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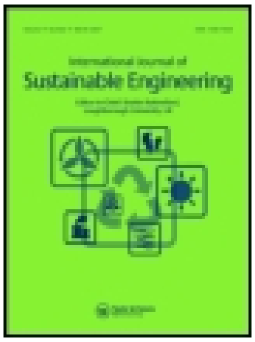

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# Performance evaluation of reverse logistics enterprise – an agent-based simulation approach

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**ABSTRACT**

Reverse logistics (RL) has been applied in many industries and sectors 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 returns. The returned products can be remanufactured, have parts harvested, or 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 simulation model. 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 the agents are measured and recommendations are given to improve their performance, leading to the enhancement of the total performance of the RL enterprise. The approach is applied to a case study involving cell phone remanufacturing.

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Performance measurements; reverse logistics; agent-based simulation; cell phone remanufacturing/recycling



## Introduction

The evolution of electronic products has been constantly transforming people's lives. Over the years, systems have become less cumbersome and processes have become simple and more effective. From the first communication device, the papyrus, to the latest smartphone, technology and electronic products have played an important role in revolutionising people's way of living. In 2012, the computer and electronics manufacturing sector contributed nearly $6.8 billion to Canada's GDP (Government of Canada 2013).

Electronic products are being used extensively as integral devices in day-to-day life. They are looked after carefully when in use, and should receive the same care once they become obsolete. Old electronic products can be reused or recycled instead of being disposed of in landfills. To this end, there are interesting recovery options, such as resale, remanufacturing or refurbishing, repair, reconditioning, parts harvesting and recycling (Kara, Rugrungruang, and Kaebernick 2007). In addition, used electronic products consist of precious metals 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 remarkable benefits for the environment as well: a used product can be kept away from a landfill, and the materials from a used product can be reused, thereby preserving valuable virgin materials (fresh raw materials) 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. 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.

Across all industries, return percentages vary from 5 to 50% (Li and Olorunniwo 2008). RL takes the sole responsibility in setting up the platform for a successful practice.

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 government or environmental organisations, like the waste electrical and electronic equipment (WEEE) directive on the original equipment manufacturers (OEM), so OEM take responsibility to collect their 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, Zhou, and Ieromonachou 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

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advantages, ecological, economic and social, will be termed as 'EES' throughout this paper.

There are five other reasons to return a product: (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 US, remanufacturing industries are active in at least 125 different product categories (Lund 2012). The most common returned products are laptops, computers, cell phones, toner cartridges, televisions, network devices and single-use cameras.

Electronic goods are present in nearly every North American household in the twenty-first century, and recently the cell phone has become one of the most revolutionary, with 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 28 million (CWTA 2013a), with a total population of 35.5 million as of 1 July 2014 (Government of Canada 2014). The number of cell 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 models arriving in the market increases and as the life span of cell phones decreases, the number of cell phones becoming obsolete every day increases. In 2013, recycle my cell (RMC), along with other recycling initiatives, recovered 1,067,266 cell phones for either remanufacturing or recycling in Canada (CWTA 2014).

This research paper considers a cell phone remanufacturing process and emphasises the day-to-day activities of this remanufacturing organisation. In general, any organisation 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. The purpose of measuring an organisation's performance is to gather information that would be helpful to make data-driven decisions and eventually improve the existing performance of the organisation (Guerra-López 2012).

This research aims at measuring the performance of an RL enterprise. The proposed method used is agent-based simulation technique. Remanufacturing or refurbishing an electronic product typically involves six entities/organisations: Collector, Sorter, Refurbisher, Recycler, Supplier and Distributor. Each of these is considered a separate agent with a unique behaviour and objective. The performance of each agent can be measured, and recommendations for improvement are provided for each of them with the aim to improve the overall performance of the RL system. The main reason to consider the agent-based simulation technique over other modelling techniques remains in its ability to capture the system dynamics and consider each entity.

The remainder of the paper is organised as follows. The following section is concerned with a review of the RL literature, and more specifically, previously published methods for evaluating the performance of an RL enterprise. The section on Problem statement of this research is provided. Following that a section on the modelling approach along with the generic RL process flow and agents' decisions and actions is presented. Then, a section outlines the Case study on cell phone remanufacturing activities with the help of RL process flow and simulation. Finally, the conclusion and recommendations for future work are presented.

## Literature review

A review of literature is conducted to identify the relevant models that may include and represent the complexity and dynamic nature of a reverse logistic system. Through the review, our findings about RL performance measurement relate mainly to two modelling areas that are analytical and simulation modelling techniques. Under the analytical approach, we found models in performance management, fuzzy logic and game theory. In simulation modelling, a much less models are available in the literature. Among those we surveyed, we list the most relevant including agent-based simulation models. The paragraphs below report the most appropriate papers in each of these two modelling approaches and elaborate on their strengths and limitations for addressing the complexity and dynamics of RL enterprise.

In analytical approach models, Neely, Adams, and Kennerley (2002) define performance measurement as 'The process of quantifying the efficiency and effectiveness of past actions'. Yellepeddi (2007) presents a quantitative methodology referred to as performance evaluation of reverse logistics (PEARL). He used Analytical Network Process and fuzzy logic to create a reverse logistics overall performance index (RLOPI) framework that would evaluate the performance of a RL enterprise. Shaik and Abdul-Kader (2014) use a combination of Balance Score Card and a performance prism to develop a comprehensive performance measurement for RL enterprises. The decision-making process was based on DEMATEL, and the research included a total of 24 performance measures that considered 6 performance perspectives. The decisions involved during RL activities are quintessential. Using a qualitative approach, Lambert, Riopel, and Abdul-Kader (2011) develop a RL decision conceptual framework that is flexible and takes into account different scenarios. The framework also includes performance measures at the three strategic, tactical and operational levels of management. The model is designed by considering seven important elements/entities in the RL system. Each entity's actions and decisions are identified and a decision framework is provided. To test the applicability and flexibility of the model, the decision framework is applied to three real-world case studies. This framework can be used as a skeleton for industries to structure their RL activities. The above-indicated methods and approaches while mainly focused at the strategic level, do not address explicitly the uncertainty or the dynamics of the RL enterprise.

To overcome the uncertainties in RL, Bai and Sarkis (2013) propose a flexible framework for RL that could accommodate changes according to the concurrent needs. This framework is evaluated using neighbourhood rough set model, and the effective performance measures for RL are found. Likewise, Zhang, Zhou, and Ieromonachou (2013) study the effects of uncertainty on the economic performance of RL operations. These papers do not capture the dynamics of the RL enterprise.

Fuzzy logic has been used by many authors to measure the performance of a RL system, and a comprehensive performance evaluation consisting of six indices covering both qualitative and quantitative measures is developed by Xiong and Li (2010). This research touches upon the importance of EES benefits as well. Additionally, Trappey, Trappey, and Wu (2010) develop 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 uses fuzzy logic to evaluate the performance with the help of critical success factor and analytical hierarchy process (AHP). These models do not capture the dynamical nature of the RL enterprise.

