An Information–Centric Modelling Approach for Product Recovery

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Abstract

This thesis reports the research undertaken to aid the system designers for recovery industry with tools and techniques to better understand the recovery business and analyse it under various circumstances. The principle objective of the research is to develop modelling and analysis tools and techniques for the small and medium enterprise operating in the recovery industry taking into consideration their information requirements.

A mathematical formulation is presented for a reverse logistics network design by considering the capacity constraints for the facilities and multiple product scenarios. A simulation based genetic algorithm approach is also presented for determining the optimal configuration of the network. These approaches have been implemented by developing an optimization tool in Visual Basic which utilises a simulation model built in Arena to evaluate the fitness functions.

An information–centred formal model for product recovery enterprises is also presented. The business knowledge is conserved for later reuse by the information–centric approach. The valuable information throughout the design process is collected and shared by both management and designers.

The modelling approach is demonstrated with the help of two example problems. The first problem is hypothetical involving single product. It provides an understanding of the main elements of the approach. The second example is that of IT product recovery and redeployment, which is motivated by industrial experience. A web browser based interface has been developed to present and modify the different views populated in the database. The web browser based interface makes it more easily accessible to members of the management team who are not experts in database management. The dynamic analysis of the systems under consideration is done in a distributed environment using the prototype distributed simulation platform developed.

In summary, this research has produced prototype tools and models, which can aid the system designers in recovery industry in the design and redesign process by means of easy and accessible information sharing capabilities.

Keywords: product recovery, reverse logistics, recovery network, genetic algorithm based optimisation, enterprise modelling, information sharing, simulation, distributed simulation,

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Introduction

1.1 Background

The continuous growth in consumer waste in recent years has seriously threatened the environment. Environmentally conscious manufacturing and product recovery has become an obligation to the environment and to society. Many countries are contemplating regulations that force manufacturers to take back used products from consumers so that the components and materials retrieved from the products may be reused and/or recycled. Businesses and governments have recognised that recovery offers advantages over disposal in terms of natural and financial resources, and they are building and supporting infrastructure to recover the used products. The driving factors for companies include the desire to profit from retrieving and reselling still–valuable products and product assets, the need to manage product returns from leasing programs, quick manufacturing cycles, the need to procure parts to support longer-term warranty programs, concerns about toxic liabilities from disposal of products bearing their brand name, and greener industrial ethics and consumer markets. Governments at all levels are developing waste handling prohibitions, regulations, or incentive programs to encourage alternative disposition of electronic waste and considering policies to make the producer or the consumer of products more responsible for ensuring their safe disposition.

Remanufacturing is rapidly emerging as an important form of waste prevention and environmentally conscious manufacturing and recovery of used products and materials is becoming a field of rapidly growing importance. The scope and scale of product recovery have expanded tremendously over the past decade. Firms are discovering it to be a profitable approach while at the same time enhancing their image as environmentally responsible, for a wide range of products. Recent changes in government legislation in various countries and increasing customer awareness towards greener products have forced manufacturers to rethink their business strategies. This has also resulted in new business opportunities in the area of remanufacturing and a large number of small and medium enterprises (SMEs) have appeared in the recovery industry. These SMEs include reprocessing and recycling companies as well as freight forwarders and warehousing companies.

1.2 Experience Gained from the Industry

During the exploratory phase of this research, one of the UK's leading IT product recovery firms was visited in order to build an understanding of the recovery industry and gain awareness of the current industrial state–of–the–art. The company is mainly involved in redeployment and resell of IT products from a variety of customers. Their product mix includes all types of IT products, i.e. desktop and laptop computers and peripherals. From the experience gained from the visit and subsequent correspondence with them and other company representatives, the author concluded that there is a shortage of information in almost every aspect of the recovery operations. This includes data related to the specification of incoming products, their processing requirements and the prospective market.

1.3 Motivation

Most business nowadays is highly competitive and ever changing. Recovery firms however have to deal with additional challenges, commonly processing a myriad of different used products originating from various sources. Customer demand and returns, which are largely dependant on the state of the art in technology, change without any warnings and unfortunately a third party recovery firm has little control over them. As a result, such companies must not only quickly adapt to the changes but also continuously evolve to survive in the market. They must be versatile, open to change and able to design and modify their own facilities and processes in parallel with new situations.

The process of enterprise modelling is employed in order to create an abstraction of a complex business. Enterprise modelling provides designers with modelling and evaluation tools to facilitate understanding and enable progressive design of the enterprise. The author believes that an information centric approach to enterprise modelling will enable the management of a recovery company to understand the dynamics of their business systems and analyse their company's performance. The recovery operations are mainly labour intensive and hence experience is automatically associated with human operators. The nature of an information centric approach will also help a recovery enterprise to conserve the knowledge of their processes.

1.4 The Research Question

Based on the experience gained from industry and an initial review of background literature on remanufacturing and product recovery, the author devised the following research question:

> *"How to provide Fast, Flexible Information for Planning, Modelling, Analysis and Re-engineering for independent recovery SMEs?"*

Figure 1.1 shows the key problems associated with this question, represented by shaded arrows going into the research question. The raw material for the recovery industry is the used products from end users but the origin for such products is geographically diverse and quantities available are varied and uncertain. In order to compete in the market, companies need to have a wide product mix. In the case of recovery companies, the product variety is even broader as the recovery companies need to deal with products of more than one brand. This increases complexity as different products are likely to have been manufactured by different OEM suppliers, each using their own techniques and methods. The market nowadays exhibits ever changing product specifications and technology, creating challenges for all kinds of companies. However, in the case of the recovery industry, this problem is even worse as the above changes are driven by OEM

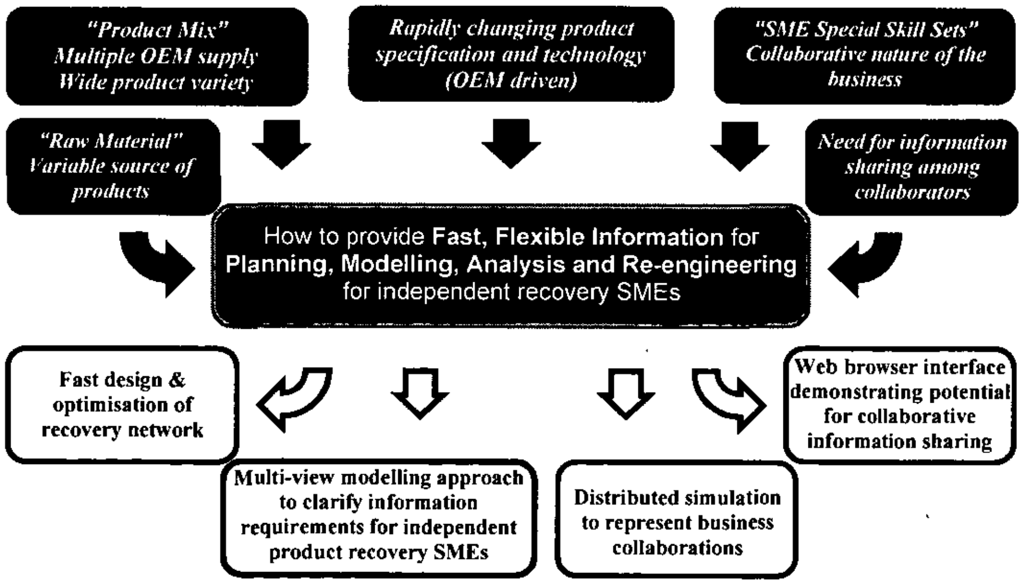

Figure 1.1: The research question

interest and the independent recovery SMEs have no prior information about it. SMEs usually often succeed by providing specialist services or skills and therefore need to work in a collaborative environment, specialising in only certain aspects of the operations cooperating with other SMEs. In such scenarios, there is a need for the sharing of the information among all the collaborators.

Figure 1.1 further explains the approaches taken in this research to address the above research question. A fast approach for design and optimisation of the recovery networks is presented in Chapter 6. A multiple view modelling approach is presented to address the information requirements for independent product recovery SMEs and this is discussed in Chapter 5. For examining the models created, this research utilises simulation experiments of "what-if" type. To mimic the collaborative nature of the business, distributed simulation approach is adopted and explained in Chapter 7. The potential for collaborative information sharing is demonstrated with the help of a user friendly web browser based interface and shown in Chapter 9. The next subsection lists the aims and objectives of the research for addressing the research question.

1.5 Aims and Objectives of the Research

Transparency of information is the key for any company to quickly adapt to the changing market scenarios. The overall aim of this research is to develop modelling and analysis tools and techniques for SMEs operating in the recovery industry taking into consideration their information requirements. In order to achieved this aim, the major objectives of this research are as follows:

1. To develop a tool for deciding an optimal network configuration for the recovery companies. This is important as an efficient logistics network is critical for the recovery industry as procurement is a major function within the recovery process.
2. To design and propose an information–centric approach to the modelling of recovery SMEs. This would be a valuable asset for the recovery company enabling management to maximise their use of easily accessible information that can be interpreted to meet multiple requirements and design perspective.
3. To develop simulation models for dynamically analysing the system with "what–if" experiments. A platform for distributed simulation also needs to be built in order to imitate the flexible collaborative nature of the recovery industry. This is needed to enable the product recovery business to be very flexible and redesign

itself quickly to maximize exploitation of business opportunities and minimise costs.

1.6 Summary of Research Work Undertaken

Acquisition is one of the major activities undertaken in product recovery and therefore to address the research objective 1 and the design of an efficient recovery network, this research presents a mathematical formulation for a reverse logistics network design by considering the capacity constraints for the facilities and multiple product scenarios. A simulation based genetic algorithm approach is also presented for determining the optimal configuration of the network. The use of simulation helps in incorporating the uncertainty associated with the product returns.

Research objective 2 is addressed by presenting an information–centred formal model for product recovery enterprises. The use of an information–centric approach ensures that the business knowledge is conserved for reuse. It enables collection of valuable information throughout the design process to be shared by both management and designers. Commonly SMEs in the recovery industry work in collaborative environments involving information exchange between the different entities within and outside the enterprise. Hence an information–centric approach becomes a necessity in such scenarios.

The modelling approach adopted utilises different views to show the different aspects of the enterprise. Examination of these different views and in particular of the performance view, has been used to address research objective 3. A web browser based interface has been built in order to make the model information easily accessible to the management team. Since the recovery industry largely works in collaborative environments, the web browser interface can be extended for information sharing among the collaborating parties. For analysis of the performance view of an enterprise operating in such an environment, a platform for distributed simulation has been created.

2

Review of Existing Literature

During the exploratory period of this research, the author surveyed the literature in the area of environmentally conscious manufacturing, product recovery, enterprise modelling, modelling and simulation, distributed computing including application of multi-agent systems. This chapter presents a summary of selected research in the relevant areas.

Chapter Outline

2.1 Material and Product Recovery

Increasing interest in re-use of products and materials is one of the consequences of growing environmental concern throughout the past decades. The continuous growth in consumer waste in recent years has seriously threatened the environment. During the industrial revolution, environmental issues were not addressed when designing and manufacturing products. However, in the recent past, Environmentally Conscious Manufacturing (ECM) has become an obligation to the environment and to society itself. ECM is forced primarily by governmental regulations; however there is an increasing demand for "greener" products from customers as well [1].

Waste reduction has become a prime concern in industrialised countries. In view of depleted landfill and incineration capacities efforts are made to re-integrate used products into industrial production processes for further use. A concept of material cycles is gradually replacing a 'one way' perception of economy. Several countries have enforced environmental legislation by charging producers with responsibility for the whole life cycle of their products [2, 3].

One of the major areas within ECM is product recovery, which is the transformation of used and discarded products into useful condition through re–use, re–manufacture and recycling. Johnson and Wang [4] define the recovery process as a combination of remanufacture, reuse and recycle whereas Thierry *et al.* [3] divide recovery into repair, refurbish, remanufacture, cannibalise, and recycle. There are mainly three reasons for material and product recovery:

- hidden economic value of solid waste
- market requirements
- governmental regulations

The two major directives from European legislation, namely the directive for end–of–life (EoL) vehicle [5] and the directive for waste from electrical and electronic equipment (WEEE) [6] makes it obligatory for the original equipment manufacturer to take–back and reuse, recover or recycle all used products at their EoL. These directives also provide incentives for products which are designed in ways that reduce the EoL recovery costs. The following subsections report the work done in the area of product and material recovery, however a discussion on product recovery is also presented later in Chapter 3.

Material Recovery or Recycling

The process of retrieving the material content of the used and non-functioning products is termed as recycling. As previously mentioned it is mainly driven by economic and regulatory factors.

The economic value of used products is the reason for several recovery infrastructures, including the economically–driven recovery process, which finds its application in industries like automobiles and consumer electronics [7, 8]. A typical computer contains gold, silver, palladium and platinum. The amount of precious materials is much higher in earlier manufactured electronics products. Recovery of precious materials from consumer electronic products requires proper equipment and is generally completed in mass. Besides the recovery of highly valuable materials, other materials such as plastics are now being recovered due to environmental concerns [9]. Regulatory electronics recycling is also practiced.

An efficient methodology for carrying out material recovery is discussed by Johnson and Wang [4]. Their methodology incorporates an initial study to determine the percentage of product which is recoverable, the initial cost/benefit estimates of recovery and the initial goals of material recovery options, identifying the disassembly level which generates a preferred sequence of disassembly which will maximise the value gained from recovery and the implementation stage of strategies developed in the previous levels. Krikke *et al.* [10] propose a model to evaluate recovery strategies for the product including disassembly, recycling, reuse and disposal without violating the physical and economical feasibility constraints.

An approach to recycling system planning for used products at their end-of-life phase is proposed by Hentschel *et al.* [11]. The authors consider design and process attributes as well as the uncertainties that are likely to arise in a recycling system. In order to incorporate these attributes into the proposed approach, the authors utilise fuzzy-set theory and group technology.

Product Recovery or Remanufacturing

Lund [12] describes remanufacturing as "...an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Usable parts are cleaned, refurbished and put into inventory. Then the product is reassembled from old parts (and where necessary new parts) to produce a unit fully equivalent or sometimes superior in performance and expected lifetime to the original new product."

Another definition of remanufacturing is given by Fleischmann *et al.* [13] as a process of bringing the used products back to 'as new' condition by performing the necessary operations such as disassembly, overhaul and replacement. Remanufacturing is also referred as recycling–integrated manufacturing. Industries that apply remanufacturing typically include automobile industry, electronics industry and tyre manufacturers. In remanufacturing systems, as in conventional production systems, there are operational, manufacturing, inventory, distribution and marketing related decisions to be made. However, the existing methods for conventional production systems cannot be used for the remanufacturing systems. Remanufacturing environments are characterised by their highly flexible structures. Here, flexibility is required in order to handle the uncertainties which are likely to arise. Hence a shop floor control system for such an environment should be very flexible.

2.1.1 Issues related to the Process of Recovery

The operational activities for product recovery differ from those for a traditional manufacturing process and require a different approach for addressing them. Product recovery exhibits a high level of uncertainty regarding the availability, quality and quantity of the product, because of the nature of the product source (end–users). The following sections discuss the research work done in the various fields of product recovery.

2.1.1.1 Logistics Operations

Logistics Network or Supply Chain

Logistics is the management of the flow of goods, information and other resources, including energy and people, between the point of origin and the point of consumption in order to meet the requirements of consumers. Logistics involve the integration of information, transportation, inventory, warehousing, material-handling, and packaging. For a traditional company, a logistics network or *supply chain* is the system of organisations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer and supply chain activities transform natural resources, raw materials and components into a finished product that is delivered to the end customer. A number of research works have been published in the past addressing the issues related to planning, strategy and control of supply chains [14-17].

Reverse Logistics

Management of logistics is a major issue in any recovery process [18] as the process of recovery starts from the procurement of the used items from the users. The logistics management for procurement of used products is quite different from the forward flow supply chain as the former has a converging nature of flow apposed to the diverging nature of distribution of the later. The logistic systems designed for the procurement of used goods are commonly referred to as *reverse logistics* [13]. Like normal supply chain systems, reverse logistics need to address issues related to transportation, freight control, temporary storage, distribution, etc. However, reverse logistics pose additional complexities in terms of uncertainty. A great amount of research in reverse logistics has addressed the additional challenge arising from the fact that the source of the used products are the end-users and therefore there is a high uncertainty of availability of the product at the collection centres. Reverse logistics is defined as a supply chain that should be designed to efficiently manage the flow of products or parts destined for remanufacturing, recycling, or disposal and to effectively utilise resources [19]. Reverse logistics focuses on managing flows of material, information and relationships for value addition as well as on the proper disposal of products.

For a large company, maintaining the reverse distribution of used products may be an easy task. However, for SMEs, carrying out the logistic operations itself may create extra burdens. In such scenarios, the logistic operations need to be outsourced to companies called third party logistic providers (3PLs). A 3PL is a firm that provides outsourced or "third party" logistics services to companies for part or sometimes all of their supply chain management function. 3PLs typically specialise in integrated warehousing and transportation services that can be scaled and customised to customer's needs based on market conditions and the demands and delivery service requirements for their products and materials. It is already known that 3PLs play important roles in forward logistics operations [20]. Now due to the increasing demand for remanufacture, their role must also be considered in reverse distribution. The main advantage of outsourcing services to 3PLs is that these 3PLs allow companies to get into new business, a new market, or a reverse logistics program without interrupting their existing forward flows; in addition logistic costs can be greatly reduced [21]. As discussed earlier, one of the main difficulties associated with implementing reverse logistics activities is the degree of uncertainty in terms of the timing and quantity of products. Thus, managing return flow usually requires a specialised infrastructure and relatively high handling cost and time. For that reason, demand for reverse logistics services from 3PLs is increasing [20].

Recovery Network

One of the initial publications addressing distribution issues was by Gottinger [22]. Thereafter, several models have been proposed which focus on aspects such as product recycling, planning and/or distribution [23-25].

Recently, a number of case studies have also been reported in the literature addressing the design of logistic networks in the product recovery context. Kroon and Vrijens [26] address the design of a logistics system for reusable transportation packaging. They discuss the role of the different actors in the system, economy, cost allocation, amount of containers and locations of the depots. Castillo and Cochran [27] discuss the distribution and collection of reusable bottles for a soft drink company while Duhaime *et al.* [28] address the same issues for reusable containers for Canada Post. Alshamrani *et al.* [29] develop a heuristic procedure for route design and pickup strategy for a network inspired by blood distribution by the American Red Cross. Krikke *et al.* [10] address the remanufacture of photocopiers and as remanufacturing is a labour intensive process they compare two remanufacturing options for the company; one coinciding with the existing manufacturing network and the other in another country where labour is cheap. Barros *et al.* [30] report a case study discussing the design of a logistics network for recycling sand coming from construction sites as waste in The Netherlands. While 1 million tons of sand used to be landfilled per year, re-use in large scale infrastructure projects, e.g. road construction, is considered a potential alternative in line with environmental legislation. Recycling of carpet waste is addressed by Louwers *et al.* [31] and Realff *et al.* [32, 33]. Louwers *et al.* [31] consider the design of a recycling network for carpet waste. High disposal volumes (1.6 million tons of carpet waste landfilled in Europe in 1996) and increasingly restrictive environmental regulation on the one hand, and a potential of valuable material resources (e.g. nylon fibres) on the other hand has lead the European carpet industry to setting up a joint recycling network together with some chemical companies. Through this network carpet waste is collected from former users and pre-processed to allow for material recovery. Realff et al. [32, 33] proposed a robust approach extension to a design model for carpet recycling previously considered in Ammons *et al.* [34]. In this a number of scenarios are identified and a solution is sought which minimizes the maximum deviation from the optimal objective values of the individual scenarios. The authors concluded that the solution performed remarkably well over the scenarios they considered

A mixed integer linear programming (MILP) model for the recycling of industrial by–products in the German steel industry has been developed by Spengler *et al.* [35]. From the above examples, it is obvious that most research in the area of reverse logistics network design has been case specific. Fleischmann *et al.* [24] present a generic model for the design of a reverse logistic network considering the impact of inclusion of product recovery on the forward network. They optimise the model by taking into account both the flows. A MILP formulation is proposed extending the traditional warehouse location problem and integrating the forward chain with the reverse chain. This work has subsequently been extended by Salema *et al.* [36] where capacity constraints, multi–product scenario and uncertainty were added.

Disassembly

Disassembly has gained a lot of attention in the literature due to its role in product recovery [37]. Gupta and Taleb [38]define disassembly as a systematic method for separating a product into its constituent parts, components, subassemblies, or other groupings. Disassembly activities take place in various recovery operations including remanufacturing, recycling and disposal. Even though approaching disassembly as the reverse of assembly may sound reasonable, for complex products, the operational characteristics of disassembly and assembly are quite different. The general operational characteristics of disassembly and assembly systems are highlighted by [39] and shown in Table 2.1.

Both operational and physical differences between assembly and disassembly imply that the assembly planning knowledge may not be used 'as is' for the disassembly planning issues. Therefore new techniques and methodologies need to be developed to specifically address disassembly planning. Disassembly planning problems can be broadly divided into two categories:

Disassembly levelling: The disassembly levelling problem can be defined as achieving a disassembly level to which the product of interest is disassembled to keep profitability and environmental features of the process at a desired level. Penev and de Ron [40] discuss the determination of optimum disassembly level and sequences for products. For this purpose, the authors utilize graph theory to represent the possible stages of the

Table 2.1: Comparison of assembly and disassembly system [39]

System Characteristics	*Assembly*	*Disassembly*
Demand	Dependant	Dependant
Demand source	Single	Multiple
Forecasting requirements	Single end item	Multi-item
Facility and capacity planning	Straightforward	Intricate
Manufacturing system	Dynamic and constrained	Dynamic and constrained
Operations complexity	Moderate	High
Flow process	Convergent	Divergent
Direction of material flow	Forward	Reverse
Inventory by-products	None	Potentially numerous
Availability of scheduling tools	Numerous	None

disassembly process and alternative disassembly strategies for every sub-assembly and treat the optimisation problem as a least distance problem. Zussman *et al.* [41, 42] introduce a quantitative assessment tool which aids designers in choosing product designs that are more suitable for recycling. Cost analysis of disassembly, dumping, recycling and total recovery is performed by taking the uncertainty conditions of recycling into account. The authors also analyze the end-of-life options of products in order to minimize waste and maximize the benefit gained from recycling.

Disassembly process planning: A disassembly process plan is a sequence of disassembly tasks which begins with a product to be disassembled and terminates in a state where all the parts of interest are disconnected. One of the first papers in this field is by Subramani and Dewhurst [43], which utilizes a 'branch and bound' based algorithm to find a disassembly sequence that minimizes the total disassembly cost. Beasley and Martin [44] emphasize the importance of identifying the geometric relationships among the parts in the process of disassembly process plan generation. Lambert [45] develops a quantitative method for the disassembly of complex products by creating a graph showing all possible disassembly strategies and associated cost and revenue values. This work is extended and reported in [46].

Disassembly is a mostly labour intensive process. However, there is some research in the area of automation in disassembly. Automated disassembly relies on sensors and algorithms for image processing, grippers for product handling, a decision tool for disassembly task planning, and robotic tooling for disassembly [47]. Dario and Rucci [48] propose a framework for object perception in order to automatically identify parts or materials for disassembly. Karlsson [49] compares real-time image data to a database using fusion methods to determine which disassembly operations a robot should perform.

Remanufacture

Due to the high uncertainty and variability of available parts, the (re)manufacturing processes for used products cannot be approached in the same way as those for traditional manufacturing. Gupta and Taleb [38] and Taleb and Gupta [50] present an algorithm that can be applied to a product structure where there is a certain demand for components and a need to know the number of root items to disassemble in order to fulfil the demand for those components. The algorithm is designed for a single product case by using the modified reverse MRP algorithm. Hoshino *et al.* [51] present a mathematical model formulation for a recycle-oriented manufacturing system and analyse it using an optimisation model, which is designed for a system producing a single product with multiple parts. Due to the high degree of uncertainty, it is important to control the flow of parts at the remanufacturing shop floor level. Guide and Srivastava [52] and Guide *at al.* [53] use a simulation model of a Naval aviation depot's aircraft engine components workshop to evaluate various part order-release strategies in a remanufacturing environment.

Capacity planning is another critical issue in the recovery process. Release of various part types simultaneously from disassembly adds to the uncertainty of the part availability. Therefore, it becomes quite important to apply forecasting techniques for the planning of the activities. Marx-Gomez *et al.* [54] use a neuro–fuzzy technique to forecast the return rate of used product. The management of inventory becomes quite complex in a recovery environment and the available techniques for conventional manufacturing are not always transferable to it [55].

The boundary of a typical inventory management system within product recovery environments is depicted in Figure 2.1. In this context, an inventory control model is required to keep track of returned products, tested disassembled parts, as well as new parts. Inventory includes returned product, remanufactured parts, components or units, parts that are functional and sold as–is or used as spares, materials that are destined for resale as scrap, new parts manufactured in–house or purchased, work–in–process and finished goods [56].

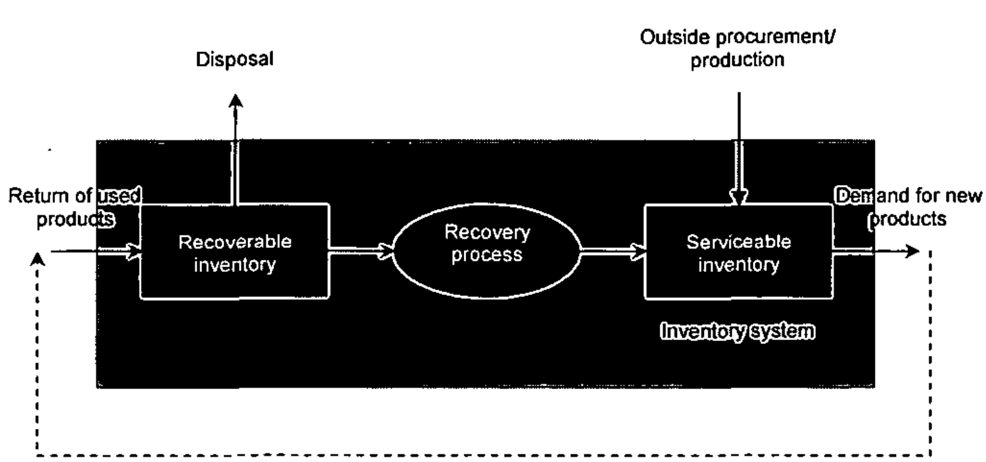

Figure 2.1: Framework inventory management with returns [13]

Fleischmann *et al.* [13] list the following complicating factors in the applicability of existing models for inventory management for product recovery environments:

- As a result of return flow, inventory level between new component replenishments may not only decrease but may increase as well.
- In the case of product recovery in integrated manufacturing systems there are two options to fulfil demand, namely reuse (i.e. recovered parts) or new order new or bought–in components), resulting in an additional decision–making task requiring coordination.
- Two sources of supply, i.e. recovery and new order, lead to a two–echelon inventory system.

Therefore, the traditional methods and tools are not directly applicable in product recovery environments. Both periodic and continuous review models for product recovery systems considering independent stochastic return and demand occurrences have been developed. Examples of periodic review models include: model in which returned products can be reused directly [57], model with a setup cost [58], model with separate inventories for serviceable and recoverable parts [59] and model considering effects of non-zero leadtimes for orders and recovery [59, 60].

Summary of identified current research challenges to be addressed in this research

So far this chapter has shown that there are clear difference between traditional manufacturing processes and remanufacturing processes, particularly relating to the higher levels of uncertainty and risk that exists and to unavailability or delays in obtaining information for planning the necessary range of possible remanufacturing tasks that may be required for products obtained by a product recovery firm.

Therefore any information or planning support tool for the product recovery industry should

1. Enhance flexibility and agility in redesign of business processes to improve the company's ability to exploit current market conditions
2. Improve communication and information flow to reduce uncertainty and support planning activities.

3. Provide opportunities to explore and assess alternative solutions or courses of action for improved and informed decision making.

With these requirements in mind, potential approaches for the design and implementation of information support systems have been considered and reviewed. As model–based approaches have many benefits for understanding, structuring and presenting information, the remainder of this chapter will examine published literature on enterprise models and simulation models to assess their applicability for the product recovery industry.

2.2 Enterprise Modelling

Enterprise models are useful abstractions of reality employed to clarify, expose and manage the highly complex activities of an enterprise. They are computational representations of the structure, activities, processes, information, resources, people, behaviour, goals, and constraints of a business, government, or other enterprise. They can be both descriptive and definitional—spanning what is and what should be. The role of an enterprise model is to achieve model-driven enterprise design, analysis, and operation [61]. Regardless of the nature of the business an industry is involved in, in order to remain competitive they must produce products and provide service "of consistently high quality throughout the life of the product/service, customized to local market needs, able to integrate with other products/services, environmentally benign and technically advanced". The key to achieving these capabilities is agility, which implies the ability to "continuously monitor market demand; quickly respond by providing new products, services, and information; quickly introduce new technologies; and quickly modify business methods" [62]. Nigel [63] provides four strategic principles of agility: using an entrepreneurial organisation strategy, investment to increase the strategic impact of people and information on the bottom line, using the virtual organisation strategy as a dynamic structure both inside and outside the enterprise and adopting a value-based strategy to configure your products and services into solutions for your customers.

The structure of a model can be tailored to suit particular tasks; hence the information content of the model is dependent on the modelling approach adopted. Legacy systems were developed independently and consequently do not share the same enterprise model, resulting in a "correspondence problem". As a solution to this problem, there has been an increasing interest in Generic Enterprise Models (GEM). A GEM is an object library that defines the classes of objects that are generic across a type of enterprise and can be used in defining a specific enterprise [61]. There are many architectures for enterprise descriptions, including CIMOSA, ARIS, GRAI-GIM, ICAM, GERAM, PSL and PERA [64-70].

Attempts to create industry–wide standards began to appear with the United States Air Force integrated computer-aided manufacturing (ICAM) effort in the early 1980s. A GEM for the aerospace industry was developed [67, 68]. In the ICAM model, each relation is followed by other objects in the GEM that the relation links the part object to. The Process–Specification Language (PSL) project was developed at the National Institute of Standards and Technology (NIST) with the aim of creating a language for process specification, which may facilitate complete and correct exchange of process information between manufacturing functions or companies [71]. These processes include scheduling, process planning, simulation, project management, and product realisation process modelling.

Generic Enterprise Reference Architecture and Methodology or GERAM is about those methods, models and tools which are needed to build an integrated enterprise. The architecture is generic and can be applied to most types of enterprise. The coverage of the framework spans Products, Enterprises, Enterprise Integration and Strategic Enterprise Management, with the emphasis being on the middle two [69, 72]. The Purdue Laboratory for Applied Industrial Control endeavoured in enterprise modelling producing the Purdue Reference Architecture (PERA) [69, 70, 73]. PERA divides the functional descriptions of tasks and functions of the enterprise into two major streams: information and manufacturing. The information stream is initiated by planning, scheduling, control and data management requirements of the enterprise while the manufacturing stream is initiated by the physical production requirements of the enterprise.

The characteristics of an enterprise have been represented in various ways, e.g. function, information, behaviour, decision making, organisation, product, and order, but the views included in individual architectures vary. For example, CIMOSA utilizes highly developed generic enterprise structures and presents four different views, focusing on different aspects of the model, i.e. function, information, resource and organisation [74, 75]. Kosanke [76] and Vernadat [77] provide a comparison of enterprise modelling methodologies and modelling constructs involved in CIMOSA. With the help of different views, the model can be looked at from different perspectives, and hence helps the designer to identify and analyse particular aspects of the enterprise. Wang *et al.* [78] propose an integrated multiple view approach, which enables system designers to describe a manufacturing system from the perspectives of function, information and dynamics. All the three independent views work in the same environment and are called in succession. Gay *et al.* [79] reports a similar work describing a flexible manufacturing system using the same views as [78]. However, in this work each view, i.e. function, information, and dynamics is examined using IDEF0, IDEF1 and SLAMII respectively. Bouti and Kadi [80] report the modelling of an automated manufacturing system for function, behaviour, and structure by using IDEF0 and Petri net. They conclude that the multi-view modelling approach "provides the complete system knowledge necessary for accurate and correct understanding of the system's normal operation and consequently makes reliability analysis easier".

Harding and Popplewell [81] present a factory data model containing a variety of views, namely strategic, resource, business process and performance view, with the focus on information modelling. Their approach to enterprise design differs from the approaches above as it enables designers and management to gradually build a progressively more detailed factory design, starting from very simple partial models. With the inclusion of a strategic view and performance view, the developing designs can be regularly checked and their performance evaluated against strategic plans so that management can be confident that the proposed factory will meet their business objectives.

2.3 Computer Simulation

The following subsections provide a survey of existing research work in the area of computer simulation. Later in this thesis, Chapter 7 discusses simulation in distributed environments with initial background of general standalone simulations.

