the performance of a system. Traditional methods include Balance Score Card (BSC) approach or a list of measurements to calculate the performance of a system. Several scholars have provided new approaches to evaluate the performance. Few authors have even developed a new methodology to measure the performance of the system. Each of the methods will be discussed in the following section.

3.2.2 Methods:

In management, decision-making process takes place at three levels: strategic level, tactical level and operational level. Each of the three levels is important to be considered while evaluating the performance of a system. Several performance evaluation techniques have been proposed in the literature for the three levels of management. A quantitative methodology called PEARL (Performance Evaluation of Reverse Logistics) was developed with the help of Analytical Network Process (ANP) and Fuzzy Logic to create a RLOPI (Reverse Logistics Overall Performance Index) framework that would evaluate the performance of a RL enterprise. This research included nine measures in four departments: Storing & Sorting, Gate Keeping, Asset Recovery and Transportation (Yellepeddi, 2007). A combination of BSC and performance prism was used to develop a comprehensive performance measurement for the RL enterprises. The decision making process was based on DEMATEL. The research included a total of 24 performance measures considering 6 performance perspectives (Shaik and Abdul-Kader, 2014).

Fuzzy logic has been used by many authors to measure the performance of a RL system. A comprehensive performance evaluation consisting of 6 indices covering both qualitative and quantitative measures was developed using fuzzy logic by Xiong and Li, (2010). This research touched upon the importance of EES benefits as well. Trappey et al., (2010) developed a combined quantitative and qualitative model using genetic algorithm and fuzzy logic cognitive maps to measure the performance of a RFID enabled RL enterprise. The research included 28 measures and was illustrated using cold food container returns as an example. Jun (2009) also used fuzzy logic to evaluate the performance with the help of Critical Success Factor and Analytical Hierarchy Process (AHP).

In an exploratory research across 109 companies in Czech Republic, it was found that the most often cost measure was the transportation cost with 66%. Most companies gave importance to RL efficiency and neglected effectiveness calculations while measuring the performance of their company’s RL system (Škapa and Klapalová, 2012). Therefore, by considering effectiveness measurement also along with the other measures, a comprehensive performance measurement list for a RL enterprise can be achieved.

Pochampally et al., (2009) developed a mathematical model using Quality Function Deployment (QFD) and Linear Physical Programming (LPP) to measure the performance of a reverse supply chain. A step by step explanation of the measurement process with a numerical example was provided. The metrics for evaluating a reverse supply chain were presented and the satisfaction level of the supply chain with regard to each of the measure was calculated towards the end.

3.2.3 Frameworks:

Various efforts by scholars have gone into developing a performance evaluation framework. A performance evaluation framework was developed using BSC, AHP and Data Envelopment Analysis (DEA) by Tonanont et al. (2008). The model was illustrated using consumer electronics industry as a case study. A measurement methodology to calculate the time parameters and value recovery time of returns was developed with the help of lean techniques. The objective was to reduce the cycle time of a product in a RL system (Rajagopalan and Yellepeddi, 2007).

To develop a model for evaluating the performance of a RL tire industry, Huang et al., (2010) conducted a survey among three companies. The model consisted of 64 measures generated from 5 different dimensions: financial, operational, learning and growing, reserve relationship, and risk control. Important order-based performance measures were identified by DeCroix et al., (2008) for a multi-product assemble-to-order system. The effect of basic operational level performance measures on the value of component commonality was also addressed.

3.2.4 Problems:

Goals and measures of a company are sometimes not aligned together. To address this issue, goal setting theory methodology was deployed to align the RL goals with its metrics. The performance metrics were then found using exploratory approach with open ended questions from industry professionals in the defence sector. The research also touched upon the common challenges faced by companies in RL. The important finding from the research was, by matching the goals and metrics, a RL system could perform even better. One interesting result concludes that communication contributes to 13% of common challenges in RL (Hall et al., 2013).

The supply planning problem in a remanufacturing system is an important issue to consider in reverse logistics enterprise. During reassembly, it is possible to reassemble a product by procuring parts from an external supplier or by overhauling a returned product and reusing the parts from the product. However, the process needs to be cost-effective in the remanufacturing system. In deciding whether to buy the parts from external suppliers or overhaul the existing returned product was optimally found by Kim et al., (2006) with the help of a mathematical model, the objective function in the model was to maximize the remanufacturing cost savings.

This model was extended by many authors using various other methods. A multi-agent theory was proposed by Chenglin and Xinxin, (2008) to solve the same problem by considering three different agents namely, Manufacturing Agent (MA), Supplier Agent

(SA) and Collector Agent (CA). A mathematical model for each of the agents was presented, where each agent aimed at minimizing the operating cost, which helped to minimize the total operating cost of the whole chain. The optimal number of parts to procure and overhaul were ultimately found. The paper touched upon the effect of recovery rate on the performance of the reverse supply chain. However, only one parameter -- recovery rate and two measures: cost and profit were considered in the model.

A genetic algorithm was then proposed by Kannan, (2009) to solve the same supply planning problem. In this work, a generic model for a remanufacturing system capturing the supply planning problem was presented. A mathematical model with an objective function to maximize the total cost savings was optimised using genetic algorithm. The optimal values for the production planning were determined and the effect of disposal rate on profit was also studied to understand and improve the performance of the system.

3.2.5 Decisions in RL:

The decisions involved during RL activities are quintessential. Authors Lambert et al., (2011) developed a RL decision conceptual framework that is flexible and takes into account different scenarios. The framework also included performance measures at the three levels of management. The model was designed by considering seven important departments in the RL system. Each department's actions and decisions were identified and a decision framework for each department was provided. To test the applicability and flexibility of the model, the decision framework was applied to three real-world case studies. The framework can be used as a skeleton for industries to structure their RL activities.

3.2.6 Uncertainties in RL:

The uncertainties in RL are another serious issue to consider while measuring the performance. To overcome the uncertainties in RL, Bai and Sarkis, (2013) proposed a flexible framework for RL that could accommodate changes according to the concurrent needs. The framework was later evaluated using neighbourhood rough set model and the effective performance measures for RL were found. Zhang et al., (2013) studied the effect of uncertainty on the economic performance of RL operations. The effects of manufacturer's investment and legislations uncertainties on the performance were the two main factors considered in the model. Two economic measures were considered in the model: incremental return rate (measure of profitability on investment) and profit. A systems dynamic model was constructed and simulation was performed to calculate the measures and provide recommendations for improvement. The important finding from the paper was, when the number of collection points in the RL network increases, then the profit from remanufacturing increases.

3.2.7 Need for computer based program:

Performance measurement was emphasised more by authors Li and Olorunniwo, (2008) when evaluating the performance across three companies. In the process, a generic or typical RL process flow and a set of key performance indicators were provided with the help of interviews and industrial visits. The importance of technology to link information and communication among different actors in the system to make the system more effective were also highlighted. The authors concluded that better control systems are required to evaluate the system performance.

A performance measurement framework consisting of 6 performance measurements and 23 metrics in the reverse supply chain for the automobile green supply chain was proposed with the help of survey and questionnaire (Olugu et al., 2011). Each performance measure was evaluated based on the importance and applicability level. It was found that management commitment was the most crucial measure in the reverse supply chain. This framework was also evaluated using fuzzy logic (Olugu and Wong, 2011). The paper concluded that the evaluation process could be improved with the help of a computer based program to enhance its accuracy and run the model more quickly. A simulation model could be a promising option for the above requisite.

3.2.8 Importance of communication in RL:

A similar study was aimed at performance measurement of both forward and reverse supply chains and the importance of integrating the material and information flow among reverse and forward supply chains for full-fledged improvement in design, sourcing, manufacturing and forecasting was also emphasised. By sharing information across all the channels in the supply chain, all the members of the supply chain can become aware about the needs of the company. For example, the remanufacturer in the reverse supply chain can share information on reasons for a product to return and the cause of damage of the product to the design department in the forward supply chain, thereby the designer can become aware of the problems and rectify those mistakes while designing a new product (Mondragon et al., 2011). This study was carried out with the help of a case study in a telephone operating company in the UK. This study provided awareness for the need for communication among different actors in the RL system.

3.2.9 Environment measurement importance:

Environmental performance measurement has become increasingly important in RL. Björklund et al., (2012) calculated the impact of CO2 emission on the environment and the transportation cost during RL activities. The research was presented with the help of a case study in PET (Polyethylene terephthalate) bottle industry consisting of four actors: Production Company, Retailers, Wholesalers and Breweries. The environment and economic performance were measured and the authors insisted on the balance of environment impact and logistics cost in RL. In the transportation sector, the operational and environmental performance measures were evaluated by Paksoy et al., (2011). The performance was calculated using linear programming mathematical model at the operational level. It was noted that during transportation, the environment is affected by CO_2 emission, and at the same time transportation was required in the reverse supply chain to collect the retuned products. To match this trade off, the operational and environmental measures related cost were investigated.

In order to divert carpet from landfills and better manage the reverse flow of used carpets, a simulation model was set up to address this problem. The research also included the effect of uncertainty in the model and the impact of environment on the performance of a system. Recommendations were also provided to improve the situation (Biehl et al., 2007). A simulation based approach considering the environment and the economic aspect of supply chain was used to calculate the performance of a forward and reverse supply chain by Murayama et al., (2003). The simulation results also helped in finding the optimal number, location and capacity of the disassembly stations. The importance of environment in performance calculation and the environment benefits of reverse logistics were made aware from the above studies.

Although there may be several measurement techniques like scoring techniques, mathematical models, Fuzzy Logic and many more in literature to measure the performance of a RL system. The advantage of using agent based modelling technique over the other techniques is the possibility to capture the system dynamics of the model that is unlikely in Fuzzy Logic, or scoring techniques. Also, scoring techniques are avoided since the concentration of this research is focused on performance measures at operational level. It is important to model each entity in reverse logistics with its respective actions, decision making process flow and objective during the performance measurement process to encompass the uncertainties and common challenges in RL. Agent-based modelling technique provides the freedom to model each entity in the RL system independently as an agent with a unique set of actions and decisions along with an objective. In addition, agent-based modelling helps the modeller to measure each agent's performance separately at one time collectively; having these requirements and advantages in hands, agent-based modelling technique fits as a better measurement method than other techniques for this research.

Form the above discussions, the different methods and frameworks used across different sectors by all authors were familiarised. In addition, the impact of uncertainties, the importance of communication among, the need for computer based program, the requirement for environment measurements, and the need to incorporate decisions in a RL system were made clear and aware. Addressing these requirements along with performance measurement of RL will be a real asset to the RL literature. A summary of the existing performance measures in RL along with the authors' name, year, industry focused, level of management, and the problems addressed in RL are tabulated in Table 6 below.

Table 6: Summary of performance measurements and reverse logistics literature review

Author	Year	Method	Industry	Level of management			Decision Making Process	Uncertainty	Channel Communication	Common Challenges	E^2S Advantages	Cost/Profit Calculation	Environment Benefits
				SL	TL	OL							
Shaik and Abdul-Kader	2014	DEMATEL	-	✓			✓				✓	✓	
(Hall et al., 2013)	2013	Exploratory approach with open ended questions + Content analysis + Goal setting theory	Defence	✓		✓				✓		✓	
(Bai and Sarkis, 2013)	2013	Neighbourhood rough set model	-	✓		✓		✓					
(Zhang et al., 2013)	2013	System dynamics	-	✓				✓		✓	✓	✓	

Author	Year	Method	Industry	Level of management			Decision Making Process	Uncertainty	Channel Communication	Common Challenges	E^2S Advantages	Cost/Profit Calculation	Environment Benefits
				SL	TL	OL							
(Škapa and Klapalová, 2012)	2012	Exploratory research	102 Czech	✓							✓	✓	
(Björklund et al., 2012)	2012	Multidimensional classification framework	PET bottles	✓		✓					✓	✓	✓
(Lambert et al., 2011)	2011	Decisions conceptual framework	Hydro-Quebec, Matrox Electronics, Woodflame	✓	✓	✓	✓		✓	✓	✓	✓	
(Olugu and Wong, 2011)	2011	Fuzzy logic	Automotive	✓							✓	✓	
(Olugu et al., 2011)	2011	Framework + Survey	Automotive	✓						✓	✓	✓	
(Mondragon et al., 2011)	2011	Case study	Telephone			✓			✓	✓		✓	

Author	Year	Method	Industry	Level of management			Decision Making Process	Uncertainty	Channel Communication	Common Challenges	E^2S Advantages	Cost/Profit Calculation	Environment Benefits
				SL	TL	OL							
(Paksoy et al., 2011)	2011	Mathematical model	Transportation			✓		✓				✓	✓
(Xiong and Li, 2010)	2010	Fuzzy logic	-	✓		✓					✓		
(Trappey et al., 2010)	2010	Genetic algorithm	Cold food container			✓	✓	✓					
(Huang et al., 2010)	2010	Key performance indicators + ANP	Tire	✓		✓			✓	✓		✓	
(Pochampally et al., 2009)	2009	QFD+ LPP	-	✓	✓	✓		✓			✓	✓	
(Kannan, G., 2009)	2009	Genetic algorithm	-			✓						✓	
(Jun, 2009)	2009	Fuzzy logic	-	✓						✓		✓	

Author	Year	Method	Industry	Level of management			Decision Making Process	Uncertainty	Channel Communication	Common Challenges	E^2S Advantages	Cost/Profit Calculation	Environment Benefits
				SL	TL	OL							
(DeCroix et al., 2008)	2008	Heuristic	-			✓							
(Li and Olorunniwo, 2008)	2008	Case Study	Three RL companies	✓			✓		✓	✓			
(Tonanont et al., 2008)	2008	BSC+AHP+DEA	Electronics	✓		✓				✓		✓	
(Biehl et al., 2007)	2007	Simulation	Carpet			✓		✓		✓	✓		
(Rajagopalan and Yellepeddi, 2007)	2007	New measurement method	Electronics			✓		✓		✓	✓		
(Yellepeddi, 2007)	2007	PEARL	Electronics	✓		✓		✓		✓	✓	✓	
(Murayama et al., 2003)	2003	Simulation	-			✓					✓	✓	✓

Author	Year	Method	Industry	Level of management			Decision Making Process	Uncertainty	Channel Communication	Common Challenges	E^2S Advantages	Cost/Profit Calculation	Environment Benefits
				SL	TL	OL							
Present Research	**2014**	**Agent-based model**	**Electronics**			✓	✓	✓	✓	✓	✓	✓	✓

Note: SL- Strategic Level, TL- Tactical Level, OL- Operational Level.

3.3 Literature Review on Agent-based modelling and Reverse Logistic:

Agent-based modelling technique has been used extensively in RL. There are several interesting applications; few among them are described in this section. An agent-based model to decide the pricing strategy in a dual-channel and remanufacturing supply chain was developed by Jiang et al., (2010). The model was presented with the help of five agents: manufacturing agent, retailer agent, customer agent, finance agent and business agent. Each of the agents was assigned a particular task to perform in the system. Collectively, these agents were supported by a learning agent, whose task was to study the pricing strategy of earlier remanufactured products from historical data and arrive at an optimal price for the current remanufactured product. The agents achieved each of their individual tasks and coordinated the system together to find the optimal price of a remanufactured product. The learning agent along with the other agents was implemented using a multi-agent supply chain model.

An agent-based model was used to analyse the environment benefits of tire retreading. The model was simulated with the help of agent-based simulation using four agents: tire agent, remanufacture agent, recycler agent, and collector agent. Actions and decisions of each agent were provided. The results showed that 25% of replacement market can be satisfied by retreaded tires and also this percentage could be increased by increasing the retread level. This research helped to analyse the environment benefits of retreading and showed possible reduction in scrap tires and scrap materials (Abdul-Kader and Haque, 2011).

A multi-agent theory to solve the supply planning problem was proposed by considering three different: manufacturing agent, supplier agent, and collector agent (Chenglin and Xinxin, 2008b). Agents with the aim to minimize the total cost, worked together to decide the optimal number of parts to buy from the supplier and the optimal number of products to dismantle to satisfy the needs of the remanufacturer.

Several other authors have contributed to similar problems in RL using agent-based modeling approach. A summary of the papers with their problem addressed, objective and use of agent-based model in RL are given in Table 7. The use of agent-based modelling approach has helped RL systems achieve their goals successfully. This research will use agent-based modelling technique to measure the performance of a RL enterprise. By going through the existing literature of RL and agent-based modelling approach, it was found that this application is first of its kind. The measurement of RL performance using agent-based modelling technique will be a new addition to the RL and agent-based modelling literature.

Table 7: Summary of agent-based modelling technique and reverse logistics literature

Article	Year	Agent-based model purpose					Objective				Problem Addressed					
		Decision- making	Information Flow	GUI	Multi –Agent Theory	Trading Agent Competition	Minimize cost	Minimize total time	Minimize waste	Maximize profit	Remanufacturing	Materials	Disposal Management	Environmental Benefits	Pricing Strategy	Supply Planning
(Yang and Wang, 2007)	2007		✓										✓			
(Chenglin and Xinxin, 2008b)	2008		✓		✓		✓				✓					✓
(Xu, 2008)	2008				✓											
(Golinska, 2009)	2009		✓	✓				✓								
(Jiang et al., 2010)	2010				✓					✓	✓				✓	
(Abdul-Kader and Haque, 2011)	2011	✓							✓		✓			✓		
(Golinska and Kawa, 2011)	2011		✓									✓				
(Xing et al., 2012)	2012					✓				✓	✓					

3.4 Literature Review on Remanufacturing:

The literature on remanufacturing is an interesting study and vast. A brief outline of some of the relevant published models is described in this section. Decisions on when to upgrade a part in a product and whether to upgrade a part or maintain its specification were found with the help of a mathematical model by Kwak and Kim, (2010). It is usual in part upgrading process, that the process is not economical, it involves work in addition to remanufacturing and also purchase of new parts that are up-to-date in the market, this adds up to the overall remanufacturing cost. The increase in remanufacturing cost eventually increases the selling price of the product. The study was aimed at keeping the remanufacturing cost (with part upgrades) low that would help to have a reasonable selling price in the market. In this way, a remanufactured product (with part upgrades) will be equally preferred alongside a new product in the market.

A model for positioning a product in the market after remanufacturing was presented by Kwak and Kim, (2013). A mathematical model was formulated to find the optimal specification and the selling price of a remanufactured product with the objective function to maximize the remanufacturing profit. Two versions of the model were provided, one for take back by ‘waste stream system’ and the other for take back by ‘market driven system’. Both models were demonstrated with the help of desktop computer as an example.

At some instances when products are large, like RADAR remanufacturing, repair operation stations are far apart and it is difficult to keep track of all parts location in the factory, there is a possibility that the part may be lost or even unaware of the location. A framework for identifying components in a remanufacturing process was provided by Ferrer et al., (2011). The method used to identify components was with the help of RFID technology. The parts that are disassembled were labelled with RFID tags so that they can be tracked easily. By doing so, less time, cost and labour were needed when reassembling the product. They evaluated the efficiency of remanufacturing with and without RFID tags using RADAR remanufacturing as an example and found that RFID tags provided substantial improvement in their process.

3.5 Literature Review on Cell Phone Remanufacturing:

Cell phone recycling and remanufacturing has also received much importance in the literature. Usually when phones come for remanufacturing, they are either in faulty or non-faulty condition (Mondragon et al., 2011; Franke et al., 2006). There are several constraints like availability of components/phones, demand for the product, condition of the received product, cost of remanufacturing the returned product, the number of resources required for remanufacturing, and many more. In addition, different models come for processing. This affects the production planning and capacity of the remanufacturing facility as each model would require different set of disassembly operations. In order to solve this complexity, a combinatorial optimization algorithm was developed to find the optimal number of phones to be allocated to a particular treatment that will be a cost effective process (Franke et al., 2006).

In cell phone remanufacturing, there are two uncertainties in production. The path of a particular cell phone is not certain, as few cell phones may undergo all processes but whereas some cell phones may skip few processes. Secondly, the repair process time of all cell phones is not constant; cell phones may require different processing time depending on their return condition. To address these two uncertainties in remanufacturing process routing for telephone remanufacturing, an analytical method based on Graphical Evaluation Review Technique (GERT) was proposed (Li et al., 2013). This approach was able to calculate the average process time and process route of telephones. Though there are various papers addressing similar problems, few focuses on evaluating the cell phone remanufacturing performance. As cell phone has reduced lifetime and increased returns, it is imperative to evaluate the performance of a cell phone remanufacturing industry to have an efficient process.

3.6 Gap in Literature:

By examining the existing literature, it has been found that, the need for a generic performance evaluation framework considering the uncertainties, communication among actors, environmental benefits, and decisions in RL with the help of a computer based program is an imperative subject.

It was also found that the performance evaluation of a RL enterprise using agent-based modelling technique, and performance evaluation of a cell phone remanufacturing industry has not been addressed in literature before. A deep review of literature was helpful in understanding the RL concepts, find problems and blanks in the RL literature.

This research has stepped forward to fill the gap and overcome the limitations and drawbacks of previous related literature. This research will focus on the performance evaluation of a RL enterprise at operational level using agent-based modeling technique. A generic performance evaluation model incorporating a list of performance measures, process flow and decision making model for electronics remanufacturing industry will be provided. The model will be explained with the help of cell phone remanufacturing case study. The research will take into account the uncertainties, need for communication and the environmental benefits of RL in the venture. The model will be simulated with the help of computer based program, ProModel 7.5 software. By fulfilling the above needs, this research will stand as a seminal research contribution to the RL literature.

CHAPTER 4

PROBLEM STATEMENT

After reviewing the RL literature and by understanding the current needs, the problem statement for this research was penned down.

To measure the performance of an RL enterprise using agent-based modelling technique with the help of cell phone remanufacturing as a case study and provide recommendations for improving the RL enterprise.

4.1 Research Importance:

The main objective of this research is to evaluate the performance of a RL enterprise using agent-based modelling approach. In addition, the problems pertaining to RL will also be covered. To be more specific, the problems that will be touched upon are the uncertainties, communication, decision making process, computer based program and environmental benefits.

To recap the problems mentioned earlier, the problem related to uncertainty arises from five directions: the time of return, quality of return, quantity of return, processing time of a returned product, and processing route of a returned product. All the five issues are uncertain, since they are dependent on the customers using the product (Li et al., 2013; Yellepeddi, 2007). This will be major problem the research has to tackle with.

The importance of communication among different actors in the RL system has been stressed by many authors. Communication may include sharing data, information, and resources. By incorporating communication among different actors in the RL system, the system can work together to have a better outcome and have an efficient process flow (Hall et al., 2013; Huang et al., 2010; Li and Olorunniwo, 2008; Mondragon et al., 2011). The other problems related to decision making framework, computer based program and environment benefits will also be addressed. The next section will explain how this research will undertake the problems and contribute to the RL literature.