An important number of papers dealt with reverse logistics and closed-loop supply chains (CLSC) using game theory. Among these papers, we report the following. Fallah, Eskandari, and Pishvaee (2015) address a competitive CLSC network design under uncertainty with a primary goal to investigate the impact of simultaneous and Stackelberg competitions between two closed-loop supply chains on their profits, demands and returns. This game-theoretic approach is empowered by possibility theory. Esmaeili, Allameh, and Tajvidi (2016) study the short- and long-term behaviour of agents in implementing the appropriate collecting strategy in a two-echelon CLSC. They use both the Stackelberg game for the short-term for pricing models by considering and comparing different collection strategies; and for the long-term behaviour of companies, the collection process is examined using evolutionary game theory. Yan (2012) model a multi-echelon CLSC with 3PRLP under the consideration of impacts of environmental legislation on scrap recycling. In their model, they considered a one-leader (manufacturer) and multi-follower Stackelberg game. While the game theory has an important contribution to this area of research, it remains difficult to explain and present to decision-makers, and more importantly as the number of players increases in the game, the analysis of the gaming strategies becomes intricate and complex.

With regard to multi-agent modelling, Chenglin and Xinxin (2008) propose a multi-agent model to solve the supply planning problem by considering three different agents: manufacturing agent (MA), supplier agent (SA) and collector agent (CA). A mathematical model for each of the agents is presented, with the aim to minimise the operating cost and ultimately, minimise the total operating cost of the whole chain.

An important 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. 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 (Mondragon, Lalwani, and Mondragon 2011). This study is carried out with the help of a case study in a telephone operating company in the UK and provides awareness for the need for communication among different actors in the RL system.

Addressing RL performance measurement implies the consideration of environmental performance measurement. As such, Björklund, Martinsen, and Abrahamsson (2012) evaluate the impact of $CO_2$ emission on the environment and the transportation cost during RL activities. The research was presented with the help of a case study in Polyethylene terephthalate (PET) bottle industry consisting of four actors: Production Company, Retailers, Wholesalers and Breweries. The environment and economic performance are measured and the authors insist on the balance of the environmental impact and logistics cost in RL. In the transportation sector, the operational and environmental performance measures are evaluated by Paksoy, Bektaş, and Özceylan (2011) and are calculated using linear programming model at the operational level.

In terms of simulation modelling approach, Abdul-Kader and Haque (2011) present an agent-based simulation model to analyse the environmental benefits of tire retreading. The model considers 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 the replacement market can be satisfied by retreaded tires and that this percentage could be expanded by increasing the retread level. This research helps to analyse the environment benefits of retreading and shows possible reduction in scrap tires and scrap material. Another study explores ways in which wastes carpet can be reduced. In order to divert carpet from landfills and better manage the reverse flow of used carpets, a simulation model is presented by Biehl, Prater, and Realff (2007). This research work also included the effect of uncertainty and the impact of environment on the performance of a system. Recommendations were also provided to improve the situation. Another simulation-based approach considering the environment and the economic aspect of supply chain is used to calculate the performance of a forward and reverse supply chain by Murayama, Hatakenaka, and Oba (2003). The simulation results also help 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 are made aware from the above studies.

Although there may be several measurement techniques to assess the performance of a RL enterprise, like scoring techniques, mathematical models and fuzzy logic, the advantage of using agent-based simulation (ABS) techniques 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, agent-based simulation technique provides the possibility to model each entity in the RL system as a separate agent to measure and improve its performance. More importantly, scoring techniques, as they are mostly applied at the strategic level, are avoided since the focus of this research is performance measure at the operational level. Because of these advantages, the agent-based simulation technique fits as a better measurement method than other modelling techniques for this research. The strength of the ABS approach over existing solution methods is appreciated because of its flexibility in handling complexity and tackling uncertainties explicitly. It is a forthright method to explain to decision-makers by showing with the help of animation how the system under study behaves. This review of literature is a motivation source to address the performance evaluation of a RL enterprise using agent-based simulation technique, and the consideration of a cell phone remanufacturing industry contributes more because it has not been studied in the reviewed literature.

## Problem statement

The central issues for RL are that manufacturers, particularly those producing smartphones, do not have a reclamation process that maximises the potential profits. The purpose of this study is to measure the performance of an RL enterprise using agent-based simulation technique; and thus, addresses and compensates for the limitations and drawbacks of previous studies. The performance measurement of the RL enterprise will be at the operational level of management. A generic model incorporating process flow diagrams and related RL activities and decisions for the agents will be presented and discussed in the next section. A cell phone remanufacturing as a case study is then used to show the applicability of the research approach. The selection of a cell phone is motivated by the high and increasing volume of sales and the lifecycle of this product, which is getting shorter due to technological advances and very competitive market. The model will be simulated using the commercial package Promodel software. By fulfilling the above needs, this research will stand as seminal study on RL enterprise performance measurement.

## RL enterprise – generic model

In this section, we present the different agents composing the RL enterprise and elaborate on the actions and decisions that every agent may make in this context. 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 endow 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 simulation technique. The model is designed in such a way that each entity/company in the RL network is represented by an agent. In this agent-based simulation model, a set of performance measures for each agent will be identified and evaluated. Assessing the performance of each agent may lead to stating specific recommendations for improving it. This may lead to improving the performance of the RL enterprise.

### *Agents, actions and decisions*

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

(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).

Figure 1 in Lambert, Riopel, and Abdul-Kader (2011) shows the main flows among different agents (or elements). A detailed description of each agent including responsibilities, process, actions, decisions, performance measures and goal will be given in the next section. The charts presented in Figures 1–6 below are generic to any returned product. However, the unshaded boxes denote the actions and decisions related specifically to the cell phone remanufacturing case study considered in this research and presented later in Section 5.

### *Collector agent (CA)*

The CA holds the key position in a RL system. In the electronics and the metal management RL enterprises, the collector acts as the channel leader (Choi, Li, and Xu 2013). The main role of the CA in a RL system is to collect the product that comes for return. These 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 and depending on consumer electronic products, the collectors may be OEMs, independent recyclers (IR), retailers, customers or non-profit organisations (see Figure 1, box, 3, 4, 5, 6 and 7). The actions and decisions taken by the CA agent are depicted in Figure 1.

In the model, at the first step in box 2 of Figure 1, is the decision block. At this step, it is collectors' responsibility 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; however, for toner cartridges, the OEM and IR mainly take responsibility to collect the used products. Similarly, the collection methods vary from one product to another. This proposed model incorporates a wide range of collection methods, making it generic.

In the next step, or box 9 of Figure 1, the CA collects the product and decides whether to compensate the customer with a replacement product, either new or old, during the interim period of repair or remanufacturing (Mondragon, Lalwani, and Mondragon 2011). For a product category, if compensation is required then the action passes on to 'replace product', where the customer is given a replacement product. If compensation is not required for the product category, a replacement product is not given to the customer. The action now passes on to the next decision block, or box 11, 'incentive'. In this stage, the collector inspects the collected product for basic operations, like turning on/off and other key functional operations. If the product passes 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, the customer may have to pay fine. If there is no misuse, the product passes on to the next stage: 'update quantity level', or box 17.