Simulation involves the development of descriptive computer models of a system and exercising those models to predict the operational performance of the underlying system being modelled. This section presents a review of two classes of research in the area of simulation: system design and system operation. System design generally involves making long-term decisions such as facility layout and system capacity/configuration. Models are typically created and used for a single design exercise and model run time is not a significant factor during the simulation process. System operation, on the other hand, involves making decisions on a much shorter time schedule.

System Design

System design involves making long-term decisions and research related to this area has been reported by several authors. Kleijnen [82] presents an overview of the design and analysis of simulation experiments for sensitivity analysis. Schroer and Tseng [83] describe the simulation modelling of complex manufacturing systems while general issues associated with simulating automatic assembly systems are reported by [84]. Heavey and Browne [85] describe the use of simulation in a specific approach to manufacturing system design. A simulation model for analyzing computer-aided manufacturing systems is presented by [86]. Pritsker [87, 88] describes the application of Simulation Language for Alternative Modelling (SLAM) to a pharmaceutical manufacturing design problem.

Williams and Celik [89] describe the analysis of an automobile final assembly line using simulation with particular emphasis given to the material handling processes and conveyors on the line. Similarly, Williams and Gevaert [90] describe the analysis of a production system at an automotive supply company. The simulation model is based on a proposed configuration and operational information and is used to verify that the proposed system will meet required production rates and to predict the relative performance of alternative configurations.

Noble and Tanchoco [91] develop a framework for material handling design justification. The simulation component is used primarily to evaluate design alternatives as part of the overall framework. General use of simulation to model material handling systems is described by Banks [92], whilst Raju and Chetty [93] describe a modelling and simulation approach for automated guided vehicles using timed Petri nets. In particular, they describe a software package, SIMAGVS, which extracts the dynamic behaviour of the system from the Petri net model and creates an Ada simulation of the system. Shang [94] uses a SLAM II simulation model as an evaluation function for an optimal design procedure of material handling system for an flexible manufacturing system (FMS), which uses a Taguchi approach in conjunction with a response surface methodology (RSM).

Shinn and Williams [95] describe the process of simulating a cellular manufacturing system using specific systems as a reference. Shang and Tadikamalla [96] use a combination of simulation and optimisation to evaluate the design of a cellular manufacturing system. Nandkeolyar *et al.* [97] describe the use of a simulation model to predict the performance of a manufacturing cell for a manufacturer of hydraulic flow control components. The model was used to provide justification for a reconfiguration of a traditional facility into a cell-based system. Kamrani *et al.* [98] describe a three-phase methodology for designing manufacturing cells. Simulation modelling and analysis comprises the third phase and is used to analyze the system and justify the final design. Caprihan and Wadhwa [99] use a simulation experiment to evaluate the impact of routing flexibility on the performance of an FMS using makespan as the performance measure. The study is designed to help system designers determine the levels of flexibility to be included in an FMS at the system design stage.

System Operation

A review of the research related to simulation study of the FMS scheduling is reported in Chan *et al.* [100] and Chan and Chan [101]. Trentesaux *et al.* [102] propose a distributed management system to aid the simulation of FMS. Gupta *et al.* [103] describe an integrated simulation-based approach to the operational planning and scheduling problem in advanced manufacturing systems involving part loading, release, routing and dispatching problems. Andersson and Olsson [104] use simulation for capacity planning in a situation where labour is the primary capacitated resource. The simulation provides performance and utilisation information as part of a decision support system. Oboth *et al.* [105] use simulation to test the feasibility of an AGV routing scheme developed by a route generation technique. Smith *et al.* [106] and Drake and Smith [107] discuss the use of a discrete event simulation for controlling a flexible manufacturing system. They seek to use the same simulation model for system design, analysis and control. Veeramani and Wang [108] and Veeramani *et al.* [109] describe a methodology for modelling and simulation of an auction-based shop-floor control system.

Bai *et al.* [110] use simulation to analyze the performance of an example production system under different control policies. The experiment considers five input control strategies and four dispatching rules for a three-machine, single product system with re–entrant product flow. The objective of the research was to evaluate the feasibility of using simulation for production control policy selection. While the experiment proved successful, the authors report that the simulation time required grows very quickly with the numbers of control parameters considered and that optimisation procedures are needed to control the number of simulations required. Bischak [111] describes the use of simulation to evaluate the performance of a textile-manufacturing module with moving workers. Black and Schroer [112] describe a pull-based apparel manufacturing cell that uses process decouplers to improve system performance. The simulation model estimates work-in-process levels, worker and machine utilisations and the time that each worker spends at a machine. Black and Chen [113] use a similar simulation model to predict the effect that adding operators will have on the improvement in throughput rate.

Callantine *et al.* [114] conduct a simulation of integrated air and ground operations to demonstrate procedures, flight management automation, data link technology, and air traffic control decision support tools for improving Air Traffic Management efficiency. A Stochastic Hybrid Model for Air Traffic Control Simulation is presented by Glover *et al.* [115]

2.4 Distributed Computing

Distributed Computing deals with hardware and software systems containing more than one processing element, storage element, concurrent processes, or multiple programs, running under a loosely or tightly controlled regime. In distributed computing a program is split up into parts that run simultaneously on multiple computers communicating over a network. Distributed computing is a form of parallel computing, but parallel computing is most commonly used to describe program parts running simultaneously on multiple processors in the same computer. Both types of processing require a program to be divided into parts that can run simultaneously, but distributed programs must often deal with heterogeneous environments, network links of varying latencies and unpredictable failures in the network or the computers. [116]

2.4.1 Parallel and Distributed Simulation

Parallel and distributed simulation is concerned with issues introduced by distributing the execution of a simulation program over multiple computers. Parallel simulation is the execution of simulation on multiple central processing units that need to interact frequently (e.g. thousands of time in a second) while distributed simulation is the execution of simulations on loosely coupled systems where interactions take much more time and occur less often. In both the cases, the execution of a single simulation model comprising of several simulation modules is distributed over multiple computers [117].

Koh *et al.* [118] describe the use of distributed simulation for solving job-shop scheduling problems. The authors highlight two primary problems with simulation-based scheduling: external data requirements; and computational burden. They propose to overcome these problems by building their system on a relational database system

(RDBMS) and by using multiple processors in a distributed fashion. Jernigan *et al.* [119] describe the use of distributed simulation to simultaneously generate and evaluate alternative schedules for a flexible manufacturing system.

2.4.2 Multi-Agent Systems

An example of loosely coupled distributed computing systems is multi-agent systems (MAS). MAS is a system composed of multiple interacting intelligent agents. In computer science, an agent is software that assists users and will act on their behalf, in performing non-repetitive computer-related task. Agents are used for operator assistance, communication or data mining etc. and often work based on fixed pre-programmed rules.

MAS can be used to solve problems which are difficult or impossible for an individual agent or a monolithic system to solve. MAS has been applied to a very wide area of research . In manufacturing, MAS find application in process planning, [120-123], project management [124-126], and scheduling and control [127].

2.5 The Research Gap

In the area of product and material recovery, substantial amounts of work have been carried out addressing the problems specific to certain companies and in most cases, these companies are large OEMs. The work related to logistics management is mainly focused on the issues like merging the reverse logistics with the traditional supply chain of the OEMs. The problems faces by the SMEs have attracted little attention from the research community. The collaborative nature of SMEs means that they need to maintain an efficient network of logistics and related logistics information as well as material transfer information. However there is no research done in the area of information and enterprise modelling specifically for the SME sector.

From the survey of the available literature, the author concluded that there are a number of enterprise and information modelling approaches available and each of them has certain advantages and shortcomings. Although, these approaches have not previously been applied specifically to the SME sector, it was clear from the review that enterprise modelling offered potential for clarifying the requirements of remanufacturing SMEs and sporting their need for rapid and flexible planning and restructuring. Apart from that, the advances in networked computing aids facilitate the testing of such models in a virtual environment.

3

Product Recovery

The aim of remanufacturing is to bring the parts of a product or the product as a whole to a desired level of quality to reuse, resell or reassemble. This chapter discusses the activities, functions and operational issues in recovery processes. There is a high uncertainty about the quality and quantity of products due to the fact that retired products originate from multiple locations. Hence the product recovery processes become quite different from the traditional ones. This chapter therefore also discusses the different possible business scenarios for the recovery industry.

Chapter Outline:

3.1 Introduction

Information on the industry generally and the SME sector in particular was gathered via industrial visit, a questionnaire and email communications in addition to reviewing the available literature. The author contacted one of the UK's leading IT product recovery firms and visited it to get insights into the business. This visit was followed by email communications with the concerned managers to clarify doubts. At the same time, several other OEMs and independent recovery companies were contacted by email and requested to fill up questionnaires. The typical questions included in the list were about the types of product mix, market and process etc. The following subsections present the current state of the art in the recovery industry based on the understanding built during the exploratory phase of the research.

3.2 Recovery of Materials and Products

The recovery process can be defined as a combination of remanufacture, reuse and recycle [4]. It can be motivated by the hidden economical value of the solid waste, market regulations and/or government regulations. Material recovery mostly includes disassembly for separation and processing of materials (e.g. carrying out necessary chemical operations) on used products. The major purpose of the recovery process is to minimise the amount of disposal and maximise the amount of the materials returned back into the production cycle. Product recovery includes disassembly, cleaning, sorting, replacing or repairing bad components, reconditioning, testing, reassembling and inspecting. The recovered parts or products may be deployed in repair or remanufacturing of other products and components or may be sold separately.

Recovery can be achieved in different ways. In general, two forms of recovery for the used products are commonly recognised, i.e. recycling or material recovery and remanufacturing or product recovery. Recycling mainly involves separation and processing of materials from used products so that the amount of disposal can be minimised and the amount of material going back to the production cycle can be maximised. In contrast, remanufacturing is recovering the product as a whole through a series of operations, which may include disassembly, replacing or repairing non–functional components, reconditioning and reassembling. Unlike repairing, remanufacturing includes disassembly of the product into components and restoring them to like–new condition before reassembling them. This may involve a number of cosmetic operations. Figure 3.1 shows a typical unit flow in remanufacturing. It is similar to conventional production systems in that remanufacturing requires operational, manufacturing, inventory, distribution and marketing related decisions to be made. However, due to high uncertainty, the remanufacturing environments need to be highly flexible. Hence, existing methods for conventional production systems cannot be used for remanufacturing systems.

This chapter attempts to familiarise the reader with details of typical product recovery processes. The following sections discuss the activities, functions, operational issues, and business scenarios of recovery processes.

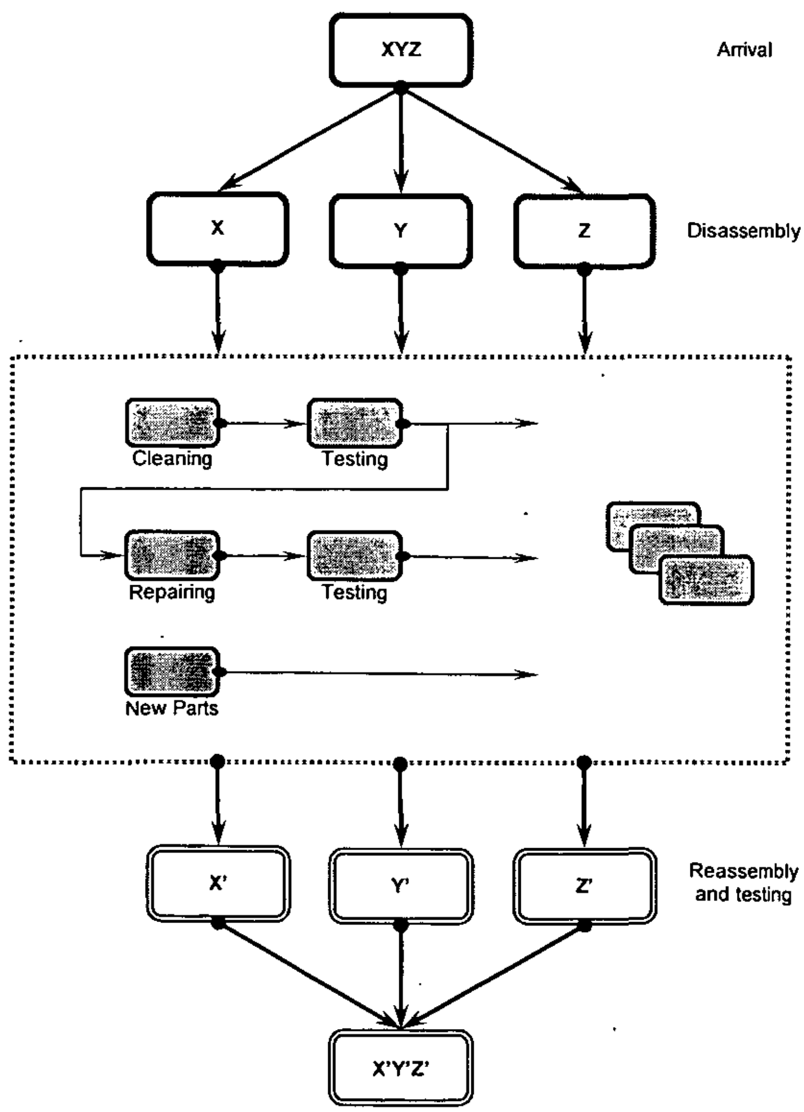

Figure 3.1: Typical part flow in remanufacturing

3.3 Recovery Activities

The recovery activities include collection of used products, reclamation, reprocessing, redistribution of recovered product and safe disposal of waste. A flow diagram for the product recovery activities is shown in Figure 3.2, which endeavours to encompass all the available options. Once the product is collected, a decision must be made regarding its eligibility for recovery. For products to be determined eligible for recovery, their condition needs to be assessed to enable proper routing to the appropriate recovery channel. Generally all the products need cleaning before checking for major faults. The assessment process may need prior disassembly or material separation and shredding in order to perform thorough inspection. These processes may require special resources in some cases, for example in cases where they need to be carried out in purpose-built facilities. If the product as a whole is unsuitable for recovery, it may still be possible to recover some components. Therefore the product is disassembled if needed and the same question asked about the components. All the disassembled parts are checked for

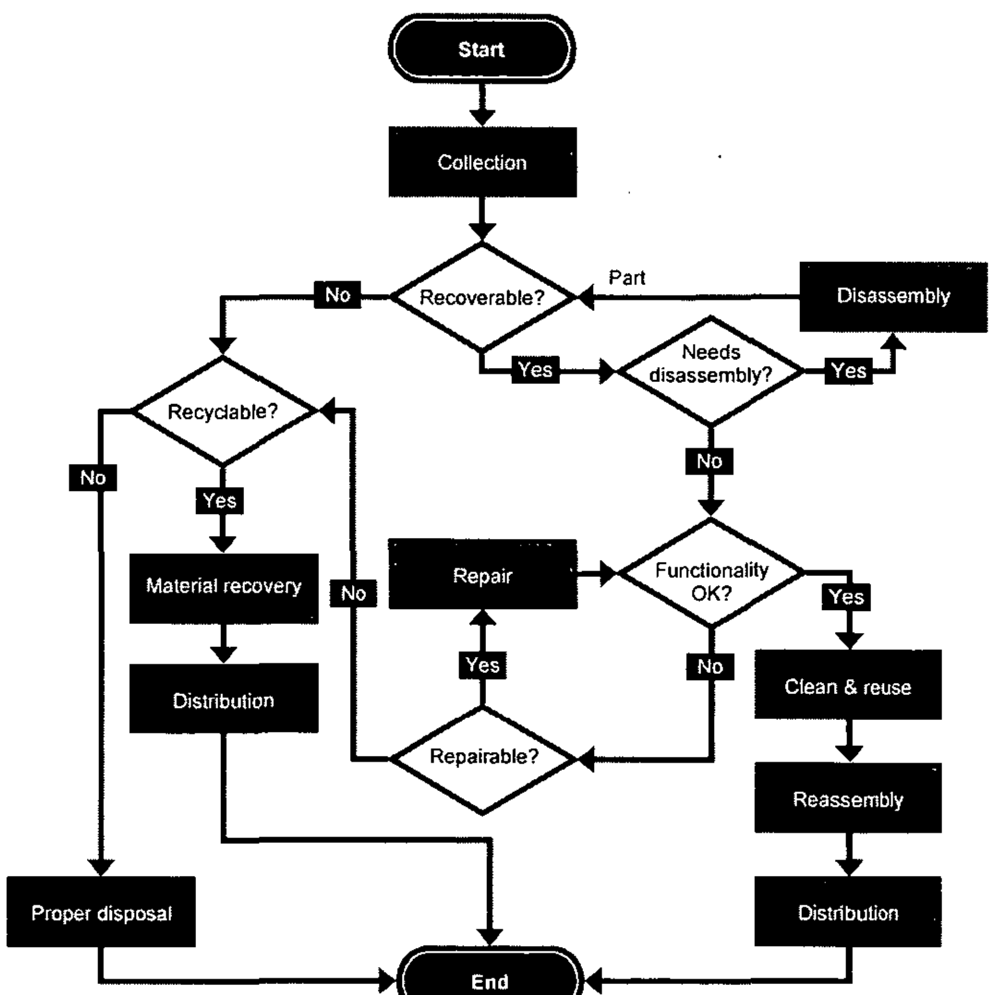

Figure 3.2: Material flow in product recovery: A generic view

their functionality. The repairable non–functional parts are sent for repair work. Then after a final testing, they are made available for reassembly. At every stage of testing, the discarded parts are also checked for their suitability for recycling processes. The components failing in all these checks are finally sent for safe disposal. While making decisions regarding the suitability for reclamation of product or parts, it is important the decisions are economically justified.

3.4 The Recovery Functions

In recovery systems, there is a reverse flow of products and this involves different parties functioning collaboratively as they work towards the common target of delivering refurbished or recycled products or parts back into the market. Like any other production system, recovery systems have the following basic functions:

3.4.1 Logistics

In a recovery system, logistics involve procurement as well as delivery. Unlike traditional systems, the raw material for recovery companies comes from the consumer as used products. This makes the procurement function the most problematic for recovery companies. If the source is a large volume consumer and is tied to the company with a service or maintenance contract, then the situation is much easier to manage as the product mix is known and the quality, quantity and timings can be predicted. If on the other hand, the products that are sold in the retail market go to different locations in different quantities, then only general assumptions can be applied about the availability of used product. For example, a location with large or dense population will tend to produce a large volume of used product.

Apart from the used product, the recovery company also needs consumable raw materials to be acquired from its suppliers. This is because during the recovery process, the product is likely to need repairs and additional components and sub-assemblies are also likely to be required.

Although it is not always necessary, the market for the recovery company may also be the source of used product itself. This is especially true in the cases where the recovery company is under a service or maintenance contract, and the remanufactured products are sent back to the consumer. In other cases, refurbished products are sent to the retailers through the same or similar channels to those used for conventional products.

3.4.2 Inventory Management

Inventory management for recovery systems is also different from traditional systems as in this case, the inventory consists of both old and used products. Storage of such products and components generally demands extra care and maintenance. For example, an old refrigerator can result in a culture of bacteria and fungi and it can spread to the entire storage area. Therefore an initial inspection is necessary in almost all the cases.

Decisions about discarding the products are likely to also be dependant on the type and age of the product and this is quite important as this function in the recovery systems influences whether the products coming from the customer are likely to be obsolete and no longer compatible with the new technology. In such cases, the recovery of product may be economically unattractive. The author's experience with the industry has shown that a major part of the inventory may be kept in hope that the returned product will be used in near future, however a lack of demand in the market can prohibit this inventory from going into the production line and therefore high inventory ties up expensive storage space.

As the product goes through the disassembly and inspection processes, the requirements of repair and hence new components required are identified. Therefore, the inventory also includes new components and sub-assemblies.

3.4.3 Production

For a recovery system, the production function starts from planning of disassembly and ends at final assembly of the remanufactured product. This includes shop floor scheduling for disassembly, repair and reassembly. As the quality of the products is highly uncertain, regular inspection is essential at every stage. Due to the inclusion of disassembly and repair, this function is more labour intensive than traditional manufacture using new parts and materials and there is little scope for automation.

3.4.4 Marketing

Recently the awareness about environment friendly products has greatly increased and customers are more likely to consider a remanufactured product. This trend has also been seen in the retail shoppers. With the help of incentives and discounts, companies have been able to attract attention towards the remanufactured products. In addition to these markets, remanufactured products may well also be targeted to the developing and under developed countries directly or through charities working there, due to the cheaper costs of remanufactured goods.

3.5 Operational Issues in the Process of Recovery

Operational activities within a product recovery environment are different from traditional manufacturing activities. In general a high level of uncertainty regarding the timing, quality and quantity of returned product exists. Therefore, the level of agility and flexibility of remanufacturing companies needs to be high. The following subsections discuss the operational issues for a product recovery environment.

3.5.1 Collection

Collection of the used items and their packaging is one of the major issues in a product recovery environment. Conventional manufacturing environments have a diverging effect distribution, i.e. the manufactured products are delivered from a single source to multiple destinations. However, in a product recovery process, used products originate from multiple sources and are brought to a single product recovery facility. The logistic systems designed for such operations are commonly referred to as *reverse logistics*. Like normal supply chain systems, reverse logistics need to address issues related to transportation, freight control, temporary storage, distribution, etc. However, the flow in reverse logistics is convergent unlike the normal supply chain which has a divergent flow. There is also an additional challenge as generally the source of the used products is the end–user and therefore there is a high uncertainty of availability of the product at the collection points.

Reverse Logistics is therefore the movement of the goods from a consumer towards a producer in a channel of distribution. It defines a supply chain that should be designed to efficiently manage the flow of products or parts destined for remanufacturing, recycling, or disposal and to effectively utilise resources. Reverse logistics focus on managing flows of material, information and relationships for value addition as well as on proper disposal of products.

3.5.2 Disassembly

Disassembly is the systematic process of separating a product into its constituent components or subassemblies. It is an important process in product recovery and is essential in almost all types of processes including remanufacturing, recycling and disposal. Disassembly is often misunderstood as being the reverse of assembly, however the operational characteristics of disassembly and assembly are quite different and hence the assembly planning knowledge cannot be used 'as is' for the disassembly planning. Disassembly planning is broadly divided into two categories. *Disassembly levelling problem,* is defined as achieving a disassembly level at which the product of interest is disassembled to keep profitability and environmental features of the process at a desired level. *Disassembly process planning* is determination of an optimal task sequence, beginning with a product to be disassembled and terminating when all the parts of interest are disconnected.

3.5.3 Inventory Planning and Control

Inventory planning and control comprises of all the activities and procedures used to control and maintain the stock levels to support production at minimum cost. Inventory control and planning is well understood for conventional manufacturing systems. However, due to the presence of the following factors, it becomes more complex in remanufacturing and recycling environments:

- probabilistic recovery rates (quantity and timing) of parts implying a high degree of uncertainty in material planning
- unknown condition of recovered parts until inspected, leading to stochastic routings and lead times
- the part matching problem (its difficult to always reuse components from different assemblies to make a new product because the components need to be matched)
- the problem of imperfect correlation between supply of used items (for remanufacturing) and demand for remanufactured units.

3.5.4 Production Planning and Control

Traditional production planning and control approaches are not adequate for recovery processes due to the uncertainty and increased variability of parts. For a recovery environment, the planning decisions include how much and when to disassemble, remanufacture and recycle. The complexity arising in such systems regarding production planning and control depends on the form of recovery undertaken, i.e. direct reuse, product or material recovery. For direct reuse, the processes involved are minor repair and conditioning, while for material recovery, major processes are necessary. However, the processes for direct reuse and material recovery are simpler to manage than the processes needed for part recovery, which require complex planning. This is due to the individual repair requirements for different returned products which makes it difficult to define a predetermined sequence of production steps. This creates uncertainty which makes planning difficult.

Another critical problem in recovery processes is capacity planning. Along with uncertain routing on capacity, release of various part types simultaneously from disassembly may create further capacity problems due to the common use of repair facilities. Therefore appropriate forecasting techniques become important for activity planning. This issue is addressed by [54] using a neuro–fuzzy technique to forecast the return rate of used product.

3.6 Product Recovery Scenarios

The product recovery begins with the collection of used goods. Collection may be done by a variety of methods and entities. The parties involved in collection may be the retailer, remanufacturer, independent recycler, city council or charity organisations. The appropriate method for collecting the used products varies in different situations. In some cases, the customer is involved in the return process, and may be motivated by some discount for the next purchase given by the recovery company. The factors involved in deciding the collection method to be used and frequency of collection are product characteristics, market conditions and locations of collections centres.

Due to government legislation and consumer awareness, many companies have started to take back their products at the end of their life. However, to exploit the business opportunity, many independent recovery companies (IRCs) have also appeared in the recovery industry. These IRCs are SMEs and recovery or recycling is their main business. Based on this, there are two distinct business scenarios possible in recovery industry:

1. Recovery of the products by original equipment manufacturer (OEM)
2. Recovery of the products by independent recovery company (IRC)

In the first scenario, the OEM is responsible for recovery of products, and the customer is generally a high volume consumer so it is economical for the OEM to directly collect from the customer. Also, certain types of products, for example electronic consumables, can be recovered by the OEM even when the market comprises of small volume

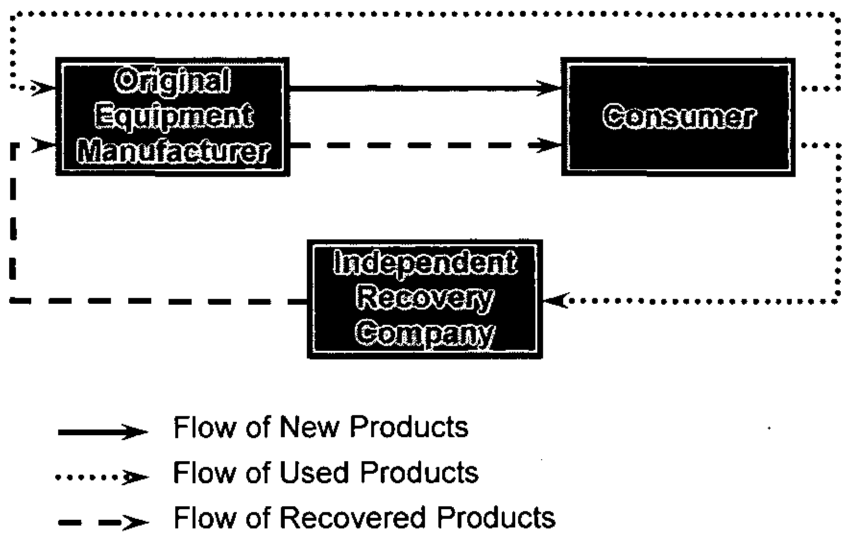

Figure 3.3: Recovery Scenario 1

consumers. The OEM takes its own product as input for the recovery processes and in the first instance aims to recover the product and re–sell it to the original market. In this scenario the OEM uses its existing logistics infrastructure for the reverse logistic operations and the recovery process is combined with the remanufacturing processes. This requires a significant extension of the scope of the business and manufacturing operations and expansion of facilities to include the required resources to undertake the recovery processes. In some cases, an IRC is also involved in this scenario. As shown in Figure 3.3 the OEM, instead of carrying out the recovery itself, contracts out the recovery job to an IRC, who does not have to worry about the procurement and marketing and can concentrate purely on core remanufacturing functions. The benefit of employing an independent entity in the recovery process lies in the fact that it provides flexibility and enhanced opportunities for the OEM as well as for the IRC. Depending upon the penetration in the market, the OEM may employ more than one IRC for different sectors of the market. This allows the OEM to concentrate on development of the new product ranges while the IRC can focus on the recovery process and thereby improve the efficiency of the process involved.

In the second scenario, the recovery is carried out solely by the IRC (Figure 3.4), which is an independent company dedicated to the recovery business. The IRC is responsible for all the recovery functions viz. procurement, transport, disassembly, production and finally marketing of the refurbished products. In this scenario, the IRC's product range is only restricted by the type of products that it wishes to deal with and hence it can deal

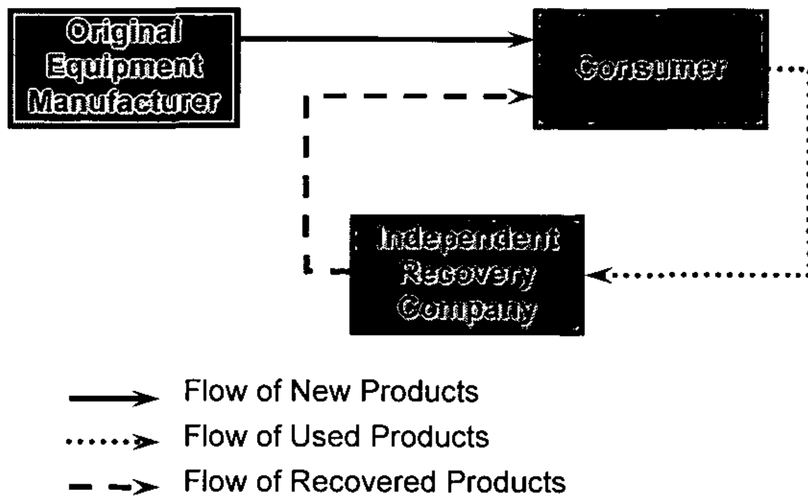

Figure 3.4:Recovery Scenario 2

with products from different OEM brands. Increasing the number of products and product types received may bring further complexities in operation management, therefore the IRC may choose to specialise in a few types of products, so that quality can be controlled well even by a small sized company.

One of the major problems for an IRC is the fact that it has little control over the market trend. With the introduction of new products, OEMs can change the market trend or can introduce new products according to the consumer demand. With the availability of different products in the market, the IRC needs to re-engineer itself to suit the new requirements of the recovery processes.

The above scenarios represents two different configurations; however both of them can exist in a single case of product. The planning issues for the managers in both scenarios include transport problems, inventory management and production planning. From collection points to the warehouse and recycler, from warehouse/disassembly/remanufacturing units to the recycler and finally to the supplier/market, the frequency and timing of the transportation needs to be decided. At the warehouse, as the storage space is limited, decisions regarding the economy of storage of items need to be taken care of. Based on the demand of the final products, new components will also need to be procured.

4

Research Methodology

This chapter outlines the research methodology adopted in this work.. It summarises the approaches taken in order to achieve the understanding of the problem and the methods adopted to map the aims and objectives of the research work to possible solutions.

Chapter Outline:

4.1 The Exploratory Phase

First of all, the available literature including research articles and theses were studied in order to build an understanding of the recovery business. Various companies working in this area were contacted. One of the leading independent companies in the UK IT product recovery industry invited us to visit their facilities. This visit helped the author to become familiar with the business nature and the problems faced by the company. The visit was followed by several email communications with the company personnel. Also the personnel in this company led the author to other contacts in the industry. A questionnaire was created to be sent out to all known companies for their feedback, but regrettably it received only limited attention from the industry. One of the contacts made, who worked for an IT and consumer electronics major, provided the author with their recent thesis in the area of 'producer responsibility' and also responded to a lot of queries raised by the author on email. The above activities provided the author with an understanding of the business dynamics in the concerned area and hence enabled the research gap to be identified (the first two shaded boxes in Figure 4.1).

4.2 Recovery Network Optimisation

It was discovered that procurement is a major issue within the recovery processes and hence an efficient recovery network is very important. To also gain understanding of activities involved in recovery and remanufacture, the author selected a typical product which commonly passes through recovery networks for remanufacture, i.e. a toner cartridge and disassembled/reassembled it and modelled its costs and recovery process using information identified on websites (see Chapter 8). Most of the published research work addressing the reverse logistics network design issues was found to be case specific. The most generic work in this area had been reported by Fleischmann *et al.* [24], in which they presented a generic mathematical model for the design of a reverse logistic network considering the impact of inclusion of product recovery on the forward network. The model is optimised taking into account both the flows. This work was chosen to be the basis of building the recovery network optimisation problem in this research.

The independent recovery company essentially deals with multiple products and storage space was found to be one of the major concerns of the management. Hence, the mathematical model was extended by introducing capacity constraints and multiple products. An optimisation tool based on a genetic algorithm (GA) was developed for the recovery network configuration. The GA optimiser used simulation runs for calculating the fitness functions for candidate solutions. The use of a simulation model makes it possible to capture the uncertainty associated with the recovery processes.