4.2 Research Contribution:

To address the above problems, this research was tailored to fit in all the 5 needs with the main objective to measure the performance of RL using agent-based method. A brief introduction to the solution of each the problems and how this research has planned to solve them will be provided in the following paragraphs.

At the outset, the need for decision making framework can be satisfied by agent-based decision making model. As previously introduced, there are six actors in a generic RL model: collector, sorter, remanufacturer/refurbisher, recycler, supplier, and distributor. Each of these actors will be modelled as separate agents in the model that can take actions and make decisions on its own. They will be independent from each other and the main RL system. The agents are decentralized in terms of location and each agent has a decision making process characterized by their behavior or role in the RL system. Collectively, they work together to achieve the required goal of the system.

For the need to measure the performance with the help of a computer based program to enhance accuracy and calculate the measures even faster, an agent-based simulation is a pragmatic resolution. As agent-based modelling has the property of individuality, it makes it easy to model each agent as a separate sub-system. By doing so, there will we six sub-systems; the sub-systems will then work together to form the whole RL system. It is now possible to measure the performance of each agent separately and at one time collectively. This advantage will lead to increased accuracy and will help to provide recommendations for each agent separately.

Having modelled the agents separately, it is now possible to measure each agent's performance separately. The environmental benefits contributed by each agent can now be calculated easily. Along with the other operational level measures, the environmental benefits will also be calculated; thus solving the problem related to environment performance requirement. The problem related to uncertainties in RL will be remedied by measuring the system's performance and providing recommendations according to the deficiencies caused by the uncertainties. The factors that pullback the systems performance because of the effect of uncertainties will be identified and attenuated.

The last problem related to communication requirement, will be again solved with the help of agent-based model. The agents are customized to communicate with each other in the RL model. The communication may be made possible by sending and receiving messages in the decision making model. The agents communicate with each other to make the process effective and reduce the uncertainties. A new agent or an interconnected database will be introduced to enhance the communication and information flow among the agents. A detailed explanation will be provided in the methodology and recommendations sections. A summary of research solution is provided in Table 8.

Table 8: Summary of research contribution

#	Problem/ Need	Solution
1)	Decision making framework	Agent-based decision making framework
2)	Uncertainties	Recommendations from agent-based simulation
3)	Communication among actors	Interconnected Database System and agent-based decision making model
4)	Computer based program	Agent-based simulation
5)	Environment measurement	Environment benefits calculations by agent-based simulation

CHAPTER 5

METHODOLOGY

This research presents an agent-based modelling approach to evaluate the performance of a RL system. The framework will cover three components: decision making process, RL process flow and performance measures. The framework is designed with the aim to be generic and could be adaptable to any product or any remanufacturing situation. First, a detailed description about agent-based modelling technique will be elucidated in the following section.

5.1 Agent-based modelling approach:

Agent-based modeling is an individual centric, decentralized approach to design a model. It consists of agents, an environment, and a communication link between them (Castiglione, 2006).

5.1.1 Agents:

Agents are computational entities that are discrete and possess a unique behaviour, a goal and a set of rules. Agents can be active entities, subsystems in a system, computer programs or part of a computer program. Examples of agents are organizations (firms, companies in a supply chain), social actors (individual people) or conscious entities (robotic agents, agents in economy). According to Wooldridge and Jennings (1995), an agent is defined as, "*a software process that follows the properties of autonomy, social ability, reactive, proactive, veracity, mobility, benevolent, and rationality*."

Agents can be modeled as simple representation or complex decision-making tools. Agents can decide and act on their own. The decision making process is based on agent's intelligence and information from the environment. Each agent has a set of rules, and interacts with other agents accordingly. They then together form the overall behaviour of the system. The rules written for each agent can be based on either logic or computer algorithms. As the model time elapses the agents become intelligent and possess the ability to make decisions and actions on its own (Castiglione, 2006).

A model can have several agents; these agents again can be assigned a set of rules and goals to mould their behaviour in the system. The agent and the others agents are engulfed in an environment. The agents adapt and change their behaviour according to the environment needs. The environment can be compared to a system from modelling perspective. All the agent's actions strive together to form a synergy, to achieve a common goal or a higher-level goal than each agent's goal. The primary motive for an agent is to do its assigned role and work with the other agents to achieve the system's goal (Castiglione, 2006).

A model of an agent and its environment is shown in Figure 8. The agent is placed in an environment and it acts according to its assigned rules and goals. The agent performs its actions and then senses the environment needs and updates its rules. The goals of the agents are not changed but may include new goals according to the environment needs. The next time before action, an agent decides its actions based on the environment needs. In this way, the agent is flexible enough to accommodate itself according to the environment and at the same time tries to achieve the assigned goal. This process is repeated until the end time or the system's goal is achieved.

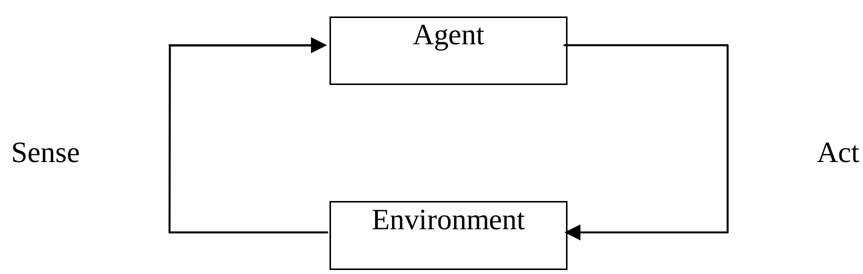


Figure 8: Agent-based model according to Bussmann et al., (2004)

5.1.2 Properties of Agents:

An agent possesses several properties that shape its character and behaviour. The properties of an agent are explained below. The properties of agents are extracted from (Wooldridge and Jennings, 1995).

5.1.2.1 Autonomous:

The prime and important property of an agent in agent-based modelling is the ability of an agent to be autonomous. This property helps an agent to frame its own behaviour by understanding the system's requirements. The agents can engage in tasks and take actions without external control. This is very much helpful for a dynamic system in which the parameters are stochastic and change abruptly. The agents with the help of this property can change its actions and decide on the best solution, according to the present goals of the system, instead of being monotonous in its actions. In addition, by the term autonomous, it means agents can be identifiable and disguisable in terms of spatial, temporal or functional attributes from the other agents in the environment.

5.1.2.2 Social ability:

The next important attribute of the agents is social ability. It is essential for an agent to interact with other members (agents) in the system to coordinate all the activities and strive towards the system's goal. The interaction among agents can be made possible by sending and receiving messages, spoken dialogues, or information flow with the help of commands in the computer system (Castiglione, 2006). By interacting with one another, communication, information flow, and awareness about system requirements among all the agents in the system could be improved.

5.1.2.3 Reactivity:

In a stochastic system, when the model is loaded with uncertainty, the agents can react to the changes over time and respond according to the current requirement. This ability helps the agent to possess the quality of being reactive. This is very much helpful in financial markets, when there is a continuous fluctuation in prices.

5.1.2.4 Pro-active:

Interestingly, agents are not just reactive but they are also proactive. An agent does not act according to the environment all the time but also acts on its own by understanding the system needs. This property helps the agent to be consistent and independent in its actions in achieving the systems goals.

5.1.2.5 Mobility:

The agents are also free to move in the environment or any spatial space. They start at a point and move in random directions according to the system's requirements. The movement of agents is based on the model and the system needs. Not all models posses this property, only a few according to the requirements of the system are modelled with the agent mobility property. When agents are not stationary, like birds in a flock movement, then the agents (birds) can be modelled with this property but whereas when agents are stationary, like the companies in a supply chain, then this property does not play an important role.

5.1.2.6 Veracity:

The agents do not communicate false information knowingly. This property is an assumption according to (Wooldridge and Jennings, 1995).

5.1.2.7 Benevolent:

Benevolence is the property of an agent to have unique behaviour and a goal in the model. The agent's behaviour and goal will not conflict with the other agents' behaviours and goals. The agents will help one another in achieving the system's goal.

5.1.3 Building an agent-based model:

Agent-based modelling approach is also called as individual based modelling and falls under the umbrella of computational modelling techniques (Gilbert, 2008). Agent-based modeling is a connection of artificial life, artificial intelligence and game theory (Castiglione, 2006). In designing an agent-based model, the modeller should focus on three components: 1) identify the actors in the system as agents; 2) assign behaviour to those agents; 3) and work on an agent's interaction with the other agents in the system. Any complex system that has internal states, inherent timings and different reactions in different modes can be modelled with the help of agent-based modelling.

In the first stage of modelling a problem, an agent is assigned a set of rules to follow and a particular goal to achieve, the rules and goals shape the character of the agent in the model. The agents interact with one another in a particular range; it may be global interaction or local interaction. The company's or system's goals are shared among all agents in the system, the agents then work together to achieve the system's goals. The dynamics of the system arises over the course of time by the interaction of agents. Over the duration, as and when the agents interact with each other and the environment the system goal is achieved.

Agent's behaviour is characterised by state determined automata. Agents have internal states and inherent timings. They can be modelled with the help of a state chart that may be linked to a process flow diagram. When a command or timing trigger is received the agent transcends from one state to another state and performs the required action. For complex problems, agents have random access memory to store large amount of data (Castiglione, 2006).

Sometimes it is possible to model a problem with many agents. This type of modelling approach is called multi-agent theory. Bussmann et al., (2004) defined multi-agent system as a collection of interacting agents. In this research, multi-agent theory is incorporated along with agent-based modelling technique to achieve the desired research goal. Also, agent-based systems can be used for many purposes, to study the system dynamics, evaluate the system and many more. In this research it is used to evaluate the system's performance. The simulation of an agent-based model is called as agent-based simulation.

5.1.4 Examples:

Agent-based modelling comprises of several interesting examples. An early example includes a simulation model to generate a swarm of flocking birds. Each bird (agent) is assigned an autonomous behaviour. The birds coordinate with the others and flock together to achieve the system's goal (Castiglione, 2006). Typical examples of agent-based models are immune colonies, financial markets, companies in a supply chain, product in a market, people in an environment and many more. Any entity that has individuality and is present in an environment to perform a set of actions can be modelled as an agent using agent-based modelling. Examples of agents alone include, people, operating stations, companies, projects, products, and vehicles as shown in Figure 9.

Figure 9: Few examples of agents: a factory, butterfly, car, tire and a person.

To recap, the significant features of agent-based modelling are the following: each agent in the model is independent, possesses a goal, performs tasks, and makes decisions on its own. These features characterise the agent in the model and endows a unique behaviour to the remaining agents. The agents interact with one another and the system's behaviour is the outcome of their interactions. These features led to the idea to model the RL system using agent-based modeling technique. The model is designed in such a way that each company in the RL network is represented by an agent. In this agent-based model, a set of performance measures for each agent will be identified and evaluated. Following the measurement, recommendations for improvement for each agent will be provided leading to the total improvement of RL system performance. Each agent will have a unique objective as well.

5.2 Reverse Logistics Process Flow:

A typical RL process flow would involve the participation of six sub-systems/agents: the collector, sorter, remanufacturer or refurbisher, recycler, supplier and distributor. In the real-world RL situation there are primarily four companies: the collector, recycler, supplier, and distributor. The sorter and the remanufacturer are part of the recycling company as departments or sub-systems. The process flow of a product from the collector to the distributor and the operation involved in each of the sub-system or agent were understood with the help of the existing RL literature and from interviews with RL experts. The process flow is designed with the help of cell phone remanufacturing processes in mind but has undergone some modifications to adapt to all the products and the remanufacturing process in RL. The process flow is depicted in Figure 10. The flow of a product in the RL system will be explained below.

A retired product seeks its entrance into the RL system through the collector. A collector is usually a drop-off location where customers can drop or send their old products. The collector then transports the products to a processing facility that might be hosted by an OEM or IR (Independent Recyclers).

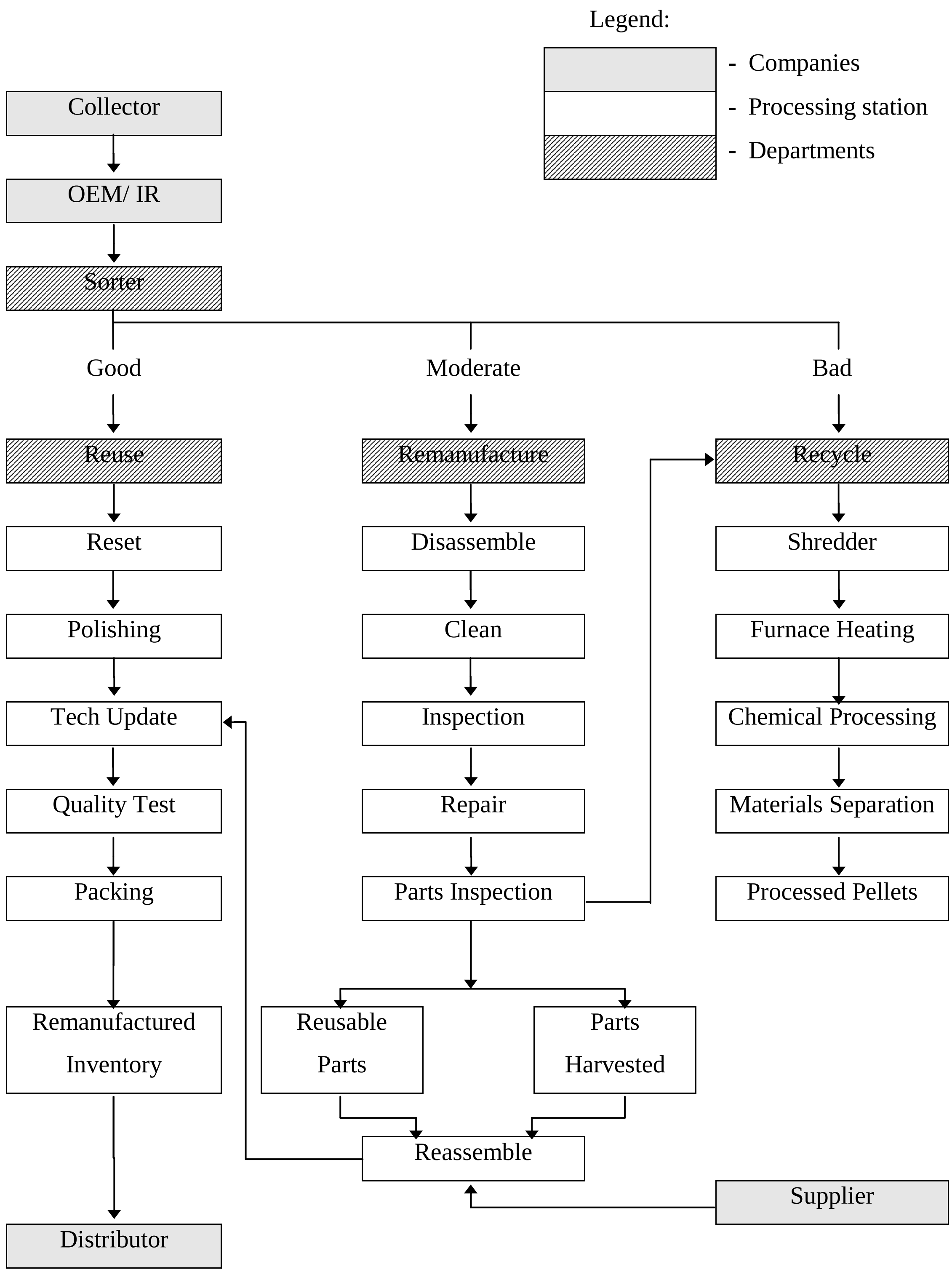


Figure 10: Generic RL process flow

The OEM and IR, classify the products into different category levels based on the product's quality at the Sorting department. In general, the products are checked for reuse, remanufacture and repair operations (US EPA, n.d.). The Sorting department sorts the products into three categories: good, moderate, and bad. The products once classified enter their respective processing station. The good products enter the reuse operation stage, moderate ones go to the Remanufacturing department and the bad ones are sent to the Recycling department.

The reuse operations involve activities like general cleaning, polishing, reset, technology update, quality test and final packing. Once these operations are performed the products are sent to the stockroom located in the Remanufacturing department. The remanufacturing operations include complete disassembly, cleaning & inspection of each part and repair of any part if required. During the process if a part is bad, it is recycled and replaced by a new part. In the case when majority of the parts are bad then the good parts alone are removed to be parts harvested and the product is recycled.

Once the parts complete all of these operations they are brought together for final reassembly. At this stage, if there is a shortage of parts, then the required parts are bought from the supplier. Once the product is reassembled, it moves on to the reuse processing station's technology update stage. Then followed by the quality test stage; this stage is to make sure the product satisfies all basic requirements and performs as like as new product (as assumed in this thesis). The product is then packed, labelled as a remanufactured product and sent to the remanufactured products inventory. The remanufactured products are transported to the distributor to be sold. The products are now given a total new life in terms of appearance and functionality with the help of remanufacturing or reuse operations. A customer can choose a remanufactured product over a new product as they perform equally as good as a new product and also the price is less than a new product.

The recycling stage includes operations like shredding, furnace heating, chemical processing, material separation and pellet formation. The bad products are initially shredded into small pieces, the small pieces are heated in a furnace to remove plastic materials, the remaining particles undergo a chemical processing stage to separate different kinds of materials, and in the final stage the separated materials are processed into pellets. These pellets can be reused in a new part formation (Ahmadi et al., 2003) or reused for other purposes. In this way retired products can be kept away from landfill by reusing their materials in a meaningful way. Both remanufacturing and recycling activities, give products and materials a new life, generate profit, and keep the environment clean. These advantages symbolise RL activities. The next paragraphs will introduce the different agents, and the functions of each agent in the model will be elucidated.

5.3 Agent-based decision making process:

In general, a RL system consists of separate companies or entities that work independently and contribute to the total success of the RL system. In the real-world scenario, each company has a set of functions to perform and a goal to achieve. The companies perform their required actions to achieve the company’s goal. Having noticed the availability of several entities, independency, actions & decisions to make by the entities, goal to achieve, and the presence of an environment, it is possible to model the RL system using agent-based modelling technique. With the help of agent-based modelling technique the companies will be considered as agents in the model. The agents (companies) will act independently and be present in a RL environment (system). Each agent has an objective and set of actions to perform.

In a RL system, there are six independent actors: collector, sorter, remanufacturer/ refurbisher, recycler, supplier and distributor. These six actors can be considered as independent entities or agents. They are listed below,

1. Collector Agent (CA),
2. Sorter-Cum-Reuse Agent (SCRA),
3. Remanufacturer Agent (RMA),

4. Recycler Agent (RCA),
5. Supplier Agent (SA), and
6. Distributor Agent (DA).

A conceptual illustration of an agent-based model is shown in Figure 11. The decision making process of each agent will be explained in the following section. A detailed description about each agent including their responsibilities, process, actions, decisions, performance measures, and goal will be given in the next section.

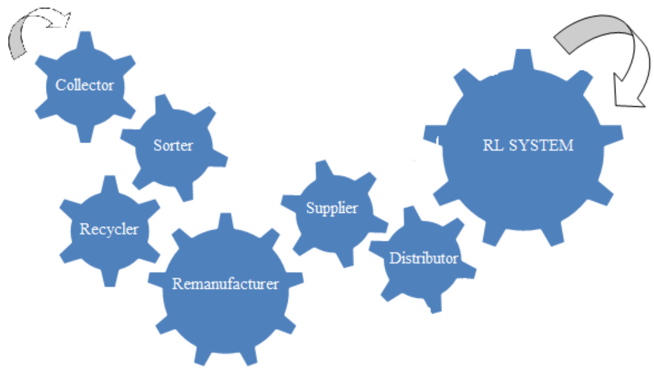


Figure 11: Conceptual agent-based model of a RL system

5.3.1 Collector Agent (CA):

The Collector Agent (CA) holds the key position in a RL system. In the electronics and the metal management RL enterprises, collector acts as the channel leader (Choi et al., 2013). The main role of the CA in a RL system is to collect the product that comes for return. The returns may be in person, by post, at a drop-off collection point or at a processing facility. Wherever it is, the CA takes responsibility in setting up the platform for a successful RL system by establishing its activities in a safe, cost-effective and time-efficient manner. The collectors should also understand that returned products are valuable and may also contain toxic materials, so they should handle them safely. In the real-world scenario, the collectors may be OEMs, Independent Recyclers (IR), retailers, customers, or non-profit organisations. The agent-based decision making process of collector agent is depicted in Figure 12.