After the 'incentive' and 'fine' decision blocks, the collector's inventory level is updated according to the number of returns per day. One of the significant features 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, the collector sends the products to the remanufacturing facility for processing. If there is no demand, the product stays at the collector's inventory. Similarly, when the time to return a product is reached, for example, the last day of the month or year, the collector automatically sends the products to the remanufacturing facility.

These actions and decisions follow a specific structure. Once the inventory level is updated, the collector waits for a product request from the sorting-cum-reuse agent (SCRA). If there is such a request from SCRA, then the collector transports the products to the SCRA. If there is no request, then the product stays in the collector's inventory. According to an interview at a

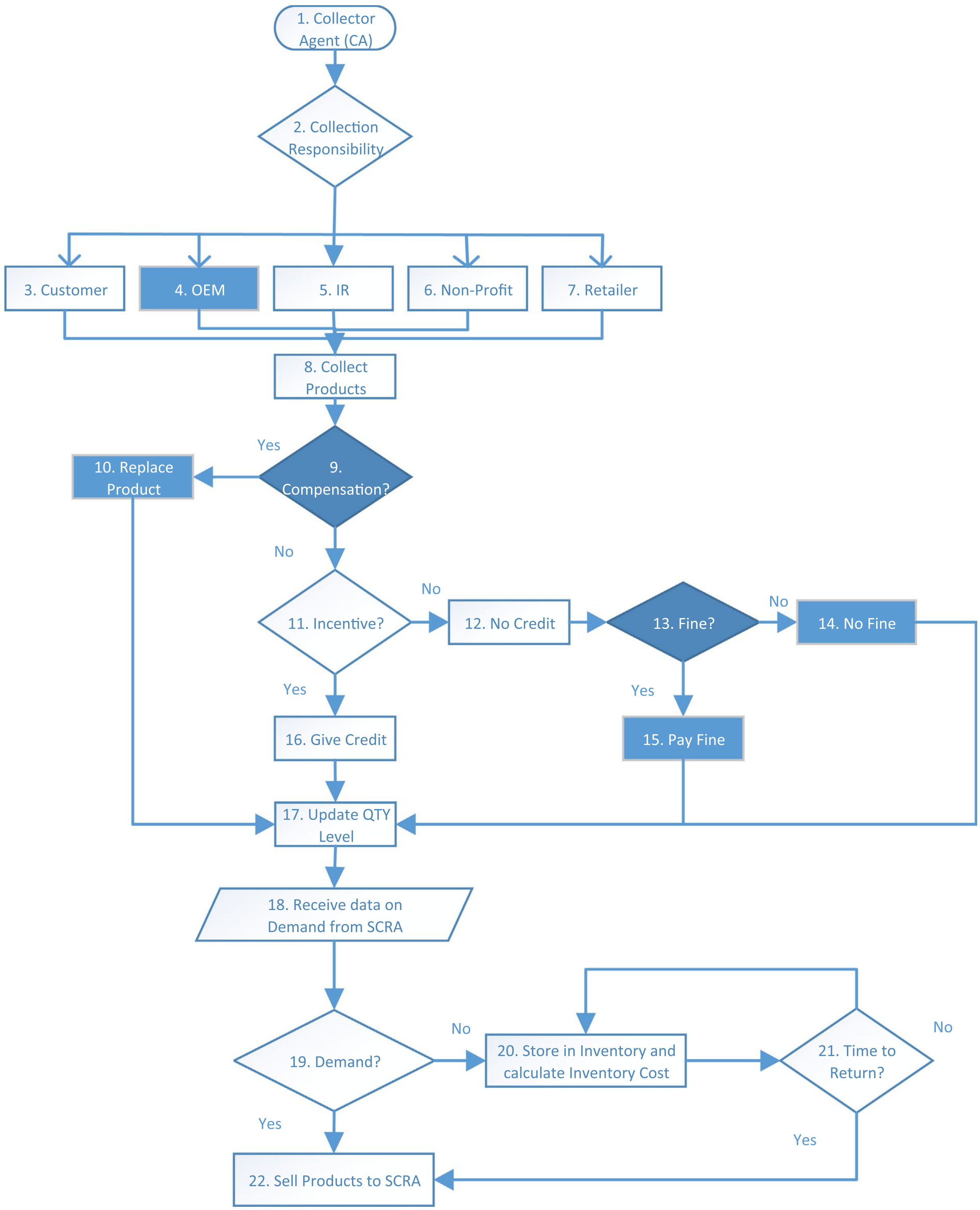


**Figure 1.** Collector agent (CA) – decisions and actions.

local collection centre, returned products are sent to the processing facility once a year. Therefore, 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, then the products are sent to the SCRA. Otherwise they remain in the collector's custody.

The common performance measures that can be calculated by the CA are the inspection time, the inventory levels and the input level of the CA. The objective of the CA 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. Likewise, the other agents in the system are made aware of the number of products returned per day and can plan their work accordingly.

### *Sorting-cum-reuse agent (SCRA)*

The SCRA is considered as part of the OEM organisation or independent recycler (IR). SCRA is the first stage in both OEM and IR processing facilities. The SCRA has two functions to perform:

sorting the returned products per their quality and performing reuse operations. The decisions and actions of SCRA are illustrated in Figure 2.

In the first step, as shown in box 2 of Figure 2, the SCRA periodically receives information regarding demand from the DA for products. If there is demand for a product, the SCRA decides to sort that product ahead of other products, and then ranks other products according to the time of request from the DA. This procedure is like FCFS rule. If there is no demand request from the DA, then the SCRA sorts the products randomly by assigning a time for each kind of product. After the first step, the SCRA passes on the information about demand and the number of products required by DA to the CA, who then sends the required quantity to the SCRA for processing. In the ensuing action (see box 6), the SCRA collects the products from the CA and increments the SCRA inventory level by the number of products received in a batch from the CA.

The pivotal decision block in the SCRA is the quality decision block; the SCRA may either perform manual or automated tests 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 (US EPA, n.d.). Based on the quality test requirements, bad products traverse through the sorting stage, and the information on the quantity level is sent to the Recycling department or RCA agent. Likewise, if the products are classified as moderate, the same action is performed