4.3 Enterprise and Information Modelling

The initial experimental work using simulation models highlighted the quality and importance of information required to effectively plan a recovery network. The author therefore examined the literature to identify any useful information model approaches. However, the author concluded from the literature survey that there is a lack of information rich modelling approaches for the recovery industry specially in the SME sector. This was a significant research gap as such approaches are valuable to support

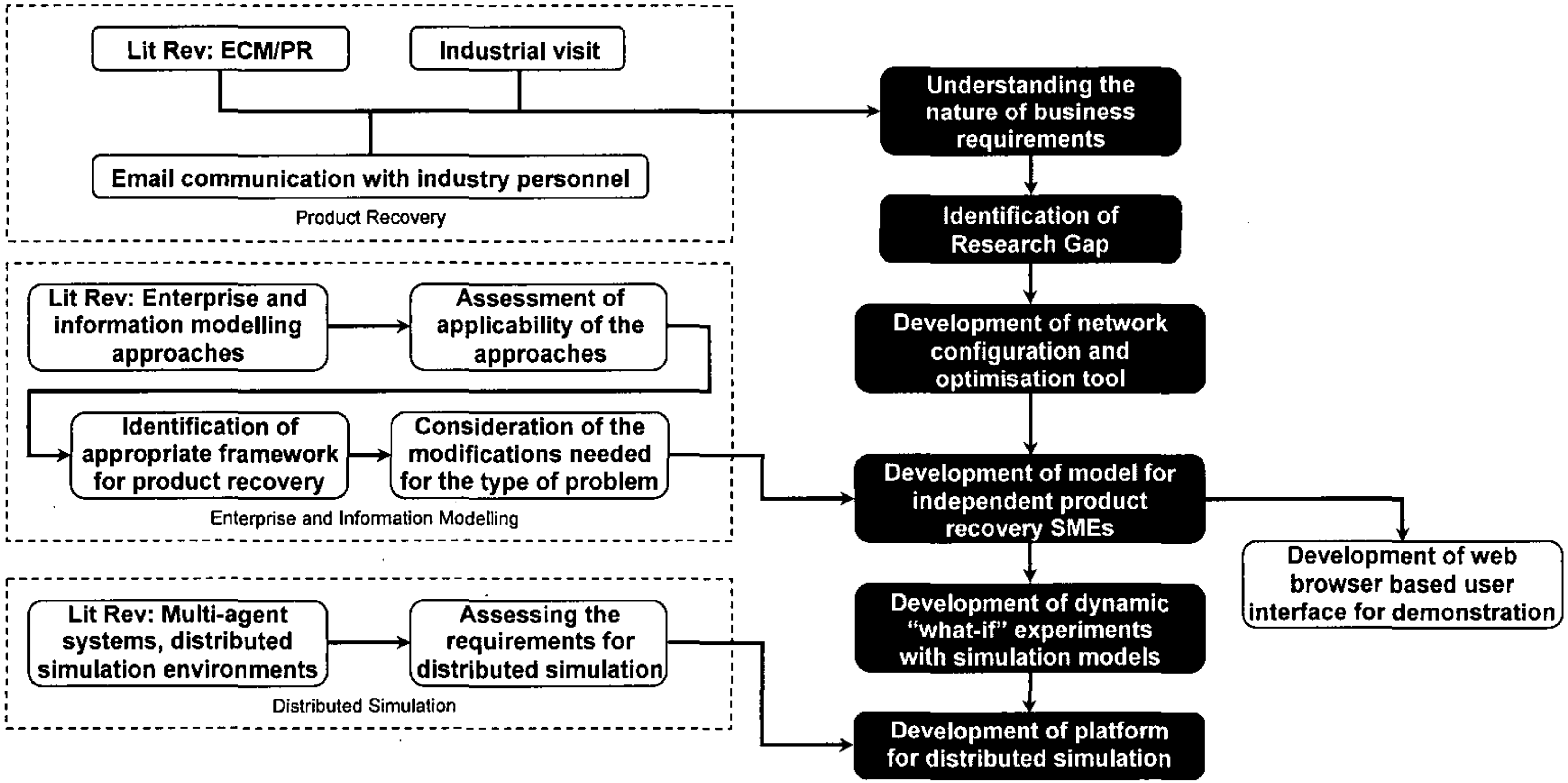

Figure 4.1: Research methodology

better understanding of business requirements and process improvement or reengineering. Also the importance of good, reliable, up–to–date information and the importance of highly responsive product retrieval and remanufacture processes were very clear from the exploratory stage of this research. Hence this research area was examined more closely. A variety of modelling approaches have been presented in the past, out of which, the factory data model presented by Harding and Popplewell [81] attracted authors' attention. This is a multiple view approach and contains a variety of views, namely strategic, resource, business process and performance view, with the focus on information modelling. Based on the above approach, an information centric enterprise model for independent product recovery SMEs was developed as part of this research work. A variety of views of the new model are demonstrated and motivated by Costa *et al.* [128], the Unified Modelling Language (UML) is used for representation of the model views. A new approach for function view modelling is also introduced, where the UML extension are exploited for adding stereotypes and properties. Information specification for the various classes are conceptualised.

4.3.1 Performance View: Simulation

The above mentioned UML based multi–view modelling approach enables information & processes to be examined, clarified and tested. It is an iterative process and allows the system designer to go back to other views from the performance view for possible changes. This research utilises "what–if" with simulation models for testing of the models. Simulation models makes it possible for the management to evaluate the model under proposed environments and analyse the result to assist their decision making. As the SMEs involved in the product recovery industry work in a collaborative manner, a stand–alone simulation may not be capable to mimic the situation. Therefore a platform for distributed simulation was developed. This platform enables the management to study their existing models using a "what–if" type of experiment as well as making it possible to examine new models from collaborators before committing to high stake ventures.

4.3.2 Demonstration of the Model Views

As part of this research, the author wanted to demonstrate how information may be shared between collaborating SMEs. It is understandable that the people involved in the management team need not be experts in handling databases. Therefore a web browser based interface is also developed to demonstrate the different views of the model. This interface brings flexibility in information sharing and a limited amount of information can be made available to potential and existing collaborators as well. Being web browser based, this is also economic and well suited for SMEs.

5

Modelling the Recovery SME

Recovery of used products and materials is becoming a field of rapidly growing importance. Recovery firms have to deal with customer demands and returns that are largely dependant on the state of the art in technology. They change without any warnings and unfortunately a third party recovery firm has little control over them as compared to an original equipment manufacturer. In such situations, these recovery companies must not only quickly adapt to changes in their competitive environment but also continuously evolve to survive in the market. This chapter presents an information–centred formal model for product recovery enterprises to provide designers with a modelling and evaluation tool to enable progressive design of the enterprise. The modelling exercise in this work involves description of the different views of the enterprise, namely strategic view, physical view, functional view and performance view.

Chapter Outline:

5.1 Introduction

A remanufacturing system is similar to the conventional production systems as it requires operational, manufacturing, inventory, distribution and marketing related decisions to be made. However, as this industry is more driven by the availability of raw material (used product) than by the demand of finished product (refurbished/remanufactured product); it involves high uncertainty. An original equipment manufacturer (OEM) involved in recovery of its products can still plan ahead for recovery of its product as it will be aware of the technology and compatibility issues of its future products. Independent recovery companies, on the other hand, have little control over these matters. In addition, OEMs can change the market trend and demand through campaigns and promotion and these changes could also be quite significant for SMEs involved in the recovery of the concerned product. In such scenarios, SMEs may need to rapidly reengineer their production and management systems to exploit the changing market and demand.

Operational activities within a product recovery environment are different from traditional manufacturing activities. In general a high level of uncertainty regarding the timing, quality and quantity of returned product exists. Therefore, the level of agility and flexibility needs to be high. One of the major issues in a product recovery environment is the collection of the used items and their packaging. Like logistics in normal supply chain systems, reverse logistics need to address issues related to transportation, freight control, temporary storage, distribution, etc. However, the flow in reverse logistics is convergent unlike the normal divergent logistics flows in supply chains. There is also an additional challenge as the source of the used products is the end–user and therefore there is a high uncertainty of availability of the product at the collection points.

Reverse Logistics is the movement of the goods from a consumer towards a producer in a channel of distribution. It focuses on managing flows of material, information and relationships for value addition as well as on proper disposal of products. For a large company, maintaining the reverse distribution of used products may be an easy task. However for SMEs, carrying out the logistic operations itself may create extra burdens. In such scenarios, the logistic operations need to be outsourced to companies called third party logistic providers. As a result, the recovery industry is largely operated by small networked companies. The most common form of collaboration in the recovery industry is between the recovery and logistic companies, however in many cases, it is between contract recovery agents and OEMs. This kind of collaborative environment demands a system where the flow of required information among the actors should be facilitated keeping in mind the confidentiality of sensitive data.

Most business nowadays is highly competitive and ever changing. Recovery firms however have to deal with additional challenges, commonly processing a myriad of different used products originating from various sources. Customer demand and returns, which are largely dependant on the state of the art in technology, change without any warnings and unfortunately a third party recovery firm has little control over them when compared to an OEM. As a result, such companies must not only quickly adapt to changes but should also continuously evolve to survive and win in the market. They must be versatile, open to change and able to design and modify their own facilities and processes in parallel with new situations.

To address this requirement for fast, flexible redesign of a recovery company's resources and business systems, this chapter presents an information–centred formal model for product recovery enterprises. The process of enterprise modelling has been employed in order to create an abstraction of a complex business. Enterprise modelling provides designers with modelling and evaluation tools to enable progressive design or redesign of the enterprise. The use of an information–centric approach ensures that the business knowledge is conserved for reuse. It enables collection of valuable information throughout the design process to be shared by both management and designers. As discussed, SMEs in the recovery industry work in collaborative environments involving information exchange between the different entities within and outside the enterprise. Hence an information–centric approach becomes a necessity in such scenarios.

The modelling exercise in this work involves description of several different views of the enterprise, namely strategic view, physical view, functional view and performance view. The strategic view helps management to build their business objectives, which in the case of a recovery company are greatly influenced by changes in legislation. The physical elements and resources in the system and their relationships are identified by the physical view. The functional view relates to the activities and associated decisions within the enterprise. Broadly, it involves acquisition of the returned product, recovery and logistics activities. Finally, the performance view helps management to determine whether the proposed enterprise can perform to the required level. For successful enterprise design or improvement, designers need to understand the importance of each view and establish suitable trade–offs between them. Dynamic analysis methods can be used for evaluation and to reduce risks and improve confidence by testing potential changes through simulation and "what if?" experimentation before the physical processes or resources are changed within the company. Thus use of a model based information–centric approach should therefore reduce the risks of expensive, inappropriate or ineffective changes being made to the enterprise or business system designs.

5.2 The Modelling Approach

An enterprise model is a computational representation of the structures, activities, processes, information, resources, people, behaviour, goals and constraints within the enterprise [61]. Enterprise modelling aids system engineers by allowing the analysis of the system by "what-if" experiments. It states the requirements and design specifications of the information system which is appropriate for the distributed nature of decision making. There are a variety of modelling approaches available in the literature as discussed in section 2.2 and their suitability for different types of industry vary.

The recovery industry as described earlier is ever changing and dealing with rapidly changing product mix and specification. In such scenarios, the companies must not only quickly adapt to the changes but also continuously evolve to survive and compete in the market. The modelling approach applicable to these kind of companies should be able to support continuous redesign of the system as well as assessment of performance of the proposed changes. The modelling approach used in this research is adopted from the factory data model [81]. The factory data model is a multiple view approach and it utilises an object oriented approach in its design. The various views in this approach include strategic, business processes and performance view. This approach is more applicable to the type of industry under consideration compared to the other multiple view approaches because of the nature of the design process involved. In particular, with the help of performance view, the designers can progressively analyse the partially populated models and get back to the other views for possible amendments. The use of discrete event simulation to model and evaluate variety of processes combinations in a dynamic performance view of a reengineered manufacturing system using the Factory Design Process (FDP) were examined by Harding and Popplewell [81]. This is especially relevant to the author's current research as the initial work carried out to examine and optimise the recovery network (Sections 4.2 & 6.2) provided a dynamic performance view of parts of a recovery SME and its interactions with collaborating logistic providers. The FDP

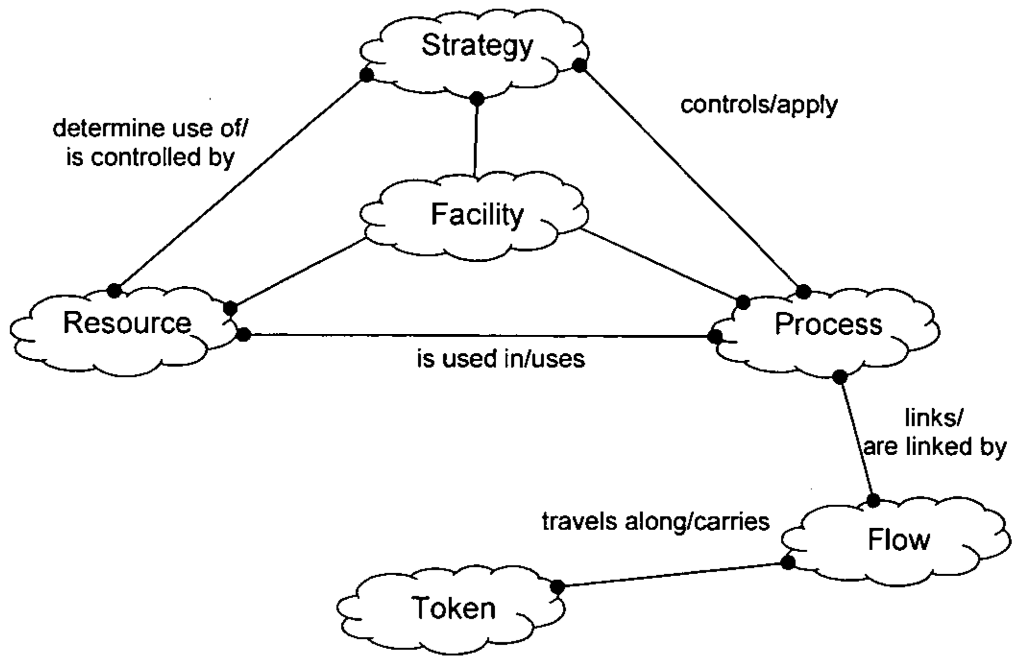

Figure 5.1: Key classes from factory data model (adopted from [81])

approach was therefore adopted as appropriate to this research since it enables the system redesign to be seen as an evolving process.

Despite being different, all enterprises have common characteristics which can be captured in five base classes, i.e. Process, Resource, Strategy, Facility and Token. These five classes are shown in Figure 5.1 using Booch representation [129], where the clouds represent the object classes and the lines represent the relationships between them.

Objects from the process class hierarchy capture functions, processes or activities within the business of the enterprise. Information describing and defining this class may include details of the process, other processes it may be a part of, duration, who/what is controlling it, its status, costs etc. The resource class hierarchy describes mechanisms capable of performing an action. Resource objects can range from human resources to machinery, tools, vehicles etc. the strategy class objects capture the knowledge and methods used to make decisions within different business levels. In real systems processes and resources are arranged into different facilities, related to business functions. Therefore objects from the facility class hierarchy have been included to help designers to view the organisation. The flow class objects connect independent processes and activities into a system with a purpose, while the objects from the token class represent the business objects that flow or move through the enterprise's system and processes. A detailed description of each of the main object classes can be found in [81] and [130].

5.3 Implementation of the Modelling Approach

The implementation process is about the clarification of what is required, the generation of ideas, the analysis of the existing or possible systems, the comprehension of what already exists and how systems really work, the identification of possible design solutions and the evaluation of alternative solutions [131]. Different views of the system are presented so that the different perspectives of the design can be understood. Each view behaves in its own particular way and can support the design team at various different levels of abstraction.

In the remainder of this chapter, the various viewpoints are represented with the aid of Unified Modelling Language (UML), which is an object oriented modelling language containing a set of symbols. It also contains a group of syntactic, semantic and pragmatic rules [132]. UML may be regarded the successor of the Object Oriented Analysis and Design methods that proliferated during '80s and '90s (including the Booch Methodology which was used in the original FDP research). In 1997, UML became recognised and accepted as a potential notation standard by Object Management Group for modelling multiple perspectives of information systems [133]. UML offers direct support for the design and implementation of each aspect of an information system and provides an integrated notation for their representation. In addition to supporting the main relationships between these representations, the application of UML provides a natural migration process through the different development phases and perspective of the system, such as functionality, analysis and design, implementation, etc. [128]

The UML specification supports extensions and Eriksson and Penker [134] show how these can be used to represent key business modelling concepts, including how to define business rules with UML's Object Constraint Language (OCL) and how to represent business models with use cases. Using these extensions, business architects may add stereotypes and/or properties to the UML in order to suit their particular situations.

5.3.1 Strategic View

This view helps management to state their strategies as goals and objectives. It is used for validation as it states the business goals. It helps managers and designers by telling them what is required and how the business should be performing. Then operational rules need to be determined and implemented to enable the company to carry out their strategies. The strategic view should be one of the first views to be considered but should then be revisited later in the design cycle, as the operational rules for defining priorities are required. The primary objective of every company generally relates to increasing the profit and growth of the company, however the tactics adopted to achieve this objective will differ from scenario to scenario and effective operational rules to embody these tactics are critical for the competitive success of the company. In product recovery, strategic opportunities come in the form of lowering procurement cost, establishing necessary assessment and inspection facilities, reducing the disposal cost, reducing cost and time of inventory storage, etc.

Figure 5.2 shows the strategic view of a typical product recovery company using a UML object diagram. The top level goal for the company is to increase market share, which is a common goal for any business. However, different businesses will adopt different approaches and hence will have different "sub-goals" to achieve it. As discussed earlier, procurement of used product is a major activity for product recovery. Lowering the costs associated with procurement will significantly lead to high profits.

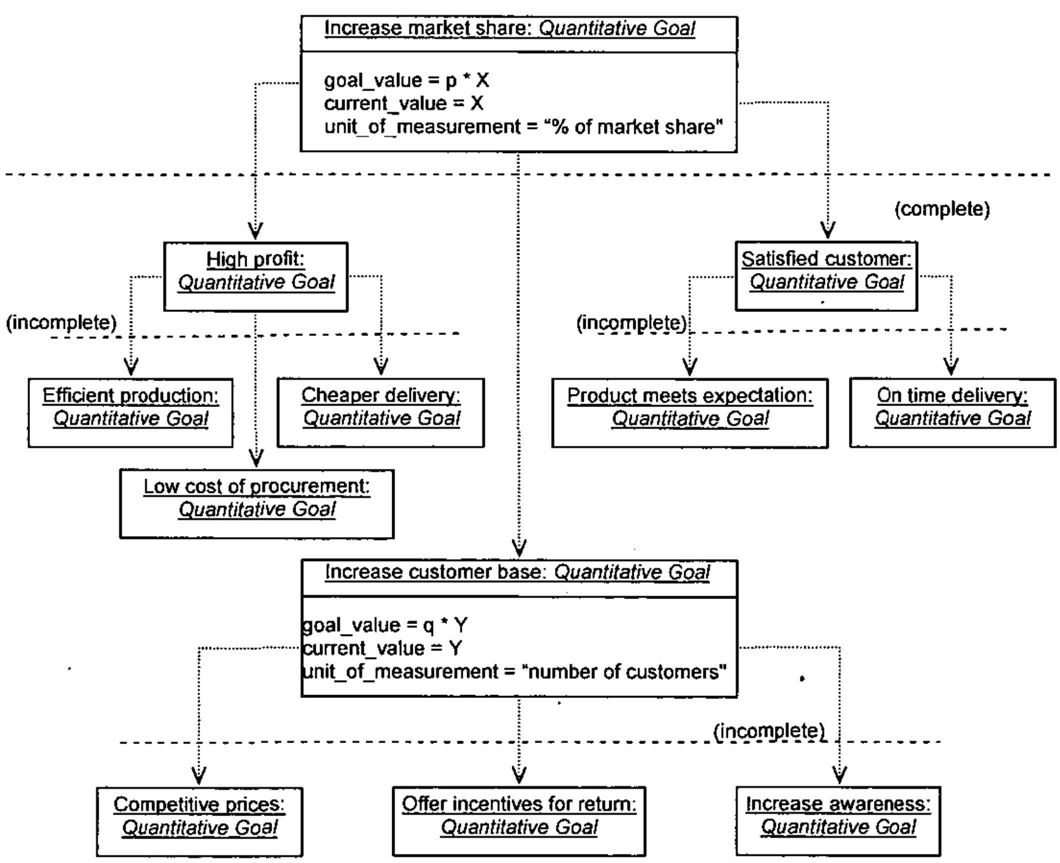

Figure 5.2: Strategic view of the product recovery enterprise

The customers for a product recovery company could include an OEM (which has contracted the company for the recovery of its product returns) or end users looking for good remanufactured products which are cheaper than new goods. In the case of product recovery, one of the things that often needs to be done is to campaign about the importance of reuse and remanufacturing of product and make potential customers aware of the fact that these refurbished products are cheaper and more environment friendly. Apart from individual end users, in some cases high volume consumers turn out to be the perfect client for recovered product as they can act as the source of used products as well as a destination for remanufactured products. However, while campaigning to attract new customers, it is also necessary to maintain the satisfaction level of existing customers by quality assurance and timely delivery.

It can be noticed in Figure 5.2 that some of the sub-goals are marked 'complete' while some are marked 'incomplete'. This is because during the revisions or redesign of the enterprise, the state of the system changes according to situations and the model should therefore be flexible and help managers to understand the progress towards achieving particular goals. It should be noted that the enterprise under consideration is working in a collaborative environment, and therefore the interpretation of the goals can be different in various cases. For example, if the company is an independent recovery company, it will aim to satisfy the end user, however a contract recovery company will primarily try to meet the OEM's standards. In a collaborative environment, the performance of the company is quite influenced by the performance of other collaborators. So the enterprise needs to be aware of its collaborators' performance. This is shown in the next view.

5.3.2 Function View

The business functions or activities which are essential to the operation of the enterprise are shown by the *function view*. The function view is primarily for information gathering and formulation. At the later stages of designing, when more detailed information is available, it can be replaced by a *business process view*.

To better understand the requirements of the function view, it is useful to include an *organisational view*. This allows the designer to define the main functions and processes step by step. Later these can be refined and more details can be added when necessary. Figure 5.3 presents the organisational view of the product recovery company. Discussion of departmental responsibilities through the organisational view may facilitate the production of the function view. For example, one of the major influences in a product

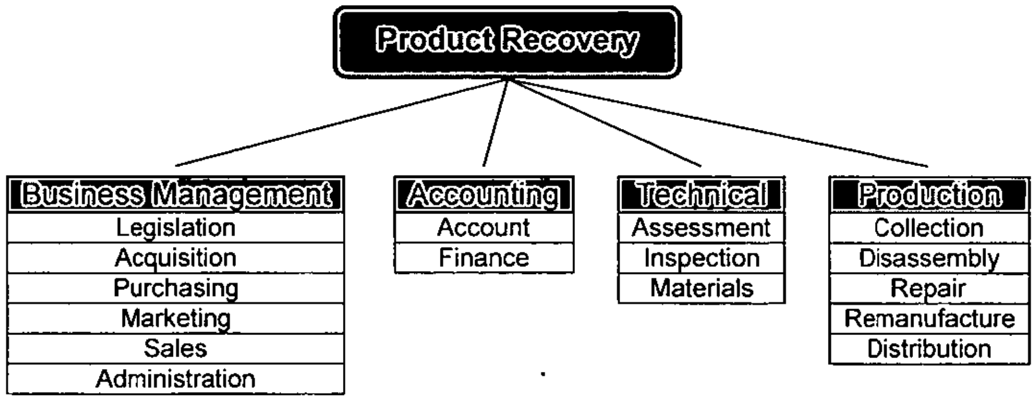

Figure 5.3: Organisational view of the product recovery enterprise

recovery company's strategy is the government legislation. The management needs to constantly keep an eye on the changes in legislation and the working of the government bodies and committees so that its products comply with legal requirements and standards. On the other hand, the company must make use of any business opportunities arising due to such changes. Inclusion of a legal or legislation function in the organisational view will ensure that these considerations are taken care of when generating the function view.

Unlike a traditional manufacturing company, there are two distinct types of raw-materials sources, the major one being the user who returns used products at their end of life; hence the acquisition function is needed in the organisational view. In addition remanufacturing processes require other consumables or critical components which need to be purchased. In the case of a traditional company, the acquisition/purchasing and marketing/sales functions will always belong to different departments. However, in a product recovery company, they can stay with the same management group as in this context, the production is more driven by availability of used products than by the demand in the market. Administration is a common function for any department, however in Figure 5.3, it has been included only in the business management function where it represents administering the whole company rather than the department itself.

After defining the top level functions within the departments in the organisational view, the functional view can be developed by the additional refinement of these functions. Figure 5.4 shows one such refinement. Modelling becomes useful when it enables the behaviour and performance capability of the factory design to be analysed and assessed before undertaking the implementation. The organisational and functional views

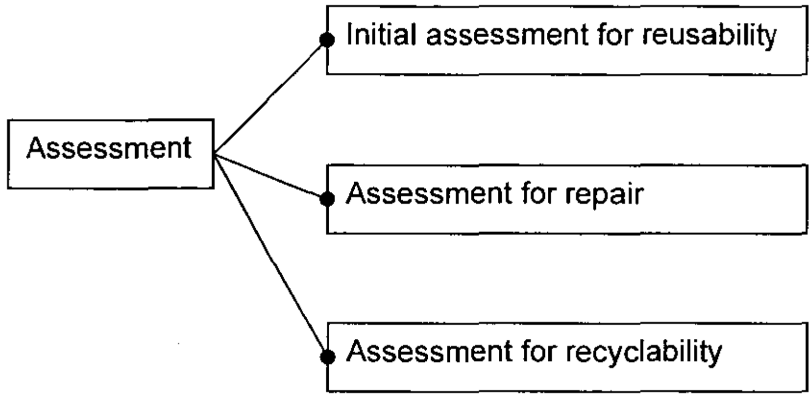

Figure 5.4: First phase of refinement of business functions

described above help building an essential comprehension of the business elements and structure of the enterprise.

Understanding the business elements and enterprise structure leads to the understanding of the business behaviour by the application of the business process view. The basic function view (as introduced by Harding and Popplewell [81]) gives the designers information about the processes in the company. However, with the business process view, an attempt has been made to capture all the relevant information related to the functions concerned so that the system designer can relate the various goals, resources and objects in the system to the functions. Hence, in the current research in order to capture these additional information, Eriksson–Penker business extension are applied to the UML activity diagram [134]. The processes are presented by stereotyping an *activity* to a <<*process*>>. Based on the goals set in the strategic view, the business processes are identified and specific information associated with them are gathered. Figure 5.5 shows the business process view using UML activity diagrams with the involvement of departments of the enterprise in it. It shows the activities, what it is controlled by, its goal and its output. The small grey boxes indicate the departments the activity belongs to. When the business process view is taken, the order of processes or activities become important so that the model captures the way in which the processes are linked. Once the structure of one or more business processes has been achieved, the relationships between the business functions and business processes can be examined. Business processes may be refined and details may be added as and when required.

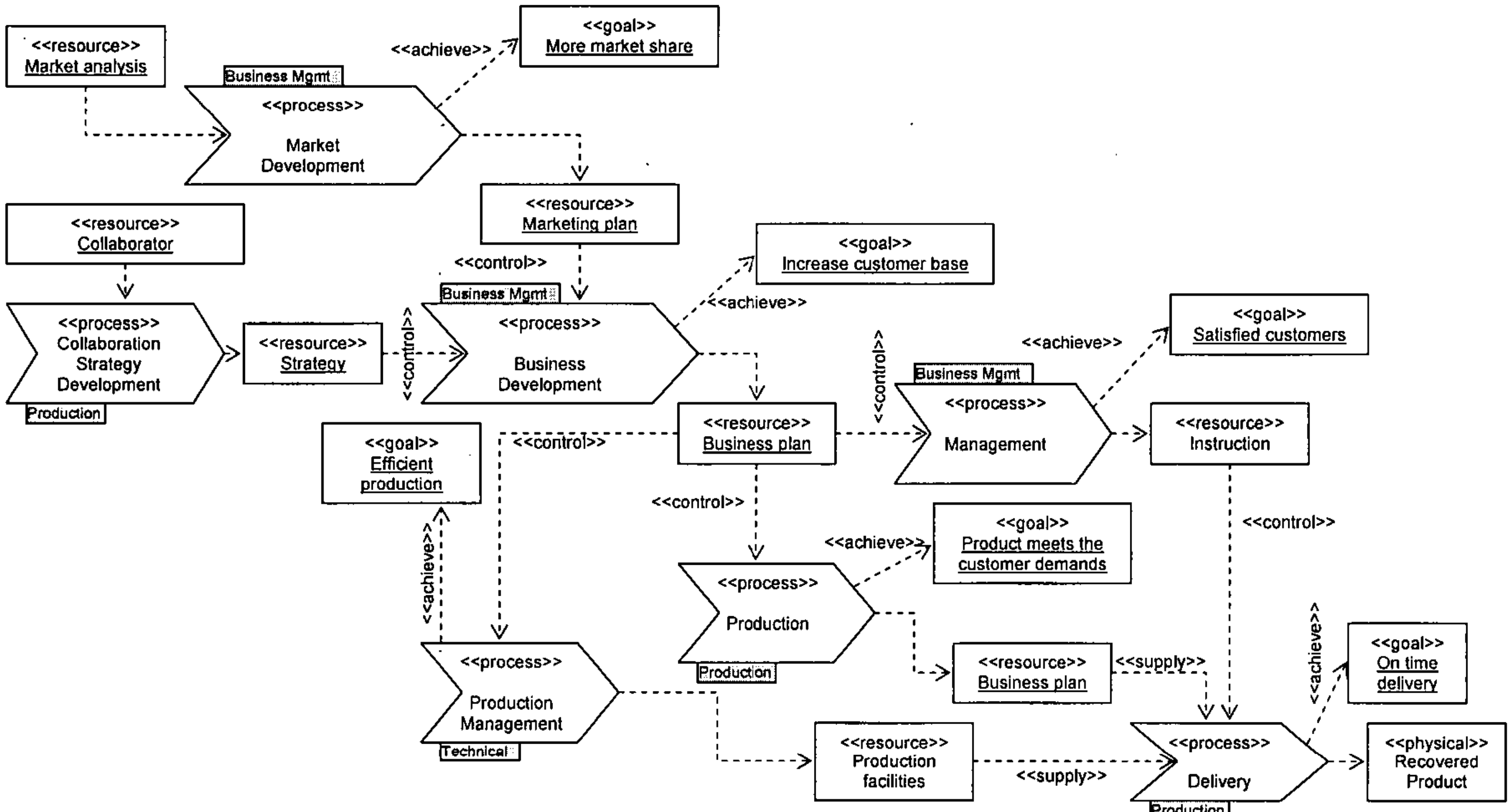

Figure 5.5: Business process view of the product recovery enterprise

5.3.3 Informational View

Before the operational performance of the redesigned enterprise can be considered, it is important to examine the physical resources and other objects in the system. This is done by taking an informational view. UML object diagrams are used to show the information related to objects and entities. Figure 5.6 shows the details of different objects in the system. For example, the information regarding the product include its type, condition, serial etc. Product pr1 belongs to product class ABC123 and it is an electronic component. Its condition is the numeric value 2, which could mean it is in recyclable condition (out of a number of certain conditions like reusable, recyclable or disposable). If recovery is carried out, it will need parts s039 and c120. It also contains the serial number given by the OEM at the time of production, which actually can help in getting the technical details about it from the database. This information is passed across the enterprise when needed and used at different places according to the situation. Many papers have been published about research into informational modelling of product and resource and these include [74, 75, 78, 135, 136]. Because of the vast body of existing work in the are of product and resource modelling, the author use existing class hierarchies such as reported in [75, 136]by adapting them for use in the product recovery context. Before discussing the flow of information in and across the enterprises, performance view is presented in next sub section.

5.3.4 Performance View

Once a sequence of processes and the resources they use have been identified, it is possible to look at the information from a *performance view*. The performance view helps

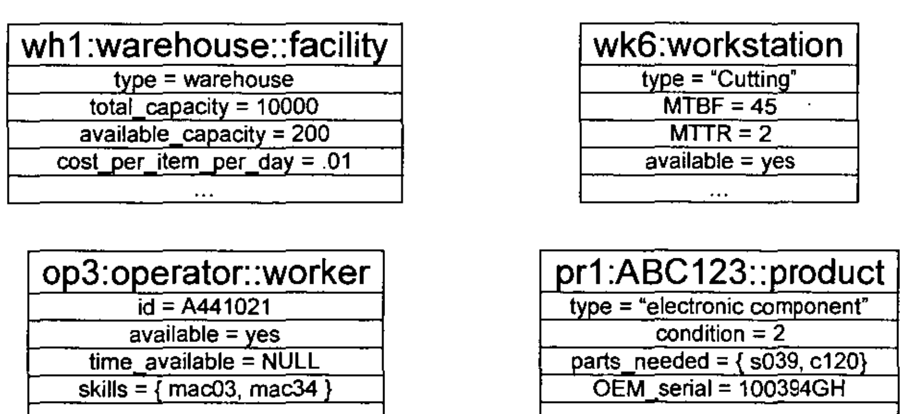

Figure 5.6: UML object diagrams used to show the entity/object information

managers and designers to examine if the proposed enterprise can perform to its expectations and hence it provides them with valuable feedback at various stages of the design. There are several methods for performance measurement. The performance view proposed in this research uses two approaches for performance evaluation. Static evaluation uses performance metrics, like lead time, throughput or costs etc. On the other hand, dynamic evaluation uses simulation technology enabling 'what-if' experiments to be carried out. Dynamic evaluation gives the designer a better insight of how the proposed enterprise will work. This research has focused on the assessment of dynamic performance of the system with the aid of simulation models. Following the simulation experiments and assessments, the designs can be refined further by revisiting the previous views.