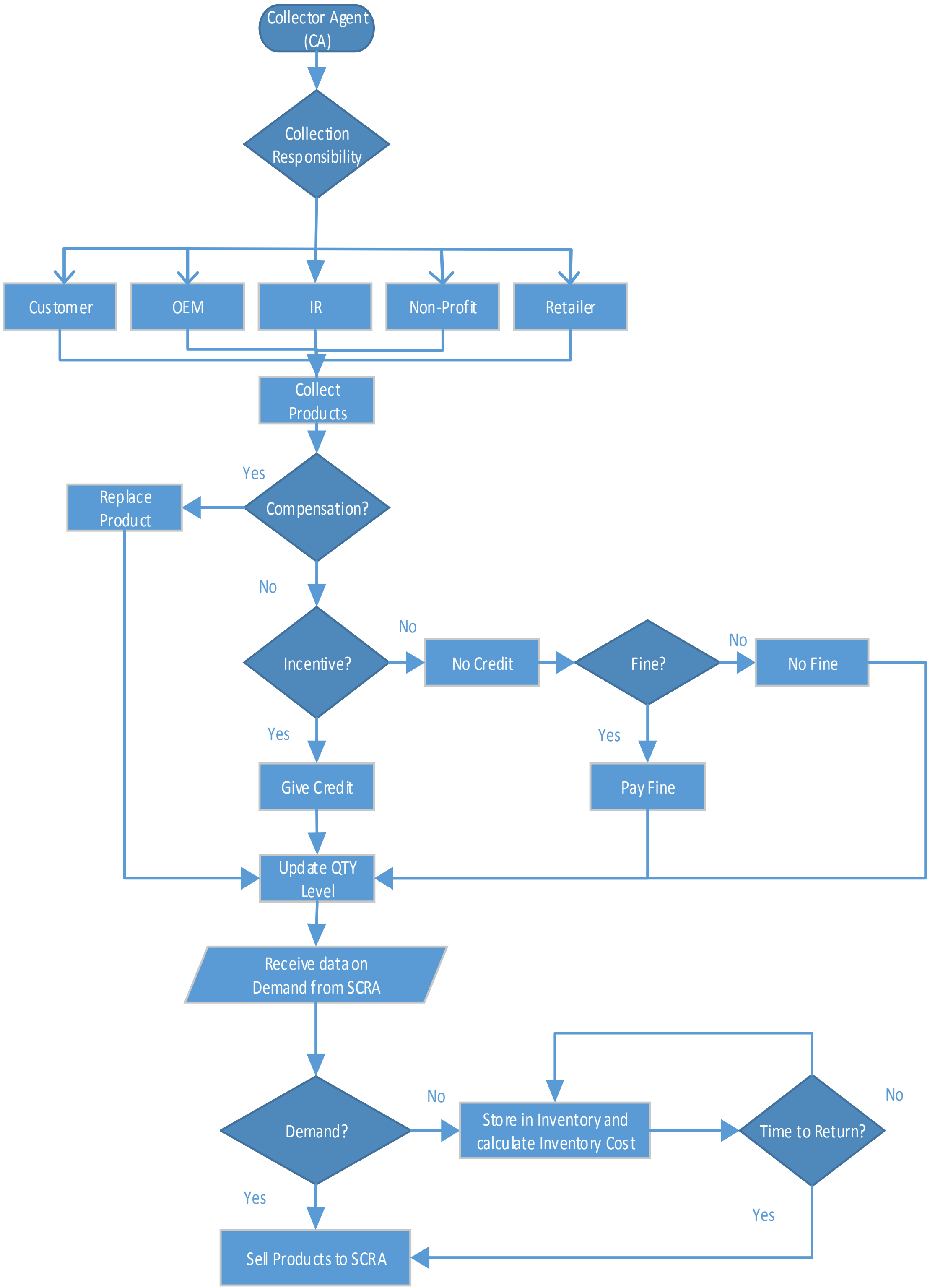


Figure 12: Collector Agent (CA)

In the model, at the first step, there is a decision block to decide who should collect the returned products. For example, in the case of cell phones, the OEM is not involved in the collection process but the retailers take responsibility to collect the returns; and for toner cartridges, the OEM and IR mainly take responsibility to collect the used products and vary similarly for other type of products. The model has included a wide range of options to make the model more generic encompassing all electronic products return.

In the next step, the collector collects the product and decides on whether to compensate the customer with a replacement product (either new or old) or not during the interim period of repair/ remanufacturing (Mondragon et al., 2011). If it is required, the action passes on to 'replace product' where the customer is given a replacement product, if not a replacement product is not provided. In the following stage, the collector inspects the product for basic operations that a product could perform, like turn on/off, and other key functional operations. If the product is able to pass the basic inspection then based on the policy set by the collectors, the customer may either receive credit towards his/her new product or an incentive for the return. If the product does not pass the basic operations test, then the product is tested intensively to make sure the product is not severely damaged, if it is severely misused, sometimes the customer may have to pay fine. If there is no misuse, the product passes on to the next stage, update quantity level.

After the following decision blocks, the collector's inventory level is updated according to the number of returns per day. One of the significant feature of this model is that, the RL activities are both demand and time driven, i.e. when there is a demand from the customers for a remanufactured product then the collector sends the products to the remanufacturing facility for processing if not the product stays in the collector's inventory. Similarly when the time to return a product is reached for example the last day of the month or year then the collector automatically sends the products to the remanufacturing facility. The actions and decisions of these will be explained in the following paragraph.

Once the inventory level is updated, the collector waits for the request from the Sorting-Cum-Reuse Agent (SCRA) for products. If there is a request from SCRA for products then the collector transports the products to the SCRA, if there is no request then the product stays in the collector's inventory and the cost of inventory is calculated. According to an interview at a local collection point, it was stated that returned products are sent to the processing facility once a year. So, to incorporate this situation, there are periodic checks (once in a month or year) if it is time to send the product to processing facility, if it is the scheduled day for sending them, then the products are sent to the SCRA, if not they remain in the collector's custody. This concludes the decision making process of the collector.

The common performance measures that can be calculated at the collector agent are the inventory cost, inspection time, the inventory level and the input level of the collector. The objective of the collector agent in the model is to monitor the quantity level of the returned products periodically, so that the collector is ready to supply the products to the SCRA when there is an immediate request. Also the other agents in the system can be aware of the number of products returning per day and can plan their work accordingly.

5.3.2 Sorting-Cum-Reuse Agent (SCRA):

The SCRA is part of the OEM or IR and it is not an independent company. SCRA is the first stage in both OEM and IR processing facilities. The SCRA has two functions to perform; they sort the returned products according to their quality and perform reuse operations. The actions and decisions corresponding to them will be elucidated in the following paragraph. The decision making process of SCRA is illustrated in Figure 13.

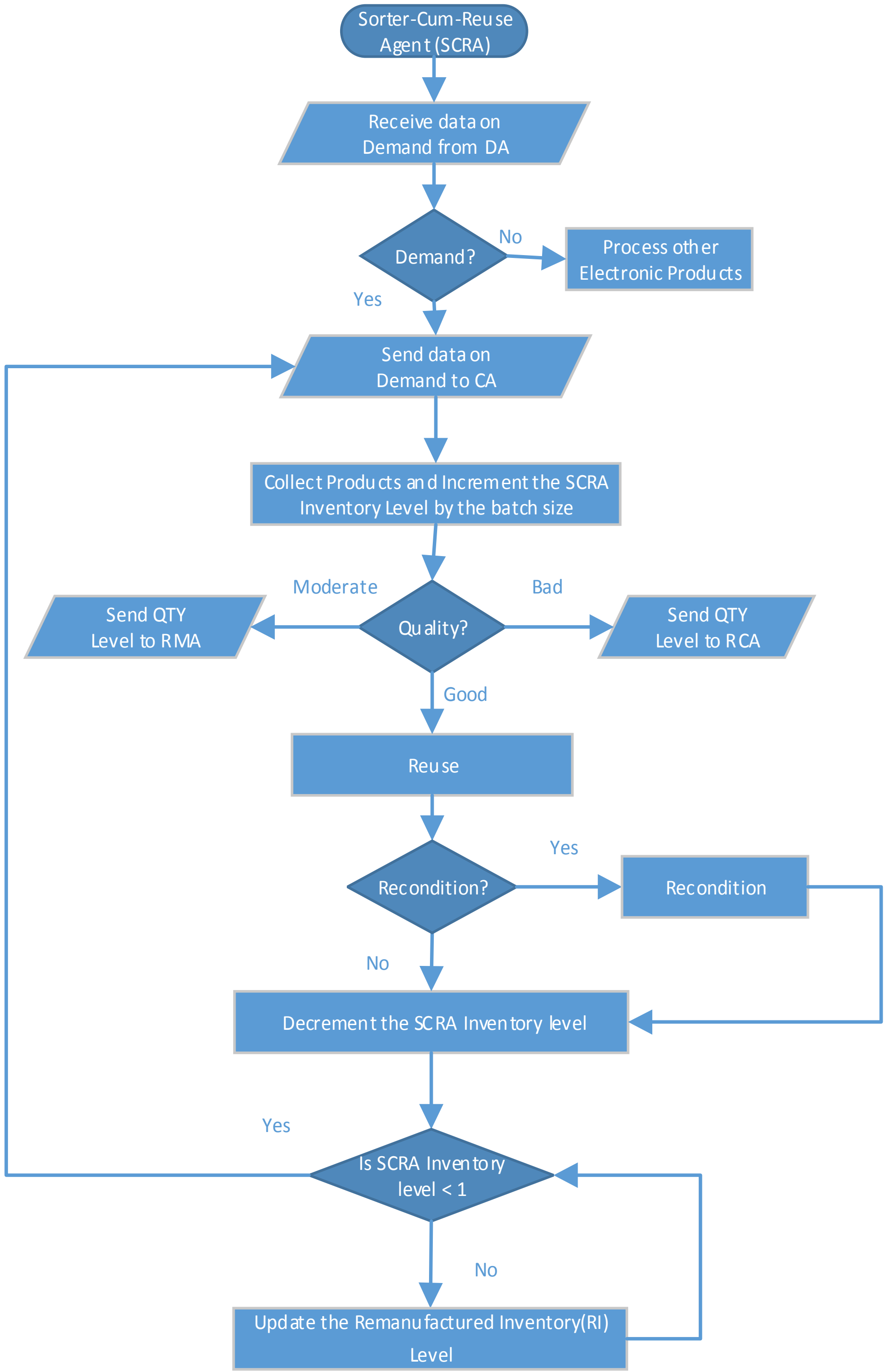


Figure 13: Sorting-Cum-Reuse Agent

In the first step, the SCRA periodically receives information regarding demand from the DA for products. If there is demand for a particular product then the SCRA decides to sort that particular product first ahead of other products and similarly ranks other products according to the time of demand request. If there is no demand then the SCRA sorts all products equally at different time intervals for each type of product. After receiving information on the demand information for a particular product along with the quantity required, the SCRA passes on the message to the CA, who then sends the required quantity to the SCRA for processing. In the next action, the SCRA collects the products from the CA and increments the SCRA inventory level by the number of products received in a batch.

The pivotal decision block in the SCRA is the quality decision block; the SCRA may either perform manual tests or automated ones to classify the products based on their quality. Generally, the Sorter classifies the products into three categories based on their quality: good, moderate and bad. Based on the quality test requirements, if the product quality is bad then it falls under the bad category. As the bad products traverse through the sorting stage, the quality level of the bad products level is updated and the information on the quantity level is sent to the Recycling department. Similarly if the products are classified as moderate, the same action is performed and the information on moderate products quantity level is sent to the Remanufacturing department. If the product is classified as good then the SCRA performs the required reuse operations.

There are a couple of reuse operations as explained in the RL process flow section. After all the operations are performed, the action passes on to the next decision block whether to recondition or not. Reconditioning might involve operations like painting or surfacing the remanufactured product. For few products, reconditioning is required and for few others, it is not required. So, the SCRA decides on this operation, if it is required then the product is sent for reconditioning operation. After the required operation, the SCRA inventory level is decremented by the number of products processed. If the reconditioning operation is not required then the product passes directly to the SCRA inventory level decrement stage. In the next step, the SCRA's inventory level is checked, if it is less than one, then the command passes on to the ‘send data on demand to CA’ step and a new batch of products is collected for processing and the same process follows. If the SCRA inventory level is greater than one, then the command reaches the ‘Update Remanufactured Inventory (RI) level stage’. In this stage, the RI level is incremented by the number of products remanufactured.

The update on the RI level helps the DA to become aware about the number of products ready to be bought for sales. The important measure for the SCRA is the sorting time because this is an important stage and any improvement can lead to a huge reduction in time & cost of the process. The other key measures include lead time, sorting effectiveness, utilization, throughput, agent capacity and output quantity level. The main objective of the SCRA is to reduce the sorting time.

5.3.3 Remanufacturing Agent (RMA):

The remanufacturing or the refurbishing agent can be independent or part of the IR or OEM. It is primarily responsible for the remanufacturing operations in the company. The actions and decisions that take place in the RMA are as described below.

The products that are classified as moderate usually enter the RMA department for remanufacturing. Once the RMA receives information on the quantity level of the moderate products from the SCRA, it collects the products for processing from the SCRA department. In the first step the products is completely disassembled and the individual parts are placed separately. A manual inspection is done on each part and depending on the parts condition they may undergo one of the following processes: reuse, repair, recycle, recondition, refill, or Parts Harvest (PH). The list includes all possible operations for a product. Depending on the product the operations might vary, for example, a cell phone might not require refill operation but whereas a toner cartridge or a similar refilling equipment might require the refill operation. This is the first decision block in the agent.

The parts are inspected for functionality and physical appearance. A part can be reused as it is if it is good, similarly if a part is slightly damaged but can be repaired then the part is repaired. Once the part is repaired, it is inspected to see if it is in good condition, if not good or if the part is not repairable then the part is recycled. Similarly if the part is severely damaged then the part is recycled at the first step. The last decision, to harvest a part or not is determined by the condition of the other parts of the product. If a majority of the parts of the product are in repair condition and it is not economical to repair the entire product then the bad parts along with the product are recycled and the good parts are harvested. The harvested parts can be either reused in other products or sold to the SA to make profit. The parts are not immediately sold to the SA but stored in the inventory and based on the demand request from the SA the parts are sold.

Following this decision stage, the parts move on to the next stage, 'check part count before reassembly.' All the parts required for a product are placed together before reassembly and checked to make sure if all the parts are present. If there is a shortage, the decision is to either buy from the SA or procure for the PH inventory. The parts count is again checked and then reassembled to form the final product. The moderate product is now remanufactured and given a total new life as a new product in terms of appearance and working condition. The product moves to the RI and the RI level is updated by one each time a product is remanufactured.

The key performance measures that are essential for the RMA include, lead time, cycle time, throughput, work-in-process, utilization, agent capacity, parts harvested inventory level, and output quantity level. The RMA aims at keeping the operations cost as low as possible, this is the main objective of the RMA in the RL system. The decision making process of the RMA is depicted in Figure 14.

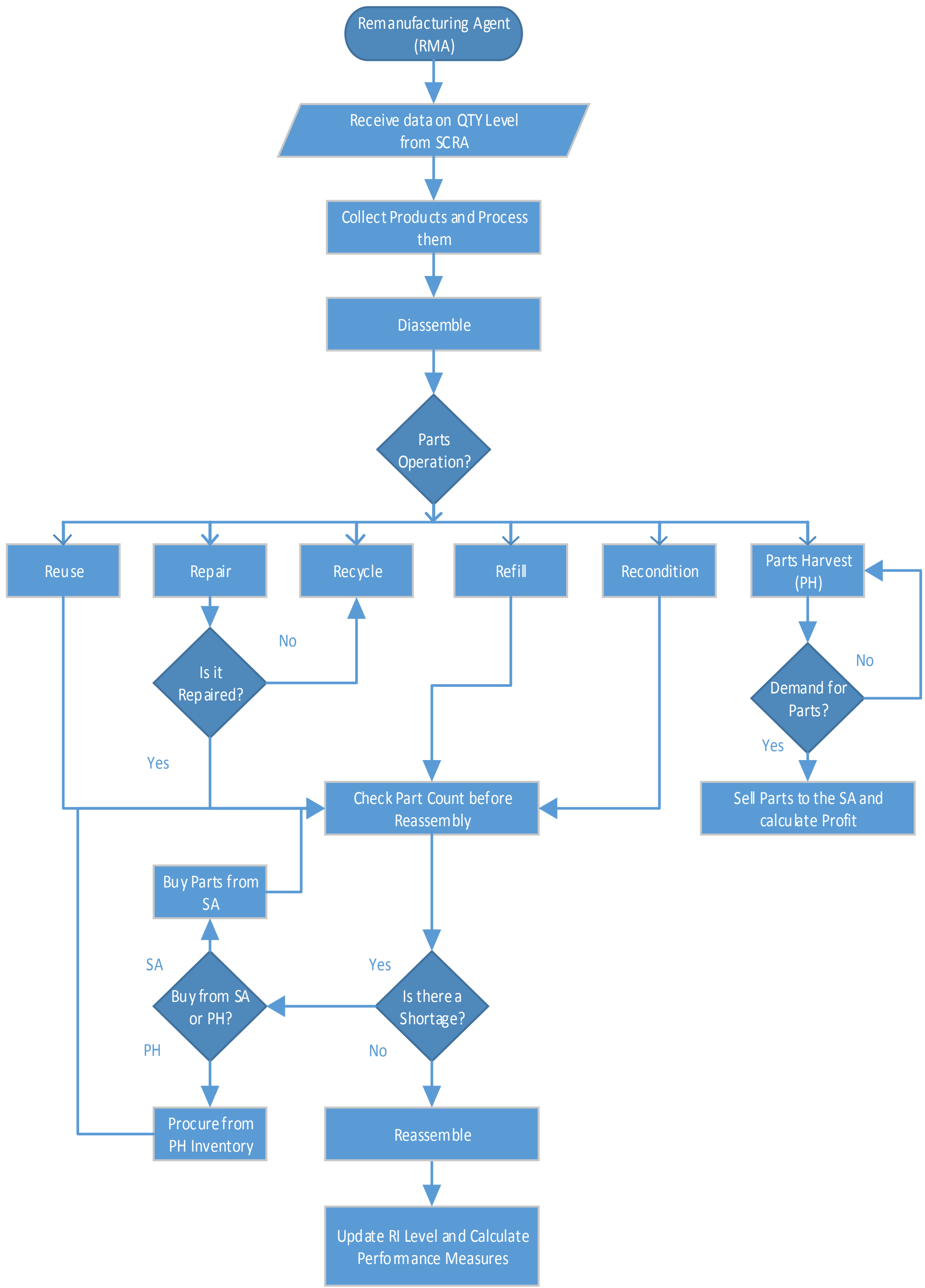


Figure 14: Remanufacturing Agent

5.3.4 Recycler Agent (RCA):

The RCA is the next agent in the RL system. The RCA is one of the departments of the recycling company (either IR or OEM) along with SCRA and RMA. The sole purpose of the RCA is to recycle the products that are classified as bad by the SCRA. The actions and decisions of the RCA are shown in a flowchart in Figure 15. The important operations of the RCA are discharging and material recovery. The objective of the RCA would be to maximize the material recovery.

The actions and decisions that take place at the RCA are as follows. Similar to the RMA, the RCA first receives information on the number of products that would come for recycling from the SCRA, and then collects the products for processing. Few products like toner cartridges contain powder or liquid that needs to be discharged before recycling. Therefore at the first step, the product is inspected by a decision block to either discharge the powder/ liquid or not. If yes, then the action to discharge the powder/ liquid is performed; otherwise the action passes directly to the next stage -- to shred the products. Once this decision block is completed, the products are pulverized to their material form. The different materials are then separated in the next action block by means of chemical processing.

Once they are separated, the material recovered level is calculated. The material selling decision is then made, it can be either sold to the raw material extractors or the electronic parts manufacturing company; in both ways they are beneficial. If they are sold to the raw material extractors then the environmental benefits from not extracting a new material is calculated and likewise if they are sold to the electronic parts manufacturing company then the profit from selling the materials is calculated. The important performance measures for the RCA include the material recovery level, recovery rate and the output quantity level.

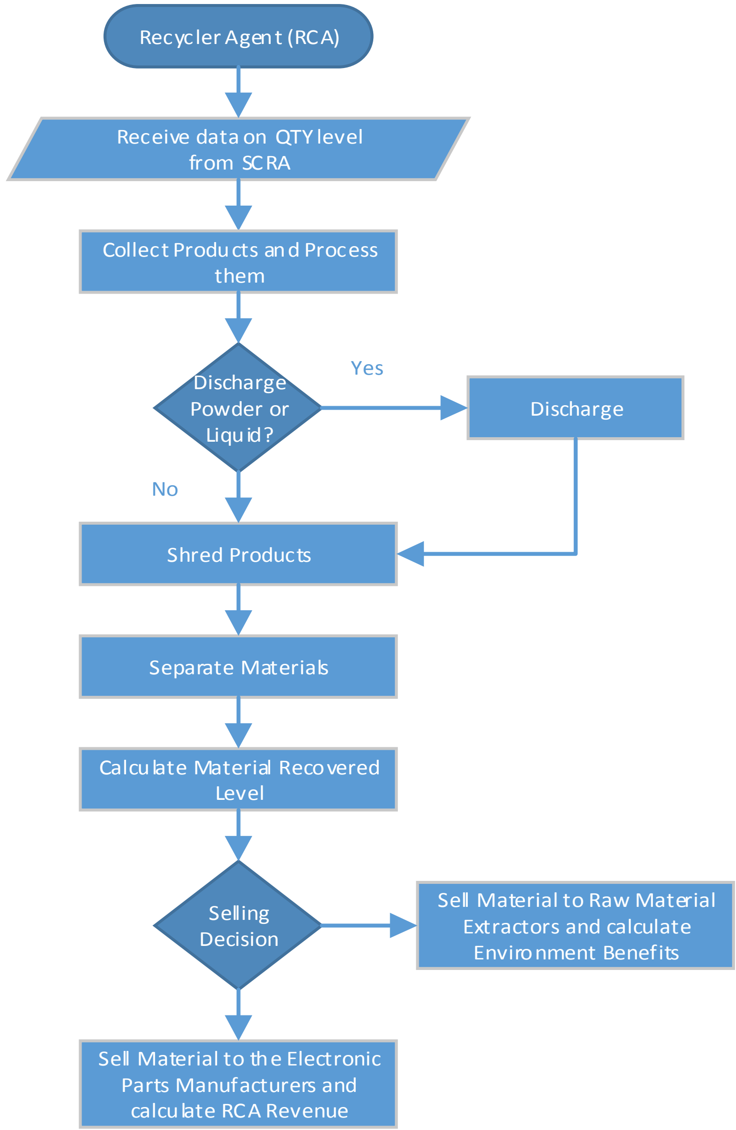


Figure 15: Recycler Agent

5.3.5 Supplier Agent (SA):

The SA is an external company and not part of the IR or OEM, it acts independently. The role of the SA in a RL system is to provide parts for the RMA when there is a shortage of parts at the reassembly station. There will be no performance measures considered in this agent. The actions and decisions that correspond to the SA are shown in Figure 16. The SA regularly produces parts and stores them in their inventory. If there is a demand for parts from the RMA then the SA sells the parts to the RMA; if not, the SA sells the parts to the OEM in the FSC.