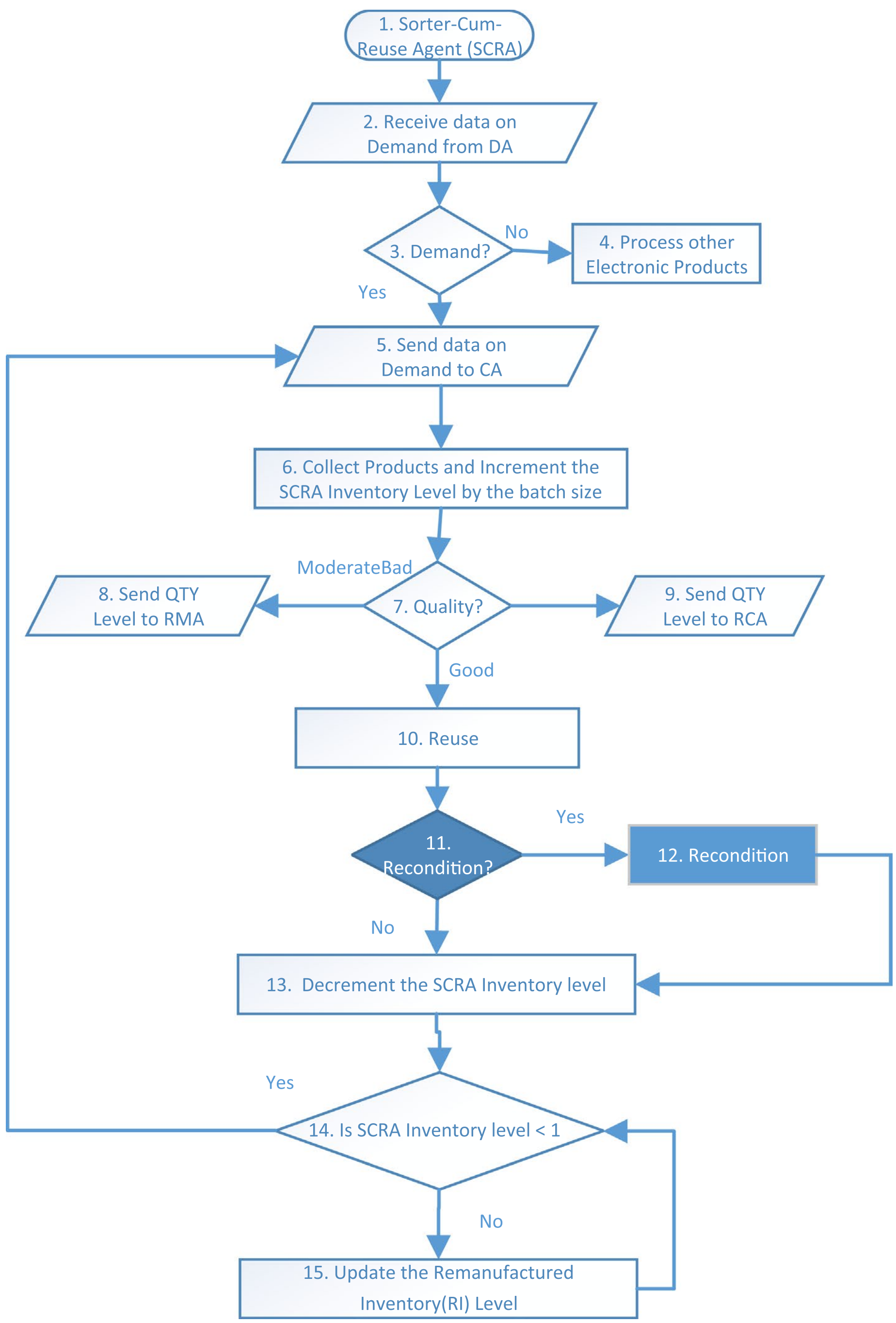


Figure 2. Sorting-cum-reuse agent (SCRA) – decisions and actions.

and the information on moderate products quantity level is sent to the RMA agent. If the product is classified as good then the SCRA performs the required reuse operations. See boxes 8, 9 and 10 in Figure 2.

After the reuse operation, the action passes on to the next decision block, which decides whether to recondition or not. Reconditioning might involve operations like painting or surfacing the remanufactured product; some products require reconditioning, while others do not. The SCRA therefore 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 a request 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 'Update Remanufactured Inventory (RI) level stage is made'. In this stage, the RI level is incremented by the number of products remanufactured.

The update on the Remanufactured Inventory, RI level highlights the number of products that are ready to be procured for sales to the DA. The important measure for the SCRA is the sorting time because this is an important stage and any improvement can lead to a significant reduction in the time and cost of the process. Other key measures include lead time, sorting effectiveness, utilisation, throughput, agent capacity and output quantity level. The main objective of the SCRA is to reduce the sorting time.

### Remanufacturing agent (RMA)

The remanufacturing or the refurbishing agent can be independent or part of the OEM and is primarily responsible for the remanufacturing operations in the company. The flowchart of the RMA is shown in Figure 3.

There are several actions and decisions that take place in the RMA. The products that are classified as moderate usually enter the RMA department for remanufacturing. Once the RMA receives information on the quantity of returned items that are classified as being of moderate quality by the SCRA, it collects the products for processing from the SCRA. In the first step (see box 4 of Figure 3), the products are completely disassembled and the individual parts are placed separately. A manual inspection is done on each part, and depending on the parts condition, will undergo one of the following operations: reuse, repair, recycle, recondition, refill or parts harvest (PH). Depending on the product type, the operations might vary. For example, a cell phone does not require refill operation, whereas a toner cartridge or similar refilling equipment might require the refill operation. The decision of which operation is to take place is decided in the first decision block by the RMA agent.

The parts are then inspected for functionality and physical appearance. A part can be reused as is if it is good. If, however, 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 operational condition. If it is not operational, or if the part is not repairable, then the part is sent to the recycling agent (RCA). See also box 12 and 8 of Figure 3. Similarly, if the part is severely damaged, then the part is recycled at the first step itself. 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 a product are in a 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 supplier agent, SA.

Following the 'parts operation' decision stage (box 5), 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 from the parts harvest (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 new life as a new product in terms of working condition. The product moves to the RI level, which 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, utilisation, parts harvested inventory level, agent capacity and output quantity level. The RMA aims at keeping the operations cost as low as possible, which is the main objective of the RMA in the RL system.

### Recycler agent (RCA)

The RCA is another 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 4. The important operations of the RCA are discharging and material recovery. The objective of the RCA would be to maximise the material recovery.

Like 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. Products like toner cartridges contain powder or liquid and need to be discharged before recycling. Therefore, at the first step, the product is inspected by a decision block (box 4), where it is decided whether to discharge the powder/liquid. If product is to be discharged, then the action to discharge the powder/ liquid is performed; otherwise, the action passes directly to the next stage where products are shredded. Once this decision block is completed, the products are pulverised 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 level of material recovered is calculated. In the next step, the material selling decision is made. It can either be sold to the raw material extractors or the electronic parts manufacturing company, both of which are beneficial. If they are sold to the raw material extractors, then the environment benefit of not extracting a new material is calculated. 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.