Detailed information related to processes and resources is needed to build the performance view. A detailed simulation model needs data related to machine breakdown history, maintenance requirements, operational rules, etc. With the help of an informational view, the behaviour of real systems can be mimicked by building the performance view and using this to understand the utilisation of different resources in the system and to help make decisions about capacity etc. During this research simulation models were created using the Arena software [137] and the information required to build the simulation model was taken from the enterprise model.

5.4 Informational Flow

Figure 5.7 shows the flow of information in typical product recovery activities. If all the activities are performed by one actor, the information flow will be simple to manage and access. However, the product recovery industry essentially works in networked and collaborative environments, which complicate the situation further. In such scenarios, the enterprise requires easy access to information from relevant departments maintaining confidentiality of sensitive data when dealing with its collaborators.

Figure 5.8 shows a typical flow of information in and across two networked companies performing the same activities as those in Figure 5.7, but in collaboration. One of the companies is involved in independent recovery while the other is a logistics provider. So the first job of collecting the used product from the user is the responsibility of the logistics provider whilst the rest of the production work, i.e. assessment, disassembly, repair, remanufacturing, etc. are done by the independent recovery company. The

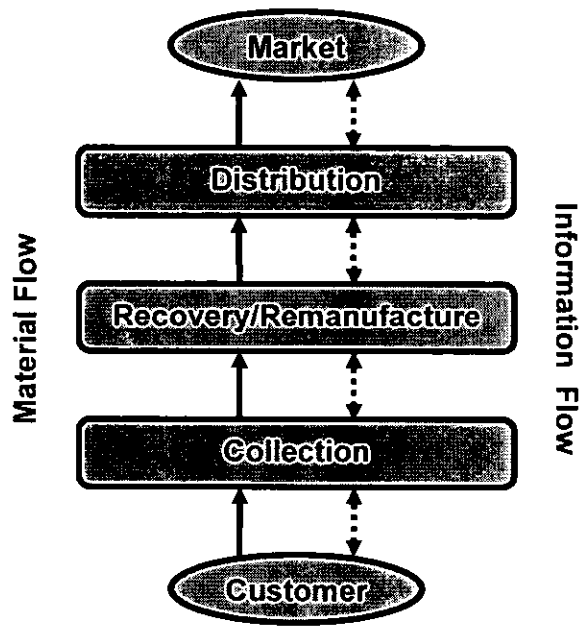

Figure 5.7: Material and information flow in product recovery

business management departments of both the companies handle the job of communicating with the outer world, whilst the other departments need to contact and exchange relevant information among themselves.

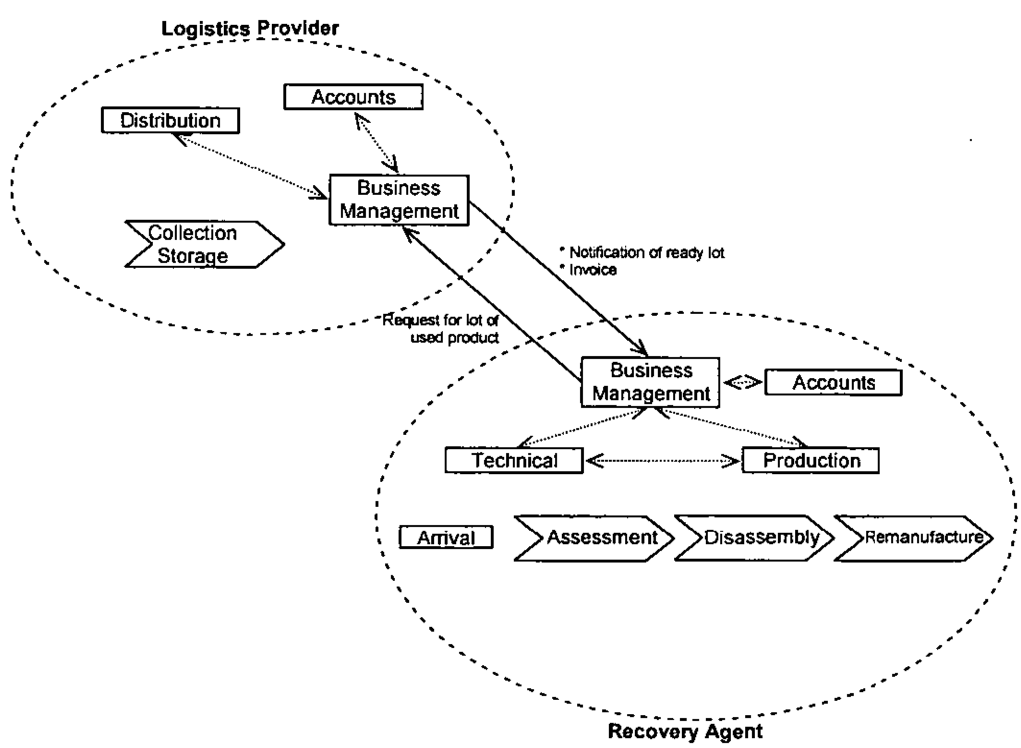

Figure 5.8: Typical information flow in a network of two collaborating enterprises

Based on this concept, the performance view of the proposed model can be extended to evaluate the enterprise in the presence of "dummy" collaborators. Though it makes the simulation modelling part more complex, it brings the model closer to reality and hence results in higher confidence levels of the evaluation. The following chapters discuss the development of the platform and model of the distributed simulations. In order to achieve this, Arena has been used in conjunction with Visual Basic, and the communication between different simulations has been carried out though an agent based system.

5.5 Conclusion

In order to survive in the ever changing recovery market, SMEs involved in product recovery must be ready to redesign and adapt to the requirements of new products in an effective and competitive manner. The research reported in this thesis is built on the belief that better, faster and more flexible enterprise redesign can be achieved if it is executed through an information centric formal model for product recovery enterprises as presented in this chapter. The aim of the proposed model is to aid the designers with modelling and evaluation tools to enable the progressive design or redesign of the enterprise. A variety of views of the model and their functionality have been presented and discussed. However, the simulation models presented in the performance view will be examined in greater details in the next chapters. A new representation of the business process view is shown. While populating the model, discussions and validation with research supervisor ascertained that the accuracy of the approach is maintained. The model can be evaluated using any of the viewpoints designed for this purpose. The views are presented in unified modelling language (UML), which is an industry standard. The model is generic in nature and takes care of the networked and collaborative nature of the industry.

6

Modelling and Optimisation of Product Recovery Networks

An appropriate logistics network is an important element of the infrastructure of any product recovery company. Small and medium enterprises (SMEs) constitute a major fraction of the product recovery industry with a different business objective and scale of operation from those of original equipment manufacturers (OEMs). This chapter addresses the network design issues for SMEs involved in product recovery activities. A mathematical formulation is presented in an SME context and a subsequent simulation model is developed. A genetic algorithm approach is presented for optimizing the network for a single product scenario.

Chapter Outline:

6.1 Introduction

Implementation of product recovery requires setting up an appropriate logistics infrastructure for the arising flows of used and recovered products. Physical locations, facilities, and transportation links need to be chosen to convey used products from their former users to a producer and to future markets again in efficient, cost effective ways. Reverse logistics encompasses the logistics activities all the way from used products no longer required by the user to recovered products that are again usable in a market. As discussed earlier in this thesis, the study of reverse logistics can be broadly divided into three areas: *distribution planning*, which involves the physical transportation of used products from the end user back to the producer; *inventory management*, which is the process of managing the timing and the quantities of goods to be ordered and stocked, so that demands can be met satisfactorily and economically; and finally *production planning*, which despite not being a logistics activity, influences the other two greatly.

The main activities in reverse logistics are the collection of the products to be recovered and the redistribution of the reprocessed goods. The reverse logistics problem looks quite similar to the normal forward distribution problem; however there are some differences. The reverse flow of goods is convergent in nature, so the products need to be collected from many points. Therefore cooperation of the senders becomes important as product packaging is generally problematic. Products flowing in the network tend to have low value. On the other hand, time is generally not as important an issue as it is in forward distribution. Taking these issues into consideration indicate that reverse logistics need different priorities and design than forward distribution flows and therefore they need new networks to be constructed. The major issues concerning the design of a recovery network are the determination of the number of tiers in the network, the number and location of collection/drop–off and intermediate depots and the interaction of the reverse chain with the forward chain.

This chapter presents a mathematical formulation for the reverse logistics network design considering the capacity constraints for the facilities and multiple product scenarios. A simulation based genetic algorithm approach is also presented for determining the optimal configuration of the network. The use of simulation helps in incorporating the uncertainty associated with the product returns. The simulation experiments are planned with the objective of deciding the location and capacities of different facilities of the system. It is a macro level design problem so the majority of the simulation decisions at the micro level were based on assumptions and probability.

6.2 The Recovery Network

In the present literature, much of the published work addresses problems involving big market players like Hewlett Packard, Canon, Dell and other original equipment manufacturers (OEMs) in the electronics industry. Similarly, the published research work dealing with other types of industries focuses on the original manufacturers' point of view. However, as previously highlighted, the recovery industry largely consists of smaller, independent recovery companies. These companies are not OEMs, so for them merging their procurement process with the distribution is not of great importance as their markets are quite different from those of OEMs and their markets for recovered products may well be different to the sources of products for remanufacture. As these companies are SMEs and recovery is their main job, the design of an efficient recovery network is extremely important as the damage caused by network inefficiency cannot be compensated from other means. This chapter presents a mathematical model for the design of the network of a third party recovery firm. The formulation is based on Fleischmann *et al.* [24] however the context is quite different as Fleischmann *et al.* ([24]) present a generic model for companies wanting to integrate reverse logistics into their existing supply chain. In contrast the context of the initial network design formulation presented in the next section is to address network design issues for SMEs dealing with remanufacturing of returned items. The proposed model also takes into account the capacity limits of the facilities. For the sake of simplicity, a single product scenario has been formulated and developed first and this is then converted to a multiple product model.

6.2.1 Mathematical Model for a Single Product Recovery Network

The motivation for the model comes from the author's experience with industry. Three facility levels are considered, i.e. collection points which are responsible for collecting the used products, warehouses where returned products are stored and plants which finally reprocess them (Figure 6.1).

While establishing a distribution network, it should be taken into account that facilities have limitations on the number of products they can store or process. These limitations are due to various factors like availability of space, number of workers and workstations etc. The network model addresses these limitations by incorporating capacity constraints for each facility.

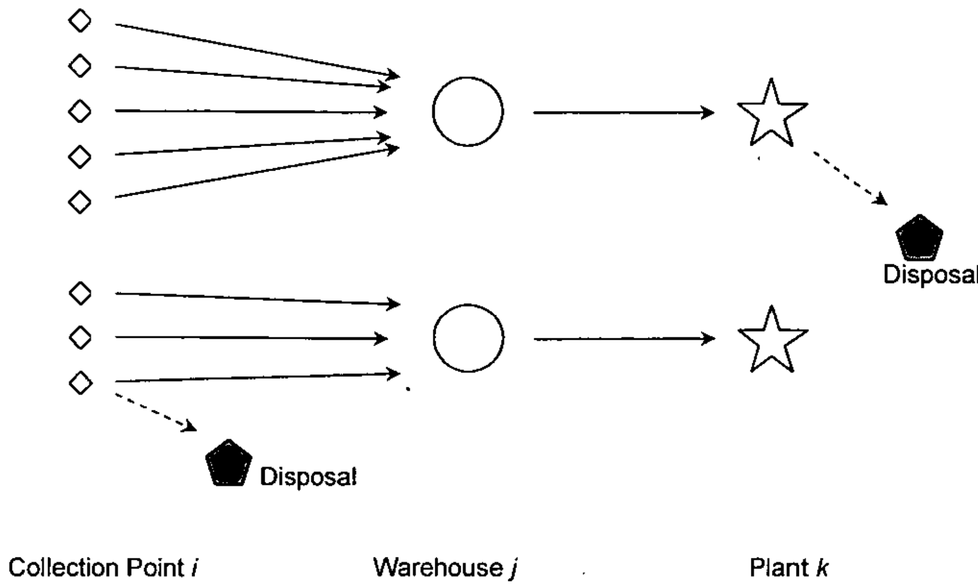

Figure 6.1: Recovery Network

The proposed recovery network model involves the following index sets, variables and parameters:

Index Sets

$i \in I$; where $I = \{1, \ldots, N_c\}$ fixed locations for collection points

$j \in J$; where $J = \{1, \ldots, N_w\}$ potential locations for warehouses

$k \in K$; where $K = \{1, \ldots, N_p\}$ potential locations for plants

Costs

F_i^c Fixed cost for enabling collection point i for inspection

F_j^w Fixed cost of opening warehouse j

F_k^p Fixed cost of opening plant k for disassembly and reprocessing

T Collective cost of storage at collection points, warehouses and plants

P Unit penalty cost for not processing returned product

t^{cw} Unit transportation cost from collection point i to warehouse j

t^{wp} Unit transportation cost from collection point i to disposal site l

c^p Unit cost of reprocessing

c^d Unit cost of disposal

C_{ijk} Cost of reprocessing returned product from collection point i coming through warehouse j at plant k

D_{ijk} Cost of disposing of the returned product coming from collection point i through warehouse j and plant k

S_{ijk} Cost saving by disposing the discarded returned product at inspection enabled collection point i (and not traverse it through warehouse j and plant k)

If d_{pq} be the distance between points p and q in the distance matrix; we calculate the above costs as follows:

$$C_{ijk} = t^{cw} d_{ij} + t^{wp} d_{jk} + c^p + T \qquad 6.1$$

$$D_{ijk} = t^{cw} d_{ij} + t^{wp} d_{jk} + c^d + T \qquad 6.2$$

$$S_{ijk} = t^{cw} d_{ij} + t^{wp} d_{jk} + T \qquad 6.3$$

Variables

$$x_i^c = \begin{cases} 1; & \text{if collection point } i \text{ is enabled with inspection facility} \\ 0; & \text{otherwise} \end{cases}$$

$$x_j^w = \begin{cases} 1; & \text{if warehouse } j \text{ is opened} \\ 0; & \text{otherwise} \end{cases}$$

$$x_k^p = \begin{cases} 1; & \text{if plant } k \text{ is opened} \\ 0; & \text{otherwise} \end{cases}$$

y_{ijk} fraction of returned products served by collection point i, warehouse j and plant k

z_i fraction of the returned product at collection point i which can not be reused (chosen with a random distribution)

Parameters

R_i return from collection point $i; i \in I$

M_i^c maximum capacity of collection points $i; i \in I$

M_j^w maximum capacity of warehouse $j; j \in J$

M_k^p maximum capacity of plant $k; k \in K$

Using the above notation, the mathematical formulation to minimise the sum of the fixed, variable and penalty costs is as follows:

$$\min FC + VC + PC \qquad 6.4$$

Where,

$$FC = \sum_{i \in I} F_i^c x_i^c + \sum_{j \in J} F_j^w x_j^w + \sum_{k \in K} F_k^p x_k^p \qquad 6.5$$

$$VC = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} R_i C_{ijk} y_{ijk} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} R_i z_i \left(D_{ijk} - S_{ijk} x_i^c\right) \qquad 6.6$$

$$PC = \sum_{i \in I} R_i \left(1 - \sum_{j \in J} \sum_{k \in K} y_{ijk}\right) P \qquad 6.7$$

Subject to:

$$\sum_{j \in J} \sum_{l \in K} y_{ijk} + z_i = 1, \quad \forall i \in I \qquad 6.8$$

$$\sum_{j \in J} \sum_{k \in K} R_i y_{ijk} \leq M_i^c x_i^c \quad \forall i \in I \qquad 6.9$$

$$\sum_{k \in K} \sum_{i \in I} R_i y_{ijk} \leq M_j^w x_j^w \quad \forall j \in J \qquad 6.10$$

$$\sum_{i \in I} \sum_{j \in J} R_i y_{ijk} \leq M_k^p x_k^p \quad \forall k \in K \qquad 6.11$$

$$0 \leq y_{ijk}, z_i \leq 1 \qquad 6.12$$

$$x_i^c, x_j^w, x_k^p \in \{0,1\} \qquad 6.13$$

The above formulation minimises the fixed cost for the setup of facilities and costs involved in the recovery/disposal processes. The three terms in equation (6.5) represent the cost of installing inspection facilities at collection/drop-off points and setup costs for warehouses and reprocessing plants. The first term in equation (6.6) maps transportation costs and reprocessing/disposing costs for the reprocessing/disposing of product, while the second term in this equation involves cost savings for the product if the collection point it is coming from has inspection facilities installed. The returned products which are not processed due to the capacity constraints pose a loss and are mapped by equation (6.7). Constraint (6.8) ensures that all the returns are taken into consideration. Equations (6.9–6.11) make sure that the capacities of the facilities are not exceeded.

The formulation is generic in nature and can reflect recovery scenarios for various kinds of products. The disposal of unusable products from collection points as well as from plants may involve sending them to a third party recycler/disposer or to the remanufacturer's own facility and the associated transportation cost. This model just requires the flow of such items to leave the network after sorting.

6.3 Optimisation of the Model

One of the major characteristics of problems concerning reverse logistics activities is the uncertainty associated with the return of products. The stochastic nature of these problems means that most of the analytical models become either too simplistic or exceptionally complex. Discrete event simulation is regarded as the most suitable analysis tool for such situations and is largely used to evaluate "what-if" scenarios [83, 106, 138]. In this research, a simulation based approach is used for the optimisation of the model.

6.3.1 Solution Methodology

A general simulation based optimisation method consists of two essential components: an optimisation module that guides the search direction and a simulation module for evaluating the performance of candidate solutions. The decision variables create the environment in which the simulation is run while the output of the simulation runs is used by the optimiser to progress the search for optimal solution (Figure 6.2).

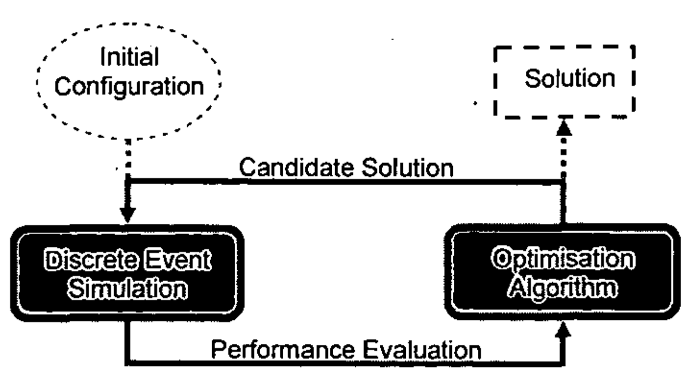

Figure 6.2: Simulation based optimisation approach

In the existing literature, a number of simulation–based optimisation methods have been reported, which include gradient based search, stochastic approximation, sample path optimisation, response surface, heuristic search methods and evolutionary algorithms [139, 140]. There are several metaheuristic optimisation algorithms present in the literature like tabu search (TS), simulated annealing (SA), ant colony optimisation (ACO) and genetic algorithm (GA). The performance of TS and SA deteriorate significantly as the problem size and solution space increases [141]. ACO approach is best suited for travelling salesman problem and needs to be manipulated to addresses other types of optimisation problems [142, 143]. According to an empirical comparison of search algorithms by Lacksonen [144], GA appears to be the most robust to solve large problems though it requires a large number of replications. GA has therefore been adopted in this research to perform stochastic search for solutions. The details of the algorithm are discussed in later subsections.

6.3.1.1 Simulation Model

A simulation–based optimisation method has been developed for the optimisation of a network design problem, keeping the constraints within the model logic. The simulation model has been created in Arena 10.0 [137], which was selected over other available simulation software because of its seamless integration with other software supporting Microsoft technologies. Arena exploits two Windows technologies that are designed to enhance the integration of desktop applications. The first, ActiveX Automation allows applications to control each other and themselves via a programming interface. The second technology exploited by Arena for application integration addresses the programming interface issue. In this research, the code for the optimisation algorithm has been written in Visual Basic [145] and uses the Arena model for the evaluation of candidate solutions. The reader may wish to refer to the section in Appendix describing the suitability of Arena in this research.

In the simulation model, the entities representing returned products in the model are generated on a daily basis and the number of products is decided by normal distribution with a mean proportional to the population of the customer zone. Each entity carries attributes of its origin customer zone, warehouse and plant locations and reusability. The decision whether a facility is open or not is coded in the candidate solution sent over by

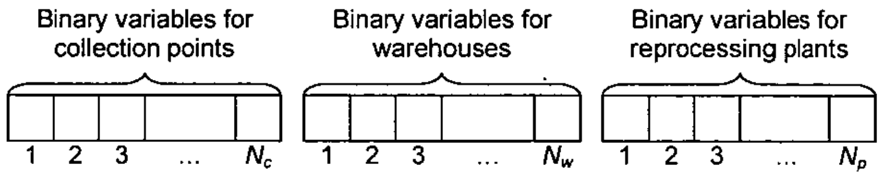

Figure 6.3: Genetic representation of the chromosomes

the GA code while Arena VBA blocks decide what alternative facilities are available for the entity to use.

6.3.1.2 Genetic Algorithm Representation and Operations

One of the most important aspects of genetic optimisation is the chromosome encoding for representation of a typical solution. The encoding depends largely on the nature of the problem. In this case, the chromosome is an array of binary variables as shown in Figure 6.3. The individual binary arrays for facilities at all the tiers are concatenated to form chromosomes for binary representation of the solution. As the chromosome consists of variables of uniform nature, the genetic operations are performed on the whole of the chromosome at once. Each binary variable in the chromosome represents the installation of the associated facility.

Crossover and *mutation* are two basic genetic operations for the optimisation search. The crossover method applied in this work is Single Point Crossover illustrated in Figure 6.4. In this method, a position is selected randomly. The binary string from the beginning of the chromosome to the crossover point is taken from one parent and the rest is copied

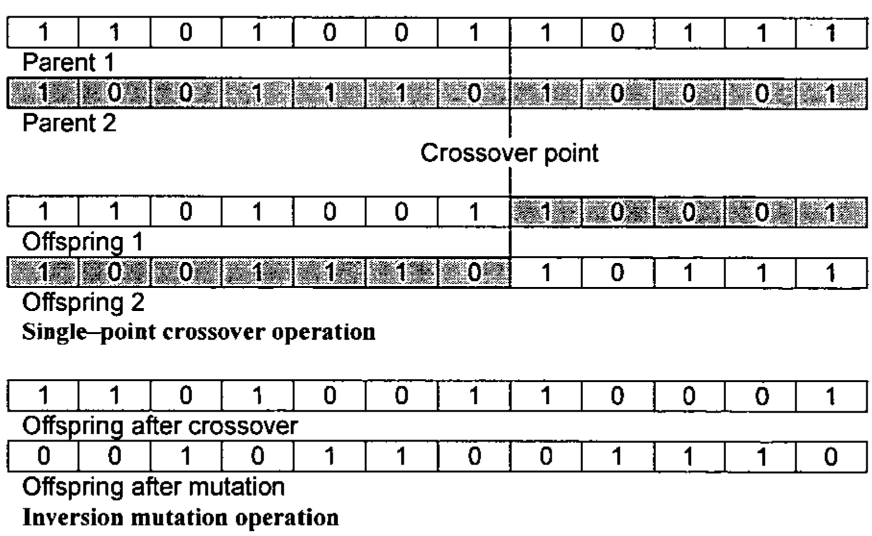

Figure 6.4: Genetic operations

from the other parent. As shown in Figure 6.4, this operation can produce two offspring chromosomes using one crossover point. In this work, the parents are selected by roulette wheel selection and both the produced offspring chromosomes are included in the new population. To maintain the diversity of the population, and save the search from getting trapped in local optima, GA uses another operation called mutation. Based on the mutation probability, the produced offspring is subjected to mutation operation, using Bit Inversion Method (although several other methods could be used instead). In this method, the binary bits of the chromosome are inverted (a NOT binary operation is applied) as shown in Figure 6.4.

The best values of these probabilities for a particular problem is decided with a small set of experiments. First a couple of arbitrary sets of values are chosen. Then a sample problem is chosen and it's time horizon is reduced by a great factor and accordingly the costs are adjusted. For example if a 1 year problem is reduced to 1 day, the associated annual costs are also reduced accordingly. Now the average iteration time for comes down to few seconds from original 2–4 minutes. With the help of these reduced examples, the algorithm is ran for different sets of the probabilities and the appropriate values of the probabilities were determined. These sets of probabilities vary for different types of problems and hence need to be determined for individual problem.

6.3.2 Test Problems

6.3.2.1 Problem Description

A hypothetical example of a single product recovery enterprise has been used to analyse the model. The structure and functionality of the hypothetical company is based on experience gained from the product recovery industry and the design of the reverse logistic network for an SME dealing with printer cartridge remanufacture is considered. It is assumed that the SME procures used cartridges from certain customer zones through its collection points spread across the UK (Figure 6.5). The collection points procure used cartridges from independent retailers and high volume users irrespective of their condition (reusable/unusable). The returns coming from the customer zones are assumed to be proportional to their population. The collection points may or may not have facilities to sieve out unusable products. If the products are found to be unusable in an inspection enabled collection point they are sent directly to the disposal site. This saves costs of storage and transportation of the unusable product at different tiers of the

Figure 6.5: Location of candidate facilities (C: Collection Points, W: Warehouse, P: Plant)

network. From the collection points, the cartridges are sent to warehouses for storage. Plants have facilities to inspect and reprocess the products.

The design problem poses several questions for the decision maker in the SME. For example, depending on the location of collection points, the nature of the returned product will vary. Some collection points with large volumes of returns might actually have benefits if they are enabled with inspection facilities. The location of the warehouses and plants is another strategic issue to save transportation and handling cost. The complexity of the problem multiplies as the numbers of tiers and products increase.

6.3.2.2 Generation of Example Problems

Based on the above description and understanding built from a survey of the available literature, the ranges of costs and parameter values were decided as listed in Table 6.1. Ten data files were created with values uniformly distributed in the ranges as shown in Table 6.1 for the optimisation tool to create random example problems. The example problems are created in accordance with the problems presented in Fleischmann *et al.* [24]. This approach was adopted as Fleischmann's research was the most generic found in the literature.

Table 6.1: Parameters and Costs (in GBP) for the SME example

Description	*Parameter*	*Value*
Fixed installation cost per collection point	F_i^c	[4000, 8000]
Fixed setup cost per warehouse	F_j^w	[8000, 11000]
Fixed setup cost per plant	F_k^p	[32000, 40000]
Transportation costs per mile	t^{cw}	0.008
Transportation costs per mile	t^{wp}	0.005
Reprocessing cost per product	c^p	10.0
Disposal cost per product	c^d	2.5
Return per 1000 residents	R_i	0.1

6.3.3 Simulation Based Optimisation Tool

A tool has also been developed in Visual Basic to handle the GA based optimisation task for the network configuration, and a screenshot of this optimisation tool is shown in Figure 6.6. This tool works in conjunction with a simulation model template created in Arena. This template contains the modules and VB codes common to all types of problems under consideration. The optimisation tool gets the basic data from the user through its GUI and loads the detailed information specific to the current network problem from this user specified data. The tool then invokes Arena to load the model template to modify the existing modules and create new ones. A screenshot of an Arena model created by this tool is shown in Figure 6.7. The model shown has 10 collection points generating a number of entities (representing returned products) on every working day based on a uniform distribution. Attributes representing origin, destination warehouse and reprocessing plant and inspection tags are created for each entity. The entity travels through the various VBA logic blocks and decision modules, which determine the destination warehouses and plants of the entity and assign it to the respective attributes. These decisions are based on the model constraints and input in the form of candidate chromosomes. Associated costs are calculated as the entity travels through process blocks before being disposed (representing products being sent to market or recycled/disposed due to infeasibility of remanufacture). Once the model is created, the data related to the model run and parameters of the optimisation are entered by user or retrieved from file to start the optimisation. The optimisation results are stored on a spreadsheet.

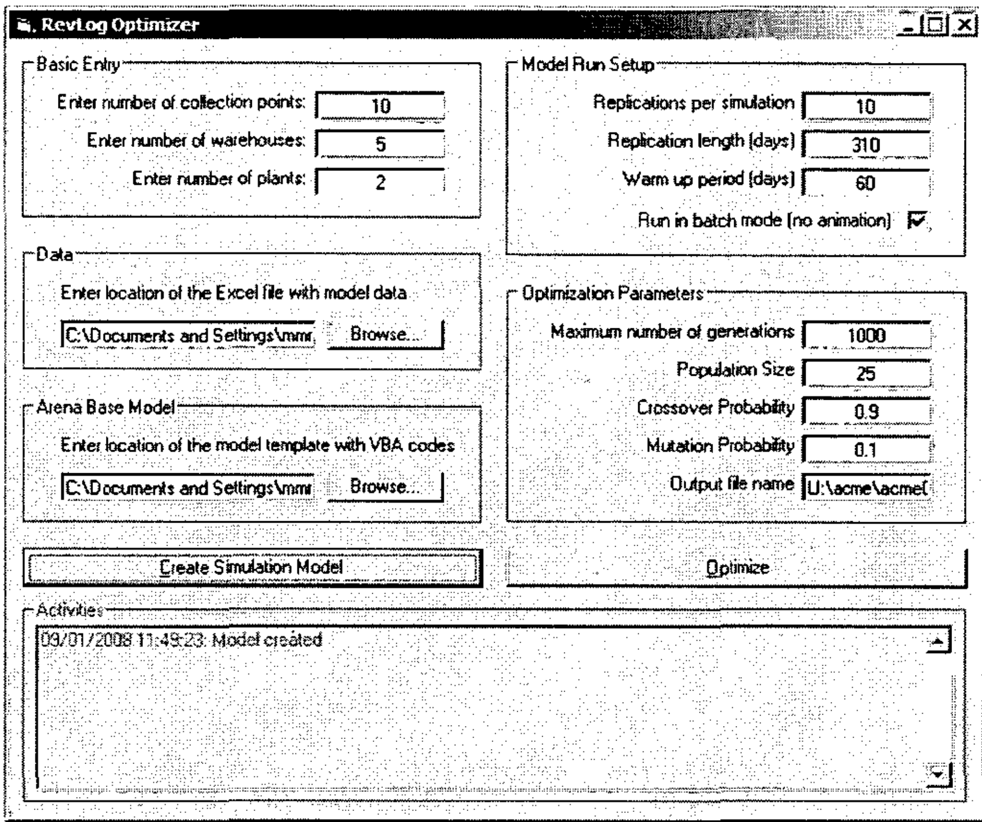

Figure 6.6: Screenshot of the optimisation tool developed

6.3.3.1 Performance of the Optimisation Approach

To test the genetic algorithm based optimisation approach, a small example of 10 candidate collection points (CP), 5 warehouses (WH) and 2 plants (PL) was considered as shown in Figure 6.5. The generated model was optimised with the developed tool and gave reasonably good solutions at around the 300th generation. Figure 6.8 shows the plot of best solutions obtained in generations for the first test set. The continuous plot in the figure shows the convergence of solution. Figure 6.9, Figure 6.10 and Figure 6.11 show different configurations of the network as obtained by the iterative optimisation process and associated costs. Note that the cost associated with the network in Figure 6.10 is not much higher than that in Figure 6.11 despite the longer traverse paths. This is due to the fact that the latter involved a fixed cost for setup of additional facilities.

The crossover probability of 0.9, mutation probability of 0.1 and population size of 25 seem to be working the best for this example considering solution quality and computational time. However, in later runs of bigger problems, the number of simulation replications was reduced to 5 to save some computational time as it was noticed that the randomness was significantly smoothed with only 5 replications.