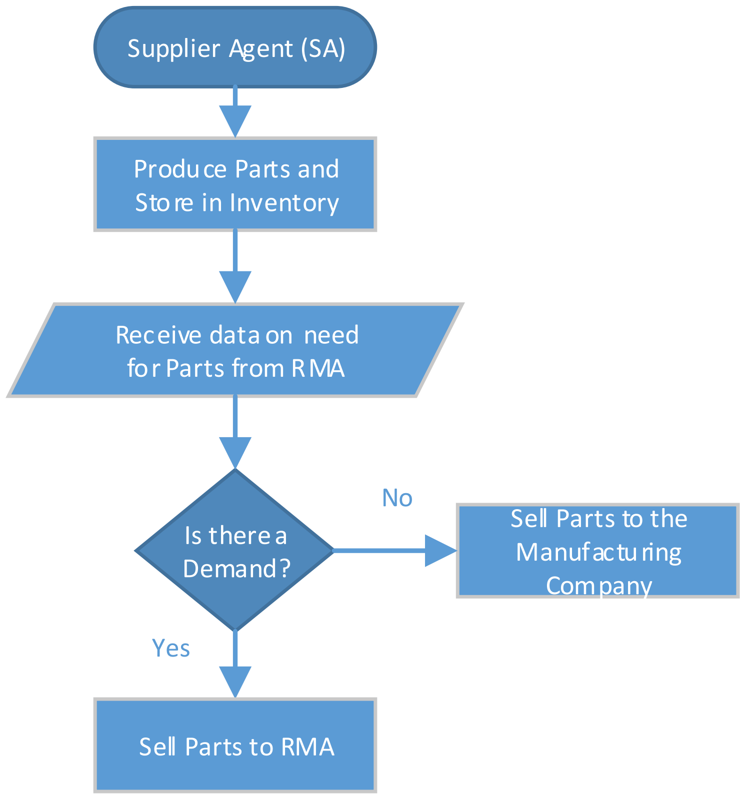


Figure 16: Supplier Agent

5.3.6 Distributor Agent (DA):

The distribution activities are carried out by the DA; it may be the OEM/ IR distribution centre or an independent distribution company. OEM/ IR have stores for their remanufactured products and similarly the distribution company may have wholesale stores or a dedicated store for remanufactured products. The DA takes care of distributing the remanufactured products in the RL system. The actions and decisions are illustrated in Figure 17.

The actions and decisions of the DA are as follows. The DA initially estimates the demand for a particular product with the help of demand forecasting techniques or with the help of previous year's sales data. The DA then sends information on demand to the SCRA requesting remanufactured products. The SCRA then procures the required quantity from the CA, remanufactures them and sends them to the DA. The DA collects the products and sells them at a marked up price for profit. The important measure for the DA is the service level. In inventory management, it is important to make sure that the desired quantity of products are available at the time of demand (Ballou, 2003). This will be measured with the help of service level. Maintaining a good service level helps the company to satisfy the customers with products on time and also have a good name.

It is equally important to satisfy the customers with a remanufactured product that is equal in performance with a new product (Lebreton, 2007). The satisfaction of the customer is analysed by asking the customers for feedback on the remanufactured product, if they are not happy the DA collects further details on the reasons for dissatisfaction and problems about the remanufactured product. This information can later be sent to the remanufacturing company for improvement. If the customers are happy with the remanufactured product, the DA does not perform a major action but the agent is satisfied with the good service.

The other measure for the DA is the output quantity level i.e. the number of remanufactured products sold per day. It is equally important to measure the output quantity level to know how many products are being sold per day so to determine the net income of the system. The main objective of the DA would be having an increased service level.

This concludes the agent-based decision making model. The agents perform their actions and make decisions to achieve their individual goals. The RL system's net outcome is achieved with the help of each agents operation. The agents work together in setting up a RL system that is an efficient and cost-effective process. The objective of the total RL system is to have a process with maximum revenue from remanufactured products. A summary of all the agent's actions, decisions, performance measures, objective are recapitulated in Table 9.

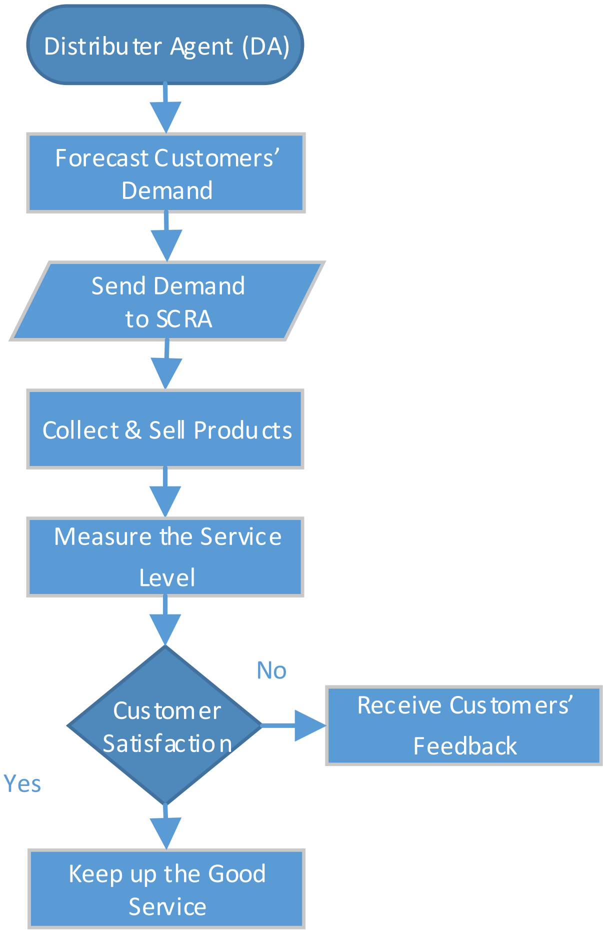


Figure 17: Distributor Agent

Table 9: Summary of agent-based decision making model

Agent	Actions	Decisions	Performance Measures	Goal
CA	Collect products, Update quantity level,	Collection responsibility, Compensation, Incentive, Fine, Demand for products, and Time to return.	Sorting time, Input quantity level, and Inventory cost.	Monitor the quantity level
SCRA	Sort products, Reuse operations,	Demand for products, Quality, and Recondition.	Sorting time, Lead time, Throughput, Utilization, Agent capacity, RI level, and Effectiveness.	Min sorting time and Monitor the quality level
RMA	Remanufacture products, harvest parts	Parts operation and Demand for parts.	Lead time, Cycle time, Throughput, Work-in-process, Utilization, Agent capacity, PH inventory level, and RI level.	Min operation cost.
RCA	Recycle products,	Powder/Liquid discharge and Selling decision.	Material recovery rate, Material recovered level, and Recycling revenue.	Max material recovery.
SA	Supply parts to RMA	Demand for parts.	-	-
DA	Distribute remanufactured products	Customer satisfaction.	Service level, Customer satisfaction, and Output quantity level	Max customer satisfaction level
RL System	Perform all activities in an efficient and cost-effective manner	-	All	Max revenue

5.4 List of performance measures:

The performance measures that are considered for this research at the operational level of management for a RL system are outlined in this section. Generally, at the operational level of management, there are many measures involved in evaluating a RL system. In this model, the main performance measure is the lead time of a product in the remanufacturing process. The other measures considered are products remanufactured per year, products parts harvested per year, products recycled per year, products reused per year, number of products remanufactured per day, input and output quantity level of each agent in a year. The performance measures considered in this model for each agent are tabulated in Table 10.

Table 10: List of performance measures

Performance Measures/Agents	**Collector**	**Sorter**	**Remanufacturer**	**Recycler**	**Distributor**	**Unit**
Lead Time			✓			Minutes
Products Reused		✓				Units/year
Products Remanufactured			✓			Units/year
Products Recycled				✓		Units/year
Products Parts harvested			✓			Units/year
Products Remanufactured			✓			Units/day
Input Quantity Level	✓	✓	✓	✓	✓	Units/year
Output Quantity Level	✓	✓	✓	✓	✓	Units/year

This concludes the methodology chapter. In this chapter, agent-based modelling technique, agent-based decision making model, RL process flow, and a list of performance measures were covered. The methodology can also be applied to electronic products like cell phones, toner cartridges, computers or any other electronic devices. The next chapter will introduce the Case Study on cell phone remanufacturing process.

CHAPTER 6

CASE STUDY: CELL PHONE REMANUFACTURING

This chapter will introduce the case study on cell phone remanufacturing. The chapter will envelop five sub-sections: 1) Introduction to cell phone and the product structure, 2) Cell phone remanufacturing process, 3) Cell phone RL process flow, 4) Cell phone agent-based decision making model, and 5) Experiments (i) Simulation, and (ii) Experiment analysis.

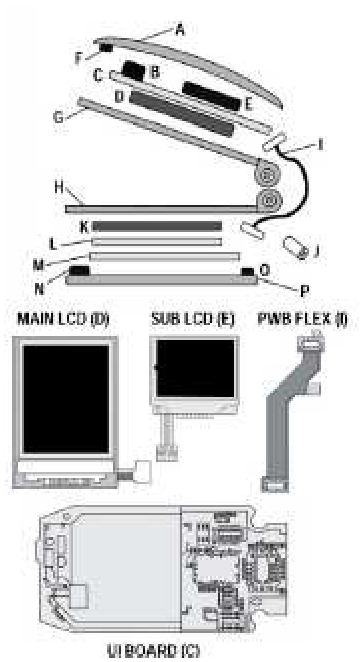
6.1 Introduction:

6.1.1 Cell Phone:

Cell phone is an electronic device used for communicating between two or more people. The first commercial cell phone, Motorola DynaTAC 8000X was developed by a team of engineers led by Martin Copper at Motorola in the year 1983 (O'Regan, 2012). Since then, several models have hit the stores and technological advancements have established cell phones as a real necessity for the day-to-day life activities. A cell phone though initially designed for making calls alone has evolved to include other features such as SMS, email, camera, media player and many more. Cell phone and mobile phone have been used interchangeably in both literature and practise. A smart phone is an extension of mobile phone incorporating the features of a PDA (Personal Digital Assistant). It functions with the help of an operating system, allows installing applications and includes features such as web browsing, Wi-Fi, GPS navigation and other touch screen facilities in addition to the features of a normal mobile phone. A cell phone may be sold either without a contract or with a contract from a network provider (Mondragon et al., 2011).

6.1.2 Cell Phone Structure:

A typical cell phone consists of parts like: housing, keypad (negligible for most smart phones), Printed Circuit Board (PCB), display, microphone, speaker, and battery (Franke et al., 2006). Cell phones also have different configurations, with keypad or without keypad, with flip or without flip and so on. A dissection of a flip cell phone with its parts is shown in Figure 18. The parts of the cell phone are labelled using capital letter in the diagram with their corresponding names listed beside it.



Part ID	Part Name
A	Cover A*(upper cover)*
B	Camera
C	User-Interface board
D	Main LCD (Liquid Crystal Display)
E	Sub LCD
F	Earpiece speaker
G	Cover B *(inner upper cover)*
H	Cover C *(inner lower cover)*
I	PWB (Printed Wiring Board) flex
J	Hinge module
K	Key pad
L	Dome sheet
M	Main PWB
N	Antenna
O	Microphone
P	Cover D *(lower cover)*

Figure 18: Structure of a cell phone with its parts, adapted from Kwak and Kim, (2010)

6.2 Cell Phone Remanufacturing:

Cell phone remanufacturing practice has been carried out for several years. A cell phone has an average lifetime of 22 months in Canada (CWTA, 2013b). Once the cell phone reaches its end of life period, it can be brought back to its useful phase by either remanufacturing or recycling the product. Remanufacturing process can be carried out at the product level and part level. Recycling process is carried out at the material level. There are many challenges for a successful remanufacturing process: falling price of new cell phones, short phone life cycle, disassembly of unfriendly designs, and transport, logistics & machining cost (Franke et al., 2006). Remanufacturing a cell phone requires complete disassembly, cleaning, inspection of all the parts, repair/replacement of parts, reassembly. Parts harvesting can also be carried out during remanufacturing process at part level. By successfully remanufacturing or recycling a cell phone, the process could lead to profit from remanufactured cell phones and environment protection from unnecessary landfills.

6.3 Cell Phone RL Process Flow:

The different companies/sub-systems that are part of the cell phone RL process (network) flow are listed below:

1. Collector,
2. Recycler/ Remanufacturer,
   - 2.1. Sorter,
   - 2.2. Remanufacturer,
   - 2.3. Recycler,
3. Remanufactured products distributor.

Each of them will be explained in the following paragraphs. The model is built based on answers given by an expert during an interview from a cell phone remanufacturing/recycling company located in Southern Ontario. A pictorial representation of the return process flow is shown in Figure 19.

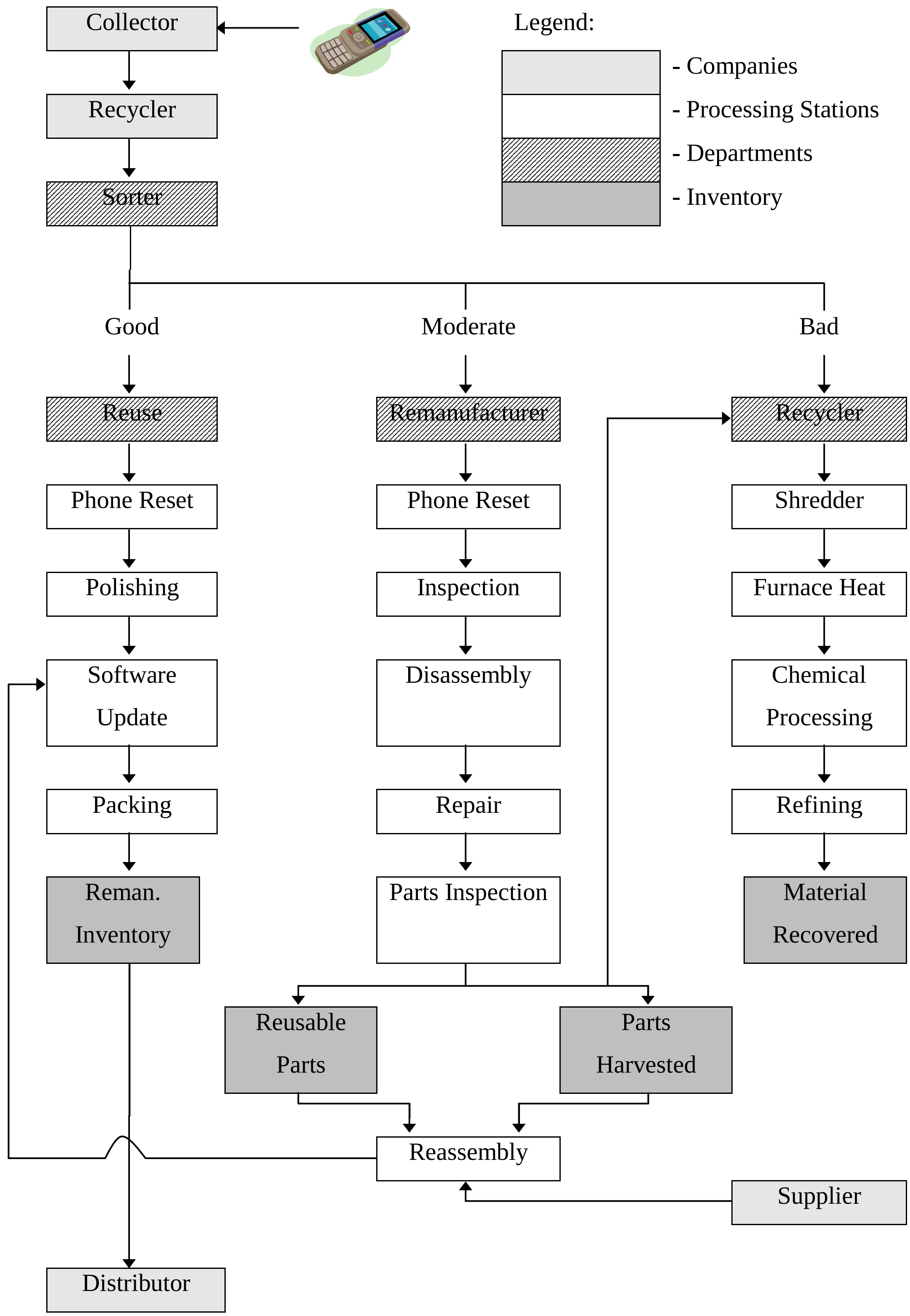


Figure 19: Cell phone RL process flow

6.3.1 Collector:

In Canada, the average age of cell phone is 22 months (CWTA, 2013b). The cell phones are then either sent for recycling or stored at home depending on the awareness among the locality. According to a recent survey by Recycle My Cell (RMC) program in association with Canadian Wireless Telecommunication Association (CWTA) it was found that 41% Canadians stored their old phone away after buying a new phone. Another 41% used it in a correct way to recycle/donate/sell/return the phone (CWTA, 2012). This number can be increased by bringing in a more sophisticated reverse logistics system across the country. The collection process of the retuned cell phones will be explained in the following paragraphs.

Reasons for Return:

First, it is important to understand why phones are returned. Some of the reasons for a cell phone return are explained below:

1. If the phone has become too old,
2. If the phone has any physical damage or technical issues related to software,
3. If the customer does not like the phone and returns it immediately after purchase under the company's return policy (usually 14 or 15 days),
4. When the contract period (1, 2 or 3 years) for the cell phone with the network provider is over or the contract has been terminated by the user, and
5. There may be other reasons as well for customers to return their phones.

The cell phones when returned are then collected in any one of the following methods,

1. Network Providers Retail Store,
2. IR (Independent Recyclers)/ Remanufacturers,
3. Public Groups/ Schools/Universities.

6.3.1.1 Network Providers Retail Store:

The customers can come in person and drop their cell phones at a network provider's retail stores. Depending on the condition of the phone and retailer's trade-in policy the customers may qualify for the trade-in program at the store.

1. ***Rebate:***

Few network providers have trade-in program at their stores. According to this policy, the customers can receive credit towards their new phone by returning their old cell phones based on few conditions. The conditions are based on the quality of the returned cell phone -- without damage or with damage. This trade-in policy process will be explained below.

1.1 Without Damage:

If a cell phone is covered under warranty and free from screen & water damage, then the customer will be offered a discount towards his/her new phone in the store. The old phone is then taken to an IR (Independent Recycler)/ Remanufacturer for reuse or recycling purpose.

1.2 With Damage:

If the cell phone is not covered under warranty or if the cell phone has screen or water damage, then the customer will not be offered a discount towards his/ her new cell phone. The old phone is similarly taken to an IR/ Remanufacturer for reuse or recycling purpose.

2. ***Without Rebate:***

2.1 Any Condition:

The return process however varies from one network provider to another network provider. Few network providers accept cell phones irrespective of the quality, network provider or OEM. The customers usually do not receive any discount towards their new phone.

6.3.1.2 IR/ Remanufacturer:

IR or the remanufacturer themselves act as collectors. They collect retired phones using three methods: using prepaid postal envelopes, drop-off location, and processing facility drop-off locations. Each of them will be explained below.

6.3.1.2.1 Prepaid postal envelopes:

The customers can send their used phone from home at their convenience using prepaid postal envelopes. The prepaid postal label for an envelope or a box can be printed at home from the collector's website (see Appendix A for a sample of a prepaid postal envelope). The customers are allowed to send a single phone using an envelope or a bulk of phones using a box. The collectors pay money to the senders for the retuned phones if they are in good working condition. The information on buyback price is available online to the public by all remanufacturing companies. For the purpose of this research, a sample buyback price list from a cell phone remanufacturing company in Southern Ontario has been taken; see Appendix B for the price list. The buyback price for a used cell phone usually ranges from $0 to $50 (Geyer and Doctori Blass, 2010). The average buyback price for a cell phone considered in the model is $54.33, based on the aforementioned pricelist.

6.3.1.2.2 Drop-off locations:

Some IRs and remanufacturers have dedicated drop-off locations for collecting retired cell phones. Customers can come and drop their cell phones at anytime of the year. The IR and remanufacturers sometimes host awareness programs about cell phone recycling to spread the word about cell phone recycling and its advantages. They also setup collections baskets at convenient locations in the locality for customers to drop their old cell phones.

6.3.1.2.3 Processing facility drop-off locations:

The processing facilities have drop-off boxes near their processing stations. Customers can come and drop their old phones. This location is not a major collection centre but a secondary collection center.

6.3.1.3 Public Groups/ Schools/ Universities:

Several public organisations like charities, non-profit organisations, and certain retail stores also participate in cell phone recycling. They do not carry out the processing operations but help the IRs and remanufacturers in collecting the used cell phones. Customers can drop their used cell phones in drop-off boxes at any of these locations. Public Schools and Universities also participate in cell phone recycling and have programs and drop-off locations around the campuses for students to throw their old cell phones. These cell phones are then sent to the IR/ remanufacturer for processing.

6.3.2 IR/ Remanufacturer:

The cell phones once collected by the collectors arrive at the IR or Remanufacturer processing facility for processing. The returned cell phones can be remanufactured to be reused or can be recycled to recover materials. The processing facilities have three departments: sorter, remanufacturer and the recycler.

6.3.2.1 Sorter:

At both the IR and remanufacturing facilities the returned cell phones are first sorted based on their quality into three categories: good, moderate and bad. Typically phones are checked for reuse, remanufacture and recycle options (US EPA, n.d.). The phones are sorted based on, functional, aesthetic & cosmetic appearance, age of the phone, and market value of the phone (Geyer and Doctori Blass, 2010). A detailed description about the classification is tabulated in Table 11 below. Once classified, the phones move to the next operation depending on the quality level. Sorting may be done by employees manually or using software programs and electronic devices. Software programs have increased sorting efficiency and effectiveness (Geyer and Doctori Blass, 2010). The condition under which quick sorting is economical with the help of electronic devices was justified by Zikopoulos and Tagaras (2008). In this model, sorting is assumed to be done manually.

Table 11: Classification of cell phones by the sorter

Quality Level	Condition	Next Stage
Good	Able to turn on/off, can dial & receive calls & messages, the screen is not damaged, can perform other basic operations, good physical appearance and not soaked in water.	Reuse
Moderate	Not able to turn on/off or cannot dial/receive calls & messages or the screen is damaged or cannot perform basic operations and not soaked in water.	Remanufacture
Bad	Not able to turn on/off plus the screen is damaged with very bad physical appearance of the phone and soaked in water.	Recycle

6.3.2.2 Reuse Operations:

The phones that are classified as good enter the reuse operation stage for basic reuse operations. These phones are good in condition and functionality, therefore they require less intense operations like cleaning and software updates. The reuse activities involve operations like phone reset, polishing, software update and packing. Initially the phone is restored to its initial factory settings and the data is erased. The phone is then polished and cleaned with basic tools to increase its aesthetic appearance. The software of the phone (especially for smart phones) is updated to the recent version. The phone is then packed and sent to the distribution company to be sold. The quality of the remanufactured phones quality is assumed to be as good as a new phone in the model.