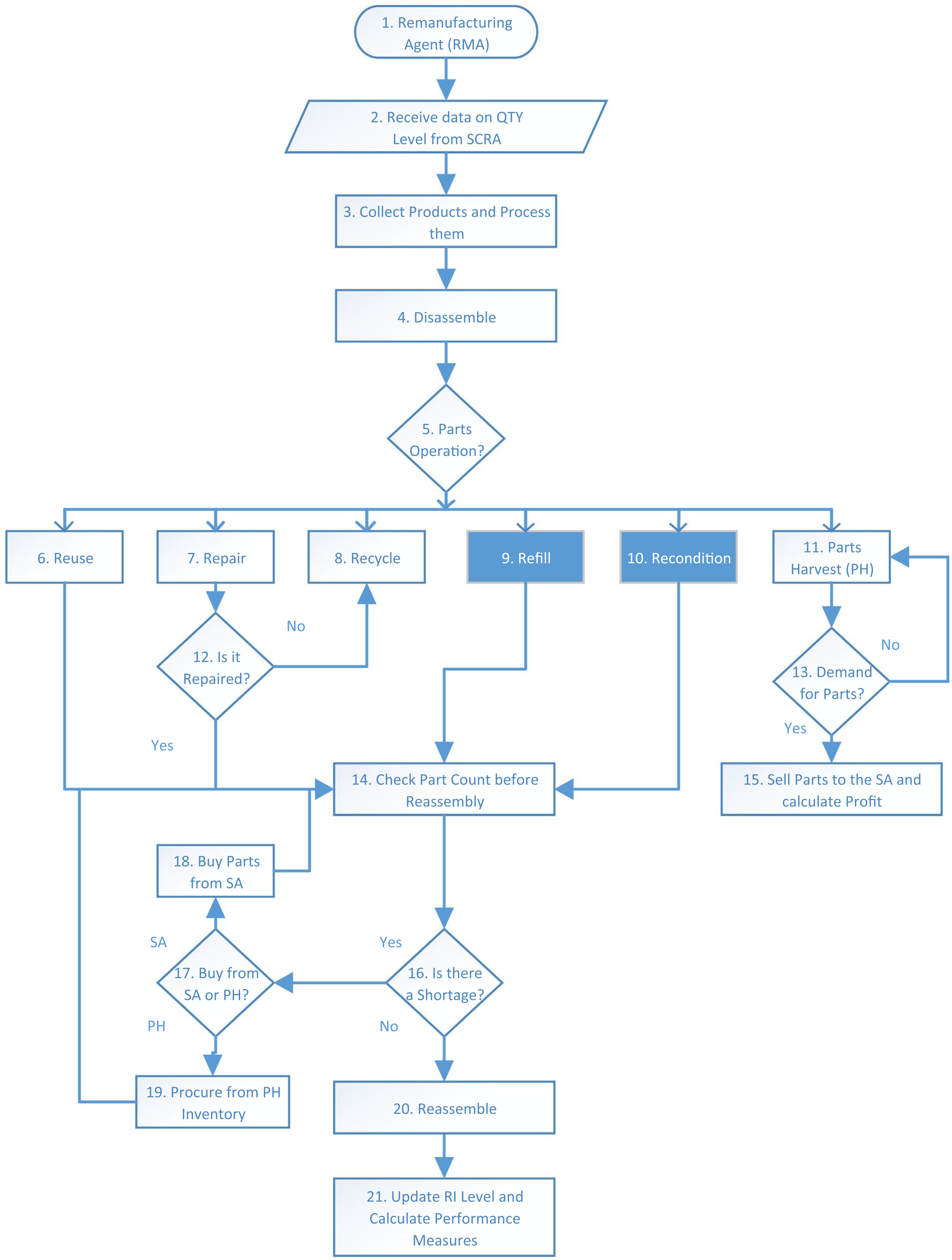


Figure 3. Remanufacturing agent (RMA) – actions and decisions.

### *Supplier agent (SA)*

The SA acts independently and is an external company that is not part of the IR or OEM. The role of the SA in a RL system is to supply parts to the RMA agent when there is a shortage of parts at the reassembly station. There will be no performance measures considered for this agent in the simulation model as it is not explicitly modelled in the case study. The SA regularly produces parts and stores them for an expected demand. If there is a demand for parts from the RMA, then the SA sells the parts to the RMA; otherwise, the SA sells the parts to the OEM in the

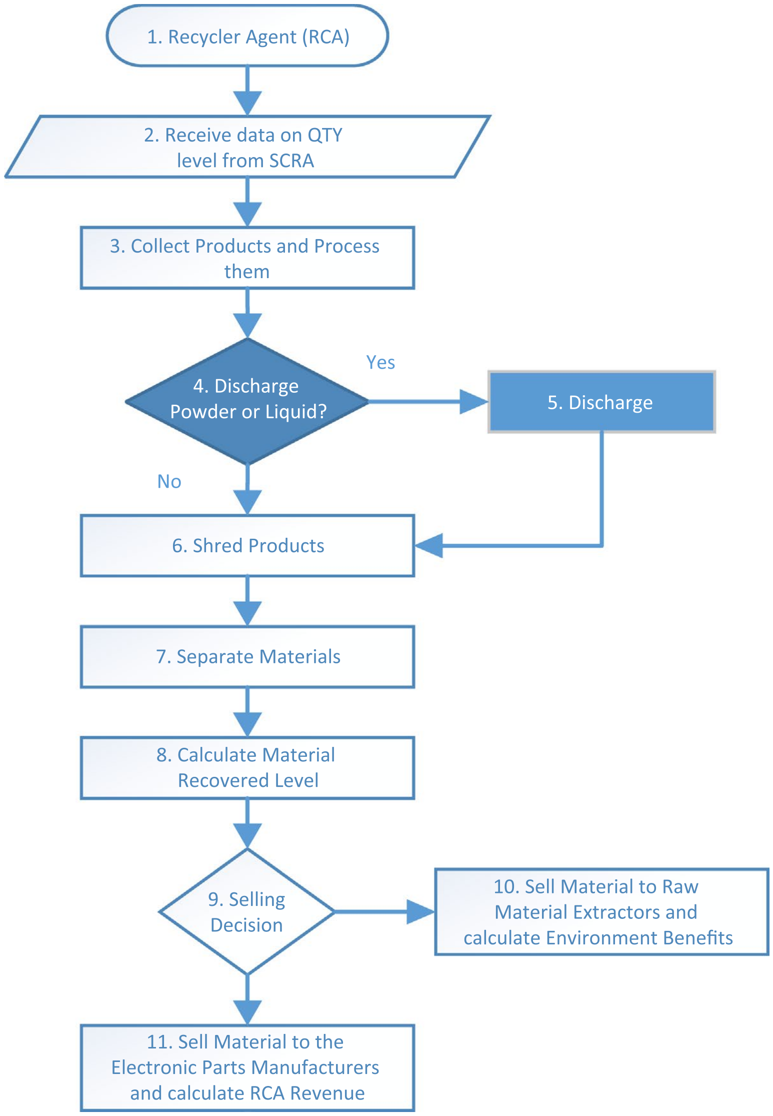


Figure 4. Recycler agent (RCA) – decisions and actions.