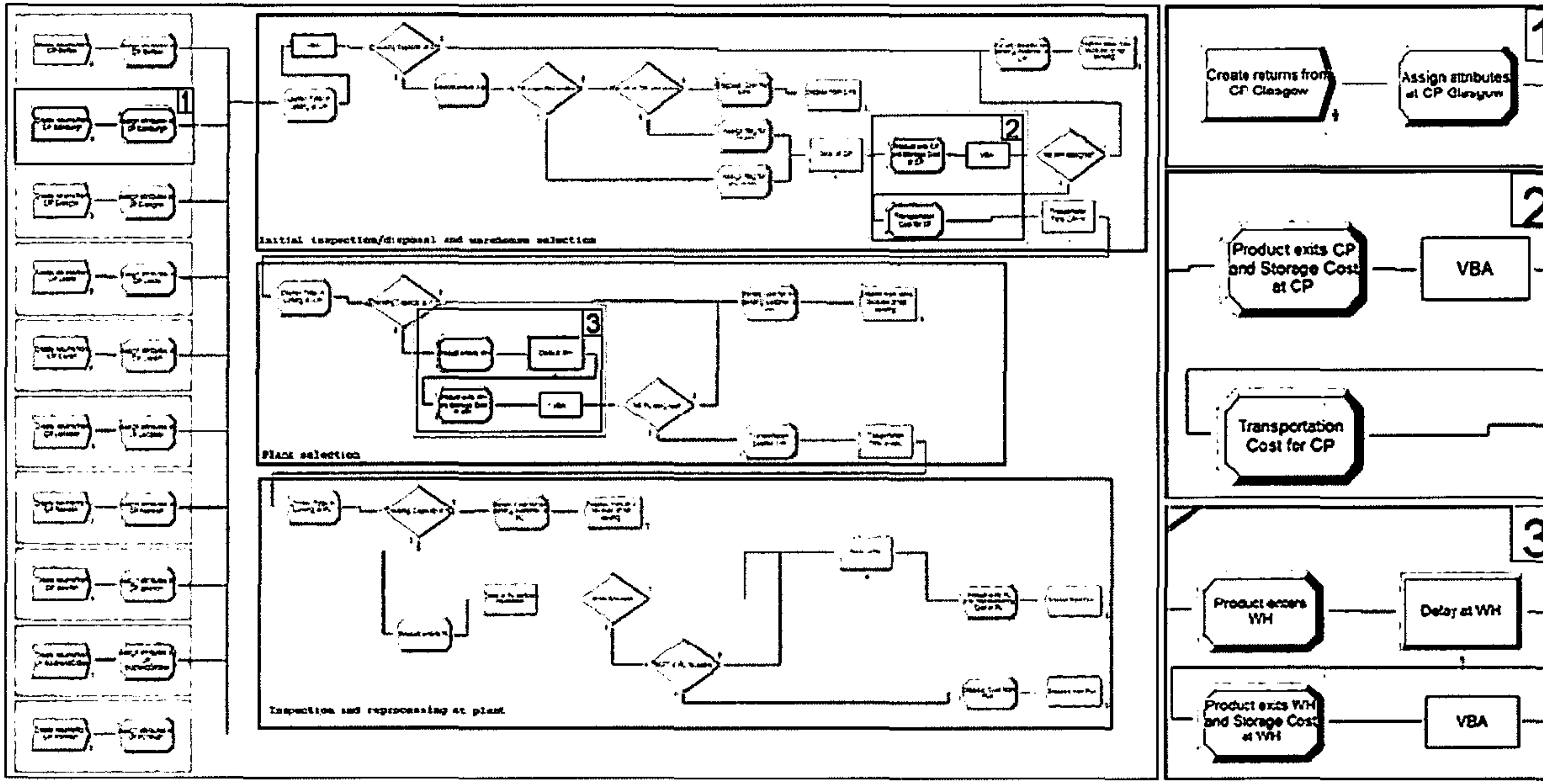

Figure 6.7: Screenshot of a model created by the optimisation tool (1. Creation of entities and attribute assignment; 2. Assignments of various costs and VBA block for decisions and 3. Entities entering warehouse and process delays)

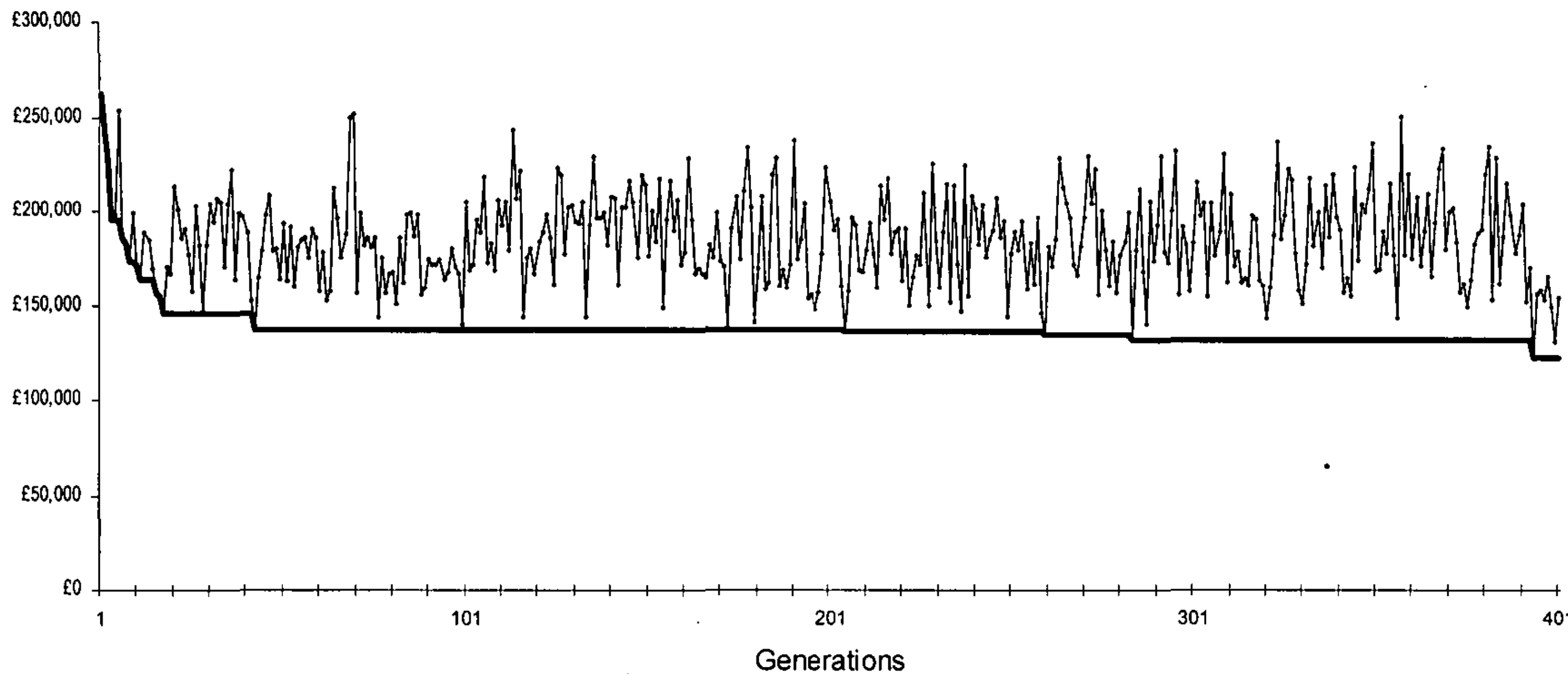

Figure 6.8: Costs of best solution in the populations and the convergance of solution over increasing generations

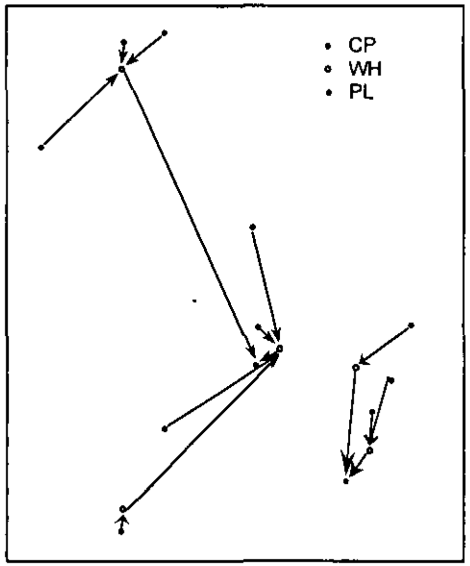

Figure 6.9: Initial configuration with all CPs inspection–enabled, all WHs working, all PLs working; cost: £233187

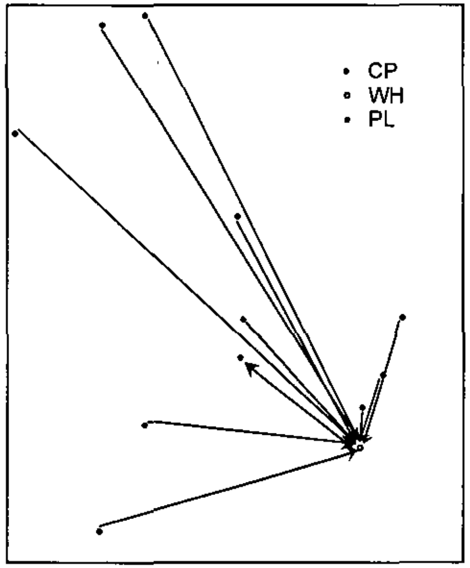

Figure 6.10: 284th generation; 2 inspection–enabled CPs, one WH working, and one WH working; cost: £131394

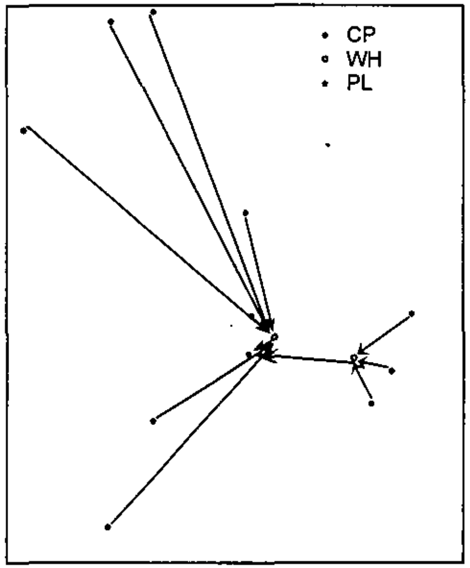

Figure 6.11: 394th generation; three inspection–enabled CPs, 2 WHs working, and one PL working; cost: £121564

6.4 Performance of the Model

After generating various simulation models specific to the problem the optimisation is started. The fixed costs associated with the setup of facilities are annual costs hence the simulation horizon is set to 1 year. The warm–up period, required for the simulation model to reach the steady state is set to 1 month. The duration of warm–up period is decided based on the observations of pilot runs of the simulation. For each candidate solution, ten replications of simulation were run to smooth out residual randomness. A large GA population will result in higher computational time and a lower one may lead to premature convergence of the solution. Hence there is always a trade–off between the computational time and solution quality while deciding the GA parameters. The GA population for this problem size is set to 25 after observing few test iterations While generating the initial population, 1 solution is predefined with all the facilities setup and the rest of the solutions in the population are randomly generated. At each generation, solutions are selected for crossover or mutation operations based on their respective probabilities. The optimisation tool is run on a Pentium 4HT Dual Processor PC running Windows XP at a clock speed of 3.06 GHz on 2 GB of RAM and took around 1-2 minutes per generation of GA.

Simulation model

The simulation model built for the optimisation is generic in nature and is modified according to the data provided by the optimisation tool and hence the model run for each problem is unique. The simulation model built for the optimisation is quite flexible in nature and the decisions with multiple influencing parameters/variables such as determination of destination facilities are taken by the VBA blocks built within it. The logic of these blocks can be slightly modified to give a competitive edge to certain facilities according to the problem scenario. Such tweaks in the logic are useful in the cases where facilities at geographically dispersed locations have different overall cost and time for processing products. Once the optimisation is finished, the models can be simulated without the help of the optimisation tool with the optimum or other set of configuration for further investigations.

In order to verify the correctness of the model, the values calculated by its logic were compared with manual calculations. It can be understood that performing the manual calculations of an entire simulation run will be impossible in terms of time taken.

Table 6.2: Reusability vs. Inspection Enabled Facilities

Probability of being reusable	0.90	0.80	0.75	0.70
Percentage of inspection enabled collection points in optimal configuration	0	9	61	83

Therefore, a random sampling approach was taken. While running the model with a specific network configuration, the simulation was stopped at certain date and all the parameters were calculated. Then based calculations were done for one day of operations and compared with the values obtained from the model simulation stopped at next day. These random verifications are carried out throughout the development of the simulation model so that its correctness was checked and assured.

Reverse Logistics Network

The optimisation was run on 10 examples generated using the values in Table 6.1. Figure 6.12 shows costs associated with the initial and optimal configurations for the various example problems. It is observed that most of the configurations came out with only a few collection points enabled with inspection facilities. This is due to the fact that printer cartridges are one of the most 'remanufacturable' products, so the probability of being reusable is high (hence the parameter settings in the model). Cartridges have very short life cycle and are generally handled with care. The short life span helps in two ways: the cartridges do not get much time to be mishandled and they do not become obsolete by the time they are returned. Hence they have a high probability of being in a reusable condition when they reach the remanufacturer. However, for a more complex product, the case is different. For example, a mobile device (phone or laptop) becomes obsolete within half of its lifespan! In such cases, having intermediate inspection sites would be helpful for channelling the product to disposal or other type of reuse/recycle site. The above observation is also backed by Table 6.2, which shows the variation in number of

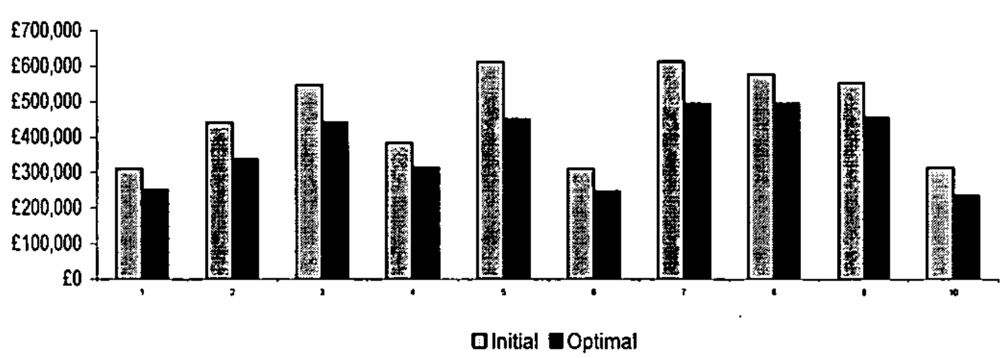

Figure 6.12: Costs associated with initial and optimal solutions

inspection enabled collection points obtained from simulation runs with different values of reusability of the returned product.

6.5 Multiple Product Scenario

The formulatiòn presented above addresses the network issue for an SME dealing with a single product. However, an SME in the independent product recovery business essentially deals with multiple products. For inclusion of multiple products, an index set of products is introduced

$l \in L$; where $L = \{1, \ldots, N_r\}$ set of products

The notations for costs, variables and parameters will change to

Costs

F_i^c Fixed cost for enabling collection point i for inspection

F_j^w Fixed cost of opening warehouse j

P_l Unit penalty cost for not processing returned product l

T_l Collective cost of storage for product l at collection points, warehouses & plants

t_l^{cw} Unit cost of transporting product l from collection point to warehouse

t_l^{wp} Unit cost of transporting product l from warehouse to plant

c_l^p Unit cost of reprocessing product l

c_l^d Unit cost of disposing product l

C_{ijkl} Cost of reprocessing returned product l from collection point i coming through warehouse j at plant k

$$C_{ijkl} = t_l^{cw} d_{ij} + t_l^{wp} d_{jk} + c_l^p + T_l \qquad 6.14$$

D_{ijkl} Cost of disposing of the returned product l coming from collection point i through warehouse j and plant k

$$D_{ijkl} = t_l^{cw} d_{ij} + t_l^{wp} d_{jk} + c_l^d + T_l \qquad 6.15$$

S_{ijkl} Cost saving by disposing the discarded returned product l at inspection enabled collection point i (and not traverse it through warehouse j and plant k)

$$S_{ijkl} = t_l^{cw} d_{ij} + t_l^{wp} d_{jk} + T_l \quad 6.16$$

Variables

y_{ijkl} fraction of returned product l served by collection point i, warehouse j and plant k

z_{il} fraction of returned product l at collection point i which can not be reused (chosen with a random distribution)

Parameters

R_{il} total return of product l from collection point $i; i \in I$

Using the above notations, the mathematical formulation for the fixed, variable and penalty costs is as follows:

$$FC = \sum_{i \in I} F_i^c x_i^c + \sum_{j \in J} F_j^w x_j^w + \sum_{k \in K} F_k^p x_k^p \quad 6.17$$

$$VC = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} R_{il} C_{ijkl} y_{ijkl} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} R_{il} z_{il} \left(D_{ijkl} - S_{ijkl} x_i^c \right) \quad 6.18$$

$$PC = \sum_{l \in L} \sum_{i \in I} R_{il} \left(1 - \sum_{j \in J} \sum_{k \in K} y_{ijkl} \right) P_l \quad 6.19$$

The constraints need to include the consideration of multiple products as well. So the modified constraints are:

$$\sum_{j \in J} \sum_{l \in K} y_{ijkl} + z_{il} = 1, \quad \forall i \in I, l \in L \quad 6.20$$

$$\sum_{l \in L} \sum_{j \in J} \sum_{k \in K} R_{il} y_{ijkl} \le M_i^c x_i^c \quad \forall i \in I \quad 6.21$$

$$\sum_{l \in L} \sum_{k \in K} \sum_{i \in I} R_{il} y_{ijkl} \le M_j^w x_j^w \quad \forall j \in J \quad 6.22$$

$$\sum_{i \in L} \sum_{i \in I} \sum_{j \in J} R_{il} y_{ijkl} \le M_k^p x_k^p \quad \forall k \in K \quad 6.23$$

$$0 \le y_{ijkl}, z_{il} \le 1 \quad 6.24$$

$$x_i^c, x_j^w, x_k^p \in \{0,1\} \qquad 6.25$$

The above formulation brings the model closer to the real world scenario by including multiple products. The same simulation based optimisation approach is used for the evaluation of the model, i.e. the optimisation in multiple product scenario is the same as that in the single product scenario. However, the simulation model needed alteration as the modules responsible for entering entities representing products needed to be modified to produce multiple products and assign attributes to the model. Also the logic of the model needs to be modified to handle multiple products.

For initial experimentation on the multiple product scenarios, The problem described in 6.3.2.1 is extended to two products. The parameters and costs associated with the second products are listed in Table 6.3. The fixed costs remain the same as in Table 6.1. The computational time increases to 2-3 minutes for a generation. With crossover and mutation probabilities of 0.85 and 0.1 respectively, the solution converges at approximately the 457th generation. Figure 6.13 shows costs of "best solution so far" at every 10th generation of the optimisation iterations.

Table 6.3: Parameters and Costs Associated with Product 2

Description	*Parameter*	*Product 1*	*Product 2*
Transportation costs per mile	t_l^{cw}	0.007	0.012
Transportation costs per mile	t_l^{wp}	0.004	0.007
Reprocessing cost per product	c_l^p	14.0	20.0
Disposal cost per product	c_l^d	2.0	1.5
Return per 1000 resident	R_{il}	0.25	0.15

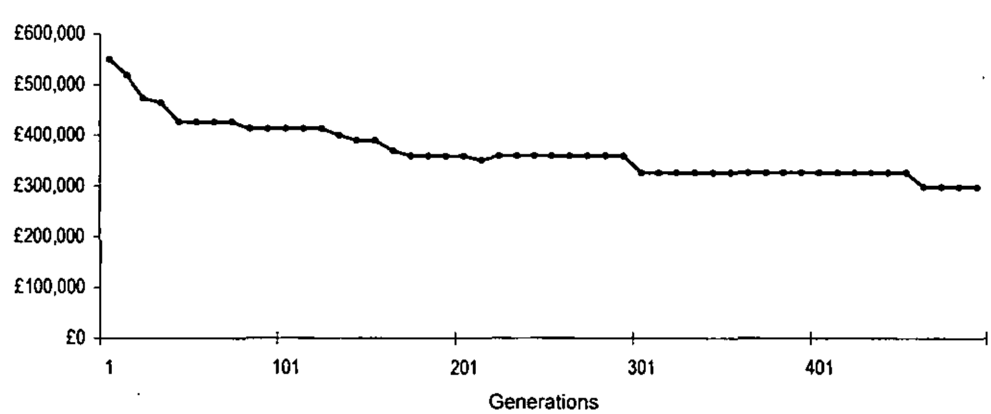

Figure 6.13: Costs of best solution so far at every 10th generations

6.5.1 Inclusion of Multiple Product in the Network

A company involved in the recovery business essentially deals with multiple products. The presence of multiple products makes the network optimisation problem more complex and has great impact on the output. Figure 6.14 shows the optimal configurations for a network optimisation problem with 13 collection points, 6 warehouse and 3 plants. Figure 6.14a is the optimal configuration with two products, in

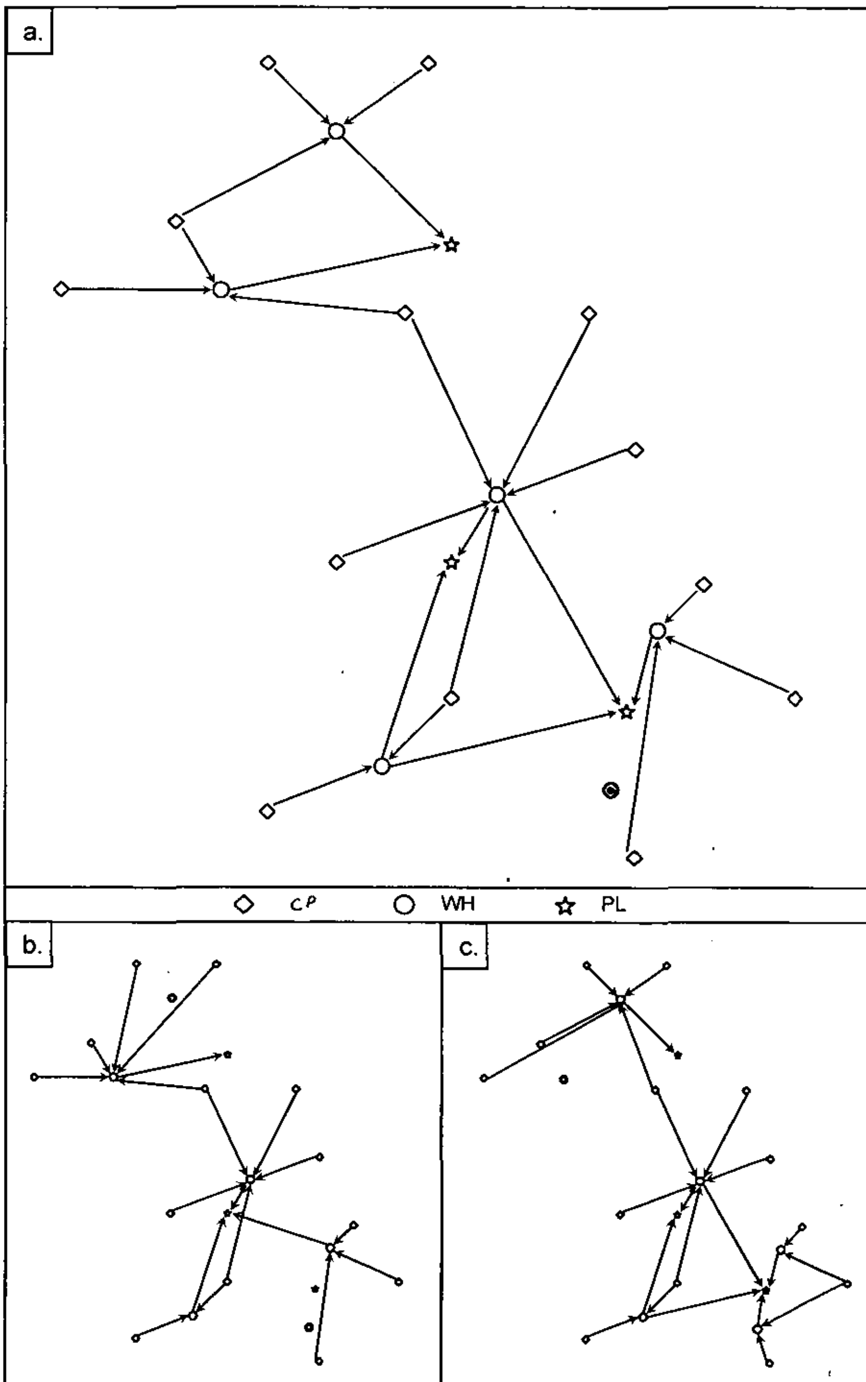

Figure 6.14: Optimised network configuration for a. two products, b. product 1 and c. product 2

which all the collection points are inspection enabled and only one warehouse is not installed. The facility which is not installed can be identified as the one which is not connected by any arrow. However, when the same problem was run with either of the products, the optimal configuration was different due to the variability of availability and quality of products at different locations (Figure 6.14b and Figure 6.14c).

6.6 Conclusions

To successfully implement the product recovery activities, an appropriate logistics network needs to be established for the flow of returned products. This chapter presents a mathematical formulation addressing the network design issues for SMEs involved in independent product recovery activities. The formulation examines the inspection and separation stages. Based on the formulation, a simulation model is created. The network configuration is optimised using a GA with fitness functions calculation done by the simulation model. The optimum configurations obtained from the optimisation are then utilised to perform further investigations.

The initial formulation presented in this chapter addresses the network issues for a SME dealing with a single product. However, the SMEs in the independent recovery business essentially deal with multiple products. Therefore a multiple product formulation is also presented later in the chapter. The example shown with the multiple product formulation takes two products at a time, which at first glance does not look a big step ahead of single product scenario. However, the major difference in formulation and modelling for both the scenarios lies in the fact that even for two products, all the calculations are done with the help of iterations, which makes it mathematically possible to introduce any number of products.

7

Simulation in a Distributed Environment

Simulation models are representations of the system of interest and are used to investigate possible improvements in the real system or to discover the effect of different policies on that system. This chapter discusses different simulation modelling approaches and the constituents of a simulation model. In order to imitate the operational behaviour of collaborative recovery industry, the simulations need to run in a distributed environment where they can communicate with simulations replicating other companies. Implementation of simulation in a distributed environment becomes complicated as it involves synchronisation and interoperability issues.

Chapter Outline:

7.1 An Overview of Simulation

Computer simulation refers to methods for studying a wide variety of models of real world systems by numerical evaluation using software designed to imitate the systems' operation or characteristics, often over time [137]. It is the process of numerical experimentation on the computerised model of the real or proposed system for the purpose of building a better understanding of the behaviour of the system for a given set of conditions. The model is used as a means of experimentation to demonstrate the likely effects of various policies. Those that produce the best results in the model would be candidates for implementation in the real or proposed system.

One of the main advantages of using simulation for analysis purposes is the fact that a simulation model can be allowed to become quite complex to represent the system faithfully. On the other hand, other methods may require simplifying assumptions for analysis.

7.1.1 General Considerations for Various Simulation Modelling Approaches

A model is a simplification of the reality, hence it is important to select the characteristics of the system to be modelled. Before creating a dynamic simulation model, the principle elements of the model must be decided based on two factors: the nature of the system to be modelled and the nature of the study to be carried out. The first factor helps in choosing the modelling approach as some modelling approaches are more suited to the certain problems than to others and the model needs to be a good representation of the system. The second factor tells the analyst the objectives of the study and what to expect as results. Considering both the factors helps the analyst to decide what level of accuracy and details is suitable for the simulation. While deciding the above factors, the following need to be taken into consideration:

Change in Time

The essence of dynamic simulation is the fact that the state changes of the system are modelled through time. One of the major advantages of simulation is that the speed of experimentation can be controlled. For analysis purpose, it is usual to speed up the simulation clock so that several weeks or months could be simulated within minutes of computational time. Therefore it is very important to decide the time flow within the simulation and how to handle it.

The simplest approach of time handling in a simulation is "time slicing", which is forwarding the clock in equal time intervals. It involves examining the model at regular time intervals. The time intervals are decided based on the nature of the system. A trade-off is necessary between the granularity of the observation and the computational time involved. If the time interval is too large then the behaviour of the system will be much coarser than the real system. On the other hand, if the time intervals are too short, then the model might be examined too frequently leading to higher computational time (there are no state changes possible while examining the model).

Most real world systems are stochastic in nature and hence include slack periods of varying length. For such systems, it always preferable to use variable time increments. In this approach, the model is only examined and updated when a change is due. These state changes are called events and this type of simulation is called next event simulation. Of course, the software performing the simulation must be intelligent enough to manage a diary of future events and hence hold more information than time slicing simulation. Nevertheless, the next event approach generally produces better results than time slicing as it automatically adjusts the time increment to represent periods of high and low activity. It should be noted that the next event approach is generic in nature since, if the events in the system occur at regular intervals, it will adjust the time interval to increment regularly, thus producing results similar to the time slicing approach.

Change in State

A system can exhibit processes involving both continuous and discrete changes in state. For example a vehicle is modelled to change its state from static to moving in a discrete manner while the speed of the vehicle should be modelled as a continuously changing element when it is accelerating. If the result of the simulations needs to include the state of the system in relation to the associated continuous variables, it can be represented by differential equations which can allow the variables to be computed at any given point in time.

It should also be noted that digital computers operate with discrete quantities only, hence changes cannot actually occur continuously for a "continuous change model" in a computer simulation. The apparent continuity is achieved by changing or inspecting the variables at various fixed points in the simulation time and thereby providing an approximation of continuous change.

Stochastic or Deterministic

The same system can be modelled by both deterministic and stochastic approaches depending upon the requirements and purpose of the modelling. For example, an inspection station at an assembly line can be modelled to inspect once after every *n* number of products pass or it can be modelled to inspect one random product in a lot of *n* number of products.

Most real world systems behave stochastically and therefore should be simulated by a model with stochastic elements, i.e. the model is built on probability distributions. Hence it is very important to understand the applicability of different probability distributions in different situations.

7.2 Discrete Event Simulation Modelling

As the name suggests, discrete event simulation utilises the next event approach discussed earlier. In discrete event simulation, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system. For example, if an elevator is simulated, an event could be "level 6 button pressed", with the resulting system state of "lift moving" and eventually (unless one chooses to simulate the failure of the lift) "lift at level 6". A number of applications of discrete event simulation involve queuing systems of one kind or another. The following subsections detail the elements of a discrete event simulation.

7.2.1 Objects in the System

As previously stated, a model is a representation of the real world system. There are two ways of modelling the physical elements of the systems:

Entities

These are the individual elements of a system that are being simulated. Entities are dynamic objects in the simulation, which move around, change status, affect or are affected by other entities and the state of the system and affect the output performance measure. Usually an entity is created (which represents the entrance of the object into the system being simulated), the entity then exists and moves around for a while as it encounters and influences different aspects of the system; it is then disposed off as the object leaves the system. However, some models might require the entities to keep circulating in the system.

Most entities in the simulation represent real objects in the system, however there are situations where fake or logical entities need to be created. These logic entities do not represent any physical object in the real world, and their purpose is simply to facilitate some modelling operations. For example, a random inspection in an assembly line can be modelled as an entity. Based on a predefined occurrence list, the inspection entity is created and the concerned element of the system is inspected and its state recorded, after which the entity is disposed off.

Resources

As the name suggests, these are the things like personnel, equipment or space which are utilised by entities. Entities often compete with each other for service from resources. When a resource becomes available, the next entity waiting in the queue seizes it, holds it for a period representing tasks being carried out using the resource and releases it when the associated process has finished. It is common practice to think of a resource as being given to an entity rather than the entity being given to the resource as an entity could need services from multiple resources.

A resource can consists of several identical items and the program keeps a count of how many of them are available. So for example, a resource can represent a group of individual servers, each of which is called a unit of that resource. There can be situations, where the number of resources vary as the simulation progresses. For example, in a restaurant the number of waiting staff (resources) serving the customers (entities) will be vary depending on the time of day. Therefore the simulation program should be able to handle such situations with variable arrays instead of static ones.

7.2.2 Variables and Processes in the System

As the simulation proceeds, the entities interact with each other and with resources; and change their state. In order to define the state of the system and entities, the model needs to record different types of data. The following paragraph discusses the components of a simulation model which are used to define the state of the system.

Attributes

These are items of information that belong to each entity. They are used to define the identity of an individual entity as well as showing its state. For example a set of three attributes for an entity could define that: 1. the entities belong to same category, 2. that each of the entities has a unique serial number and 3. whether or not an entity is ready for the next operation. Attributes can be thought as a tag containing information attached to the real world object. In programming terminology, it can be said that the attributes are local variables.

Global Variables

A global variable is a piece of information that reflects some characteristics of the system. Global variables can used for many purposes. For example, the processing cost of an entity can be represented by a variable. If the processing cost needs to be set to a different value for another set of experiments, the analyst needs to change the value of the variable only. Variables can be used to represent something that changes during the simulation. For example, the cost of carrying out process by a resource can be stored in a variable which increases every time that particular process is carried out. Most simulation software environments provide a variety of in-built variables (number of entities in a queue, current simulation time, etc.) however it is often necessary to also have user defined variables.

Statistical Variables: The purpose of any simulation model is to assess the system against different sets of conditions and for this, various intermediate statistical variables are recorded as the simulation progresses. These variables may include waiting times for a resource, length of queue, etc. These variables need to be set to zero or another constant at the beginning of a simulation run or individual replication. While creating the model, most simulation software package associates a number of built in variables with the resources. However, to quantify the aspects of specific interest, user defined variables need to also be present and exploited in the model.

Simulation Clock: The simulation must keep track of the current simulation time, in whatever measurement units are suitable for the system being modelled. The current value of time in the simulation is held in a variable called the simulation clock. In discrete-event simulations, as opposed to real time simulations, time 'hops' because events are instantaneous – the clock skips to the next event start time as the simulation proceeds and does not flow continuously and take all the intermediate values.