6.3.2.3 Remanufacture Operations:

All the cell phones classified as moderate enter the remanufacturing operation stage. The remanufacturing operations are more detailed than reuse operations. It involves complete disassembly, cleaning and inspection of each part and reassembly. The steps involved in the remanufacturing stage are the following:

1. Phone Reset,
2. Inspection,
3. Disassembly,
4. Repair,
5. Parts Inspection, and
6. Reassembly.

The phone at the first step is reset to the initial factory settings and all the data is sanitised. This is to make sure the initial user's data is not misused and at the same time the new user has the original factory settings. In the next step, the phone is inspected to find the functional faults or optimal faults (Franke et al., 2006). Following the inspection step, the cell phone is completely disassembled to inspect each part in detail. Non-flip phones are automated with flexible disassembly (Franke et al., 2006). At the disassembly stage, the parts that are in good condition are untouched; they remain in the same place. The parts that are in bad condition are repaired. If repair is not possible then they are recycled and replaced by a new replacement part (provided by the supplier company). The parts that are in bad condition and cannot be repaired at first point are recycled directly. Parts harvesting also takes place at this stage. Valuable parts that cannot be recycled but can be reused in other products are harvested. On an average the resale value of an harvested part from a cell phone is $4.07 per part (Kwak and Kim, 2010). The resale price of each part in the cell phone is tabulated in Table 12 below.

Table 12: Resale price of individual parts of a cell phone (Kwak and Kim, 2010)

Part ID	Part Name	Resale Price ($)
A	Cover A*(upper cover)*	2
B	Camera	2.5
C	User-Interface board	2.5
D	Main LCD (Liquid Crystal Display)	7.5
E	Sub LCD	4
F	Earpiece speaker	0.5
G	Cover B *(inner upper cover)*	2.5
H	Cover C *(inner lower cover)*	1.5
I	PWB (Printed Wiring Board) flex	1
J	Hinge module	0.25
K	Key pad	1.5
L	Dome sheet	0.5
M	Main PWB	10
N	Antenna	1
O	Microphone	0.5

The reusable parts along with the repaired/replaced parts are brought together for reassembly. The Disassembly and reassembly time are directly proportional to faults (Franke et al., 2006).The reassembled product is then updated with the latest software version. After all the processing activities, the phones are graded depending on the model and the amount of work that was involved before sale. Resale value usually depends on brand & model, grade, age and condition of the phone (Geyer and Doctori Blass, 2010). Once the price is determined by the remanufacturer, the phones are then packed and labelled as remanufactured product and sent to the distribution company to be sold in the market. The process time for each operation in the model has been adapted from a similar kind of study in the literature involving telephone remanufacturing (Li et al., 2013). The modelling technique used by Li et al., (2013) was an analytical model, Graphical Evaluation and Review Technique based Remanufacturing Process Routing. The process times of most stations were deterministic in the aforementioned paper, process times are often probabilistic, so statistical distributions were used for the process time of each processing station in the model. The process times of all the process stations along with the products flow ratio after an operation are tabulated in Table 13 below.

Table 13: Process time for cell phone remanufacturing operations

Adapted from Li et al., (2013)

Process	Distribution of Time (t in minutes)	Flow Ratio		
		Good	Moderate	Bad
Sorting	Exponential (0.5)	25%	60%	15%
Phone Reset	Exponential (1.5)	-		
Polishing	Exponential (4)	-		
Software Update	Exponential (3.5)	-		
Packing	Exponential (1.5)	-		
Inspection	Exponential (1.5)	-		
Disassembly	Exponential (1)	-		
Parts Inspection	Exponential (3)	60%	-	40%
Repair	Uniform (9, 15)	75%	-	25%
Reassembly	Exponential (3)	-		

6.3.2.4 Recycling Operations:

The cell phones that are classified as bad are recycled in the recycling department. Also, material recovery is preferred when remanufacturing costs are too high and demand for remanufactured phones are low (Franke et al., 2006). The phones first enter the shredding stage; many phones are placed together in a shredder and shredded into small pieces. The shredded pieces are then transferred to a furnace. The furnace is heated at a high temperature. In the process, materials such as plastics are burned and toxic fumes & gases are captured in a 'bag house' so that the environment is not affected. The remaining materials undergo a chemical process; different materials present in the phone such as Copper, Gold, Silver, Palladium and Platinum are separated. The materials are then further refined, brought to the standard form, and sold to an electronic parts manufacturer or to a raw materials extractor. The process times of all the stations are tabulated in Table 14.

Table 14: Process time for the cell phone recycling operations

Process	Distribution of Time (t in minutes)
Shredding	Normal (10, 1)
Furnace Heating	Normal (15, 2)
Chemical Processing	Normal (10, 1)
Refining	Normal (15, 2)

A cell phone contains valuable materials that can be sold in the market after recycling. The common material compositions of a cell phone are listed in Table 15 along with their weight in the cell phone and their value in the market.

Table 15: Cell phone material composition with their weight and value (Sullivan, 2006)

Metal	Weight (g)	Value ($)
Copper	16.0000	$ 0.03
Silver	0.3500	$ 0.06
Gold	0.0340	$ 0.40
Palladium	0.0150	$ 0.13
Platinum	0.0003	$ 0.01

6.3.3 Remanufactured products distributor:

The distribution activities may be carried out by either an independent distribution company or by a cell phone remanufacturing company. In the case of an independent distribution company, cell phones will be purchased from a remanufacturing company and later sold in store or online. The cell phone remanufacturing company will sell the phones directly in store or online. The average selling price of a remanufactured cell phone by the cell phone remanufacturing company is $200. This information was attained from a remanufacturer's website.

6.3.4 Cost and Price calculations:

This section will provide cost calculations for a cell phone in a RL system. The total cost for a remanufactured cell phone was calculated with the help of published data by Nikolaidis (2009). This paper gave details on profit margin for a remanufactured cell phone. The profit margin was equal to 5-10% for a remanufactured cell phone. The total cost for a remanufactured cell phone will be equal to the remanufacturing cost and acquisition cost of a cell phone. The average selling price of a remanufactured phone was found from the company's website to be $200. With the help of profit margin and average selling price, the average total cost was found to be $180 for a remanufactured cell phone. The calculations are shown below,

<u>Given:</u>

Average profit margin for a remanufactured cell phone = 10%,

Average selling price of a remanufactured cell phone = $200,

Acquisition cost of a returned cell phone = $54.33.

<u>To Find:</u>

Total cost of a cell phone (in dollars) = x,

Remanufacturing cost of a cell phone (in dollars) = y,

$$x = Revenue\ (1 - Profit\ Margin)$$

$$x = 200\ (0.9)$$

$$\boxed{x = 180}$$

Thus, the total cost for a remanufactured cell phone= $180. From the total cost, the remanufacturing cost can be determined. The average acquisition cost or buyback cost of a returned cell phone for the remanufacturer is equal to $54.33.

$$x = y + Aquisition\ Cost$$

$$y = x - Aquisition\ Cost$$

$$\boxed{y = 180 - 54.33 = 125.67}$$

Therefore, the remanufacturing cost for a cell phone was found to be as $125.67. Table 16 provides a summary of cost and price involved for a cell phone in the RL system.

Table 16: Summary of cost and price of a remanufactured cell phone

Cost/Price of a cell phone	**Collector**	**Remanufacturer**	**Distributor**
Avg. Acquisition/Buyback Cost	$ 54.33	$ 54.33	$ 200.00
Avg. Remanufacturing Cost	-	$ 125.67	-
Total Cost	$ 54.33	$ 180.00	-
Avg. Selling Price	-	$ 200.00	$ 225.00
Avg. Selling Price of a Part	-	$ 3.64	-

6.4 Cell phone decision making process:

The cell phone decision making process is based on agent-based model. The actions and decisions have been adapted from the generic decision making process (from methodology section) with few modifications according to the cell phone remanufacturing process. The actions and decisions that take place in the agents are shown with shaded boxes and continuous arrows to differentiate the agents from the generic model. The boxes not shaded with dashed lines are not considered in the cell phone case study.

The different companies/entities in a cell phone RL system are considered as agents. The agent-based model as introduced earlier consists of 6 agents: Collector Agent, Sorting-cum-Reuse Agent, Remanufacturer Agent, Recycler Agent, Supplier Agent, and Distributor Agent. Each agent of a cell phone remanufacturing process will be explained below with the actions and decisions it performs.

6.4.1 Collector Agent (CA):

The Collector Agent (CA) in the decision making process for a cell phone will be explained in this section. The actions and decision that take place in the CA are shown in Figure 20. As shown, the collection activities can be initiated by the customers, IR, Non-Profit organisations, and retailers. The OEM does not involve in the collection or remanufacturing process. However, the OEM pays some incentives to the IR to collect their brand's used cell phones. This is the first decision block, after which the phones are collected. The compensation decision block is bypassed as this does not correspond for cell phones. At the next decision block, customers are given incentives based on the collectors' policy and inspection rules. Further, the 'fine?' decision block is avoided and action passes on to the 'update quantity level' box.

The other actions and decision are generic, the CA receives information on the number of phones required from the SCRA and sends them to SCRA if 'yes', otherwise stores them at the inventory and calculates the inventory cost.

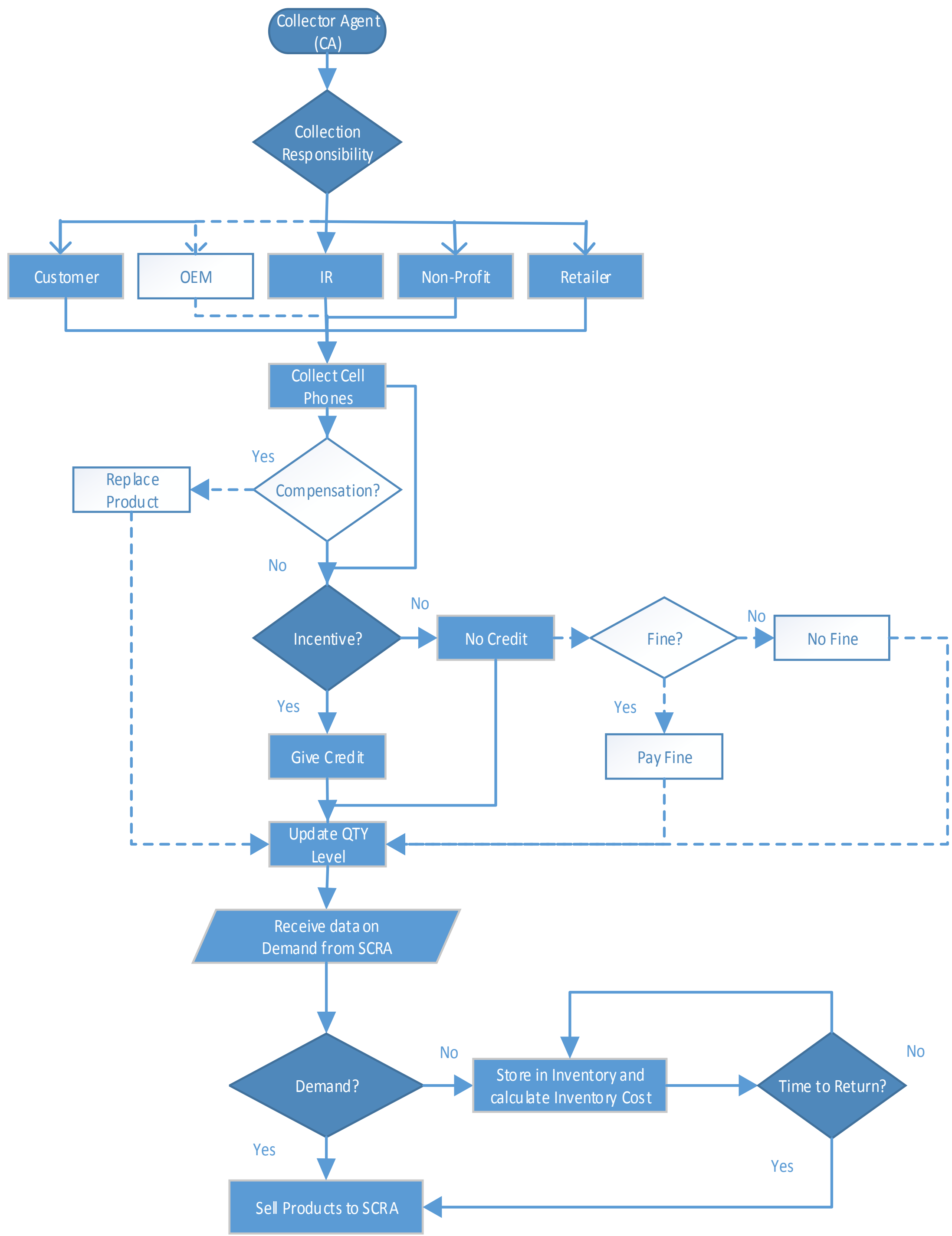


Figure 20: CA decision making process for cell phone

6.4.2 Sorting-Cum-Reuse Agent (SCRA):

The SCRA begins its activities by receiving information on demand for cell phones from the DA at the first step. If there is a demand for cell phones, the SCRA sends the information to the CA or else the SCRA processes other electronic products. The SCRA then collects the phones from the CA and increments the SCRA inventory level according to the number of cell phones collected for processing. The SCRA usually performs two actions: sorts the cell phones and performs the reuse operations. Based on the quality decision block, the phones are sent to reuse, remanufacture or recycle if they are good, moderate or bad respectively. For a cell phone reconditioning process is sidestepped as it is not required.

After reuse operation, the SCRA inventory level is decremented by the number of phones processed. In the next step, if the SCRA inventory level is less than one than the action passes on to ‘send data on demand to CA’, if not the Remanufactured Inventory level is updated. The SCRA orders phones from the CA, in the model, a random batch of 4447 cell phones is ordered from the Collector and processed. Once this batch is processed, a new batch of the same size is ordered and processed. This process goes on till the end of the year. Towards the end of the year, the number of phones collected from the CA and the number of phones processed at each category level: good, moderate and bad can be calculated. The actions are depicted in Figure 21 below.

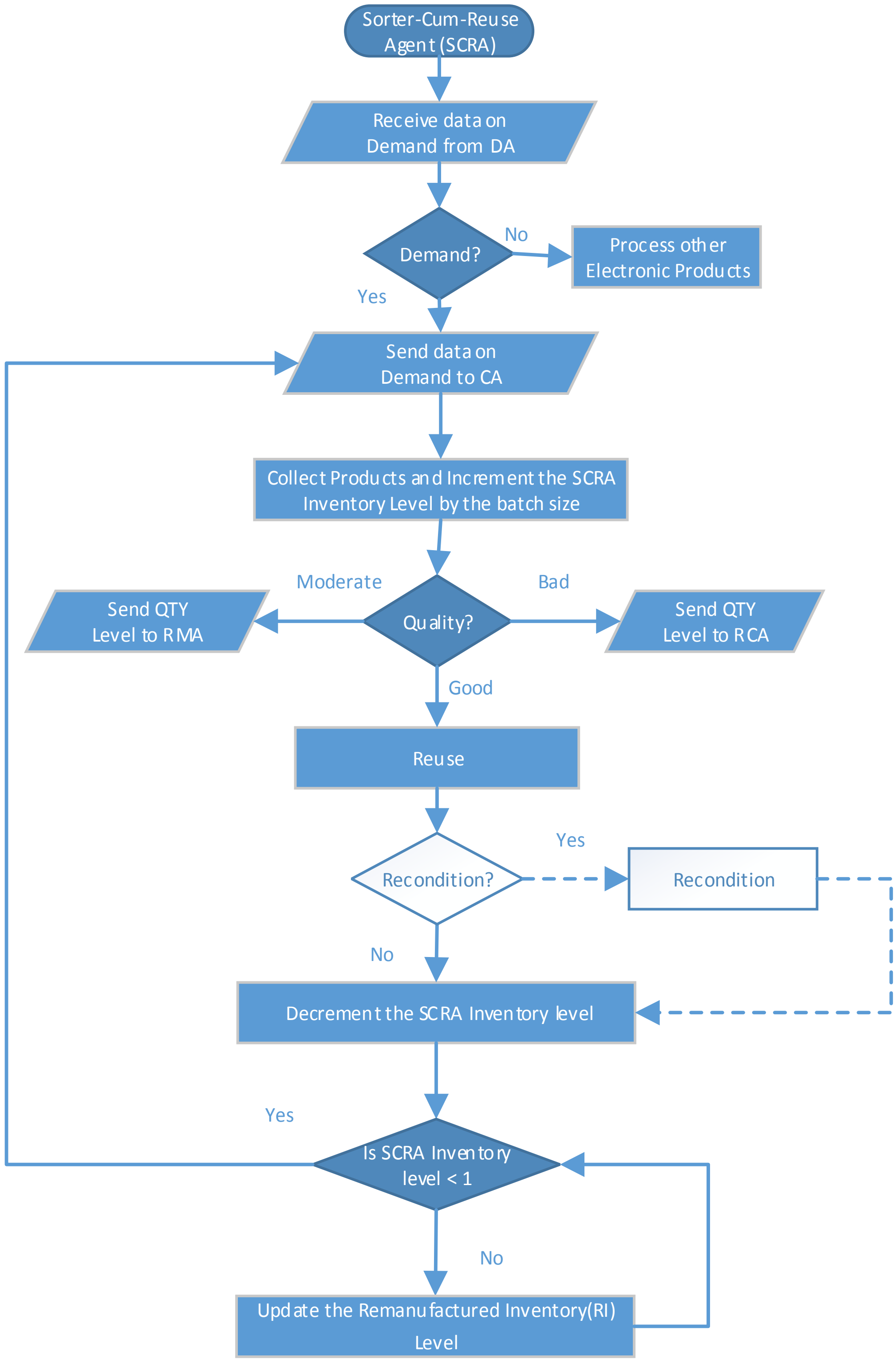


Figure 21: SCRA decision making for a cell phone

6.4.3 Remanufacturing Agent (RMA):

The RMA is responsible to carry out the cell phone remanufacturing process. At first, the quantity level of remanufactured products is received from the SCRA. Phones are received from SCRA and completely disassembled. The operation required for a part is then decided from the generic list: reuse, recycle, repair, refill, recondition, and parts harvesting. For a cell phone, only reuse, repair, recycle, and parts harvest recovery options are applicable. The disassembled parts of a cell phone are inspected if they can be reused, repaired, recycled, & parts harvested based on their quality. Then, once the recovery operations are complete, the processed parts are brought together for reassembly. The phone is then reassembled and stored in the inventory. The RI level is also updated each time a phone is remanufactured. The actions and decisions of the agent are illustrated in Figure 22.

The number of phones remanufactured per year and the revenue from remanufacturing phones per year are the two important performance measures of the remanufacturing agent.

6.4.4 Recycler Agent (RCA):

The RCA recycles the phones that are of bad quality. The major difference from the generic decision making process for a cell phone is the ‘discharge hazardous material’ decision making stage. As cell phones do not contain either of these, this stage is bypassed. Apart from this difference, the other actions and decision are similar to the generic decision making process. The phones are recycled and then sold to either raw material extractors or new parts manufacturers.

The performance measures that will be calculated at the recycler agent are: phones recycled per year, and revenue generated by recycling cell phones in a year. The recycler agent’s actions and decisions are depicted in Figure 23.