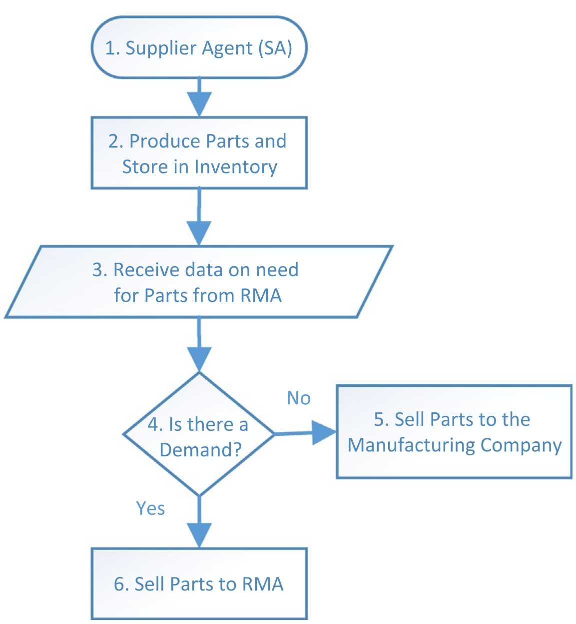


Figure 5. Supplier agent (SA) – decisions and actions.

Forward Supply Chain. The actions and decisions that correspond to the SA are shown in Figure 5.

### *Distributor agent (DA)*

The last agent is the DA. The distribution activities are carried out by the DA, which may be the OEM/IR distribution centre, or an independent distribution company. The DA takes care of distributing the remanufactured products in the RL system. The DA initially estimates the demand for a particular product with the help of 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 actions and decisions are illustrated in Figure 6.

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 is 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 by delivering products on time and maintains the company's positive reputation. It is equally important to satisfy 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 and the distributor 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 to determine the net income for the system. The main objective of the DA would be having an increased service level. To be specific, The DA agent was not explicitly included in the case study.

This concludes the agent-based simulation 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 agent 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.

## Case study: cell phone remanufacturing

In Canada, the average age of a cell phone is 22 months (CWTA 2013b). Once a cell phone is traded in, it is collected for processing. There are many collection centres throughout the country, including network providers' retail stores, public drop-off locations and recyclers' processing facilities. In 2013, 1,067,266 cell phones were collected by recycle my cell (RMC), a cell phone recycling program with other member initiatives in Canada (CWTA 2014). Per a survey by the RMC program in association with Canadian Wireless Telecommunication Association (CWTA), 41% of Canadians recycled/donated/sold/returned their used cell phones. This number can be increased by bringing in a more sophisticated reverse logistic coordination system across the country. Furthermore, the number of cell phone users is steadily increasing and some of them own more than one cell phone. So, addressing cell phone remanufacturing is a major motivation that led us to consider this case study to make aware OEMs, recyclers, and users of the economical, ecological and social benefits of such an undertake in Canada and worldwide.

This section will firstly present the input data for the simulation model that were gathered mainly from published papers; then, interviews conducted by the first author with managers from a cell phone remanufacturing firm in Southern Ontario, Canada, have helped clarifying the actions and decisions of the different agents involved in the simulation model. The assumptions and the steps the model takes to simulate this agent-based approach are indicated. Results and discussions for potential improvements of the RL enterprise are lastly offered.

### Input data

The process time for each operation in the model has been adapted from a study involving telephone remanufacturing (Li et al. 2013). Their modelling technique employed an analytical model, graphical evaluation, and review technique (GERT) based on Remanufacturing Process Routing. In the study, the process times of most stations were deterministic. Since process times are often probabilistic, statistical distributions were used for the process time of each processing station in the ABS model and presented in Table 1.

For the recycling operations, the process times of all the stations are presented in Table 2.

Regarding returned cell phone classification and volume of return per year, Table 3 below reports these parameters used in the ABS model.

Figure 7 below presents all the agents, collector (CA), sorting-cum reuse (SCRA), remanufacturer (RMA), recycler agent (RCA), distributor (DA) and supplier agent. Once the SCRA agent sorts the returns into the three categories: Good, Moderate, and Bad, reuse, remanufacturing and recycling activities are

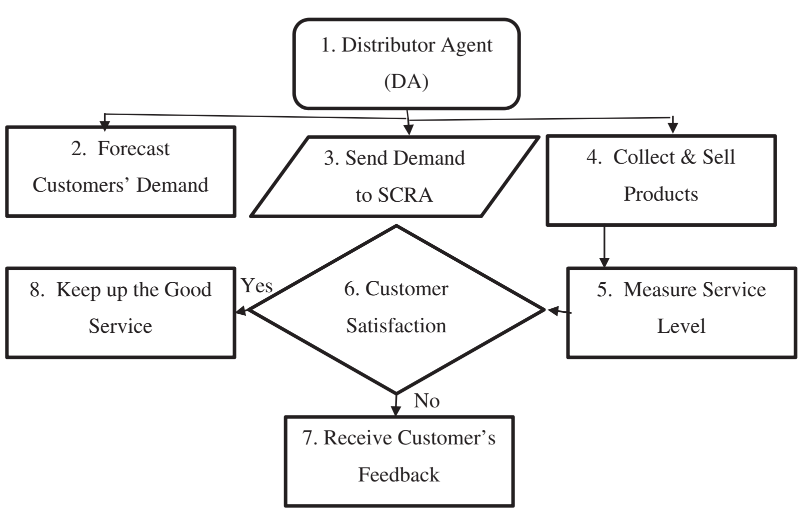


Figure 6. Distributor agent (DA) – decisions and actions.

**Table 1.** Input data – process time for remanufacturing operations.

| Process | Distribution of time ($t$ in minutes) | Flow ratio | | |
|---|---|---|---|---|
| | | Good | Moderate | Bad |
| Sorting | Exponential (0.5) | 25% | 60% | 15% |
| Cell 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) | | – | |

summarised in the Figure along with the supplier and distributor agents. The decisions and actions of all these agents are considered in the ABS model. However, exception is made to the last two agents, the DA and the SA that are not explicitly modelled in the ABS model. In Figure 7, The collector, recycler, distributor and supplier are independent companies. The recycler company is composed of the SCRA, RMA and RCA agents.

For more details about classifying cell phones into three categories, Table 4 below presents the attributes of each category. Once classified, the phones move to the next operation depending on the quality level (see Figure 7). Sorting may be done by employees manually, or using electronic devices and software programs that may increase the sorting efficiency and effectiveness (Geyer and Doctori Blass 2010). The condition under which quick sorting is economical with the help of electronic devices is also justified by Zikopoulos and Tagaras (2008). In the present ABS model, the sorting operation is assumed to be done manually.

### Assumptions

The assumptions considered in the ABS model are as follows:

(1) There is no disposal of returned phones. All cell phones are remanufactured, have their materials recovered, or have their parts harvested.
(2) In the ABS model, the collector agent accepts all returned cell phones in a day, so none are turned away.
(3) The model is assumed to operate 240 days in a year, which is equal to 48 weeks with 5 days per week and 8 working hours per day.
(4) There are no machine failures or breakdowns of processing stations in the model. It is assumed that remanufacturing equipment is reliable and not prone to failure.
(5) Only one type of cell phone model is considered. This assumption seems reasonable given that the many cell phone models available on the market have the same major components.