The above is true for a simulation running on a stand alone computer. However, for a parallel or distributed simulation, the simulation clock needs to be continuous so that the simulations running on different machines can be synchronised. The speed of the simulation clock can be a multiple of real time and does not need to be the same as real time. Only the ratio of the simulation clock and real clock should be the same for all the participants of distributed simulation.

Queues

Sometimes, the entity moving in a system has to stop for some reason and it needs a place to wait. This can happen when an entity needs to seize a resources to continue the next stage of processing but the resource is not available as it is currently tied to a previous entity. Such situations are modelled in simulations with the help of a queue. Queues follow the first in first out (FIFO) rule and theoretically can be infinite. However, modelling real world systems requires queues to have a capacity. For example a machining centre can have limited space for a buffer or a restaurant can have a limited number of seats in their waiting lounge. It should be kept in mind that the queues can be full and entities can still arrive. There should be provision for such situation in the model.

Events

Events are instances of simulated time when a state change takes place in the system. The event could be the instance when an entity enters or leaves the system or an operation starts. The simulation program maintains at least one list of simulation events. An event must have a start time, some kind of code that constitutes the performance of the event itself and possibly an end time. In some approaches, there are separate lists for current and future events. Events in their lists are sorted by event start time. Typically, events are "bootstrapped" – that is, they are scheduled dynamically as the simulation proceeds.

Process: The operations and procedures that are initiated and terminated at various events are known as processes. These processes are responsible for transforming the state of the entities and system. For example in a library, the process 'sensitise' transforms the state of a book from 'returned' to 'ready to be shelved'. There could be a number of processes in the life cycle of an entity.

7.3 Distributed Simulation

Distributed simulation is a method of computer simulation in which different parts of a simulation are run simultaneously on two or more computers that are communicating with each other over a network. Distributed simulation is a type of segmented computing, which requires the simulation program to be divided into sections that can run simultaneously. Distributed simulation requires that the division of the program take into account the different environments on which the different sections of the program will be running. For example, two computers are likely to have different file systems and different hardware components. Distributed simulation is extensively used in war–gaming by military organisations worldwide. It also finds applications in other areas like space exploration and medicine.

Distributed simulation can be used in studying a system which influences and is influenced by other systems while it is operational. This makes it a suitable tool for analysing networked organisations, which are collaborating with each other. An independent product recovery company working under contract with an OEM is one such example. This situation is different from the ones described earlier. In this case, the different machines are not running parts of a single simulation. Instead they are running their own system simulations while communicating and collaborating with each other. Due to the presence of diverse computing platforms and environments, there are some issues, which must be considered for successful implementation. These issues are discussed in later subsections, but first the suitability of discrete event simulation in a distributed environment will be discussed.

7.3.1 Synchronisation in Distributed Simulation

Discrete event simulation utilises two global data structures: the state variables for describing the state of system and an event list containing all pending events that have been scheduled for the simulation time, but have not yet occurred. Each event contains a timestamp and usually causes some changes in the state of the system being simulated. The simulation program iteratively removes the event with the smallest timestamp and processes the event by executing the codes that effect the appropriate changes in the state. In this paradigm, it is crucial that only the event with the smallest timestamp (e_{min}) is selected to be processed. If an event with larger timestamp (e_x) is processed before e_{min}, it might change some variables which should be used by e_{min}. This will result in simulation of a system where the future can affect the past, which is obviously unacceptable.

For distributed simulation on parallel machines, where parts of a single simulation are carried out on different machines, this problem can be addressed to some extent by having a shared event list. In a distributed environment where two different simulation programs are running independently, the speed of individual simulations will be different as it will depend on their own event lists. In such scenarios, the simulation clock of every participant should be synchronised with each other. Fortunately, modern simulation software provide this facility within their run setup and the simulation clock can be matched with the real clock. It is understood that an analyst is unlikely to be interested in running the simulation in real time as it will take away the benefit of studying the system's long term behaviour in shorter time. However, the simulation does not need to run in real time, instead the simulation clock should be match to a multiple of the real time clock and this clock ratio should be the same for all participating simulation applications.

7.4 Development of the Distributed Simulation Environment

The distributed environment under consideration in this research is essentially a loosely coupled system. While developing a platform for distributed simulation, the fact that the systems can have different operating environments should be considered. The issues of communication, interoperability and architecture for distributed simulation has attracted the attention of several researchers and projects in the past and some architectures for implementation of distributed simulation exist. One such architecture called High Level Architecture (HLA) was developed by the United States Department of Defence [146]. HLA provides the specification of a common technical architecture for use across all classes of simulations in the United States Department of Defence.

This research involves developing a platform for supporting the distributed simulation of recovery SMEs. This includes development of a multithreaded server, communication agents (clients) and XML parsers. Figure 7.1 shows the components of the distributed simulation implementation. The simulation program sends and receives messages to and from other programs through a server. There is a communication agent (CA) associated with every simulation program (client), which is responsible for connecting and maintaining the connection to the server. The simulation program sends the message to the XML parser, which then converts the message into XML codes and requests the CA to send it to the server. The XML message contains details of the recipient along with other information for the server to know the destination of the message. On the server side, there is another communication agent. However the server side CA is capable of maintaining multiple threads of connections (with more than one client side CA). The message received by the server side CA is sent to the server, which with the help of an XML parser, retrieves information regarding the recipient client and sends it there. XML messages received from the server are converted and mapped into instruction codes by

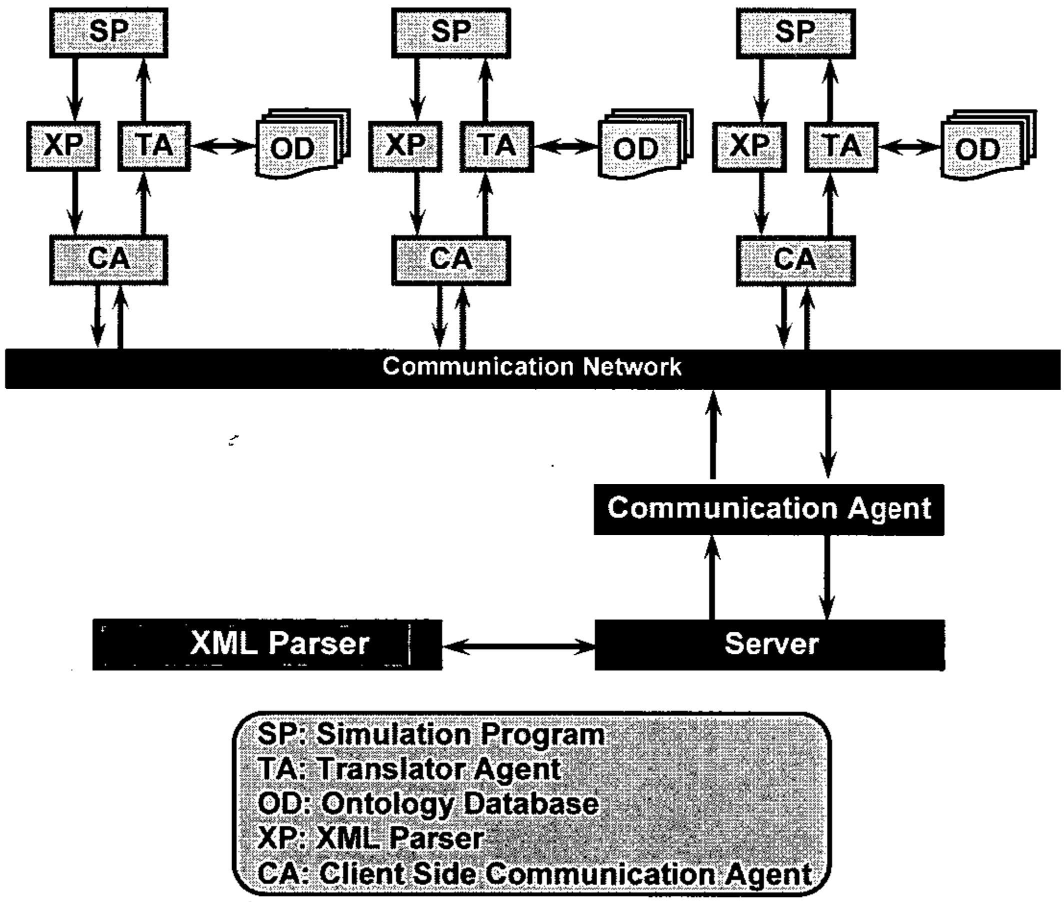

Figure 7.1: Implementation of Distributed Simulation

the translator agent (TA), and fed to the simulator program. Figure 7.2 shows the exchange of data between the simulation program and the server.

Information Sharing

The most basic types of information shared among the different simulation programs are product orders and notification of receipt etc. in the context of the collaborating recovery SMEs. However, the collaborating companies may also be interested in knowing the status of the other actors, so that they can assess the feasibility of an operation and schedule its future tasks. To capture different aspects of the messages that could be transferred, the simulation program uses XML for communicating to other simulations. XML or Extensible Markup Language is a general-purpose markup language. It is classified as an extensible language because it allows its users to define their own elements. Its primary purpose is to facilitate the sharing of structured data across different information systems, particularly via the Internet [147]. The use of XML in data transfer facilitates inclusion of all the relevant information into one document.

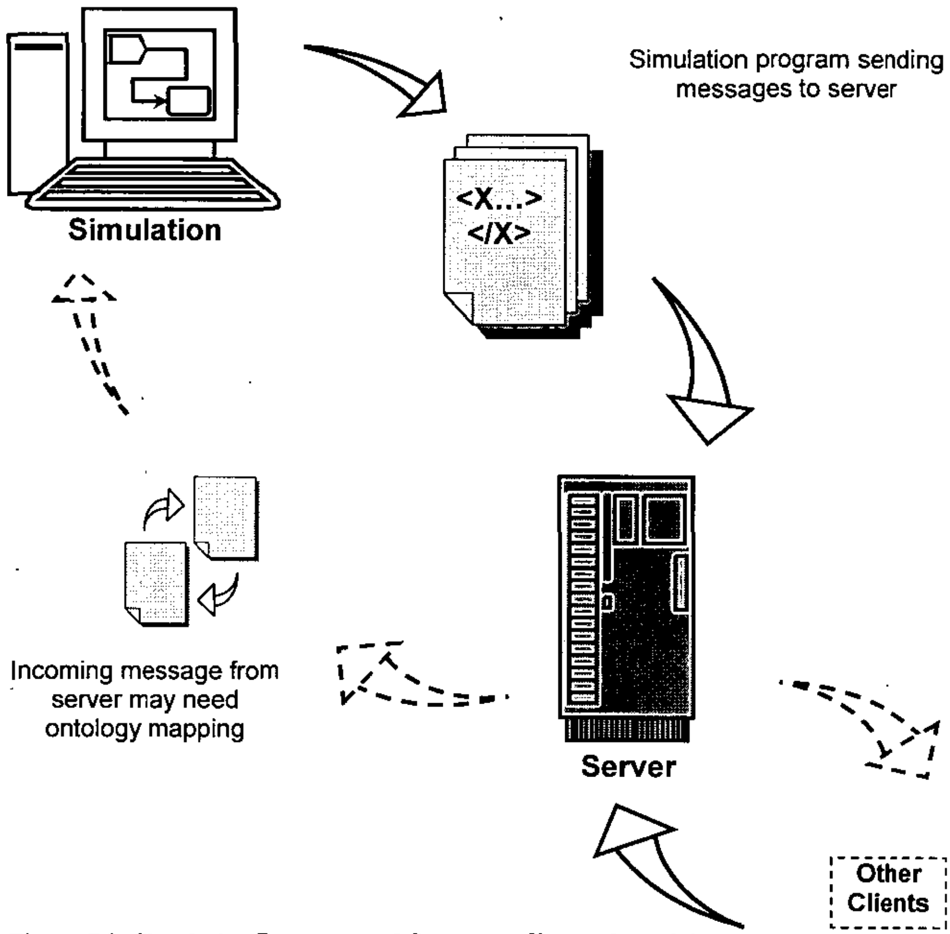

Figure 7.2: Simulation Program and Server sending and receiving messagess

This includes the id of the recipient client in its header, using which the server channels the message to the appropriate destination. At the client side, the information embedded in the documents about the origin helps the TA in deciding the ontological mappings. Figure 7.3 shows a typical message sent from a recovery company SME1 to logistics provider LOG1 on January 2, 2008 requesting delivery of two products with the given Universal Product Code (UPC). The products are requested to be picked up from the location SME1_site04 and delivered to location SME1_site04 on or before January 10, 2008.

7.4.1 Implementation of the Distributed Simulation

The choice of coding language for client – server applications is not limited to any particular language as long as the code conforms to the standards of communications. However, one has to consider the compatibility of the simulation software used. The

```
<?xml version = "1.0" encoding = "UTF-8">
<message to="LOG1" from="SME1" date="01/02/2008" lang="en-GB">
      <header>
            <type>delivery_request</type>
            <origin>SME1_site02</type>
            <destination>SME1_site04</destination>
            <serialno>LOG1_0045</serialno>
            <duedate>01/10/2008</duedate>
      </header>
      <content>
      <product>
            <UPC>9780134569550</UPC>
            <quantity>500</quantity>
      </product>
      <product>
            <UPC>1380569450975</UPC>
            <quantity>200</quantity>
      </product>

      </content>
</message>
```

Figure 7.3: A Typical Message Sent from the Recovery SME to Logistics Provider

simulation software used in this research is Arena [137, 148], which supports Visual Basic for Application 6.3 (VBA) for integrating user codes. Therefore the codes for the clients applications are written in Visual Basic 6. Figure 7.4 shows a screenshot of the form for the entering server details.

The clients connect to the server and send an id request. The server checks if the id is already in use and confirms it. This id is used in future for communication purpose. A subroutine within the simulation program keeps checking for new messages at very small intervals. The XML Parser and Translator Agent are compiled as Dynamic Link Library (.dll) files and referenced from within the VBA codes.

Java was chosen over Visual Basic 6 for coding the server because Java handles multithreading in a much better way than Visual Basic 6. Although newer versions of Visual Basic (.NET and 2005 edition) support multithreading very well. Use of Java in conjunction to Visual Basic also gave an opportunity to test interoperability of different

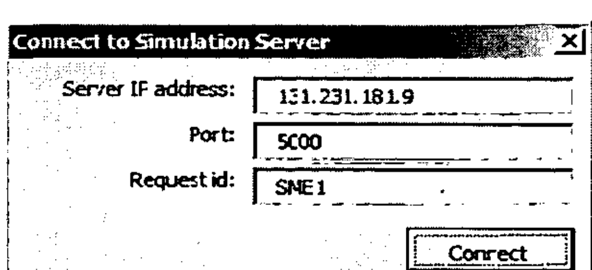

Figure 7.4: Visual Basic form at client side for connecting to the server

environments. Figure 7.5 shows the screenshot of the Java server application running and connecting two simulation clients. The codes for the XML Parser are compiled as a class file and imported by the server.

7.5 Discussions

In an increasingly complex and interconnected world it seems vital that the possible consequences of decisions and plans are explored before taking any action. Simulation modelling is one way of doing so. Modelling is a simplification and abstraction of real world systems which focuses on or emphasises the features that are deemed to be important. Simulation can be used to model and evaluate the current "as–is" state of the network to better understand its strengths and weaknesses. It can also be used as a design tool to test and compare different configurations and their potential by using "what-if" models. The ever growing recovery industry has created business opportunities for a number of SMEs which essentially work in a collaborative manner. In order to imitate the behaviour of such an industry, the simulation models representing different actors need to be run simultaneously and collaboratively. This kind of distributed simulation is relevant to the earlier network design problem where the optimisation approach makes use of simulation models for fitness evaluation. The simulation runs in the distributed environment can provide a closer approximation of the reality and feedback into the overall design and optimisation process.

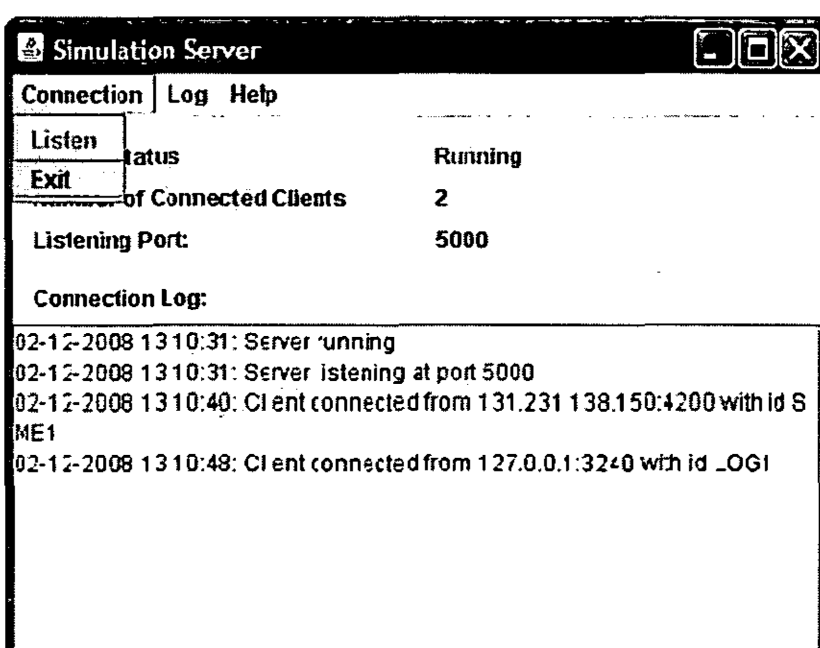

Figure 7.5: Screenshot of the server application

The synchronisation issues for the distributed platform lead to implementation of the time–slicing approach for simulations. The prototype platform developed is generic in that it can be applied to a variety of simulation environments yet it requires the participating programs to conform to the prescribed schema of message transfer.

8

Realisation of the SME Modelling Approach

Continuing from the modelling approach discussed earlier, this chapter shows the implementation of the approach with the help of a hypothetical example of toner cartridge recovery. The collection network for the products is determined using the optimisation tool developed and the different views of the model are discussed.

Chapter Outline:

8.1 Introduction

As discussed earlier, a model is a simplified abstraction of the complex reality. In a business domain, a model represents concepts of the business functions and hence includes goals, visions, efficiency and other important factors. An enterprise model serves as a basis for the information systems model, ensuring consistency and accurate requirements being passed on to the software design. The enterprise model is created with the purpose of understanding the structure of the enterprise and re-engineering it when needed.

This chapter elaborates the implementation process of the modelling approach discussed in Chapter 5 and shows a small example of single product recovery through a collaborative network. The company is hypothetical and the data related to the recovery processes and resources have been gathered from literature. The methodology adopted in this part of the research was to firstly identify a typical product for recovery & remanufacturing and then examine it in detail to gain understanding of the processes and costs involved. A particular model of toner cartridge was therefore disassembled and re–assembled using the information from the OEM website in order to understand the processes. The costs associated with the recovery process were estimated from information available on the do–it–yourself websites.

8.2 Realisation of the Modelling Approach for Recovery Firms

In order to create a model, it is necessary to understand the natural characteristics of the enterprise. Any enterprise is set up to make profit and this is achieved by delivering products and services to the customers. In the recovery context, the product take back can be seen as a service, while the remanufactured item is the product. In order to develop the various views described in Chapter 5, the following issues need to be considered.

Identification of the Business Goals

The enterprise and the market of the remanufactured products need to be studied in order to decide on appropriate strategies. The market analysis helps in understanding the characteristics of the market in which the recovery company operates. The demands for both the original and remanufactured products need to be understood and compared in order to find the scope for inclusion of the later in the market. The above is true if the recovered product is marketed by the recovery SME, however in cases where the recovery SME is tied in a contract with an OEM, its business goals change since the OEM will sell the recovered products with a label of "as new" and the recovery SME therefore does not need to worry about penetrating the market.

There must be enough customers willing to buy the products if the remanufactured product is to be successful in the market. Reasons for the customers to purchase a remanufactured product could be economical, legislative, or environment–consciousness and one of the goals for the company could be to create or stimulate these reasons if they do not already exits. Creation of market for a remanufactured product therefore requires new marketing tools.

Identification of Business Processes

Business processes for any enterprise range from management to the shop floor activities, however the business management processes for a recovery company are different from those for a traditional company as changes in government legislation are particularly important in the recovery industry. The processes are assigned to the different departments within the enterprise and this helps in defining the main functions and processes and later in refining them by adding specific details.

One of the basic requirements for a remanufactured product is to be (at worst) the same price to the end user, but normally cheaper than the original product. To make this possible, the product recovery processes need to be economic. Hence one of the objectives of the business processes is to maintain low cost of processing, right from initial inspection to final packaging.

Resource Requirements

A resource for a remanufacturing plant could be a work station, an operator or simply a buffer space, whilst the remanufacturing plant itself is a resource for the recovery company. As procurement is a very significant function in the recovery process, the vehicles for transportation become very important types of resource. In the recovery industry, most processes are labour intensive and may require special skills and know how. Hence taking care of human resources is another key issue.

The decision whether a resource needs to be setup or not should be taken in advance and analysed by using "what-if" experiments. With the help of the mathematical model presented in Chapter 6, it can be decided if the installation of inspection facilities at collection points is economical or not. With the help of the optimisation tool developed in the above Chapter 6, an optimal configuration of the network can be found to determine whether setting up certain facilities will be economically favourable or not.

Information Specification

The aim of the presented modelling approach is to provide the designer with a modelling and evaluation tool to enable the progressive design of the enterprise. For this purpose, a large amount of information needs to be stored and presented throughout the process of modelling. This includes data relating to processes, resources and products. In order for various actors of the system to efficiently store and maintain the information, the designer needs to specify what data is generated and where it is used. The typical information related to the product under recovery is technical (geometry, lists of subassemblies, material properties, etc.), state (inspected or not, condition, etc.) and process (processes needed, components needed, etc.).

8.3 An Example of Cartridge Remanufacture

As laser printers became more affordable and prevalent, an environmental concern arose over the volume of used toner cartridges that were discarded. The toner cartridge remanufacturing industry grew recognising the opportunity for profit while reducing the environmental burden by refilling and refurbishing toner cartridges. The recovery of laser printers' toner cartridges has therefore been adopted to demonstrate the modelling approach developed in this research. The following sub-sections discuss the issues related to cartridge remanufacture and present its modelling for simulation purposes.

8.3.1 Background of Cartridge Remanufacture

The following sub-sections describe the constituents of a toner cartridge and discuss the procurement and recovery processes for cartridge remanufacture.

Components of a Toner Cartridge

A typical cartridge consists of four main parts i.e. the toner hopper, drum, roller and waste hopper. The toner hopper stores the printing toner. The roller supplies a uniform coating of toner to the drum for printing. The drum is made of photo–conducting material and is responsible for printing. The excess toner is stored in the waste hopper. Figure 8.1 show the components of a Hewlett Packard LaserJet toner cartridge (HP Q1338A). The roller and drum are rotated with the help of a gear assembly housed at one end of the cartridge. Generally, the cartridges just run out of toner, whilst their components are still in good working condition. Therefore with appropriate cleaning and refilling, the cartridges are easily remanufactured.

Procurement

The procurement of used cartridges depends on the type of customer, who are broadly divided into two categories, i.e. small office users and large office users. Small office users include domestic use, home–office, shops or small organisations, while large office users include heavy users like corporate offices, universities, councils, hospitals, etc.

Figure 8.1: Components of a toner cartridge (HP Q1338A)

In the case of small office users, the volume of products is small and the procurement of used cartridges is done with the help of retailers or return packets. The customer sends the used cartridge back to the OEM in a return packet provided with the box and in return receives some incentive which is generally in the form of a discount on a new purchase. Alternatively, a customer can bring the used cartridge back to the retailer and once again, in this case they usually get some cash–back or other incentives for their next purchase. The returned cartridges may then need to be transported from the retailers to a warehouse facility to await manufacture. With the help of logistic providers, the collected cartridges are transported to the warehouse after temporary storage at collection points.

In contrast, if the customer is a high volume user; it is easier for the logistic provider or the recovery company itself to collect the used cartridges via its recovery channel. The individual user inside the organisation just needs to dump the cartridge after use into a certain 'recycle bin'. The cartridge vendor or the logistic provider will then be able to collect the used cartridges in bulk on a regular basis. This may be combined with delivery of new cartridges, but this is entirely dependant on the logistic manager's decision. The collected cartridges would then either go to the warehouse straight away or pass through the collection points deployed.

As shown in Figure 8.2, there are several channels of product take–back. Domestic and small office users return the product to the retailer or directly to the recovery company. High volume users and retailers forward the product directly to the recovery company or via collection points.

To better understand the process involved in "sorting", "disassembly" and reassembly" of the toner cartridge the author searched websites and using information found worked through the disassembly and reassembly process himself using a HP Q1338A cartridge as shown in Figure 8.1. Based on information gained from the activities the necessary, typical remanufacture process are now described in Section 8.3.1.1. The knowledge gained from these activities was also validated through further visits to supplier websites and discussion with supervisor.

8.3.1.1 Remanufacture Process

The details of the actual steps for disassembly and remanufacture will differ for different models of cartridges, however, the basic steps are the same and are as follows:

Raw Material: Receipt and Inspection of Empty Cartridges

- Toner cartridges arrive at the facility
- The empty cartridges are initially sorted as virgin or recycled
- The toner cartridges are categorised by make (for reasons of incompatibility, the cartridges from certain manufacturers may be discarded)
- The remaining cartridges are sorted by cartridge type and stored accordingly as approved in warehouse

Raw Material: New Components and Toners

- New components and toner are received
- QA inspection is performed on random components
- Print quality of the toner is tested

Cleaning and Disassembly

- Approved cartridges are taken out from warehouse
- The cartridges are disassembled and their components are inspected

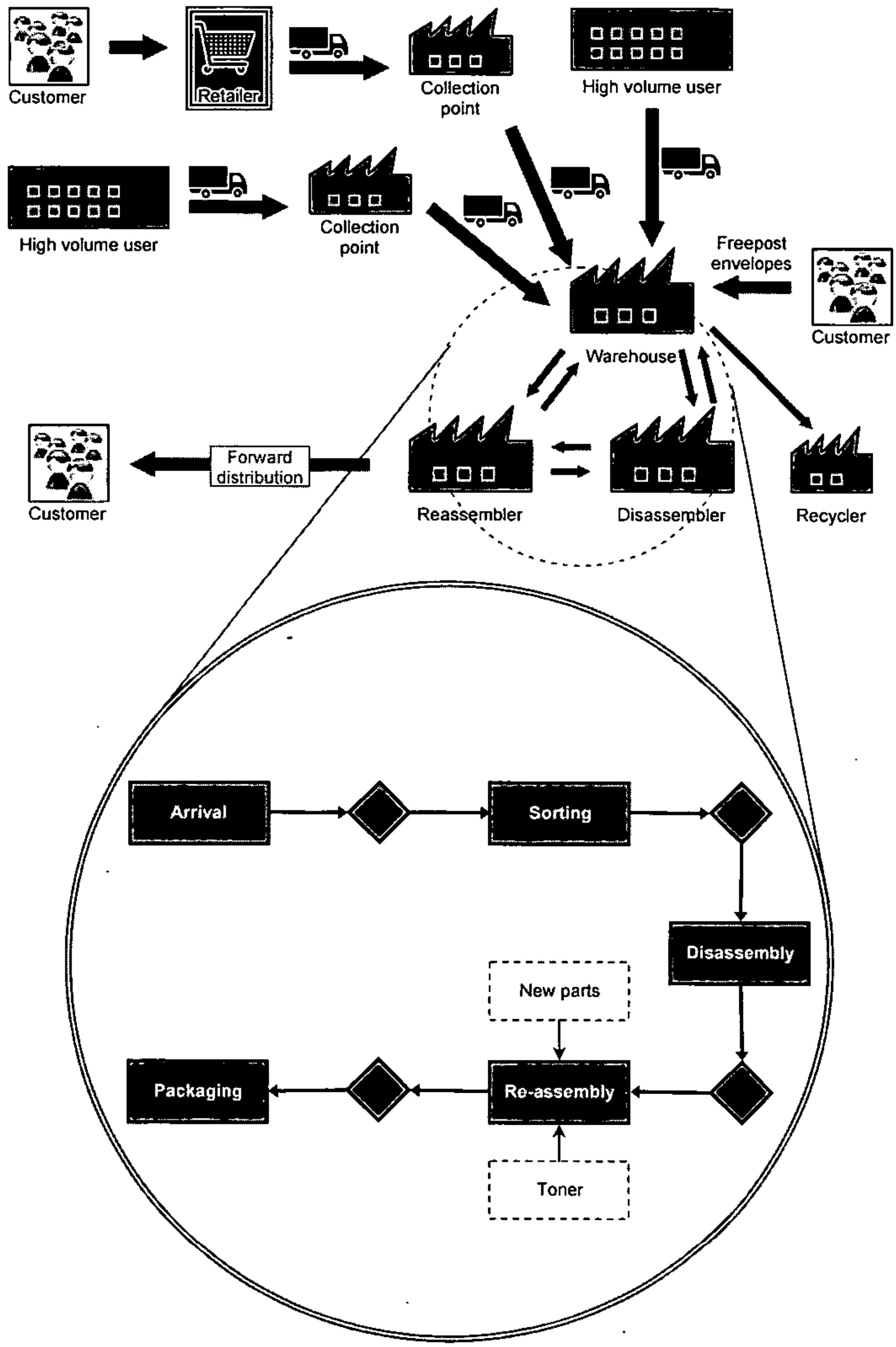

Figure 8.2: Different recovery channels in the system and process inside the disassembly/reassembly units

- Cartridge are cleaned using ionised, compressed air
- Old toner and dust is collected via duct collection filtration system
- Internal parts are inspected for wear and damage
- Worn and damaged components are removed and discarded

Parts Replacement and Calibration

- Some components are critical are they are responsible for actual imaging job. These imaging components are replaced with new and qualified components in the "toner hopper assembly" and "waste hopper assembly"
- All parts are lubricated appropriately

Toner Introduction and Cartridge Assembly

- Seals are installed in toner hopper assembly
- Toner hoppers are routed to filling stations and filled with exact amount of pre–measured toner
- The cartridge subsystems are assembled into finished cartridge

Testing

- Proper operation of all components is inspected
- Print testing for all cartridges is performed
- The prints are evaluated visually for density and consistency using OEM as standard.
- Any cartridge that does not meet production standards stage is discarded for analysis and tracking defects
- Quality Assurance review for density and consistency of printing

Cleaning and Packaging

- The cartridge is cleaned and labelled
- The cartridge is coded for date of manufacturing
- The cartridge is sealed in moisture and light resistance bag

- The cartridge is packed and it's print test with cardboard inserts
- The boxed cartridge is sent to inventory (for future sale)

Some components are critical for the performance of the cartridge in terms of print quality, so they are never reused. The steps above assume that the only new components used in the production are such components. All the other components are recovered ones. Figure 8.3 shows the generic steps in cartridge remanufacture. The steps involve

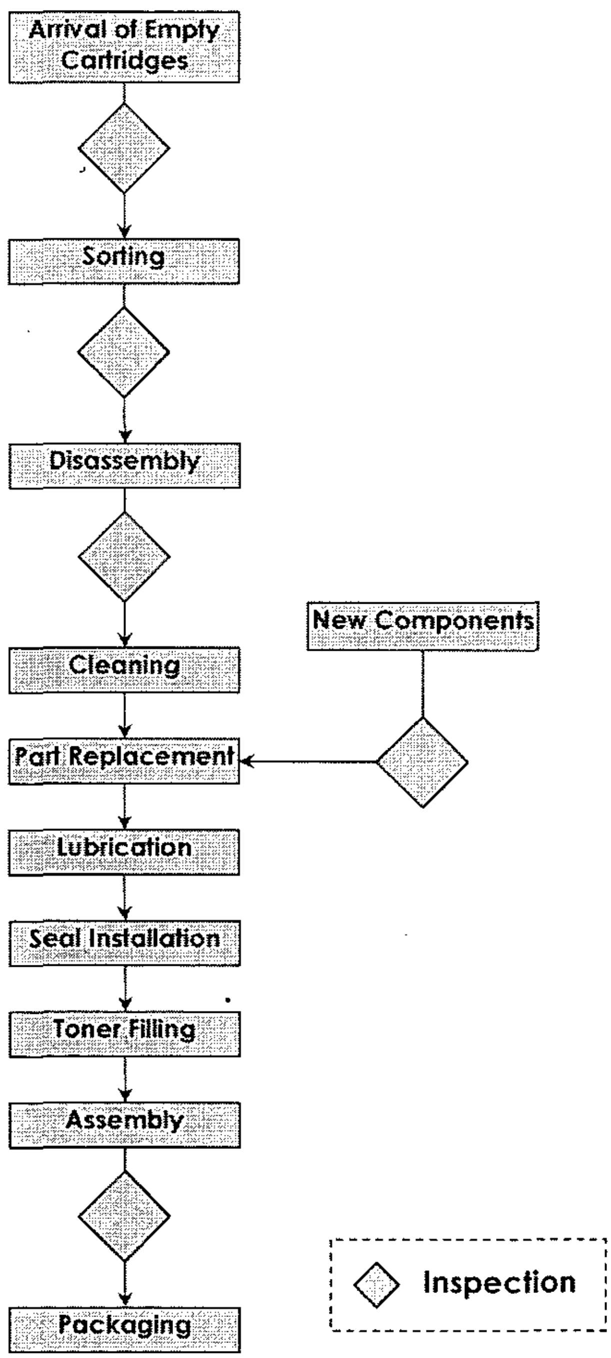

Figure 8.3: Steps for remanufacture of toner cartridge

processes in and around the warehouse, disassembly and remanufacturing facilities.