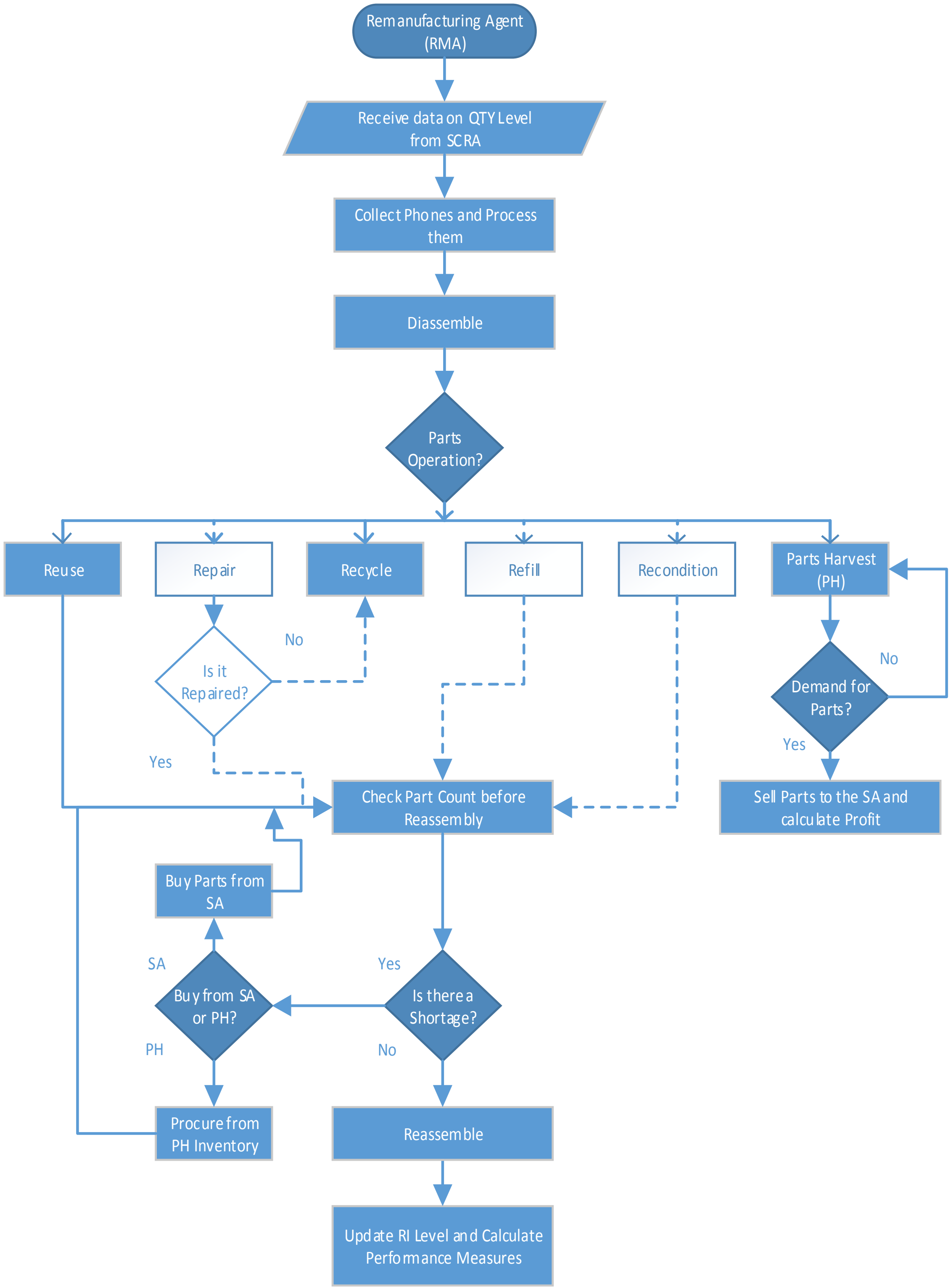


Figure 22: RMA decision making process for a cell phone

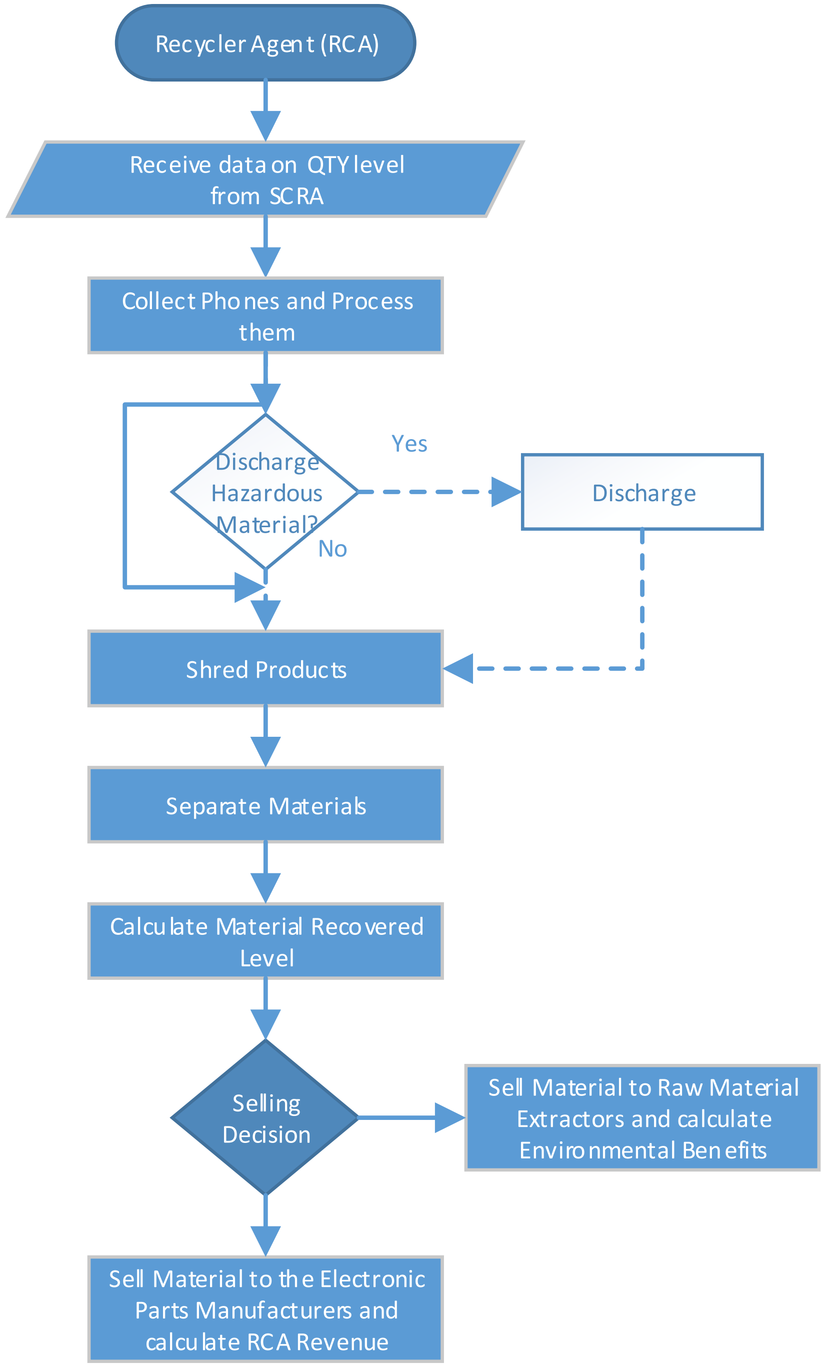


Figure 23: RCA decision making process for a cell phone

6.4.5 Supplier Agent (SA):

The SA decision making process for a cell phone is analogous to the generic decision making process. There are no major changes involved. The SA duty is to produce parts and satisfy the RMA's requirements as and when required. The SA produces cell phones parts throughout the year and sells them to either the OEM or the RMA. The decisions and actions are enlightened in Figure 24.

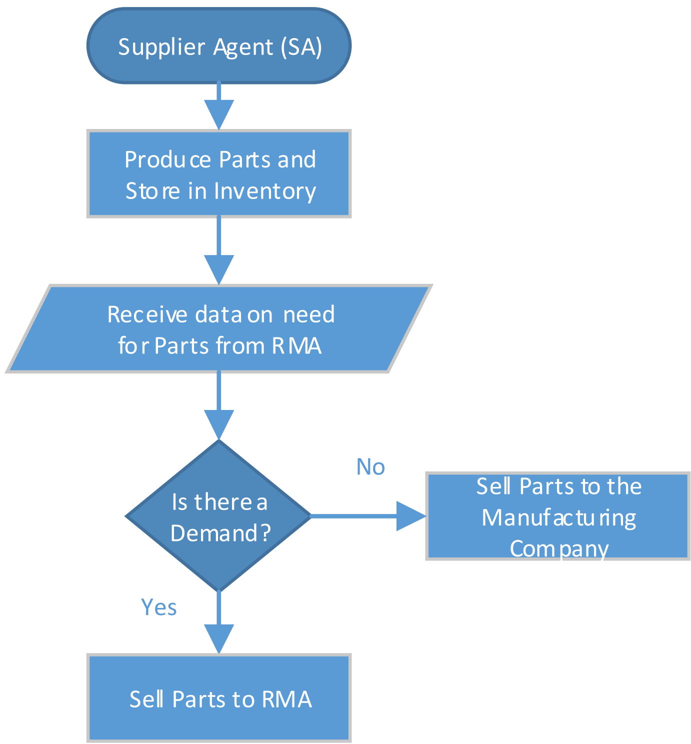


Figure 24: SA decision making process for a cell phone

6.4.6 Distributor Agent (DA):

The DA activities for a cell phone are again similar to the generic process. The DA at first step forecasts the demand for cell phones based on forecasting techniques or historical data. Forecasting method like Holts method could be used to forecast the demand for cell phones. The DA then requests the SCRA for cell phones; once the cell phones arrive, the DA sells the cell phones to the public. See Figure 25 below for decision making process for cell phones. The DA calculates the number of phones sold per year and the profit gained by selling remanufactured cell phones per year.

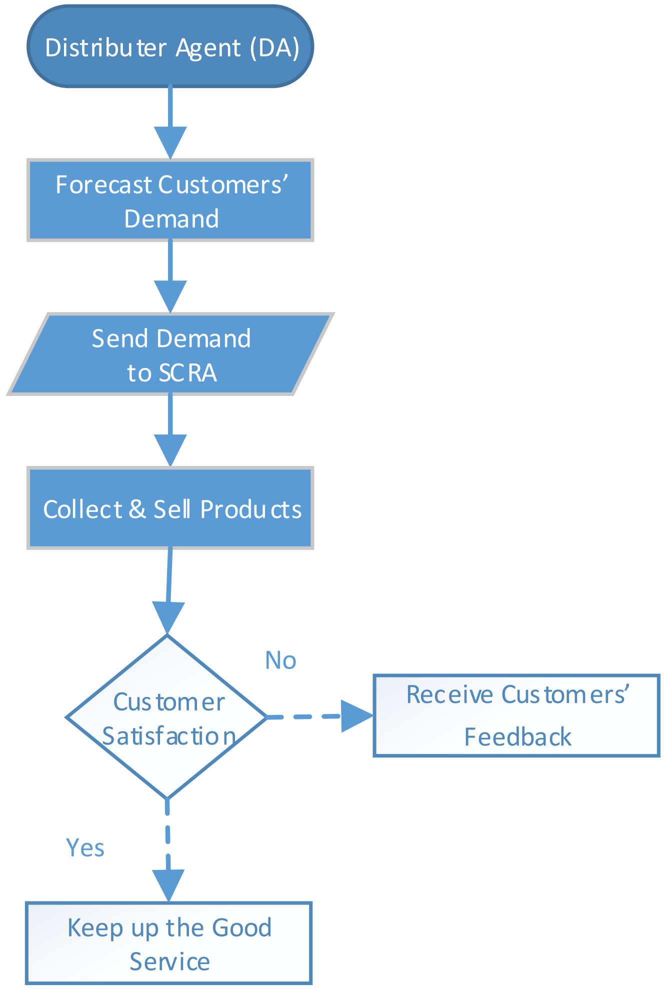


Figure 25: DA decision making process for a cell phone

This concludes the decision making process for a cell phone. The next section will introduce the Simulation experiments for a cell phone remanufacturing process.

6.5 Experiments:

6.5.1 Simulation:

A base model of the cell phone remanufacturing process was constructed with the help of the agent-based modeling technique. The software used for simulation in this research is ProModel. The parameters that are considered in the model are listed in Table 17. The different performance measures are the output in the simulation model. The simulation is run for duration of 1920 hours (considering 240 working days per year with 8 working hours per day). Warm-up period was considered to remove the transient state before collecting statistics; the warm-up period was equal to 488 hours (See Appendix C for the warm-up period calculation and graph). The model was replicated 15 times with a confidence level of 95% and error amount of 1 (Appendix D provides the calculation for the number of replications). The time unit used in the simulation is minutes.

In a year, 1,067,266 cell phones are returned in Canada. In the base model, the recycler company or the sorting cum reuse agent buys cell phones in batches of 4447 cell phones from the collector company in a year. Once the first batch is completed the second batch is ordered to the collector, and so on till the end of the year. The products are reused, remanufactured or recycled. The profit from parts harvested cell phones, remanufactured cell phones and recycled material is calculated. The environmental benefits of remanufacturing or recycling are also calculated.

Table 17: Summary of input parameters used in the simulation model

Parameters	**Value**	**Adapted from**
Classification of cell phones based on their quality	Pr(Good) = 0.25; Pr(Moderate) = 0.60; Pr(Bad) = 0.15; (Pr stands for probability)	(Nikolaidis, 2009)

Parameters	Value	Adapted from
Cell phones collected by Recycle My Cell and other member initiatives in Canada in the year 2013 (Arrival Rate, λ)	1,067,266 cell phones per year in Canada	(RMC, 2014)
Process time of each processing station in the model.	Exponential, Normal and Uniform distribution functions, and constant values. See Tables 13 & 14 for individual processing stations process time	Based on interviews and (Li et al., 2013)

6.5.1.1 Assumption:

There are few assumptions considered in the model.

- There is no disposal of returned phones. All cell phones are remanufactured, material recovered or parts harvested.
- In the model all phones that come for return in a day are collected by the Collector Agent, none of them are returned back or turned away.
- The model is assumed to operate 240 days in a year with 8 working hours per day.
- There are no machine failures or breakdowns of processing stations in the model.
- The time it takes for a product to move from one agent to the other agent (i.e., Transportation time) is zero in the model.
- Only one type of cell phone model is considered in the simulation experiment.

6.5.1.2 Results and Discussion:

Based on the cell phone RL process flow chart (Figure 19) in section 6.3, the model was simulated and the performance measures were calculated. The results are tabulated in Table 18 below.

Table 18: Simulation results

Performance Measures/ Agents	**Collector**	**Sorter Cum Reuse**	**Remanufacturer**	**Recycler**	**Unit**
Lead Time			29.59		Minutes/phone
Reused Phones		37,995			Units/year
Remanufactured Phones			99,285		Units/year
Recycled Phones				31,857	Units/year
Phones Parts Harvested			20,464		Units/year
Number of Phones Remanufactured per day			549		Units/day
Input Quantity Level	1,067,266	200,976	90,996	31,876	Units/year
Output Quantity Level	200,976	99,285	61,399	31,857	Units/year

The table above lists the lead time, reused phones, remanufactured phones, recycled phones, phones parts harvested, the input quantity level of each agent and the output quantity level. The performance measures were calculated for a year. The lead time to remanufacture one cell phone was found to be 29.59 minutes. The number of phones that underwent reuse operations was 37,995 cell phones in a year. A total of 99, 285 phones were remanufactured in one year. The number of cell phones that were recycled was 31,857 phones per one year. 20,464 cell phones were parts harvested in a year. Based on the performance measures calculated, the results will be discussed for each agent separately, and recommendations for improvement will be provided.

To validate the results, one of the performance measures, the lead time to remanufacture a cell phone was compared with a similar kind of study in literature by Li et al (2013). The authors measured the lead time to remanufacture a telephone to be 20.14 minutes using an analytical model, Graphical Evaluation and Review Technique based Remanufacturing Process Routing and a simulation model to verify the results. In the present simulation model, the lead time to remanufacture a cell phone was found to be 29.59 minutes per cell phone. This was helpful to validate the results of the present simulation model.

6.5.1.2.1 Collector Agent:

It is recommended that the collector should have an initial sorting stage. Identification and pre-sorting can reduce volume and model diversity of phones sent to the manufacturing floor (Franke et al., 2006). By having an initial sorting stage, the collector will be able to provide the number of phones in each category, good, moderate and bad to the SCRA of the recycling company. In addition, the collector could develop an 'Interconnected Database System (IDS)' among other agents that would provide information on the number of phones returned and the cause of damage for each phone and send it to the recycling company. In order to differentiate one phone's damage from another, the collector can generate a quick response (QR) code for each phone that would contain the quality level and problem of the phone. The recycler can then scan the code and save time in sorting and inspections stages. Thus, with the help of the suggested interconnected database system, the collector will be able to provide: 1) The number of phones that would come to the recycling company (i.e. quantity level); 2) The number of phones in each category (i.e. quality level); and 3) The problem or damage of the retuned phone. This would partially address the uncertainty in quantity and quality levels. Regarding uncertainty in time, it can be suggested that the SCRA have a periodic production plan on which a batch of product can be ordered at a particular time of the week according to the demand from the DA and start the production accordingly, thus attenuating the uncertainty in return time of the product.

For each reusable phone, the collector spends some cost in storing them and for trade-up programs for the customers, this adds to the inventory cost for the collectors. The inventory cost for the collector was calculated and it was found that the collector spends $7,009,384 on reusable (good and moderate) phones per year. This amount is not confined to one collector; there may be several collectors at different locations in the country. In Canada, for a return rate of 1,067,266 phones per year, the total inventory cost for all the collectors together is equal to $7,009,384 per year. The inventory cost is found using the formula given below,

$$Inventory\ cost = 20\%\ (Number\ of\ reusable\ products * value\ of\ a\ reusable\ product)(Dollars)\ per\ year$$

$$= 0.20\ (129{,}015 * 54.33)$$

$$= \$7{,}009{,}384 \text{ per year}$$

6.5.1.2.2 Sorting-cum-Reuse Agent:

The major recommendation for the sorting agent would be to have a scanning system that would sort the products according to the information sent by the collector. The information on the quality of a cell phone and the problem associated with a phone provided by the collector agent's recommended IDS would be very much useful in reducing the sorting time of a product by an operator, and eventually many products could be sorted with the same available capacity.

6.5.1.2.3 Remanufacturer Agent:

In the remanufacturer agent, the disassembly stage was identified as one of the main bottleneck. This could be rectified by increasing the number of operators in that station. Further, as different phones have different architecture, they require different disassembly process when done manually. As previously highlighted to include a bar code inside the battery cover containing information on the disassembly process is one solution to improve the disassembly process (Saar et al., 2004). The repair station was the other bottleneck in the remanufacturer agent, and it required many stations to repair a batch of phones. With the suggested IDS, the remanufacturer will be aware of the cause of damage, and will repair the part by quickly finding the right repair method for that particular damage reason, if not for this information, more time would be spend to find out the right method for repair. With the help of the suggested IDS a lot of time in the repair process could be saved. Also, the remanufacturing agent harvests parts; the number of phones parts harvested in the model is 20,464 phones per year. On an average the resale value for a harvested part from a cell phone is $4.07 per part (Kwak and Kim, 2010). Assuming a cell phone consists of 5 parts, $20.35 can be made by parts harvesting one cell phone in a year. From the model, the revenue that can be generated by harvesting 20,464 cell phones $416,442.40 per year (this is converted from the 372,448.80 USD at the rate 1.15) .

6.5.1.2.4 Recycler Agent:

In the model, the recycler agent recycles 31,857 cell phones per year. Once phones are recycled, valuable materials such as Copper, Silver, Gold, Palladium, and Platinum can be extracted. The metals present in a normal cell phone along with their weight and value is given in Table 19.

In a year, by recycling 31,857 phones, the recycler can extract 509,712 grams of copper with a value of $955.71 and similarly for other materials. This generates total revenue of $20,069.91 per year from 31,857 cell phones recycled in Canada. Thus, by recycling cell phones, revenue from valuable materials can be generated, the earth’s natural resources can be preserved, air & water pollution can be reduced, and a lot of energy can be saved (US EPA, n.d.).

Table 19: Metal content and value in a single cell phone, source for column 1, 2, and 3 (Sullivan, 2006)

Metal	Weight (g)	Value ($)	Material Recovered (g) per year	Revenue ($) from material recovery/ year
Copper	16.0000	$ 0.03	509712.0000	$ 955.71
Silver	0.3500	$ 0.06	11149.9500	$ 1,911.42
Gold	0.0340	$ 0.40	1083.1380	$ 12,742.80
Palladium	0.0150	$ 0.13	477.8550	$ 4,141.41
Platinum	0.0003	$ 0.01	10.8314	$ 318.57
Total			522,433.7744	$ 20,069.91

6.5.1.2.5 Distributor Agent:

The amount of cell phones remanufactured per year in the model is equal to 99,285 cell phones. The distributor company buys the remanufactured cell phones from the recycler company and sells the phones to the public. Assuming the average selling price of a remanufactured phone to be $225 in Canada and if the distributor sells 99,385 cell phones in a year, a profit of $ 22,339,125 can be generated per year in Canada.

This profit is not for one particular distributor alone, there may be several distributors across the country. Overall, if all the distributors in Canada sell 99,385 remanufactured phones per year, then $ 22,339,125 can be generated per year. It is not necessary that the remanufactured phones will be sold only inside the country; they can also be sold in other countries.

It is important that the reliability requirement of a remanufactured phone is equal to the reliability requirement of a new phone (Lebreton, 2007). Hence the distributor agent has to have good quality cell phones and meet customers demand on time in order to be successful. The table below summarises the recommendations given for each agent.

Table 20: Summary of recommendations for each agent

Agent	**Problem**	**Recommendations**	**Solution**
CA	The SCRA is unaware of the product's quality that comes for return.	* To have an initial sorting stage, * To have an IDS, * To attach a QR code containing the product's information.	*CA manages to store information on all the returned products * SCRA saves time in sorting the returned products
SCRA	Time of return is not known	* To have periodic production plans	Products arrive in batches every week, month or year thus rectifying the time of return problem
RMA	(i) Disassembly station was a bottleneck. (ii) Repair station was another bottleneck	(i) * To increase the capacity of the disassembly station. * To attach bar codes containing the disassembly procedure during manufacturing to ease the disassembly process (ii) The CA could input the problem associated with a product in the IDS	The bottlenecks could be removed and more products could be produced
DA	Unaware of the number of products remanufactured in a particular time period	The RMA could update the number of products remanufactured for each period of time in the IDS	The DA can now lookup in the IDS and know how many products are remanufactured and how much to order from the RMA

6.5.1.3 Environment Benefits:

The benefits of remanufacturing and recycling do not only profit the organizations but also aids the environment on a large scale. Some of the environment benefits are:

1. Reduced pollution,
2. Savings in energy,
3. Raw materials are preserved, and
4. Toxic materials are kept away from landfill.

6.5.1.3.1 Reduced pollution:

It has been found that by reusing or remanufacturing one cell phone, 15 kilograms of CO2 can be reduced from polluting the environment that would otherwise be produced during a new phone manufacturing (Seliger et al., 2006). From the experiment, by remanufacturing 99,285 phones the environment can be protected from a total of 1,489,275 kilograms of CO2 emissions. Thus pollution can be reduced and the environment can be saved from CO2 emissions.

6.5.1.3.2 Savings in Energy:

A lot of energy in terms of electricity, water, and other resources are required in the manufacturing stage of a cell phone. During the production stage of the display module and printed circuits board of a cell phone, 250 MJ of energy is consumed for one cell phone (Seliger et al., 2006). The total energy required for remanufacturing a product is 15% of the new product manufacturing energy (Gregory et al., 2009; Ilgin and Gupta, 2012). Assuming the same 15% of new product manufacturing energy required for remanufacturing a cell phone, 212.5 MJ of energy can be saved from remanufacturing one cell phone. If remanufactured phones are made avoiding new cell phones manufacturing, 21TJ of energy can be saved in a year for other purposes by remanufacturing 99,285 phones in a year.

6.5.1.3.3 Raw materials are preserved:

In the remanufacturing process existing materials are used and virgin raw materials are untouched in the process. Thus by remanufacturing, virgin raw materials can be preserved for other uses. Also, by recycling a lot of material can be recovered. These recovered materials can then be used in other products manufacturing or can be incorporated with the virgin raw materials in new cell phone production stage.

For refining one tonne of copper from raw materials, 80,000 tonnes of raw materials are required. This quantity is mined from underground. Similarly for refining one tonne of copper from recycled materials, only 14 tonnes of recycled material are required (*About OES - Updated February 22, 2013*, 2013). Thus, a large amount of virgin raw materials can be preserved during the copper refining process. In the experiment, 0.52 tonnes of material are recovered per year by recycling 31,857 cell phones as shown in Table 19, 0.52 tonnes of recycled material can be used to refine 0.037 tonnes of pure copper. Thus, by recycling, existing materials can be reused in new parts manufacturing, earth's natural resources can be preserved, and the pollution caused during raw materials extraction can be reduced.

6.5.1.3.4 Keeping toxic materials away from landfill:

Cell phone contains a lot of toxic waste included in the printed circuit boards and batteries. By reusing or remanufacturing cell phones, 99,285 cell phones per year in Canada can be kept away from the landfill and toxic waste on the environment can be reduced. This concludes the simulation experiment; the next section will introduce the experiment analysis.

6.5.2 Experiment Analysis:

Once the base model was run and the results were tabulated, experiment analysis was considered to take into account the different situations under which the model would act. Experiment analysis consists of order quantity analysis and scenario analysis.

6.5.2.1 Order Quantity Analysis:

The recycler company or the sorting cum reuse agent orders a particular amount of cell phones from the collector agent for production. In the base model, the order quantity was 4447 cell phones. In order to see the change in the recycler company's output if the order quantity is changed, order quantity analysis was considered.

In this experiment, 15 different order quantities are considered. The cell phone order quantity is varied from 2.5% to 100% of the total number of cell phones returned in a year. The percentage of the total order quantity for the year is split into 48 working weeks and ordered every working week, if the recycler has not finished producing the previous batch then, a new batch is not ordered until the current batch is completely processed. For example, in scenario 1 the recycler orders 2.5% of the total number of cell phones returned in a year from the collector, 2.5% of 1,067,266 cell phones is equal to 26,682 cell phones. The 26,682 cell phones are split equally for 48 working weeks, and in every week 556 cell phones are ordered. The experiment setup is shown in the Table 21 below.