### Simulation model parameters

The simulation is run for a duration of 1920 h, the equivalent of 240 working days per year with 8 working hours per day. The warm-up period removes the transient state before collecting statistics, and the length of the warm-up period is calculated using Welch's method and equal 488 h. The model is replicated 15 times with a confidence level of 95% and error amount of 1. The time unit used in the ABS model is minutes.

Of the 1,067,266 cell phones returned in Canada, the sorting-cum reuse agent (SCRA) buys cell phones in batches of 4447 from the collector agent (CA). Once the first batch is completed, the second batch is ordered from the CA, and so on till the end of the year. The products are reused, remanufactured or recycled. The profits from parts harvested, remanufactured cell phones and recycled materials are calculated. The environmental benefits of remanufacturing or recycling are also derived or calculated.

### Results, discussions and recommendations for improvement

Following the simulation runs, the performance measures are obtained and reported in Table 5.

Table 5 lists the lead time, and the number of reused phones, remanufactured phones, recycled phones, phones parts harvested, the input quantity level of each agent and the output quantity level. The performance measures are calculated for a period of one year. The lead time to remanufacture one cell phone is found to be 29.59 min, and the number of cell phones that underwent reuse operations is 37,995 cell phones in a year. A total of 99,285 phones are remanufactured, while the number of cell phones that are recycled is 31,857 phones, and parts harvested are 20,464 parts. To validate the results, the lead time to remanufacture a cell phone is compared with a similar kind of study by Li et al. (2013), who measured and determined the lead time to remanufacture a telephone to be 20.14 min using an analytical model, graphical evaluation, and review technique-based remanufacturing process routing, as well as a simulation model to verify the results. In this ABS model, the lead time to remanufacture one cell phone is equal to 29.59 min. This helped to corroborate/ substantiate the results of our ABS model. From the performance measures presented above, these results will be discussed for each agent separately and recommendations for improvement will be provided.

It is recommended that the collector agent (CA) should have an initial sorting stage. Identification and pre-sorting can reduce volume and model diversity of phones sent to the remanufacturing floor. By having an initial sorting stage, the collector will be able to provide the number of cell phones in each category to the SCRA of the recycling company. In addition, the CA could develop an interconnected database system (IDS) among other agents that would provide information on the number of cell phones returned, and the cause of damage for each cell phone before sending it to the recycling company. To differentiate one damage from another, the CA can generate a quick response (QR) code for each cell phone that would contain the quality level and problem. The recycler can then scan the code and save time in sorting and inspection stages. Thus, with the help of the suggested IDS, the collector will be able to provide: (1) the number of phones that would come to the recycling company, such as quantity level; (2) the number of phones in each category, such as quality level; and (3) the problem or damage of the retuned phones. This would partially address the uncertainty in quantity and quality levels. The reader may also refer to Mondragon,

Table 2. Input data – recycling operations – process times.

| 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) |

Table 3. Input parameters – classification probabilities and yearly volume.

| Parameters | Value | Adopted from |
|---|---|---|
| Classification of cell phones based on their quality | Probability (Good) = 0.25<br>Probability (Moderate) = 0.60<br>Probability (Bad) = 0.15 | Nikolaidis (2009) |
| Cell phones collected by recycle my cell and other member initiatives in Canada in the year 2013 (Arrival Rate, $\lambda$) | Per year volume: 1,067,266 cell phones | CWTA (2014) |

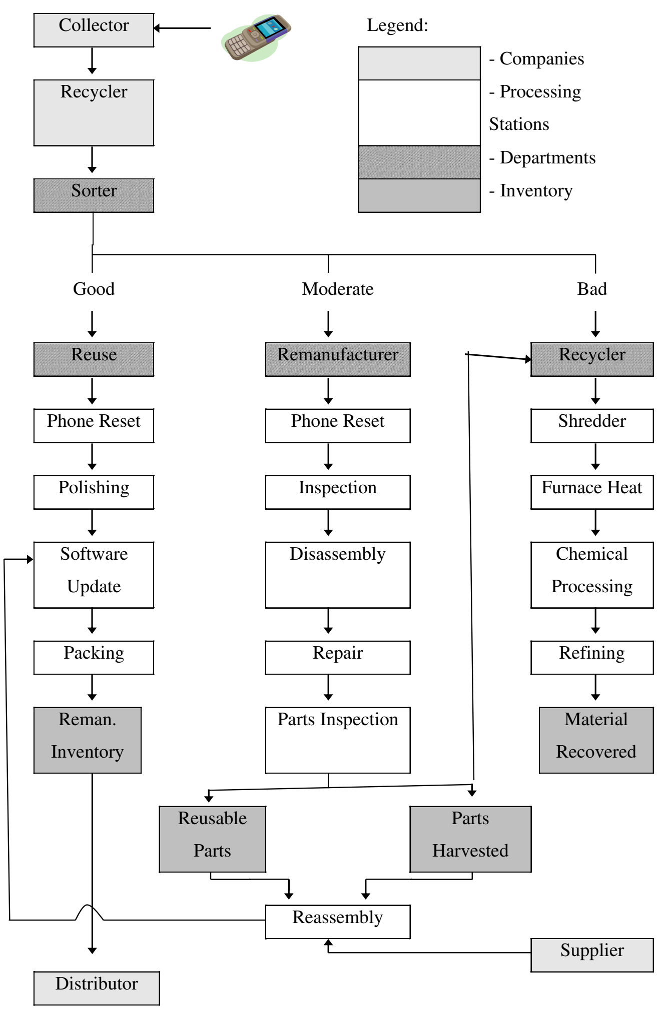


Figure 7. Cell phone RL process flow.

Lalwani, and Mondragon (2011) for a similar recommendation about information and flow among the different entities.

The main recommendation for the SCRA agent would be to have a scanning system that would sort the products per the information sent by the collector agent. The information on the quality of a cell phone and the problems associated with it provided by the CA's recommended IDS would be extremely useful in reducing the sorting time of a product by an operator. Thus, many products could eventually be sorted with the same available capacity.

Regarding the RMA, the disassembly stage has been identified as one of the main bottleneck. This could be rectified by increasing the number of operators in that station. The repair station was the other bottleneck in the RMA, and it required many stations to repair a batch of cell phones. With the suggested IDS, the RMA will be aware of the initial cause of damage, and will repair the part by quickly finding the right repair method for that damage reason. Without this information, more time would be spent finding the right method for repair. Likewise, the remanufacturing agent harvests parts. The number of parts harvested in the model is 20,464 phones per year, and 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 five parts, a revenue of $20.35 can be obtained by parts harvesting one cell phone. Based on this model, the revenue that can be generated by harvesting 20,464 cell phones is approximately $416,442.00 per year.

From the ABS model, the RCA 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 6. To elucidate this data, we consider a cell phone that has 16 g of copper. If 31,857 cell phones are recycled, the RCA can extract 509,712 g of copper, as shown in Column 4 of Table 6. Then, from 509,712 g of copper, the RCA agent can generate revenue of $15,291.36 for a price of $0.03 per 16 g. By recycling 31,857 cell phones in Canada, the total revenue for the recycler agent would be to $16,455.84. Thus, by recycling cell phones, revenue from valuable materials can be generated, the earth's natural resources can be preserved, air and water pollution can be reduced, and significant energy can be saved (US EPA, n.d.).