8.3.2 The Recovery Model for Cartridge Remanufacture

The recovery company involved in the recovery of used laser cartridges in this example is hypothetical and deals with one kind of products only. Its market includes a mix of high and low volume customers. It has its facilities for collecting, storing and processing the products at dispersed locations. The company has a fleet of transport vehicles. The company identifies a number of candidate locations for setting up its facilities, i.e. collection points (with small storage capacity), warehouses (with limited yet large storage capacity) and processing plants. This problem is the same as the example shown in section 6.3.3.1. The near optimal configuration determined using the simulation based optimisation approach is used for building the model of the recovery SME.

The primary aim of the company is to maximise its profit margin. In this case, the use of used components in remanufacture process is cheaper than the use of new components. Hence, one of the sub–goals of the company is to maximise the utilisation of procured used products. Figure 8.4 shows the goals and sub–goals of the recovery company in the database. As discussed earlier, the goals change with time and the representation of goals of the company with the help of the strategic view is valid for a given time only. The modelling approach is cyclic in nature and the different views need to be visited after the performance evaluation for further tuning. Another top level goal of the company is to maximise customer satisfaction, which is achieved by increasing on–time deliveries and shortening the delivery window.

The different views of the model need not be presented in any particular order, however in order to create a relationship between the processes and the resources used, it is preferable to create a resource view before moving to the business processes. It is evident from the steps of remanufacture in section 8.3.1.1, that the whole process is labour intensive. The resources for the company are its sorting stations, work stations, human operators and storage space. Figure 8.5 shows the database of the resources in a certain processing plant. All the work stations are equipped with inspection and

	goal_title	sub_goal_of	status	goal_value	current_value	unit_of_measurement
	increase profit margin	none	incomplete	15	11	% of final cost
	increase utilisation of procured items	increase profit margin	incomplete	70	85	% of procured items
	reduce storage time of raw material	increase profit margin	incomplete	40	20	days
	reduce storage time of ready products	increase profit margin	incomplete	25	5	days
	increase customer satisfaction	none	incomplete	95	100	% of customer
	decrease delivery window	increase customer satisfaction	incomplete	10	5	working days

Figure 8.4: Screenshot showing goals of the recovery company

	resource_name	type	situated_at	used_in_process	max_capacity	capacity_in_use
▶	work_station	equipment	plant_01	processing	10	10
	human_operator	operator	plant_01	sorting, processing, inspection_packaging	12	12
	sorting_station	space	plant_01	sorting	2	1
	temp_storage	space	plant_01	arrival_empty_cartridge	2000	1000
	storage_space	space	plant_01	storage	5000	3421
	packaging_area	space	plant_01	inspection_packaging	1	1

Figure 8.5: Screenshot showing the resources and the processes they are involved in

processing facilities. After the final assembly, the cartridges are sent for packaging where they are inspected with a test print before being sent to the work station where they are finally boxed. The boxed products are then stored until they are sent to the customer. These processes are shown in Figure 8.6. Normally a process is supposed to have an estimated or averaged completion time, however some processes can not have a definite value for completion time. For example, after packaging the product, it is stored in the stock. Though there is no activity involved while the product waits to be picked up, it engages a resource by occupying space. This process therefore continues until the product is sent out to the customer.

The understanding developed from the above leads to the construction of the business process view as shown in Figure 8.7, which helps management to determine the sequence and inter-relationships of the processes. It also shows the association of processes with the sub–goals and with the resources used. The business process view can also be used to identify how objects move through the system.

Dynamic Analysis Using Performance View

In order to analyse the operations of the system, the designer makes use of the performance view. This view aids the designer to study the performance of the model by providing feedback which can be used at various stages of the design. For dynamic evaluation of the recovery SME, 'what–if' experiments are performed using simulation models. The detailed business process view helps the designer to understand the various processes that need to be modelled during the implementation of the simulation model. A brief description of the simulation model created in Arena 10.0 [137, 148] is as follows.

	process_name	resource_used	processing_tim	time_unit	processing_cost
	arrival_empty_cartridge	temp_storage			£0.01
	inspection_packaging	packaging_area, human_operat	4	min	£0.10
	processing	work_station, human_operator	10	min	£9.80
	sorting	sorting_station, human_operato	2	min	£0.10
	storage	storage_space			£0.01

Figure 8.6: Screenshot showing the processes involved

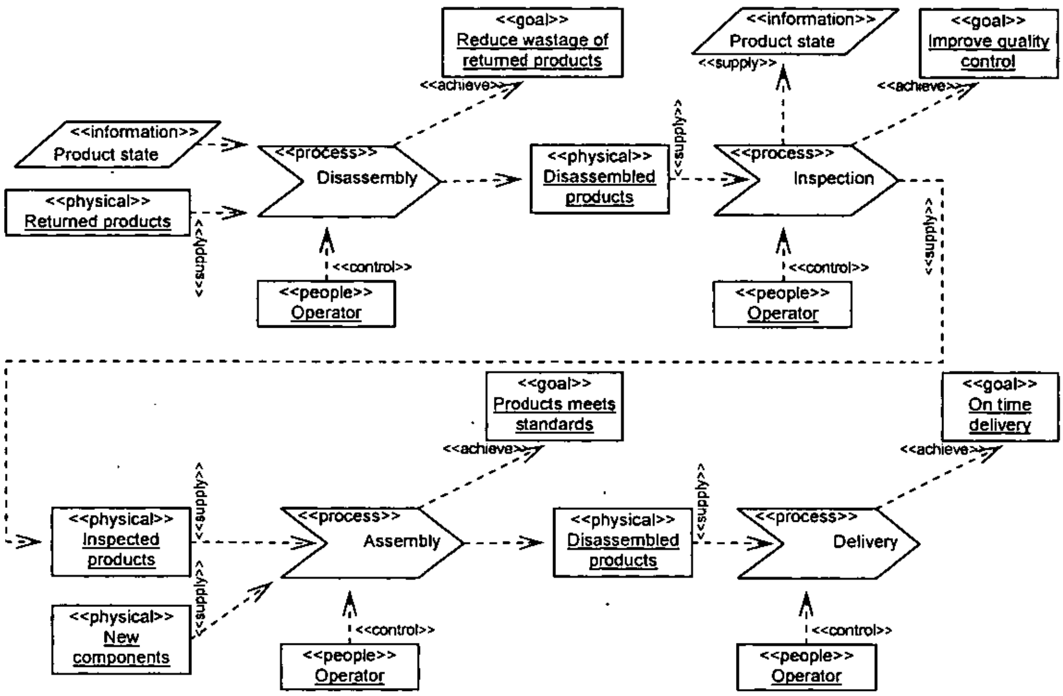

Figure 8.7: Business process view of the cartridge recovery SME

The model does not include customers. The cores (empty cartridges) arrive at various collection points at regular interval in uniformly distributed numbers. In the model, the cores are represented by creating entities at every collection point, assigning attributes to them and storing them temporarily (Figure 8.8). The transporters are called to collect the cores from the collection points in batches and transfer them to the nearest warehouse .with available storage. This transport call is carried out with the help of a 'signal module' provided by the Arena software environment. The "signal" is activated whenever the storage capacity of a collection points reaches 80% of its maximum capacity. The storage cost at the collection points is very high compared to that at the warehouse. The inventory of the cores at the processing plant is also constantly checked and if it falls below 50% of the maximum capacity, a request is sent to the warehouse to transfer cores. Another case where the transport call is made is when an order has arrived and there are insufficient cores in the inventory of the plant. Similarly, if the warehouse fails to fulfil the transfer request from the plants (due to insufficient inventory at the

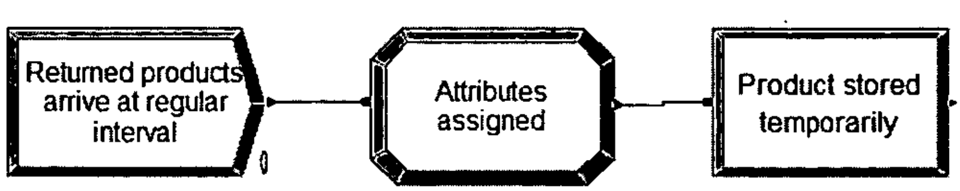

Figure 8.8: Entity created and attributed assigned before storing

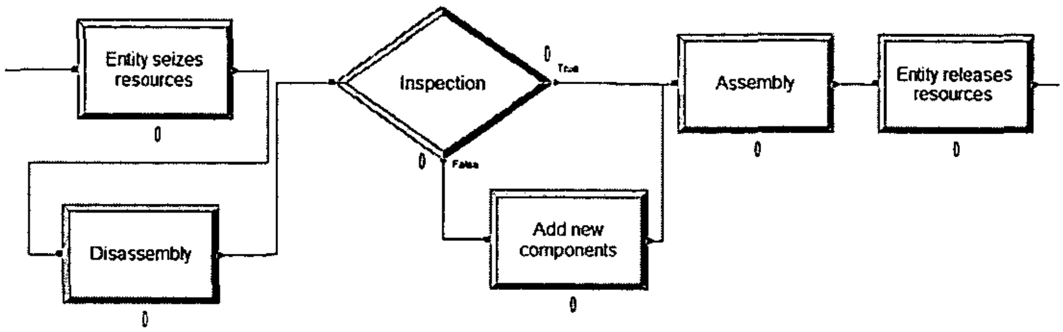

Figure 8.9: Entity seizing and releasing resources

warehouse), it will send a transfer request to all collection points in its vicinity.

Everyday a certain number of cores are released from the inventory to go into the remanufacture process. The entity representing the cores arrives at the work station and seizes the resources (human operator and work station) necessary to begin remanufacturing until the disassembly, assembly and inspection processes are carried out as shown in Figure 8.9. The final remanufactured product is subjected to a final quality testing before going to stock.

The order from the customer is modelled by using a 'create module'. In this case, the create module generates a logical entity, which makes the next module generate order details. Then it triggers a 'signal' and gets disposed (Figure 8.10). The order is registered by the model logic and it releases required number of finished products from the stock, so that they can be grouped together and sent to the customer via a transporter.

After running the simulation model in Arena 10.0, and studying the statistical variables (queue of the waiting entities at the work station, waiting time of transporters, etc), the dynamics of the system were better understood. Also it was noticed that one work station and human operators were under utilised while some collection points were not able to serve the incoming flow of returned product resulting in penalty cost.

One of the important observation regarding the sub–goal of prompt delivery was that the company had a high delivery window. This was due to the fact that the transporter was requested once the order is ready. If the transporter is located somewhere other

Figure 8.10: Creating order and signalling

than the plant site, it took some time to come and pick the order depending upon the distance. While revisiting the process view of the model, a function was added which sends a request to the transporter to come to the plant as soon as it becomes free. This reduced the waiting time for the ready order to be picked up.

8.4 Discussions

This chapter demonstrates an example implementation of modelling with the help of a small single product example. The simulation based genetic algorithm approach is utilised for determining the network of returned product collection. This chapter also discusses how different modules of Arena are used to model the activities and events. The company example used in this chapter is hypothetical and far from reality as most (if not all) companies in the recovery industry essentially deal with multiple products. However, this "single product" example provides a useful introduction to the main elements of the methods and models used in this research. The next chapter demonstrate the application of the proposed modelling approach on the recovery of electronic products.

9

Example: Recovery of IT Product

This chapter shows the application of the modelling approach on an example based on author's experience gained from visiting a recovery company working in the area of IT products recovery and redeployment. The model data has been populated in a conventional database however, the model views are shown with the help of a web browser based representation system.

Chapter Outline:

9.1 Background

Computers have become integral to modern living and commerce. However, their characteristics as products separate them from other products and create new challenges for their recovery. Computers are complex, complicated goods and contain hazardous materials which require careful disposal. However, they are marked by rapid technological obsolescence, weak recovery infrastructure and little culture or tradition for repair and reuse. These features make computer life cycles much shorter and their end-of-life reuse opportunities much more limited than some products (like the printer cartridge described in Chapter 8). Unlike service–based products (for example copy machines) computers are generally sold, not leased by the manufacturer or an agent who works closely with the forward supply chain. As a result, many details about computer products, such as their location, age, and current condition, are not available to the firm recovering them. This chapter describes the recovery of used computers and attempts to create a business model for IT products recovery based on the approach proposed in the earlier chapters of this thesis. The concepts incorporated in the proposed model are based on interaction with a leading company in IT product recovery in the UK. When possible, knowledge used in demonstrating the proposed model was validated using information on websites, by discussion with managers in recovery companies and discussion with research supervisor.

9.1.1 Challenges for IT Product Recovery

On the surface, the approach to IT product recovery is consistent with the published literature on remanufacturing, which tends to emphasize operational aspects of remanufacturing products–that is, locating end-of-life equipment, refurbishing their cores, and reselling the intact products. However, a more detailed examination of the experience of computer recovery businesses reveals a different story. There is very little potential for resale of computing products more than 6 months old. This is because most end–of–life computers contain obsolete technologies and outdated architectures, therefore products enter the remanufacturing business with little reusable potential. As a result, instead of focusing on recovering and rebuilding product cores, most IT product recovery businesses engage in "demanufacturing" computers– that is, disassembling products and atomising assets to divert waste and recapture value wherever practicable. Taken in composite, these computer recovery operations illuminate the difference between remanufacturing (refurbishment-oriented) and demanufacturing (recycling-oriented) as complementary remanufacturing strategies. The commonality is that both involve a whole host of operational choices, such as which products to collect, how to organize the shop floor, or which markets to seek for selling process outputs.

An average desktop computer consists of three primary subassemblies: the monitor, the chassis (the box, often called mistakenly 'the CPU'), and input/output peripherals such as keyboards, mice, or speakers. These subassemblies contain the various recoverable parts. The chassis contains hard disk and optical drives, circuit boards with integrated circuit (IC) chips, impact-resistant plastic casings, an internal metal framework, small batteries, motors, power supplies, and cables. The monitor is housed in an impact-resistant plastic shell. A cathode ray tube based monitor is composed of a leaded glass funnel and coated glass front panel, a cathode, and circuitry, while a liquid crystal display based monitor contains composite display panel and circuitry. The peripheral equipment is comprised of minor circuitry and some movable parts, most of which are not readily saleable in their own right. The materials recoverable from this medley of components include ferrous metals, aluminium, copper, precious metals, polystyrene and ABS plastics, thermosetting epoxy plastics, leaded and unleaded glass, and hazardous wastes like batteries (see Figure 9.1). Products are often transported with appreciable amounts of paper, cardboard, and polystyrene foams, so these materials also require disposition and present parallel material management challenges. [149]

Similar to manufacturing processes, remanufacturing requires decisions about what needs to be done and how much resource and time needs to be engaged in various stages of operation. At first glance these processes can appear to be the converse of one another. However, in practice, recovery outputs are not simply manufacturing inputs. To put it briefly, physical laws, financial payback, hefty information demands, available technologies and ownership structures all affect the final goods, resulting in the fact that it is not possible to get everything back out of a product that is put into it's manufacture. Economically speaking, the payback on reclaimed assets bounds the investment that can logically be put into recovery. Reclamation is only viable if someone is willing to pay for it and therefore managers must balance the level of asset purification with market prices for materials and overall recovery profitability. In addition, remanufacturing demands new technologies of disassembly, which in some cases reveal a need for new technologies for assembly as well. Collaboration between assemblers and disassemblers is often desirable to facilitate such technological developments, as reflected by joint partnerships

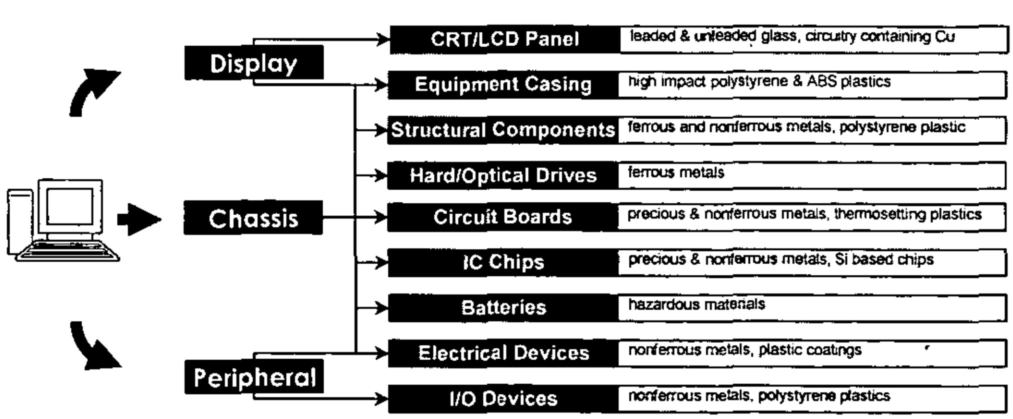

Figure 9.1: Constituents of a desktop computer (adopted from [149])

and vertical integration to improve communication and control along the supply chain. From a logistical standpoint, managing recovery operations requires detailed information about product quantity, quality, timing, and composition–data which are particularly challenging to procure.

9.1.2 Business Opportunities for IT Product Recovery

The recovery of IT product is generally seen as an end–of–life asset management service for high volume customers; which includes remarketing, redeployment, recycling and disposal. In such cases, redeployment is one of the major business opportunities for the recovery company. Redeployment extends the IT product lifecycle and is more cost effective than normal upgrade. The recovery company can take a required number of units and undertake refurbishment, hardware upgrade, configuration, individual customisation, and then redeploy the equipment back into the customer's organisation. Redeployment of IT products takes advantage of the fact that in most cases, the upgrade does not need new software licenses as the existing licenses can be used on the refurbished computers. It is important to note that any existing data must be comprehensively erased from the equipment and that each item is electrically safe before it is redeployed.

Another major business opportunity for the IT product recovery company is reselling the used computer equipment through its marketing channels in order to release residual value. Even though the IT equipment may be of no further use to the original customer, they may still have a value within the second user market. Remarketing redundant computer equipment releases additional value back into the customer's organisation and instead of paying operating costs of computer disposal, the customer ends up gaining some revenue. Again, in this case as well, secure data disposal and electrical safety should be ensured prior to remarketing.

There are cases where the customer does not need the refurbished computers for its own operations, but is inclined to take part in the recovery of its discarded equipments by participating in a philanthropic cause. In such cases, the recovery company can facilitate charity computer donations on behalf of its customer as part of its service offering.

For equipment which are damaged beyond repair, the recovery company needs to provide recycling services, which enhance its customers environmental credentials by taking obsolete and non-working items, recovering materials and recycling them with no residual to landfill and in compliance with current legislations.

9.1.3 Activities Involved in Computer Recovery

Like any other recovery process, the computer recovery involves 4 basic activities: acquisition, assessment, disassembly and reprocessing. The most basic questions a reverse manufacturer must ask are, which products do I want and how do I get them? That is, before a product is recovered, a recovery business must select a type of product, locate it, collect it, and transport it to a processing facility. These activities define the first stage in recovery, which is called acquisition. Reverse logistics planning and network design are used to control the timing, quantity, composition, and quality of products as they enter the recovery process. If this level of control is available, acquisition procedures can significantly reduce the uncertainty of inputs (quantity and timing) as well as the need for contingency planning and manufacturing flexibility (composition and quality). If not, intermittent and heterogeneous product flows and information asymmetry about product condition cause confusion and inefficiency in remanufacturing. These challenges are representative of current dynamics in computer recovery, as the characteristics of IT products and existing infrastructure do not facilitate sophisticated acquisition processes. With little ability to control the flow of process inputs, businesses take what used products they can find, collect, and ship to their processing facilities. The characteristics are evident in the tasks of selection, location, collection, and transportation.

This activity is performed in different manners for different types of customers. For a customer interested in charity donation or resale, the customer probably has already acquired replacement equipment and hence the entire batch of used equipment needs to be taken out of the customer's premises within a short, defined time frame. In this case using large vehicles to collect the maximum number of items in the minimum number of trips will be economical. This holds for products coming from the domestic users through retailers as well. However, if the customer is interested in redeployment, the products coming from the customer need to go back to the customer after refurbishment. The customer will be less interested in putting a stop on all its work, removing the whole lot of equipment at once, getting them refurbished and then deploying them back at its premises to start work. In such cases, the refurbishment will be a gradual process happening over a considerably long duration of time, in which a certain amount of equipment will be replaced by upgraded ones on a regular basis until all the necessary equipment have been refurbished.

Once equipment has arrived at the facility, managers must determine which assets are valuable. During assessment, businesses determine whether to repair, refurbish, renovate, recondition, retrofit, or just plain resell a product or its parts and generally do so when products first arrive and are sorted. This input appraisal and output planning parse the process inputs into revenue streams of recoverable products, recoverable parts, and recoverable materials as well as costs streams for unrecoverable wastes. Theoretically, assessment should be integrated into overall process planning and direct selection activities, but computer assessment sometimes does not occur until after the product is partially disassembled. To some extent this timing in assessment depends on whether the product is considered a marketable goods or waste upon receipt. When end-of-life products are still considered potentially marketable goods, a value-oriented approach can be used to determinate product quality and to control input variety through selective acquisition of products. That is, recovery firms can streamline assessment and improve the cost-effectiveness of subsequent recovery operations by using the acquisition process to select products based on quality or variety. For end-of-life products, product recovery can be viewed as a means of diverting computers from landfills or incineration. For this waste-oriented approach, control of input streams through active selection is usually not possible because little information about the product is available in the selection process. This dearth of data delays assessment until after acquisition. That is, if organisations can only vaguely, if at all, choose which products to acquire, they simply get whatever is in the delivery truck and work from there. This lack of control constitutes one of the greatest risks in recovery and requires repeat assessments or assessment-on-the-fly to evaluate unfamiliar products as they are disassembled. The primary challenges for conducting accurate early assessment are incomplete information about inputs and market immaturity for outputs..

Product disassembly is the stage of actual deconstruction of a product to sort its assets for reuse, recycling, or disposal. The first phase of disassembly improves the accessibility of reusable subassemblies and parts, usually by opening the product. The second phase is the removal of any reusable parts. The third phase prepares the remainder of the product for material recovery. Although not all disassembly proceeds through these stages in the same way. When disassembling, if the company wants to recover numerous valuable components for reuse or resale, it needs to disaggregate a product to preserve all of its designed components. Disaggregation processes are costly, labour intensive and time consuming, requiring careful unfastening of parts so disaggregation generally occurs only when the product is very expensive and large. A majority of the products are dismantled in such a way that certain assets were demolished to recover others. For example, to save time when recovering internal components, plastic panels and casings are often irreparably broken. This demolition, which destroys all design value, is the predominant recovery strategy when a company is interested in recycling materials instead of recovering designed assets. The disassembly of products and segregation of their assets greatly multiplies the number of recovery streams and subsequent transactions since reusable subassemblies and parts are sent to repair shops, manufacturers, or retail outlets; scrap parts are further separated and purified for material recovery; and residues are hauled away by scavengers or waste disposal companies. Process planning is needed to manage these streams efficiently, but uncooperative designs, information poverty, and constraints from upstream choices impede it.

Once a product has been disassembled the decision whether its is going to be used straight away or going to be stored in the warehouse for future processing depends on the nature of the assignment. In the case of redeployment, experienced decision makers need to assess what is needed to remanufacture the item to the required standards and acquire the necessary items from existing inventory or new purchase. When all reusable subassemblies and parts have been removed, the leftover assets are valuable only for their material contents. The goal of material reprocessing is to reclaim these materials in saleable quantities, and businesses naturally try to maximize profits by optimizing the benefits of purifying materials against the cost of doing so. Initial separation occurs by hand during disassembly, either on a disassembly line or at a workbench, to sort assets into basic categories according to material content. For robust materials like metals, the infrastructure is relatively well-developed but for glass, plastics, and hazardous wastes disposal continues to be a concern. One of the major challenges in material reprocessing is locating markets for materials and determining the appropriate purity end-point during their reprocessing.

9.2 A Recovery Information Model for IT Product Recovery

In this section, the model presented for IT product recovery has been created based on ideas and experience gained from industrial visits to one of the leading UK companies in IT product redeployment and recovery. The data related to the activities and the resources are gathered by email communication with personnel from this company and other OEM for IT products.

Transportation is carried out with the help of contracted logistics providers. The returned IT products, which mainly consist of desktop and laptop PCs are assemblies of various small components as discussed in section 9.1.1. The technical information related to the used IT products consists of information such as computer identification, origin, age, list of subassemblies and specification. The process/function information related to the IT products includes any special types of processes needed to disassemble the product, the resources used and its actors. The resource information includes the maximum capacity of the resource and the queue waiting for its availability. The IT product is a part of a recovery order which has additional information like batch size, order status, cost, customer id and due date. It also includes the list of business partners which are involved in the order. The recovery business partners have their specific goals which involve the business processes and their status which includes their required completion date. To plan and record all these activities, suitable information models and related database records are required.

To underpin the example model, an information specification has been designed and is presented in a Booch representation [129] in Figure 9.2. It identifies information entities, their relationships and associated rules and contains six information classes representing goals, IT product, recovery order, business partner, processes or functions and resources. This information structure has been used to derive the data fields for information storage. In the remainder of this chapter, different views of the recovery model will be presented using a database populated with the particular details of IT product recovery.

9.2.1 Web Based representation of IT Product Recovery Model

A web browser based representation of the system is presented to demonstrate a prototype system for recovery of IT products. The database which is created in Microsoft Access 2003 [150, 151], is accessed through Microsoft Open Database Connectivity (MS ODBC) drivers with the help of Sequential Query Language (SQL). The web server used for the purpose is Apache HTTP server with a PHP engine running on Windows platform. The source code for accessing the database and producing dynamic web pages was created using PHP embedded in an HTML body. The

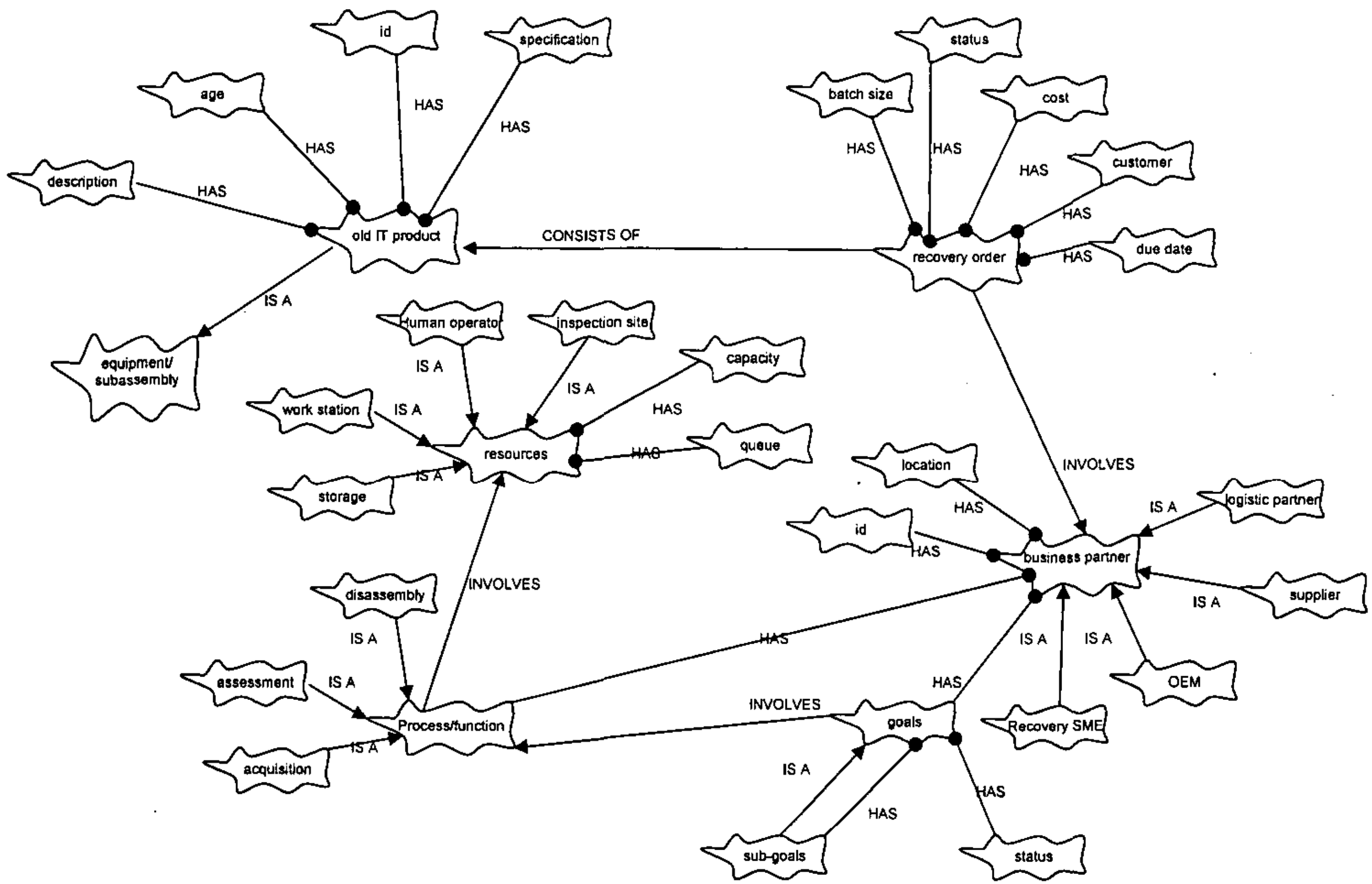

Figure 9.2: Booch representation of IT product recovery information

architecture of the system is shown in Figure 9.3. The interface is user friendly and was created keeping in mind that all the members of the management team are not necessarily experts in handling databases. In addition to presenting the data in a legible format, the web browser can also be used to update and change the entries as well. Screenshots of the browser interface will be shown in the next few sections.