Table 21: Order quantity analysis experiment set up

Scenario	**Order percentage in a year (%)**	**Order quantity per week (units)**
1	2.5	556
2	5	1,112
3	7.5	1,668
4	10	2,223
5	12.5	2,779

Scenario	Order percentage in a year (%)	Order quantity per week (units)
6	15	3,335
7	17.5	3,891
8	20	4,447
9	25	5,559
10	30	6,670
11	35	7,782
12	40	8,894
13	50	11,117
14	75	16,676
15	100	22,225

The 15 scenarios were run and the recycler company's output was calculated. The results are tabulated in the table below.

Table 22: Summary of order quantity analysis experiment results

Scenario	Order percentage in a year (%)	Remanufactured cell phones (units) per year	Recycled cell phones (units) per year	Revenue ($) per year from remanufactured phones
1	2.5	13,351	4,280	$ 3,003,896.04
2	5	26,600	8,556	$ 5,984,934.21
3	7.5	39,879	12,779	$ 8,972,842.63
4	10	53,018	17,047	$ 11,929,022.71
5	12.5	66,192	21,254	$ 14,893,231.81
6	15	79,226	25,503	$ 17,825,894.55
7	17.5	92,352	29,703	$ 20,779,119.24
8	**20**	**99,259**	**31,810**	**$ 22,333,190.92**
9	**25**	**99,394**	**31,863**	**$ 22,363,637.49**
10	**30**	**99,244**	**31,880**	**$ 22,329,806.00**
11	**35**	**99,292**	**31,899**	**$ 22,340,598.10**

Scenario	Order percentage in a year (%)	Remanufactured cell phones (units) per year	Recycled cell phones (units) per year	Revenue ($) per year from remanufactured phones
12	40	99,295	31,857	$ 22,341,486.13
13	50	99,284	31,847	$ 22,339,001.40
14	75	99,247	31,873	$ 22,330,556.24
15	100	99,357	31,893	$ 22,355,250.08

For each of the 15 scenarios, the total number of cell phones remanufactured per year, total number of cell phones recycled per year, and the revenue per year from remanufactured phones were calculated. From the 1st scenario to the 7th scenario as the order quantity increases, the number of cell phones remanufactured and recycled also increases. But after the 8th scenario i.e., at the order percentage of 20% per year, the number of products remanufactured per year becomes to stagnate as shown in Figure 26 below.

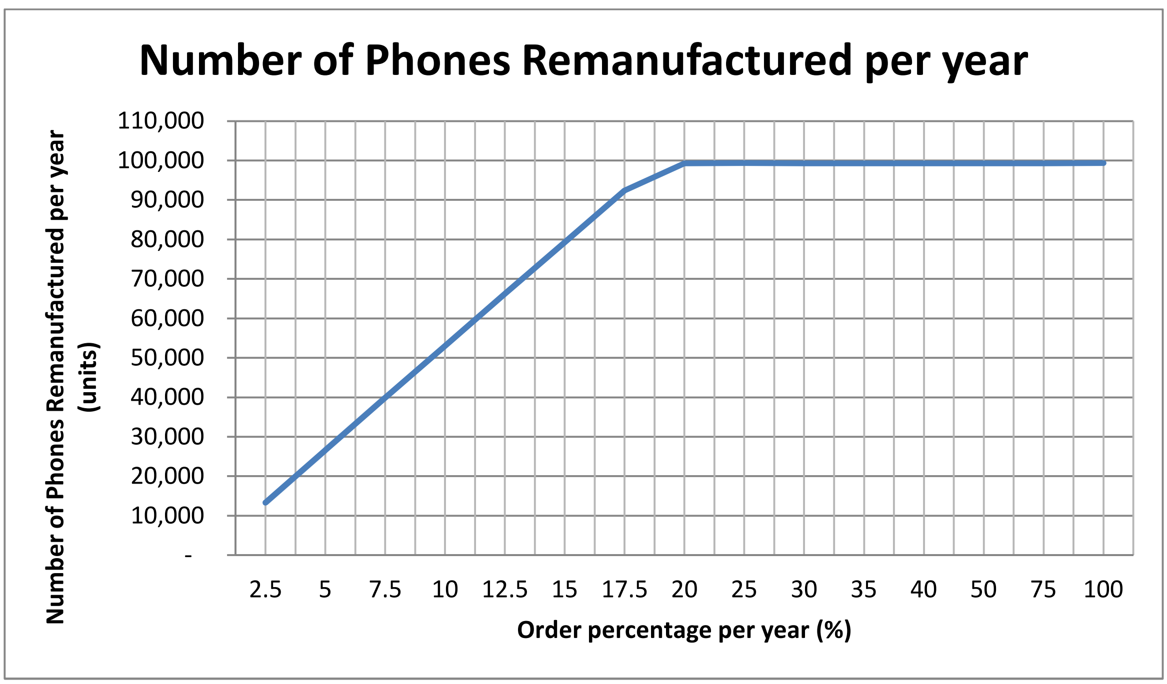


Figure 26: Number of cell phones remanufactured per year in order quantity analysis experiment

From the above experiment the following conclusions can be drawn:

(i) The present capacity of the system has the ability to remanufacture only 20% of the total number of returned cell phones in a year.

(ii) The optimal order quantity for the recycler company with the present capacity was found to be 20% of the total number of cell phones in a year. Even if the recycler company orders more than 20%, they are still going to process the same amount of cell phones and same amount of revenue as the 20% order percentage.

(iii) If the recycler company also recycles other electronic products, than it is advisable to order less than 20% and process other products during the time of the week when there are no cell phones to process.

(iv) Similarly, if the recycler company processes only cell phones and has a larger capacity than they can order 20% of the returned cell phones or more depending on the capacity of the recycler company.

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6.5.2.2 Scenario Analysis:

Scenario analysis is done by varying the input parameters of the system to study the effect on the output results of the system. The scenario analysis results can be helpful for different situation under which the model would act should a deviation in the future happens.

The sorting stage classifies returned phones into three categories namely: good, moderate, and bad. The sorting probability may vary from one organization to another.

Few organizations may prefer to remanufacture a majority of the returned products and recycle a few of them whereas other organizations may prefer the other way around, i.e., to recycle a majority of the returned phones and remanufacture a few of them. This depends on the market demand for reusable products and the remanufacturing or recycling company's capacity.

In the scenario analysis experiment, three sorting probabilities are considered: probability 1, 2 and 3. According to probability 1, remanufacturing is preferred over recycling and reuse, according to probability 2 recycling is preferred over remanufacturing and reuse. In probability 3 reuse operation is preferred over the other two operations. Scenario analysis experiment will pave way for the model to be flexible in all directions, to remanufacture or recycle or reuse most of the returns. The sorting probability data for both probability 1 and 2 have been adapted from published data, the probability 3 was an assumption. A summary of the scenario analysis experiment setup is shown in Table 23.

Table 23: Summary of scenario analysis experiment setup

Sorting Probability	Probability			Adapted from
	Good	Moderate	Bad	
1	25%	60%	15%	(Nikolaidis, 2009)
2	11.18%	26.82%	62%	(US EPA, n.d.)
3	50%	21%	29%	Assumption

In the base model sorting probability 1 was used. In the scenario analysis experiment, sorting probability 2 and 3 were used and the output results were obtained. The results are tabulated in Table 24 below.

Table 24: Summary of Scenario Analysis Experiment Results

Output Measure / Sorting Probability	Sorting Probability 1	Sorting Probability 2	Sorting Probability 3	Units
Remanufactured and Reused Phones per year	99,259	47,478	83,730	Units/year
Reused Phones per year	37,884	18,190	65,227	Units/year
Remanufactured Phones per year	61,483	29,335	18,512	Units/year
Recycled Phones per year	31,810	105,005	40,539	Units/year
Good Phones per year	37,909	18,200	65,253	Units/year
Moderate Phones per year	91,082	43,515	27,454	Units/year
Bad Phones per year	31,829	105,060	40,562	Units/year
Number of Phones remanufactured per day	549	260	462	Units/day

In the scenario analysis experiment, the number of phones reused, remanufactured, recycled per year, good, moderate, bad phones returned per year and the number of phones remanufactured per day was measured for all the three sorting probabilities. Based on the experiment, the following conclusions can be drawn.

It is apparent that in the probability 1, more phones have been remanufactured since the moderate category level in the sorting stage had higher classification percentage of 60% when compared to 25% and 15% of the reuse and recycle categories. And similarly, probability level 2 and 3 supports recycle and reuse operations respectively. Different companies have different requirements. Table 25 below summarizes the application and key findings of the scenario analysis experiment.

Table 25: Summary of Scenario Analysis Experiment:

Probability	Key Findings	Application
1	A total of 99,259 are remanufactured per year. The remanufacture can make a profit of $22,339,125 per year from the remanufactured cell phones	Companies that have both remanufacturing and recycling facility but prefers remanufacturing. And companies having independent remanufacturing facility.
2	105,005 cell phones are recycled in one year by the recycler, generating $ 66,153.15 in revenue per year from material recovery.	Companies that have recycling facility alone and outsources remanufacturing operations
3	Many cell phones are reused when compared to remanufacture and recycle A total of 65,277 cell phones are reused by the recycler per year	Companies that aim to reuse most of the cell phones and who do not have enough resources for remanufacturing and recycling.

This concludes the scenario analysis experiment; this also concludes the case study chapter. In this chapter, five sections were presented: cell phone, cell phone remanufacturing process, cell phone remanufacturing process flow, cell phone decision making process, and cell phone experiments. Useful insights and important results were found that can be helpful for practice and for contribution to the literature. The next chapter will introduce the improvement section – the interconnected database system.

CHAPTER 7

INTERCONNECTED DATABASE SYSTEM.

This chapter will summarise the recommendations provided in the case study section with the help of the Interconnected Database System (IDS).

7.1 Introduction:

The IDS can be assumed to be system similar to a LAN (local area network) where each department or company in the RL system is connected to each other with the help of a network (similar to Ethernet) and possess a common database system. A conceptual representation is shown of IDS in shown in Figure 27 below.

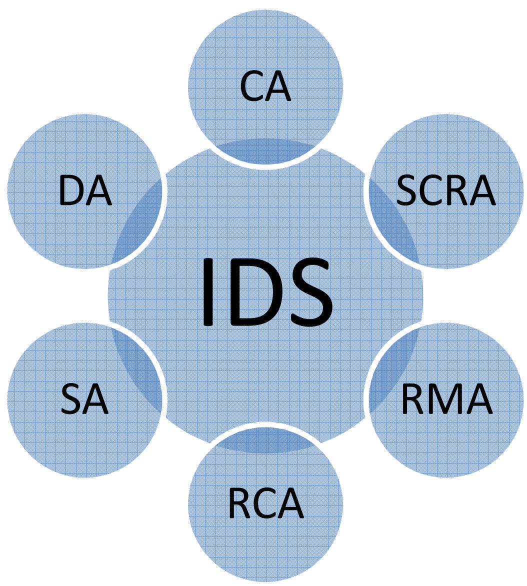

Figure 27: Conceptual representation of IDS

The agents will be able to visualise all the activities taking place in the RL system with the help of a dedicated display device for each agent. The system will provide detailed information related to the product entering the RL system. Most importantly, it will provide information on the quality of the returned product, quantity of products returned and problem associated with each product. The IDS will be assumed to be chiefly managed by the CA but all agents will be allowed to edit the system. The working of the system will be provided in the next section.

7.2 Working:

The IDS starts its activity by gathering information on quality, quantity and problem associated with each product. The CA takes responsibility to input this information on the system. See Figure 28 for a conceptual input window of the IDS adapted from a Microsoft print window.

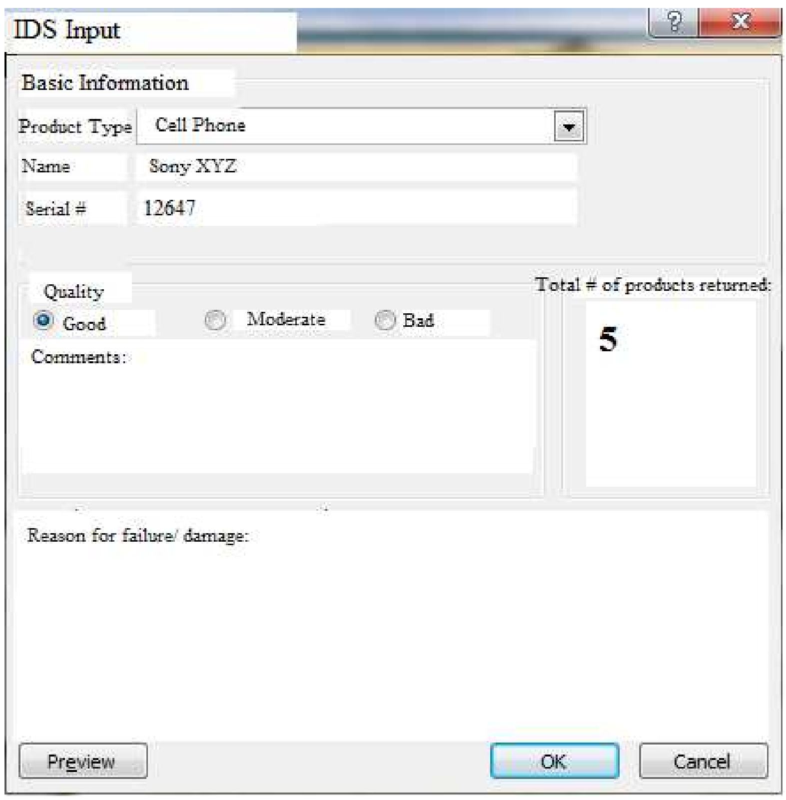

Figure 28: Sample representation of an IDS input menu

The information about the product will be added to the system by manual input method using a computer. At the first step, the CA will inspect the product and grade it based on three quality levels: good, moderate or bad. After categorising the product, the CA will enter the quality information about the product in the system. In the following step, the

CA will either find out the problem associated with the product manually or request the customer for the reason of failure. Once the reason is found, the CA will input the problem associated with the product in the system. As and when products enter the CA, the quantity level will be automatically updated.

The information will also be embedded with the product. This can be achieved with the help of a Quick Response code. As the products pass through the inspection stage at the CA, the information on quality and problem will be generated with the help of a Quick Response code and the Quick Response code will be stuck on the product. The IDS will update its main system as the products enter the RL system, and simultaneously produce Quick Response codes for the products.

At the receiving end (SCRA or RMA or RCA), the agents will be able to decipher the information embedded by the CA by looking at their individual monitor's 'product preview window' or by scanning the product's Quick Response code using Quick Response code scanner. For example, at the SCRA, the agent will be able to sort the products based on their quality just by scanning the product, since the information on quality (good, moderate or bad) is already engraved on the product's Quick Response and no other additional inspection is required. This will save a lot of time in sorting the product at the SCRA. Since the products can be sorted quickly now, IDS will help to improve the process flow.

Similarly, the RMA can look at the IDS or scan the product and become aware about the reason for failure or damage and continue with the disassembly steps. This will certainly require less time than usual because the dissembler has information on the damage and knows the exact work to be carried out. The DA will also benefit from the IDS. Since the DA has to satisfy the customers on time with their demand. The DA can become confident with the number of products entering the RL system and request the RMA for products accordingly.

A tabulation explaining the actions of IDS for each agent and the problems it can overcome for each agent are tabulated in Table 26. This is a conceptual idea and has not been implemented in the model. It is based on the results of the case study, the recommendations led to the inception of such an idea. This concept is designed to be applicable in the real world system; any possible successful application of the model will be a treat to the research concept.

Table 26: Summary of IDS actions and its remedies

Agent	IDS Actions	Remedy for the problem
CA	1) Initiates IDS by recording information on • Quality, • Quantity and • Problem associated with the product 2) Generates Quick Response code for each of the product with the above three information.	Partially addresses two uncertainties in RL. • Quality and • Quantity of the products
SCRA	Quick Response Scanner scans the information on Quality of the product or SCRA can read the information on the monitor	• Sorting time can be reduced
RMA	Quick Response Scanner scans information on Problem of the product or RMA can read the information on the monitor.	• Can reduce the disassembly time of the remanufacturing process.

This concludes the IDS chapter, a conceptual idea for solving few of the problems related to RL were addressed in this chapter. The next section will provide the conclusion and future work of this research.

CHAPTER 8

CONCLUSION AND FUTURE WORK

This chapter will provide the conclusion of this research and pave way for future way related to this research

8.1 Conclusion:

In retrospection, the research set out to measure the performance of a RL enterprise using agent-based modelling approach at operational level of management. The desired goal was achieved with the help of an agent-based model successfully. The agent based model was supported by a generic decision making process, list of performance measures, and a generic RL process flow designed for an electronic product. The research was successfully presented with the help of a case study in cell phone remanufacturing.

The decision making process was tailored to fit in any similar kind of electronic remanufacturing activities. The decision making process can be extended to other similar products with few modifications where the product may have follow different actions & decision routes as per their needs. Measures were provided to evaluate the performance of a RL enterprise at operational level; this again can be applied to any similar product to measure the performance. The list of processes and activities taking place at a remanufacturing facility was developed with the help of interviews and shaped to be generic. As previously highlighted by Rajagopalan and Yellepeddi, (2007), the need for a general list of processing activities was important while measuring the performance. The RL process flow provided in this research includes all general activities for an electronic product.

The other overarching themes that were set forward to be explored were, problems related to uncertainty, EES benefits, communication among actors, need for computer based programs, and need for decision making process. The following objectives were completed by creating an agent-based simulation model and agent-based decision making process. The experiment run with the help of agent-based simulation was able to provide recommendations to solve the problems related to uncertainty, look into EES benefits and salvage the need for a computer based program. The agent-based decision making process was able to fulfill the other two needs: communication among actors and decision making process. A brief summary of the research outcomes are given in Table 27.

The research aimed at making the RL activities a cost-effective process; measured the profit from parts harvesting, remanufactured products sales, material recovery; and calculated the environment benefits of remanufacturing. The following objectives were also achieved. Five environment benefits of remanufacturing were taken into account: pollution controlled, energy saved, cost reduced, material preserved, and protection of landfills.

Table 27: Summary of research outcomes

#	Objective	Action/ Tool	Outcome
1.	Measure the performance using agent-based modelling technique	An agent-based simulation model and decision making process was developed along with list of performance measures.	Performance was successfully measured with the help of the agent-based model.
2.	Alleviate the effect of RL Uncertainties	Agent-based simulation	IDS and periodic production planning periods were suggested
3.	To achieve EES benefits	Agent-based simulation	Environment benefits were measured
4.	Take into account	Agent-based decision	Agents were able to

#	Objective	Action/ Tool	Outcome
	communication among agents	making process	communicate with each other with the help of agent-based decision making process.
5.	Need for decision making process	Agent-based decision making process	Actions and decisions independent to each agent were designed.
6.	Need for computer based program to measure performance	Agent-based simulation	Agent-based simulation was able to satisfy this requirement

From the simulation experiments, it was found that the disassembly and repair stage were two bottleneck stations; further recommendations were provided for improvement. The optimal order quantity percentage the recycler has to order from the collector per year was found using the order quantity analysis experiment. Scenario analysis was considered by varying the sorting stage classification probability. Interconnected Database System in chapter 7 provided a conceptual model of a database system for RL system improvement. The IDS would provide information on quality, quantity and problem associated with the products that come for return. All agents will be able to retrieve the information using a display monitor or a QR scanner. This would partially address the uncertainties related to quantity and quality. To solve the uncertainty related to time, the idea to have production planning periods at the SCRA was recommended. The addition of IDS and production planning periods will alleviate the uncertainties related to RL. The importance of adding bar code information to the products at the manufacturing stage to reduce the disassembly time during remanufacturing was also highlighted. These were main recommendations the model proposed to improve each agent.

To summarise, the main objective of this research was to measure the performance of each individual company in the RL system, collectively using an agent-based modeling technique. The goal was achieved by measuring the performance of each department/ company. Further, recommendations to improve each system performance have been provided. By adding the recommendations the total performance of the system can be improved. The major advantage/capability of using agent-based modeling technique to measure the performance of the system was the ability to collectively measure and understand the performance of each individual agent at one time. This model can be extended to other products with minor revisions in the agent's decision-making model.

Remanufacturing and recycling activities in RL stand as a useful contribution to the society and environment. Social identity is indirectly controlled by RL activities (Zhang et al., 2013). A company practising RL activities has a good name in the society than the others. The profit from recovering material and remanufacturing is also a great business opportunity for the present century. Successful remanufacturing activities can not only provide the above benefits but also can reduce unnecessary waste, and maintain a greener planet.

8.2 Future Work:

The research can be extended in various directions in the future. Some of them would be to study and measure the performance of the RL system and see the effect on the economy, and the society. The effect on ecology was successfully covered in this research by measuring the environment benefits of remanufacturing. The reliability of the remanufactured phone is important to consider as well. So, a method to measure the reliability of the remanufactured phone once dispatched from the distributor agent would be an interesting study.

Generally remanufacturing rate is dependent on two factors: psycho sociological factor and functional factor (Lebreton, 2007). If psycho sociological factor takes priority and if functional requirement is ignored in remanufacturing decisions then the remanufacturing rate is nearly 0% and similarly if it is the other way around, the remanufacturing rate is near to 100%. Figure 29 below presents different product remanufacturing rates according to the two factors. In this research, one product near to 0% remanufacturing rate (cell phone) was chosen. A possible future work would be to measure the performance of an electronic product from 50% and 100% remanufacturing rate category with the help of the proposed agent-based model.

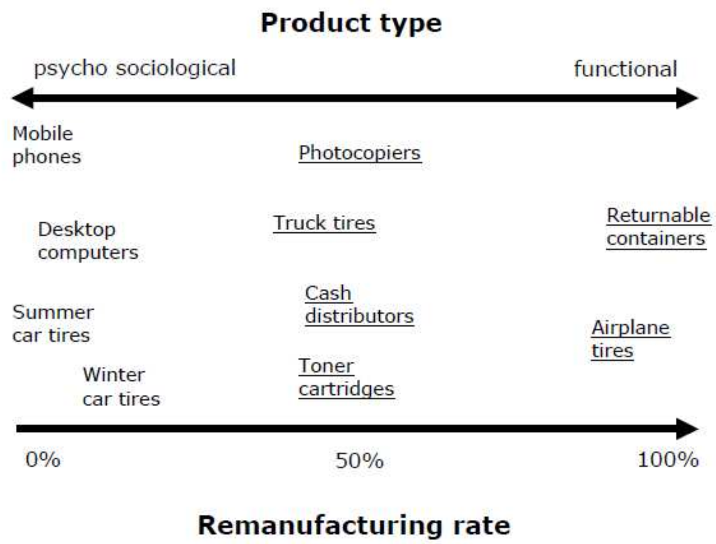

Figure 29: Remanufacturing rate based on psycho sociological and functional factors (Lebreton, 2007).