From the ABS model, the amount of cell phones remanufactured per year is equal to 99,285 cell phones. The distributor agent (DA) buys the remanufactured cell phones from the RMA and sells them to the public. Assuming the average selling price of a remanufactured phone to be $225.00 in Canada, and that the DA sells 99,285 cell phones per year, an annual revenue of $22,339,125.00 can be generated, creating a net profit of $2,482,125.00. It is good to note that the price of a remanufactured cell phone as given above is a conservative number.

### *Environmental benefits*

The benefits of remanufacturing and recycling do not only profit the organisations but also aid the environment on a large scale. These benefits are reduced pollution, energy saving, raw materials preserved and toxic materials properly disposed off and kept away from landfills. We provide in the paragraphs below some information about each of these four benefits.

### *Reduced pollution*

It has been found that by reusing or remanufacturing one cell phone leads to a reduction of 15 kg of $CO_2$ that would otherwise pollute the environment during the manufacture of new

Table 4. Classification of cell phones by the sorter.

| Quality level | Condition | Next stage |
|---|---|---|
| Good | Able to turn on/off, can dial and receive calls and messages, the screen is not damaged, can perform other basic operations, good physical appearance and not soaked in water | Reuse (see Figure 7) |
| Moderate | Not able to turn on/off or cannot dial/receive calls and messages or the screen is damaged or cannot perform basic operations and not soaked in water | Remanufacture (see Figure 7) |
| Bad | Not able to turn on/off plus the screen is damaged with noticeable flaws in the physical appearance of the phone, and soaked in water | Recycle (see Figure 7) |

Table 5. Simulation results – performance measures.

| Performance measures/ agents | Collector | Sorting-Cum Reuse | Remanufacturer | Recycler | Unit |
|---|---|---|---|---|---|
| Lead time | | | 29.59 | | Minutes/phone |
| Reused phones | | 37,995 | | | Units/year |
| Remanufactured and reused phones | | | 99,285 | | Units/year |
| Recycled phones | | | | 31,857 | Units/year |
| Phones parts harvested | | | 20,464 | | Units/year |
| Number of phones remanufactured | | | 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 |

Table 6. Metal contents and value in a single cell phone.

| Metal (1) | Weight per phone (g) (2) | Value of column (2) (3) | Material recovered per year (or 31,857 phones) (g) column (2) × (31,857) (4) | Revenue from material recovery per year ($) (3) × (4) = (5) |
|---|---|---|---|---|
| Copper | 16.00 | $0.03 | 509,712.00 | $15,291.36 |
| Silver | 0.350 | $0.06 | 11,149.95 | $669 |
| Gold | 0.034 | $0.40 | 1083.138 | $433.26 |
| Palladium | 0.015 | $0.13 | 477.855 | $62.12 |
| Platinum | 0.0003 | $0.01 | 9.5571 | $0.10 |
| Total | | | 522,433.77 | $16,455.84 |

Source for columns 1, 2 and 3 (Sullivan 2006).



cell phone (Seliger, Kernbaum, and Zettl 2006). Based on the ABS results, remanufacturing 99,285 cell phones eliminates a total of 1,489,275 kg of $CO_2$ emissions. Therefore, remanufacturing, can reduce pollution, meaning less $CO_2$ is released into the environment.

### *Savings in energy*

A significant amount 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, 250 MJ of energy is consumed for one cell phone (Seliger, Kernbaum, and Zettl 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). Therefore, 212.5 MJ of energy can be saved from remanufacturing one cell phone, and if 99,285 cell phones are remanufactured instead of manufacturing new ones, 21 TJ of energy can be saved in a year.

### *Raw materials preserved*

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

To refine one gram of copper from raw materials, 80,000 g of raw material are required. This quantity is mined from underground. Similarly, when refining one gram of copper from recycled materials, only 14 g of recycled material are required (*About OES – Updated February 22*, 2013). Thus, a large amount of virgin raw material can be preserved during the copper refining process. In the experiment, 509,712 g of material are recovered per year by recycling 31,857 cell phones, as shown in Table 6 (see row 1 and column 4). Therefore, 509,712 g of recycled material can be used to refine 36,408 g of pure copper. This is advantageous because it allows earth's natural resources to be preserved, existing materials in product form can be reused in new parts manufacturing by recycling, and the pollution involved during the raw materials extraction process can be reduced.

### *Toxic materials away from landfill*

A cell phone contains a lot of toxic waste in the printed circuit boards and batteries. By reusing or remanufacturing, 99,285 cell phones per year in Canada can be kept away from landfill, thereby reducing the amount of toxic waste in the environment.

## Conclusion and recommendations for future work

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 simulation model, which was supported by the various agents' decisions and actions and demonstrated with the help of a case study in cell phone remanufacturing.

The decisions and actions of every agent were tailored to fit in any similar kind of electronic remanufacturing activities and can be extended to other similar products with a few modifications where the product may have to follow different actions and decision routes as per their needs. The list of processes and activities taking place at a remanufacturing facility was developed with the help of interviews and designed to be generic. As previously highlighted by Rajagopalan and Yellepeddi (2007), the need for a general list of processing activities is important when measuring performance. The RL process flow diagram provided in this research accomplishes this by including all general activities for an electronic product.

The other overarching themes explored were problems related to uncertainty, EES benefits, communication among actors, need for computer-based programs to assess the RL enterprise performance. These objectives were completed by creating an agent-based simulation model. The experiment ran with the help of agent-based simulation, was able to provide recommendations to solve the problems related to uncertainty, and looked into the EES benefits. The agent-based model helped to fulfill communication among actors.

From the simulation experiments, it was found that the disassembly and repair stage were two bottleneck stations; further recommendations were provided for improvement. The IDS suggested at the CA level, would provide information on quality, quantity and problems associated with the products that come for return. All other agents will be able to retrieve the information using a display monitor or a quick response (QR) scanner. This partially addresses the uncertainties related to quantity and quality, while the addition of IDS alleviates the uncertainties related to RL. Additionally, the importance of adding barcode information to the products to reduce the disassembly time during remanufacturing was also highlighted. These were the main recommendations the model proposed to improve each agent.

To summarise, the main objective of this research was to collectively measure the performance of each individual company, agent, or department in the RL system using an agent-based simulation technique. Further, recommendations to improve each agent's performance have been provided, and by adding recommendations, the overall performance of the RL system can be improved. The major advantage of using an agent-based simulation technique is to measure the performance of the system and capture the system dynamics, as well as measuring and understanding the performance of each individual agent separately and at one time. This model can be extended to other products with minor or reasonable revisions of the agents' decisions and actions.

Apart from the recycling facility, this model is limited to a system that remanufactures a single product at a time, though a model that would remanufacture multiple products at the same time could be a possible extension of this research. Likewise, 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 a few modifications according to a product in another industry, such as mechanical products, and the performance of the product's remanufacturing activities can be measured with the help of the developed agent-based model.

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