The model is limited to a system that remanufactures a single product at a time (except the recycling facility). A model that would remanufacture multiple products at the same time could be another possible extension of this research. Also, in the cell phone remanufacturing case study, accessories like chargers, batteries, and earphones were not taken into consideration while designing the model. The model can include the accessories in the future and the performance of the RL enterprise can be evaluated. Finally, the model can be tweaked to include few modifications according to a product in another industry (e.g., a mechanical product) and the performance of the product's remanufacturing activities can be measured with the help of the developed performance measures, RL process flow and the agent-based decision making model.

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Appendix A: Pre-paid Postal Envelope Label

This is a sample prepaid postal label used by the customers to send their cell phones to the collectors for recovery. A link to the label is available online in the collector's webpage. When the customer plans to send cell phones by post, they can click on the link. This link will be directed to the Canada Post webpage, in this page information regarding, FROM, TO address and weight of the post has to be entered. Once the required information is entered on this webpage, the label will be generated. Figure 30 shows a sample label that was generated with the help of Canada Post from one of the collector's webpage in Southern Ontario.

Figure 30: Sample prepaid postal envelope

Appendix B: Cell Phone Buyback Price by Collectors

This appendix section provides information about buyback price for different cell phones. The collector pays the customer few incentives in return for old cell phones. Table 28 below provides a sample buyback price list from a cell phone remanufacturing company in Southern Ontario. This information is available online to the public and can be viewed on the company's webpage.

Table 28: Sample buyback price for retired cell phones

Make & Model	Price
Apple iPhone 3GS 16GB 15.00	$ 15.00
Apple iPhone 3GS 32GB 30.00	$ 30.00
Apple iPhone 3GS 8GB 10.00	$ 10.00
Apple iPhone 4 16GB 75.00	$ 75.00
Apple iPhone 4 32GB 85.00	$ 85.00
Apple iPhone 4 8GB 60.00	$ 60.00
Apple iPhone 4S 16GB 135.00	$ 135.00
Apple iPhone 4S 32GB 145.00	$ 145.00
Apple iPhone 4S 64GB 160.00	$ 160.00
Apple iPhone 4S 8GB 100.00	$ 100.00
Apple iPhone 5 16GB 235.00	$ 235.00
Apple iPhone 5 32GB 250.00	$ 250.00
Apple iPhone 5 64GB 270.00	$ 270.00
Apple iPhone 5c 16GB 240.00	$ 240.00
Apple iPhone 5c 32GB 260.00	$ 260.00
Apple iPhone 5s 16GB 300.00	$ 300.00
Apple iPhone 5s 32GB 310.00	$ 310.00
Apple iPhone 5s 64GB 320.00	$ 320.00
BlackBerry Bold 9900 25.00	$ 25.00
BlackBerry Q10 100.00	$ 100.00
BlackBerry Q5 50.00	$ 50.00
BlackBerry Z10 70.00	$ 70.00
BlackBerry Z30 50.00	$ 50.00
HTC 130 - Hero 5.00	$ 5.00
HTC 801a - One 195.00	$ 195.00

Make & Model	Price
HTC A320 - Desire C 10.00	$ 10.00
HTC A620m - Windows Phone 8S 40.00	$ 40.00
HTC A6365 - Legend 15.00	$ 15.00
HTC A7272 - Desire Z 10.00	$ 10.00
HTC A8182 - Desire 20.00	$ 20.00
HTC A9192 - Desire HD 20.00	$ 20.00
HTC C620e - Windows Phone 8X 50.00	$ 50.00
HTC C625a - Windows Phone 8X 50.00	$ 50.00
HTC OP4E200 - Desire 601 100.00	$ 100.00
HTC OP4E230 - Desire 601 100.00	$ 100.00
HTC PB76110 - Legend 5.00	$ 5.00
HTC PB99100 - Google Nexus One 10.00	$ 10.00
HTC PB99220 - Desire 20.00	$ 20.00
HTC PC10120 - Desire Z 10.00	$ 10.00
HTC PC36100 - Evo 4G 45.00	$ 45.00
HTC PD15100 - Panache My Touch 25.00	$ 25.00
HTC PD26100 - Surround 20.00	$ 20.00
HTC PD26110 - Surround 20.00	$ 20.00
HTC PD29130 - HD7 20.00	$ 20.00
HTC PD98140 - Desire HD 20.00	$ 20.00
HTC PG32120 - Incredible S 20.00	$ 20.00
HTC PG58110 - Sensation 25.00	$ 25.00
HTC PG58150 - Sensation 60.00	$ 60.00
HTC PG76110 - Wildfire 5.00	$ 5.00
HTC PG86310 - Inspire Evo 3D 45.00	$ 45.00
HTC PH06130 - Status 25.00	$ 25.00
HTC PH39100 - Vivid 45.00	$ 45.00
HTC PH39150 - Raider 50.00	$ 50.00
HTC PH85110 - Amaze 4G 80.00	$ 80.00
HTC PJ40110 - One S 80.00	$ 80.00
HTC PJ46100 - One X 100.00	$ 100.00
HTC PJ83100 - One X 100.00	$ 100.00
HTC PK76110 - One V 5.00	$ 5.00
HTC PL01100 - Desire C 10.00	$ 10.00
HTC PL86100 - Titan 2 15.00	$ 15.00
HTC PM23200 - Windows Phone 8X 40.00	$ 40.00
HTC PM23300 - Windows Phone 8X 40.00	$ 40.00
HTC PM59110 - Windows 8S 40.00	$ 40.00

Make & Model	Price
HTC PM63100 - One X+ 100.00	$ 100.00
HTC PN07120 - One 200.00	$ 200.00
HTC PO58220 - One Mini 145.00	$ 145.00
HTC S510 - Snap 5.00	$ 5.00
HTC S523 - Snap 5.00	$ 5.00
HTC S710a - Incredible S 45.00	$ 45.00
HTC T320 - One V 30.00	$ 30.00
HTC T9292 - HD7 20.00	$ 20.00
HTC T9295 - HD7 S 30.00	$ 30.00
HTC X325A - One X+ 100.00	$ 100.00
HTC X515M - Evo 3D 45.00	$ 45.00
HTC X520A - One X+ 100.00	$ 100.00
HTC X710A - Raider 50.00	$ 50.00
HTC X715 - Amaze 4 G 80.00	$ 80.00
HTC Z520m - One S 80.00	$ 80.00
HTC Z560e - One S 80.00	$ 80.00
HTC Z710A - Sensation 60.00	$ 60.00
Huawei Ascend P6 (Wind Mobile) 80.00	$ 80.00
Huawei Ascend W1 (Wind Mobile) 50.00	$ 50.00
Huawei Ascend G312 (Wind Mobile) 35.00	$ 35.00
Huawei Ascend Mate (Wind Mobile) 90.00	$ 90.00
Huawei Ascend Y215 (Wind Mobile) 20.00	$ 20.00
LG 320 - Flick 5.00	$ 5.00
LG 900 - Bliss 5.00	$ 5.00
LG C660 - Gossip Pro 5.00	$ 5.00
LG C800G - Eclypse 5.00	$ 5.00
LG C900 - Optimus Quantum 5.00	$ 5.00
LG D820 - Nexus 5 140.00	$ 140.00
LG E400 - Optimus L3 10.00	$ 10.00
LG E450 - Optimus L5 II 10.00	$ 10.00
LG E617g - Optimus L5 15.00	$ 15.00
LG E720 - Optimus Chic 5.00	$ 5.00
LG E900 - Optimus 7 25.00	$ 25.00
LG E960 - Nexus 4 75.00	$ 75.00
LG E971 - Optimus G 75.00	$ 75.00
LG E973 - Optimus G 75.00	$ 75.00
LG E975 - Optimus G 75.00	$ 75.00
LG P500 - Optimus One 5.00	$ 5.00

Make & Model	Price
LG P505 - Phoenix 5.00	$ 5.00
LG P700 - Optimus L7 35.00	$ 35.00
LG P705 - Optimus L7 40.00	$ 40.00
LG P769 - Optimus L9 60.00	$ 60.00
LG P870 - Escape 15.00	$ 15.00
LG P880 - Optimus 4X HD 45.00	$ 45.00
LG P920 - Optimus 3D 30.00	$ 30.00
LG P925 - Optimus 3D Thrill 30.00	$ 30.00
LG P930 - Optimus LTE 30.00	$ 30.00
LG P935 - Optimus LTE 4G 35.00	$ 35.00
LG P970g - Optimus Black 30.00	$ 30.00
LG P990 - Optimus 2X 40.00	$ 40.00
LG P999 - Optimus 2X 45.00	$ 45.00
LG T385 5.00	$ 5.00
LG VN530 - Octane 25.00	$ 25.00
Motorola 81130 - Milestone 5.00	$ 5.00
Motorola A854 - Milestone 5.00	$ 5.00
Motorola MB632 - Pro Plus 20.00	$ 20.00
Motorola MB860 - Atrix 15.00	$ 15.00
Motorola MB886 - Atrix HD 30.00	$ 30.00
Motorola XT300 - Spice 5.00	$ 5.00
Motorola XT319 5.00	$ 5.00
Motorola XT615 - Motoluxe 25.00	$ 25.00
Motorola XT687 - Atrix TV 45.00	$ 45.00
Motorola XT720 - Milestone 5.00	$ 5.00
Motorola XT860 - Milestone 3 45.00	$ 45.00
Motorola XT885 - Razr V 45.00	$ 45.00
Motorola XT886 - Razr V 45.00	$ 45.00
Motorola XT905 - Razr M 55.00	$ 55.00
Motorola XT908 - Razr Maxx 55.00	$ 55.00
Motorola XT910 - Razr 55.00	$ 55.00
Motorola XT912 - Droid Razr 55.00	$ 55.00
Motorola XT925 - Razr HD 85.00	$ 85.00
Nokia 1020 - Lumia 150.00	$ 150.00
Nokia 500 - Fate 5.00	$ 5.00
Nokia 520 - Lumia 20.00	$ 20.00
Nokia 610 - Lumia Windows 7 20.00	$ 20.00
Nokia 620 - Lumia 25.00	$ 25.00

Make & Model	Price
Nokia 710 - Lumia 25.00	$ 25.00
Nokia 720 - Lumia 35.00	$ 35.00
Nokia 800 - Lumia 40.00	$ 40.00
Nokia 820 - Lumia 40.00	$ 40.00
Nokia 822 - Lumia 45.00	$ 45.00
Nokia 900 - Lumia 40.00	$ 40.00
Nokia 920 - Lumia 85.00	$ 85.00
Samsung 222 - Chat 5.00	$ 5.00
Samsung 550 i5500 - Galaxy 5.00	$ 5.00
Samsung 551 i5510 - Galaxy 5.00	$ 5.00
Samsung A667 - Evergreen 5.00	$ 5.00
Samsung A836 - Rugby 5.00	$ 5.00
Samsung A837 - Rugby 5.00	$ 5.00
Samsung A847 - Rugby 2 5.00	$ 5.00
Samsung A997 - Rugby III 20.00	$ 20.00
Samsung B7800 - Galaxy M Pro 75.00	$ 75.00
Samsung Galaxy Tab - 8.9 50.00	$ 50.00
Samsung GT-I9300 - Galaxy S III 16GB 100.00	$ 100.00
Samsung GT-I9300 - Galaxy S III 32GB 110.00	$ 110.00
Samsung i257m - S4 Mini 150.00	$ 150.00
Samsung i317 - Galaxy Note II 120.00	$ 120.00
Samsung i337 - Galaxy S4 150.00	$ 150.00
Samsung i515 - Galaxy Nexus 35.00	$ 35.00
Samsung i527m- Galaxy Mega 160.00	$ 160.00
Samsung i535V - Galaxy S III 16GB 100.00	$ 100.00
Samsung i535V - Galaxy S III 32GB 110.00	$ 110.00
Samsung i547C - Galaxy Rugby LTE 40.00	$ 40.00
Samsung i5700 - Galaxy Spica 5.00	$ 5.00
Samsung i5800 - Galaxy 5.00	$ 5.00
Samsung i605 - Galaxy Note II 120.00	$ 120.00
Samsung I717 - Galaxy Note 50.00	$ 50.00
Samsung i727 - Galaxy S II LTE Skyrocket 45.00	$ 45.00
Samsung i727r - Galaxy S II LTE 45.00	$ 45.00
Samsung i747 - Galaxy S III 16GB 100.00	$ 100.00
Samsung i747 - Galaxy S III 32GB 110.00	$ 110.00
Samsung i7500 - Galaxy 25.00	$ 25.00
Samsung i757 - Galaxy S II LTE 50.00	$ 50.00
Samsung i757m - Galaxy SII 50.00	$ 50.00

Make & Model	Price
Samsung i8160 - Galaxy Ace II 45.00	$ 45.00
Samsung i827 - Galaxy Appeal 10.00	$ 10.00
Samsung i8700 - Omnia 7 40.00	$ 40.00
Samsung i896 - Galaxy S Captivate 20.00	$ 20.00
Samsung i897 - Galaxy S Captivate 20.00	$ 20.00
Samsung i9000 - Galaxy S 25.00	$ 25.00
Samsung i9003 - Galaxy S 25.00	$ 25.00
Samsung i9020A - Nexus S 30.00	$ 30.00
Samsung i9023 - Nexus S 30.00	$ 30.00
Samsung I9100 - Galaxy S II 50.00	$ 50.00
Samsung i9100m - Galaxy SII 50.00	$ 50.00
Samsung i917 - Focus 25.00	$ 25.00
Samsung i9220 - Galaxy Note 50.00	$ 50.00
Samsung i9250 - Galaxy Nexus 55.00	$ 55.00
Samsung i927 - Galaxy S Glide 25.00	$ 25.00
Samsung i9305T - Galaxy S III 16GB 100.00	$ 100.00
Samsung i9305T - Galaxy S III 32GB 110.00	$ 110.00
Samsung i9500 - Galaxy S4 150.00	$ 150.00
Samsung i9505 - S4 150.00	$ 150.00
Samsung i997 - Infuse 25.00	$ 25.00
Samsung L710 - Galaxy S III 16 GB 100.00	$ 100.00
Samsung L710 - Galaxy S III 32 GB 110.00	$ 110.00
Samsung M919 - Galaxy S4 150.00	$ 150.00
Samsung N7000 - Galaxy Note 50.00	$ 50.00
Samsung N7100 - Galaxy Note II 120.00	$ 120.00
Samsung N900W8- Note 3 255.00	$ 225.00
Samsung P7500 - Galaxy Tab 10.1 25.00	$ 25.00
Samsung P7510 - Galaxy Tab 10.1 25.00	$ 25.00
Samsung S5570 - Galaxy Mini 5.00	$ 5.00
Samsung S5660 - Galaxy Gio 5.00	$ 5.00
Samsung S5690 - Galaxy Rugby 40.00	$ 40.00
Samsung S5830 - Galaxy Ace 5.00	$ 5.00
Samsung S6800 - Galaxy Ace Advance 5.00	$ 5.00
Samsung S7560 - Galaxy Ace II X 30.00	$ 30.00
Samsung T369 5.00	$ 5.00
Samsung T469 - Gravity 2 5.00	$ 5.00
Samsung T479 5.00	$ 5.00
Samsung T499Y - Galaxy Mini 15.00	$ 15.00

Make & Model	Price
Samsung T589 - Galaxy Q 15.00	$ 15.00
Samsung T669 - Gravity/G-Touch 5.00	$ 5.00
Samsung T679 - Galaxy W 30.00	$ 30.00
Samsung T746 - Impact 5.00	$ 5.00
Samsung T889 - Galaxy Note II 120.00	$ 120.00
Samsung T899m - Ativ S 45.00	$ 45.00
Samsung T959 - Galaxy S 4G 20.00	$ 20.00
Samsung T989 - Galaxy S II 65.00	$ 65.00
Samsung T999 - Galaxy S III 16GB 100.00	$ 100.00
Samsung T999 - Galaxy S III 32GB 110.00	$ 110.00
Sanyo Pro 700 5.00	$ 5.00
Sonim XP1300 - Bolt 25.00	$ 25.00
Sonim XP5560 - Bolt 25.00	$ 25.00
Sony C5306 - Xperia SP LTE 50.00	$ 50.00
Sony C6506 - Xperia ZL 110.00	$ 110.00
Sony C6616 - Xperia Z 65.00	$ 65.00
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Sony ST27a - Xperia Go 20.00	$ 20.00
Sony ST27i - Xperia Go 20.00	$ 20.00
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Appendix C: Warm-up Period Calculation

The model was run for a warm-up period of 488 hours before collecting statistics to remove the transient state. The warm-up period was found using Welch moving average method in SimRunner software. The report generated by SimRunner is as follows.

Statistical Advantage Setup:

Run Length: 1920.0 hr
Sample Interval: 8.0 hr
Test Reps: 5

Objective Function terms that were measured:
*Variable: Max: 1.00 * Number_of_products_remanufactured_per_8_hours - Average Value*

The warm up period was selected to be 61 periods of 8.0 hr each for a total of 488.00 hr.

A graph is plotted against the measure considered and the periods. The moving average window is increased until the moving average plot begins to flatten out in the graph. The graph (Figure 31) below shows the period at which the moving average plot begins to flatten out.

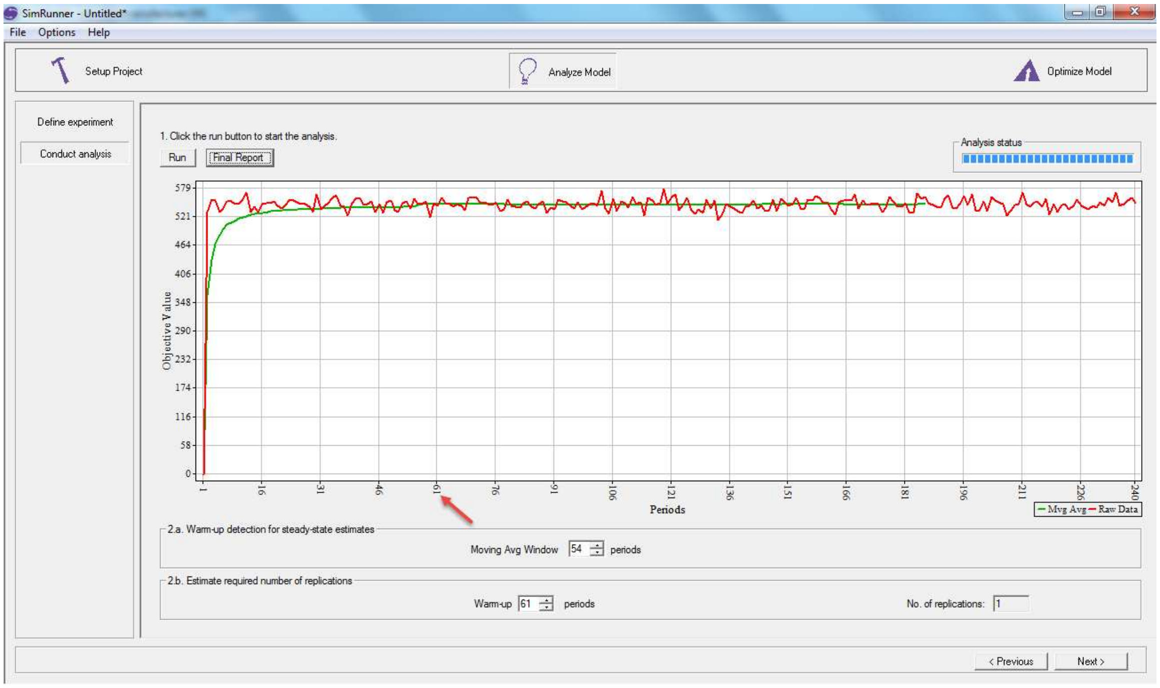

Figure 31: Warm-up Period Graph: Moving average plot for moving average window, w= 54

Appendix D: Number of Replications

The base model was run with 10 replications; for each replication a different seed value was used. Statistical procedures were used to calculate the number of replications. In order to be 95 % confident that the point estimate of the measure – *number of products remanufactured per 8 hours* does not vary by more than one product (e=1) from the true mean, 15 replications are required. The calculations are shown below.

Statistical setup:

x' – a point estimate of the mean,
μ - theoretical true mean,
a – probability that the error between x' and μ will exceed a specified error amount (e)
e – error amount

Formula:

$$\boldsymbol{N} = \left(\frac{\boldsymbol{t}_{\boldsymbol{n-1,1-\frac{a}{2}}}\,\boldsymbol{s(n)}}{\boldsymbol{e}}\right)^{\mathbf{2}} \quad \text{Equation 1}$$

N = Number of model replications
s(n) – point estimate of σ based on **n** model replications,
n – sample model replications,
$t_{n-1,1-\frac{a}{2}}$ - critical value from T-distribution

Determination of number of replications:

The base model was run for a sample of 10 replications and the mean of the measure (xi) for each replication was calculated as shown in Table 29 below. The point estimate of the mean (x') was then found to be 549.02. Later the estimate of σ , S (10) was found to be 1.73. The true mean (μ) was found from the T-distribution table to be 2.262. The obtained values were substituted in the above equation, Equation 1.

$$N = \left(\frac{2.262 * 1.73}{1}\right)^2$$

$$N = 15$$

The number of replications, N was found to be 15 using the above calculation.

Table 29: Number of Replications calculation

ith Iteration	Mean (xi)	[xi-x'(10)]2
1	549.746	0.53
2	548.675	0.12
3	549.696	0.46
4	546.867	4.62
5	548.321	0.48
6	550.525	2.28
7	548.929	0.01
8	547.588	2.04
9	552.633	13.08
10	547.183	3.36
Total	5,490.16	26.98
Average x'(10)	549.02	
Variance V(10)		2.998111304
SD S(10)		1.731505502

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Grad Studies Format Requirements

Walid Abdul-Kader <kader@uwindsor.ca> Fri, Dec 12, 2014 at 11:57 AM

To: Gowtham Ravi Sankara Pandian <ravisang@uwindsor.ca>

Hi Gowtham,

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Walid

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