Although the IT recovery company sells its products through its online shop and maintains a stock of refurbished goods, its business is mainly order driven and is similar to build–to–order companies like Dell. The company promises to deliver the ordered product within 7 days for the stocked items. For build–to–order products, the main goal of the company is to reduce the production lead time. This can come under the top level goal of increasing customer satisfaction. Storage space is a continual problem for the company due to the uncertain and irregular availability of used product. For example if a large volume customer decides to upgrade their IT system, the recovery company must take all the equipment or lose the business. The problem of storage space has been addressed by decisions to install new warehouses. However, this does not address the other challenges of "towering" inventory and avoiding obsolete stock (due to the short usable life times mentioned earlier in the chapter). Some inventory in the warehouse is comprised of products and subassemblies that might never be deployed as they are too old and obsolete to be compatible with newer systems. It can therefore be inferred that some existing inventory might need to be discarded and disposed off safely in order to save some storage space. Figure 9.4 shows how the goals of the company could be presented in the strategic view with the help of a screenshot of the web based representation system. The PHP subroutine scans the sub–goals and places them under

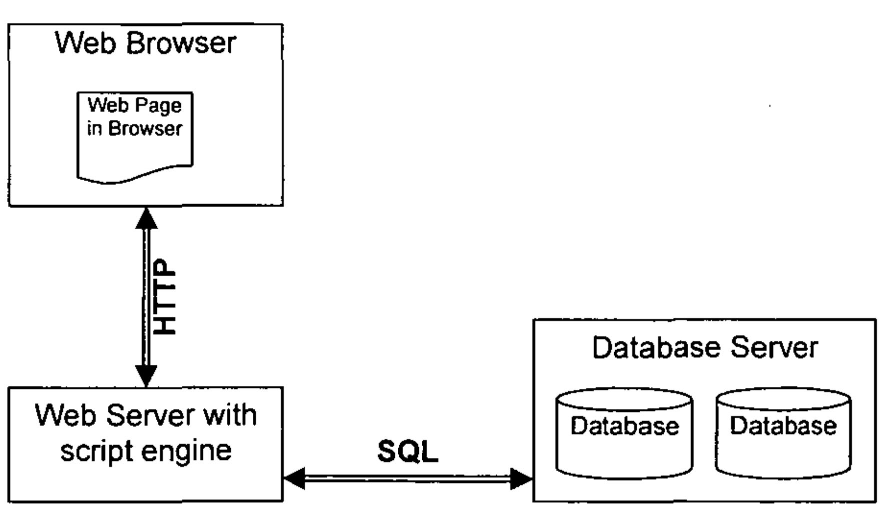

Figure 9.3: Architecture for web based representation

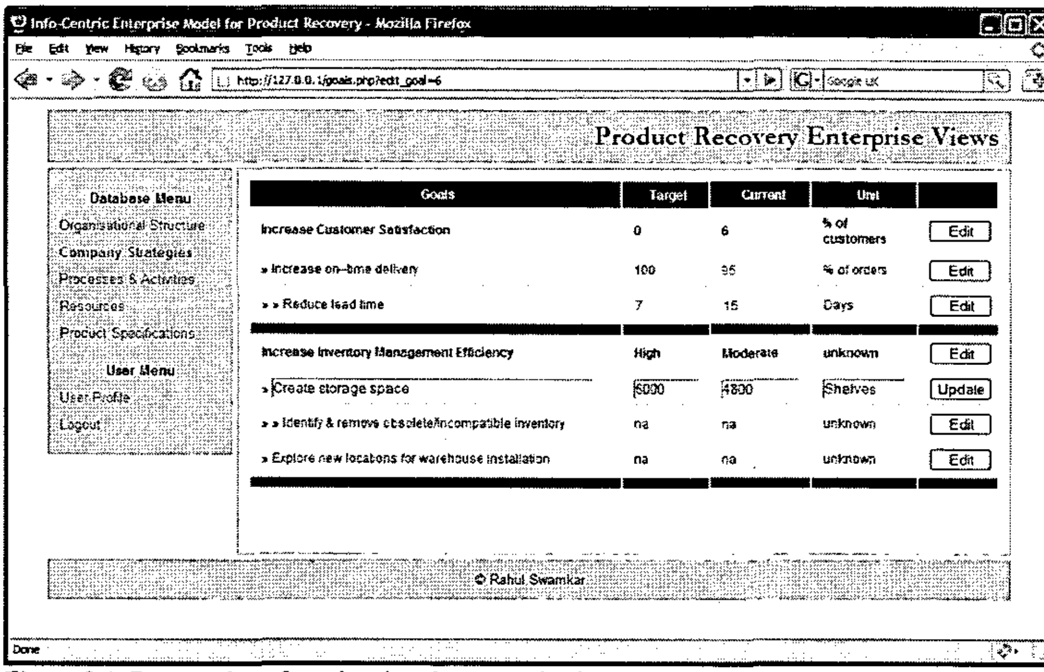

Figure 9.4: Browser interface showing the strategic view

their higher level goal. Based on the authentication power of the user, the goals can be modified or updated as they get completed. In another screenshot (Figure 9.5), the process view is shown. In this representation, a number of resources can be associated with a process using the drop down menu.

The performance view of the system has been built as a simulation model using Arena. The ActiveX and VBA capabilities of Arena makes is possible to connect to the ODBC

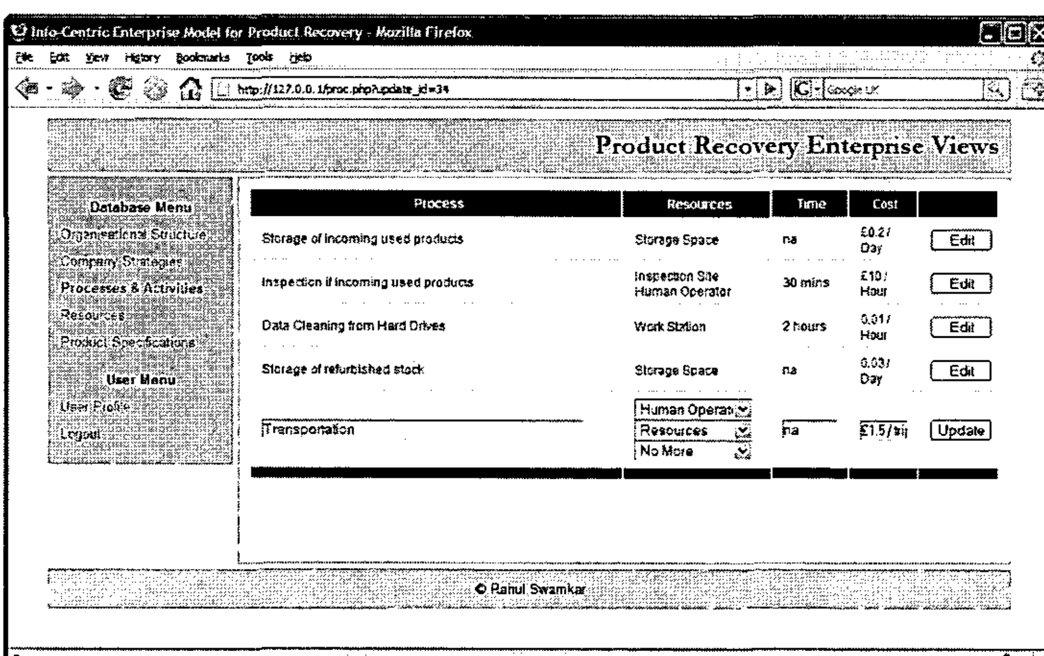

Figure 9.5: Browser interface showing the process view

driver of the database and the information can be retrieved using SQL queries. The dynamics of a product recovery company are quite different from those of the hypothetical cartridge recovery firm mentioned in the previous chapter, and exhibit both push and pull types of flow. Normally, the flow of material in a company is driven by demand; i.e. when an order arrives, the processing is carried out. However in this case, the production greatly depends on availability of the used cores. Hence, operations are carried out when raw material is available. Apart from that, if the order consists of a redeployment job, then the processing starts only when raw material comes from the customer. There are three ways for an order to arrive in the system:

1. Normal processing: On a timely basis, the used core is picked from the warehouse and processed for selling. In this case, the used core is picked from the inventory in an almost new condition and less than 6 months old. Generally, these products are returned by the customers within the 'cool–off' period when they have the right to return the item if they are not satisfied with it against full refund. In the dynamic model, such processes are triggered by creating a logical entity, at regular intervals. After triggering the processes, the entity is disposed off.

2. Order arrival: This is the traditional way of generating an order. An entity representing the order is created with uniform distribution. The entity enters an 'assign' module which assigns generated information related to the order, after which the entity is disposed off and the processes start in order to complete the order. The type of order (a resale or a redeployment order) can be determined from the values of the attribute of the order entity. In both the cases, the logistic partner (simultaneously running simulation or networked interface for human interference) is called upon to do the delivery job.

3. Human interference: With the aid of a communication agent (Chapter 7) and a custom made user interface, it is possible to insert orders at times decided by analysts. Figure 9.6 shows the screenshot of such an interface. It is coded in Visual Basic and it makes references to the communication agent compiled as a dynamic link library (DLL). When the simulation is running and is connected to the simulation server, this interface can be invoked. After making connection to the server, it can send the order in the form of an XML file to the simulation. Once the simulation receives data from the network socket connection, its

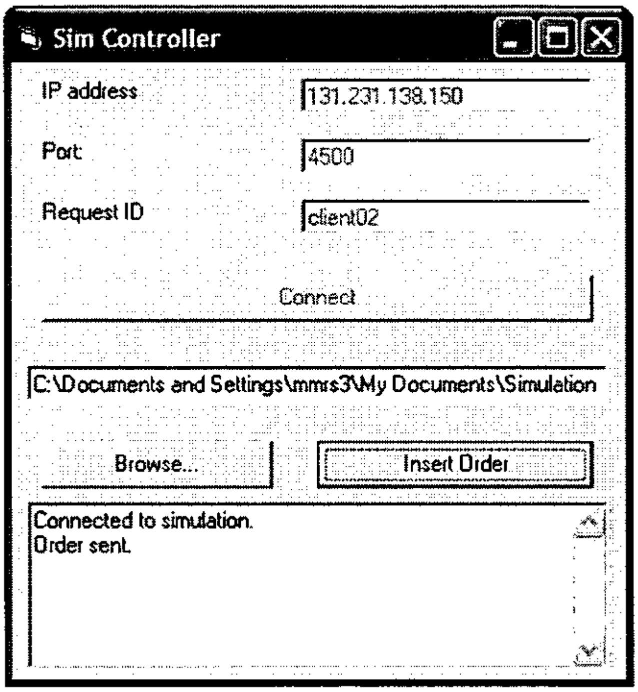

Figure 9.6: Graphical user interface for inserting order into running simulation

control goes to a specified subroutine which creates an order in a similar fashion as earlier. However, instead of creating a randomly generated order, the data is supplied by the external user interface.

The refurbished items in the stock are sold via the dedicated web portal. In the model this is represented by disposing of the entities in the stock with a uniform distribution after adding revenue to the company.

9.2.2 Sharing Information with Business Partners

As mentioned earlier, the recent growing business opportunities in the recovery industry have attracted a number of SMEs and IT product recovery is no exception to this. These SMEs work in collaboration with the OEMs as well as supporting companies like logistic providers and retail chains. Companies like IBM and Dell provide the recovery SMEs with licenses to acquire and refurbish original products of their brand and resell them. The logistics companies are contracted to provide transportation and sometimes other services like warehousing. In such a collaborative environment, the efficiency of operations can be greatly improved if enough information is provided to the business partners as well as the management of the company itself. The proposed information and model based approach that is presented in this thesis has great potential for supporting supply chains that are strongly linked through business partnerships, or even to assist virtual enterprise. The web based interface, created for representation of the different views of the model can be extended by making it accessible to other business actors within the product recovery supply chain, i.e. logistic partners, collection agents or retailers, product recovery SMEs and sometimes the OEMs. Figure 9.7 shows the recovery actors accessing the information database of the recovery SME. In any set of collaborative business network, issues of company confidentiality must be carefully balanced with the benefits of sharing information. Therefore it should be noted that the proposed model driven approach would enable management of the recovery SME to still have more access to the information than any other actors. Only relevant information is made available to each user based on his/her identification. Obviously theses kind of decisions are entirely at the discretion of the management and the current business context.

9.3 Discussions

This chapter attempts to apply the proposed modelling approach to an example of IT product recovery and redeployment. The IT industry is one of the fastest changing industries and it sees manifold changes in the latest state of the art within very short time periods, e.g. within a couple of months. For the same reason, this industry is one of the major producers of landfill waste which also includes toxic materials. To operate

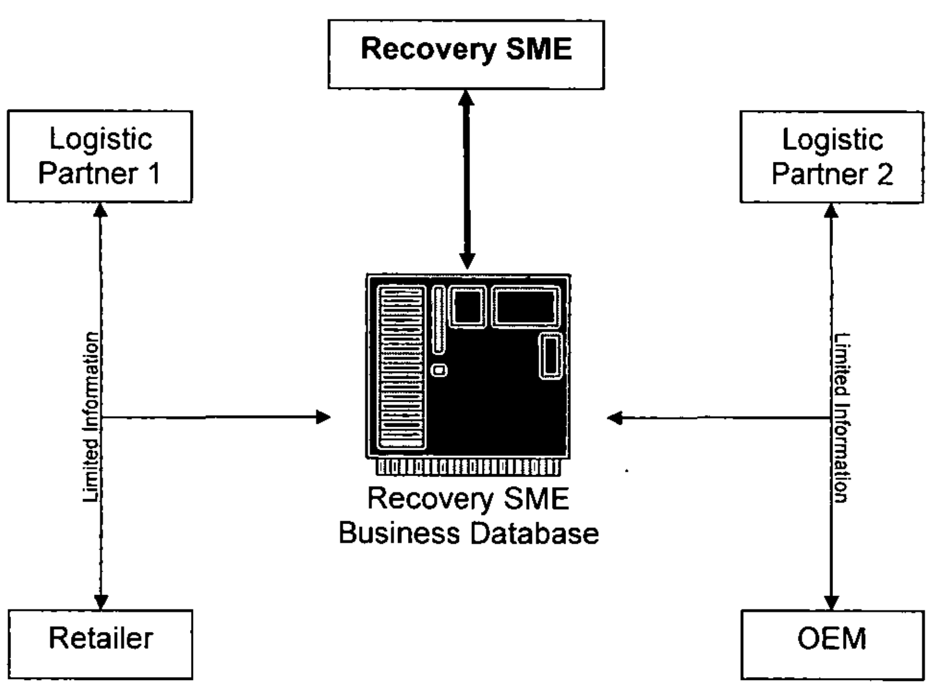

Figure 9.7: The information system for recovery partners

successfully in such scenarios, the recovery company needs to be ready to adapt quickly to changes and modify itself to suit the varying environment and product range. The drivers behind developing the proposed information centric enterprise model is to therefore to enable and empower the designers with improved understanding of the system, by providing structured and managed information with tools to help the redesign process.

The different views populated in the database for this example are presented in an easily accessible manner by using the web browser based interface. This helps the designer to understand and apply changes to the system even if they are not experts in database management. The dynamic analysis through simulation also helps the designer by providing them with feedback for improving the design of the system. This chapter also proposes an extension to the web browser interface so that business partners within the supply chain can access selected data when working in a collaborative environment. This could be useful for sharing the product information and potentially (by using dynamic views) assessing opportunities and benefits of possible collaborative activities before committing many valuable resources. This proposed extension therefore offers many opportunities for future related research.

10

Conclusions

10.1 Contributions

Product recovery and remanufacturing have been emerging as important means of waste prevention and environmentally conscious manufacturing. Companies are acknowledging it to be a profitable approach while at the same time building their image as environmentally responsible, for a wide range of products. This research looks into tasks and technologies to support SMEs operating in the area of product recovery and the research contributions can be summarised as follows:

- **Mathematical formulation**: A mathematical formulation has been developed for evaluating and optimising the recovery network for single returned product scenario based on the work of Fleischmann *et al.* [24]. This model has also been extended to incorporate multiple products to bring it closer to the commercial reality. These models are then translated into simulation models for evaluation purposes. The use of simulation models makes it possible to map the uncertainty in the product availability. This research contribution partially satisfies research objective 1.

- **The genetic algorithm (GA) based optimisation tool**: A GA based optimisation tool has been developed in Visual Basic which utilises simulation model built in Arena for calculating the fitness function. This research contribution partially satisfies research objective 1.

- **Information centric enterprise model for recovery SME**: An information centric enterprise model for the recovery SME has been designed and developed. This is based on the previously published FDP methods [81, 130, 131, 152] but has been specially modified and adapted for the particular requirements of product recovery businesses. A variety of views of the model and their functionality have been introduced and discussed. Subsequently, the information specification for the various classes are conceptualised. This research contribution satisfies research objective 2 wholly and 3 partially.

10.1.1 Additional Outcomes from this Research

In addition to the above contributions, the following outcomes have been achieved by this research:

- **Platform to support distributed simulation**: A prototype platform to support the execution of distributed simulation has been developed. This involves development of a communication agent, parser and environment independent simulation server. The concepts for the development of this prototype platform are derived from existing generic architectures however it is specific to the needs of collaborative recovery companies. This outcome also contributes to the satisfaction of research objective 3.
- **Web browser based interface for representing the views of the model**: A web browser based interface has been designed and developed for representing the various views of the model. The interface has been created keeping in mind the user friendliness and that the users do not need to be experts in handling databases. This outcome also contributes to the satisfaction of research objective 3.

10.2 Concluding Discussions and Novelty of Research

SMEs involved in product recovery need to be very flexible to changing market conditions and therefore must be ready to redesign their internal systems and processes and adapt to the requirements of new products (for recovery) in an effective and competitive manner in the highly volatile recovery market. This research presents an information centric formal model for product recovery enterprises with the aim to aid the designers with modelling and evaluation tools to enable the progressive design and redesign of the recovery enterprise. The model can be evaluated using any of the viewpoints discussed. The logistic network is important for the product recovery and an appropriate logistics network needs to be established to streamline the flow of returned products. The novel mathematical formulation provided in this research addresses the network design issues for SMEs involved in independent product recovery activities and takes care of the inspection and separation stages. The simulation model created is based on the formulation aims to reduce uncertainty and improve the design of the reverse logistics network.

The modelling approach has been demonstrated with the help of a small single product example. Although this initial example is hypothetical and far from reality, this "single product" example provides a useful introduction to the main elements of the methods and models used in this research. In the second example, the modelling approach is applied to IT product recovery and redeployment. Being one of the fastest changing industries, IT product recovery sees manifold changes in the latest state of the art within very short time periods. At the same time, this industry is one of the major producers of landfill waste which also includes toxic materials. The motivation behind developing the proposed information centric enterprise model is to enable the management team to improve the understanding of the system, by providing structured and managed information with tools to help the redesign process. A web browser based interface has also been developed to present the different views populated in the database making it more easily accessible to members of a management team who are not experts in database management.

10.2.1 Future Work

In this research, the network optimisation tool works with the simulation model in order to evaluate the fitness of the solutions. However, the simulation model used is "offline" and not actually running on the distributed platform developed later. In order to achieve overall design optimisation, the simulations running on the distributed platform can feedback to the network optimiser. On the other hand, the network optimiser can be used to evaluate the candidate solution proposed by the system designer and compare its performance with other possible solutions and hence aid the decision process.

This research also proposes an extension to the web browser interface which would enable the collaborating business partners within the supply chain to also access selected data. There are existing systems which aid the transparency of the supply chain and the business partners can share the data. However, the proposed extension could be useful for sharing the information regarding the modelling of dynamic views and assessing opportunities and benefits of possible collaborative activities before committing valuable resources. This extension with the concept of wiki [153] type pages can aid the collaborative projects like distributed supply chain modelling or information sharing environment. This will not only involve exchange of information about orders, deliveries and inventory via the web but also facilitate complex planning by linking dynamic performance views and "what-if" simulation can be carried out in a distributed environment. This proposed extension therefore offers many opportunities for future related research.

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Appendix A: Simulation Software

Simulation software is based on the process of imitating a real phenomenon with a set of mathematical formulas. Simulation software is used widely in design process of systems or product so that by imitating its operations the designer can have an idea or possible outcomes prior to the actual implementation of the operations. Advanced computer programs can simulate weather conditions, electronic circuits, chemical reactions, atomic reactions, even biological processes. In theory, any phenomena that can be reduced to mathematical data and equations can be simulated on a computer. In practice, however, simulation is extremely difficult because most natural phenomena are subject to an almost infinite number of influences. There are numerous types of proprietary and open–source packages available for the wide variety of simulation applications. A list of software packages for the simulation of industrial processes is as follows:

SIMAS II[1]: SIMAS II is devoted to the simulation of industrial mass-production installations in the fields of automated assembly and food packaging.

gPROMS[2]: gPROMS, targeted to continuous systems modelling and simulation, is designed to be both a fully-fledged simulation environment in its own right, and a simulation engine which can be embedded in vendor applications to provide a comprehensive design and operations tool.

SimBax[3]: SIMBAX is a decision support tool built specifically to fulfil the needs of the process industries in the area of material flow simulation. SIMBAX allows you to quickly evaluate and compare a variety of alternative scenarios in order to easily eliminate bottlenecks and find a solution avoiding non-productive occupation of the equipment and resources.

SES/Workbench[4]: SES/Workbench is a simulation tool for hardware architectures and complex systems in general. It supports the design of the simulation model from an object-oriented perspective and it provides both a graphical interface to enter the

[1] http://www.cimpact.ch/products/products.html
[2] http://www.psenterprise.com/products_gproms.html
[3] http://www.aicos.com/Prodlog/Simbax.html
[4] http://www.hyperformix.com/products/workbench.htm

problem definition and a graphical animation of the simulation to represent the results. It is available for a wide range of platforms, from Unix flavours to Windows NT.

WITNESS[1]: WITNESS provides a graphical environment to design discrete event simulation models. It allows to automate simulation experiments, optimize material flow across the facility, and generate animated 3D virtual reality models.

EASY5[2]: It is developed by Boeing Inc., and used to model and simulate dynamic systems containing hydraulic, pneumatic, mechanical, thermal, electrical and digital sub-systems. A complete set of control system modelling, analysis and design features is included.

SIMPLORER[3]: A simulator for industrial design, research projects and teaching purposes. External code can be embedded. Has its own language. Allows for hierarchical structures.

ProModel[4]: ProModel Optimisation Suite is a simulation-based software tool for evaluating, planning or re-designing manufacturing, warehousing and logistics systems.

AutoMod[5]: AutoMod suite provides simulation software that gives a 3D visual image of a facility as well as statistics of how the facility will perform.

DELMIA[6]: The DELMIA Resource Modelling and Simulation solution suite provides the tools to develop, create and implement resources, application routines and mechanical programming. Resources such as robots, tooling, fixtures, machinery, automation and ergonomics are defined and infused into a complete scenario of manufacturing. It allows to define complete simulations of systems such as: Factory Flow simulations, Robotic work cell setup and OLP, NC Machining, Inspection Ergonomics.

Enterprise Dynamics[7]: Enterprise Dynamics is an object-oriented software application used to model, simulate, visualize and control business processes. Most notably, a complete simulation model can be built and simulated in a full VR environment. The software can be used not only for industrial applications but is also a visual simulation tool where the user can use the 4D-script programming language to create his own models.

[1] http://www.lanner.com/
[2] http://www.boeing.com/assocproducts/easy5/home.htm
[3] http://www.simplorer.com/
[4] http://www.promodel.com/
[5] http://www.autosim.com/
[6] http://www.delmia.com/
[7] http://www.enterprisedynamics.com/

ShowFlow[1]: ShowFlow Simulation is designed to model, simulate, animate and analyse processes in logistics, manufacturing and material handling. It provides powerful visualisation and reporting tools, in particular for simulation animation. The modeller is facilitated by the availability of many simulation components ready to run. The price is also very attractive.

SIMUL8[2]: SIMUL8 allows the user to pick from a predefined set of simulation objects and statistical distributions to create the model. It also allows hierarchical modelling. Main focus on discrete event simulation.

Arena[3]: Arena has an object-oriented design and the ability to be tailored to any application area. It is based on SIMAN modelling language.

Suitability of Arena for the problem under consideration

For creating the models for the recovery systems under consideration, the author chose Arena from Rockwell Automation[4]. Arena (versions 10 and 11) was selected over other available simulation software because of its seamless integration with other software supporting Microsoft technologies. Arena exploits two Windows technologies that are designed to enhance the integration of desktop applications. The first, ActiveX Automation allows applications to control each other and themselves via a programming interface. The second technology exploited by Arena for application integration addresses the programming interface issue. Visual Basic for Applications (VBA) is a Visual Basic programming environment for inclusion in desktop applications that support ActiveX Automation. The combination of these two technologies allows Arena to integrate with other programs that support ActiveX Automation. Visual Basic code can be written directly in Arena (via the Visual Basic Editor) for the model logic as well as to automate other programs. In this research, the code for the optimisation algorithm has been written in Visual Basic and uses the Arena model for the evaluation of candidate solutions. Arena also supports simulation in real time (RT), which was required for the development and execution of distributed simulation.

Arena RT

Arena RT is the feature of Arena which increases the capabilities of Arena by adding the following elements:

[1] http://www.showflow.com/
[2] http://www.simul8.com/
[3] http://www.arenasimulation.com/
[4] http://www.rockwellautomation.com/

- It allows to run a simulation model in execution mode. In this mode, Arena can coordinate simulation logic with the external process of a real system. The external processes and Arena communicate via a messaging system, whereby entities in the Arena model send messages to the external applications to indicate simulated tasks, and the external applications send "message responses" back to Arena to indicate the tasks have been completed. Unsolicited messages can also be sent to Arena to indicate special events (e.g., the arrival of raw material or customer orders).
- It allows you to set the speed of Arena's simulation clock as a factor of the real-time clock of the resident operating system.

Using the above elements of Arena and its capability to integrate VBA codes, it was possible to create simulations that run in a distributed environment described in Section 7.3.

Appendix B: Paper published in IAMB San Diego Conference 2008

An Information–Centric Approach to Enterprise Modelling for Product Recovery

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Abstract

Recovery of used products and materials is becoming a field of rapidly growing importance. The scope and scale of product recovery have expanded tremendously over the past decade. Recent changes in government legislation in various countries and increasing customer awareness towards greener products have forced the manufacturers to rethink their business strategies. This has also resulted in new business opportunities in the area of remanufacturing and a large number of small and medium enterprises (SMEs) have appeared in the recovery industry. These SMEs include reprocessing and recycling companies as well as freight forwarders and warehousing companies.

Recovery firms have to deal with customer demands and returns that are largely dependant on the state of the art in technology. They change without any warnings and unfortunately a third party recovery firm has little control over them as compared to an original equipment manufacturer (OEM). In such situations, these companies must not only quickly adapt to the changes but also continuously evolve to survive in the market. They have to be versatile, changeable and able to quickly redesign and modify their own facilities and processes to cope with the changing situations. This paper presents an information–centred formal model for product recovery enterprises to aid the designers with modelling and evaluation tools to enable progressive design of the enterprise. The modelling exercise in this

work involves description of the different views of the enterprise, namely strategic view, physical view, functional view and performance view. The analysis of the system (as part of the performance view) has been carried out using simulation.

Introduction

In the recent past, environmentally conscious practices in manufacturing have become an obligation to the environment and to society itself. Such practices are forced primarily by governmental regulations; however there is an increasing demand for "greener" products from customers as well. One of the major aspects within environmentally conscious manufacturing is product recovery, which is the transformation of used and discarded products into useful condition through re–use, re–manufacture and recycling. (Johnson & Wang, 1995) define the recovery process as a combination of remanufacture, reuse and recycle whereas (Thierry, Salomon, Van Nunen, & Van Wassenhove, L. N., 1995) divide recovery into repair, refurbish, remanufacture, cannibalize, and recycle.

Product recovery can be achieved in different ways. In general, two forms of recovery for the used products are commonly recognised, i.e. remanufacturing and recycling. Remanufacturing is recovering the product as a whole through a series of operations, which may include disassembly, replacing or repairing non–functional components, reconditioning, and reassembling (Fleischmann et al., 1997). Unlike repairing, remanufacturing includes disassembly of the product into components and turning them to like–new conditions before reassembling them. This may involve a number of cosmetic operations. Figure 1 shows a typical unit flow in remanufacturing. It is similar to the conventional production systems in that remanufacturing requires operational, manufacturing, inventory, distribution and marketing related decisions to be made. However, as this industry is more driven by the availability of raw material (used product) than by the demand of finished product (refurbished/remanufactured product); it involves high uncertainty. An OEM involved in recovery of its products can still plan ahead for recovery of its product as it will be aware of the technology and compatibility issues of its future products. Independent recovery companies, on the other hand, have little control over these matters. In addition, OEMs can change the market trend and demand through campaigns and promotion and these changes could be quite significant for SMEs involved in the recovery of the concerned product. In such scenarios, these SMEs need to reengineer their production and management systems to cope with the changing market and demand.

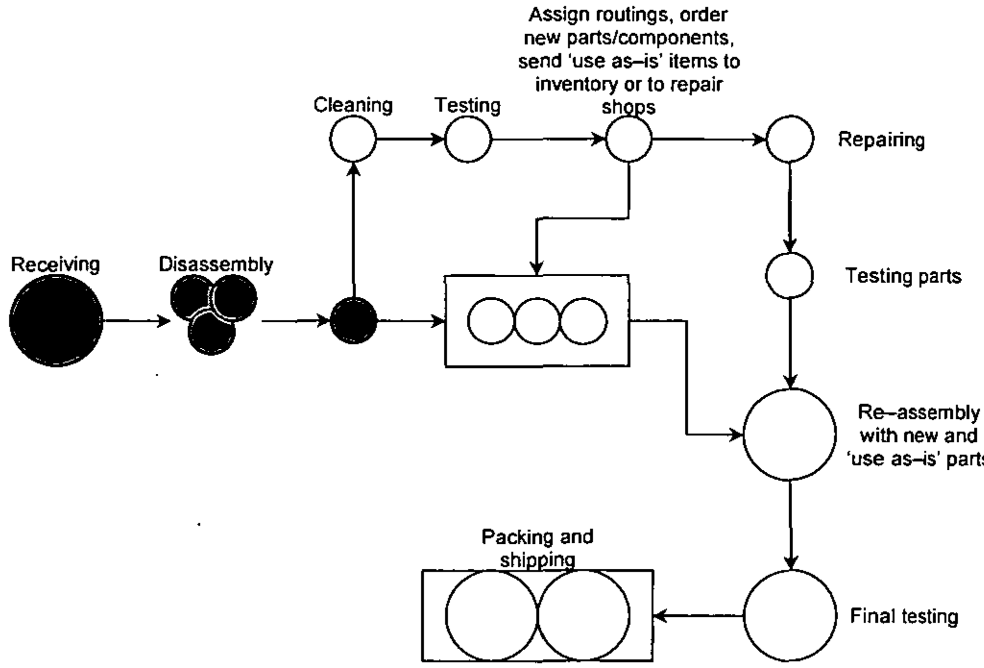

Figure 1: A typical unit (a product or a part) flow in remanufacturing [adopted from (Gungor & Gupta, 1999)]

Operational activities within a product recovery environment are different from traditional manufacturing activities. In general a high level of uncertainty regarding the timing, quality and quantity of returned product exists. Therefore, the level of agility and flexibility needs to be high. Collection of the used items and their packaging is one of the major issues in a product recovery environment (Livingstone & Sparks, 1994). Conventional manufacturing environments have a diverging effect distribution, i.e. the manufactured products delivered from a single source to multiple destinations. However, in a product recovery process, used products originate from multiple sources and are brought to a single product recovery facility. The logistic systems designed for such operations is commonly referred to as *reverse logistics* (Fleischmann et al., 1997). Like normal supply chain systems, reverse logistics need to address issues related to transportation, freight control, temporary storage, distribution, etc. However, the flow in reverse logistics is convergent unlike the normal supply chain which has a divergent flow. There is also an additional challenge as the source of the used products is the end–user and therefore there is a high uncertainty of availability of the product at the collection points.

Reverse Logistics is the movement of the goods from a consumer towards a producer in a channel of distribution. It defines a supply chain that should be designed to efficiently manage the flow of products or parts destined for remanufacturing, recycling, or disposal and to effectively utilise resources (Dowlatshahi, 2000). Reverse logistic focuses on managing flows of material, information and relationships for value addition as well as on proper disposal of products. For a large company, maintaining the reverse distribution of used products may be an easy task. However, for small and medium enterprises (SMEs), carrying out the logistic operations itself may create extra burdens. In such scenarios, the logistic operations need to be outsourced to companies called third party logistic providers. As a result, the recovery industry has largely been operated by small networked companies. The most common form of collaboration in the recovery industry is between the recovery and logistic companies, however in many cases, it is between contract recovery agents and

OEMs. This kind of collaborative environment demands for a system where flow of required information among the actors should be facilitated keeping in mind the confidentiality of sensitive data.

Most business nowadays is highly competitive and ever changing. Recovery firms however have to deal with additional challenges, commonly processing a myriad of different used products originating from various sources. Customer demand and returns, which are largely dependant on the state of the art in technology, change without any warnings and unfortunately a third party recovery firm has little control over them as compared to an OEM. As a result, such companies must not only quickly adapt to the changes but also continuously evolve to survive in the market. They must be versatile, open to change and able to design and modify their own facilities and processes in parallel with new situations.

This paper presents an information–centred formal model for product recovery enterprises. The process of enterprise modelling is employed in order to create an abstraction of a complex business. Enterprise modelling provides designers with modelling and evaluation tools to enable progressive design of the enterprise. The use of an information–centric approach ensures that the business knowledge is conserved for reuse. It enables collection of valuable information throughout the design process to be shared by both management and designers. As discussed, SMEs in the recovery industry work in collaborative environments involving information exchange between the different entities within and outside the enterprise. Hence an information–centric approach becomes a necessity in such scenarios.

The modelling exercise in this work involves description of the different views of the enterprise, namely strategic view, physical view, functional view and performance view. The strategic view helps the management to build their business objectives, which in the case of a recovery company are greatly influenced by changes in legislation. The physical elements and resources in the system and their relationships are identified by the physical view. The functional view relates to the activities and associated decisions within the enterprise. Broadly, it involves acquisition of the returned product, recovery and logistics activities. Finally, the performance view helps management to determine whether the proposed enterprise can perform to the required level. For successful enterprise design or improvement, the designers need to understand the importance of each view and establish a suitable trade–off between them while using dynamic analysis methods for evaluation and reducing risks and improving confidence by testing potential changes through simulation and "what if?" experimentation.

The Modelling Approach

An enterprise model is a computational representation of the structures, activities, processes, information, resources, people, behaviour, goals and constraints within the enterprise (Fox & Gruninger, 1998). Enterprise modelling aids system engineers by allowing the analysis of the system by "what-if" experiments. It states the requirements and design specifications of the information system for distributed nature of decision making. The modelling approach used in this paper is adopted from the factory data model (Harding & Popplewell, 1999). Factory data model utilises an object oriented approach for its design.

Despite being different, all enterprises have common characteristics which can be captured in five base classes, viz. Process, Resource, Strategy, Facility and Token. The five classes are shown in Figure 4, where the clouds represent the object classes and the lines represent the relationships between them.

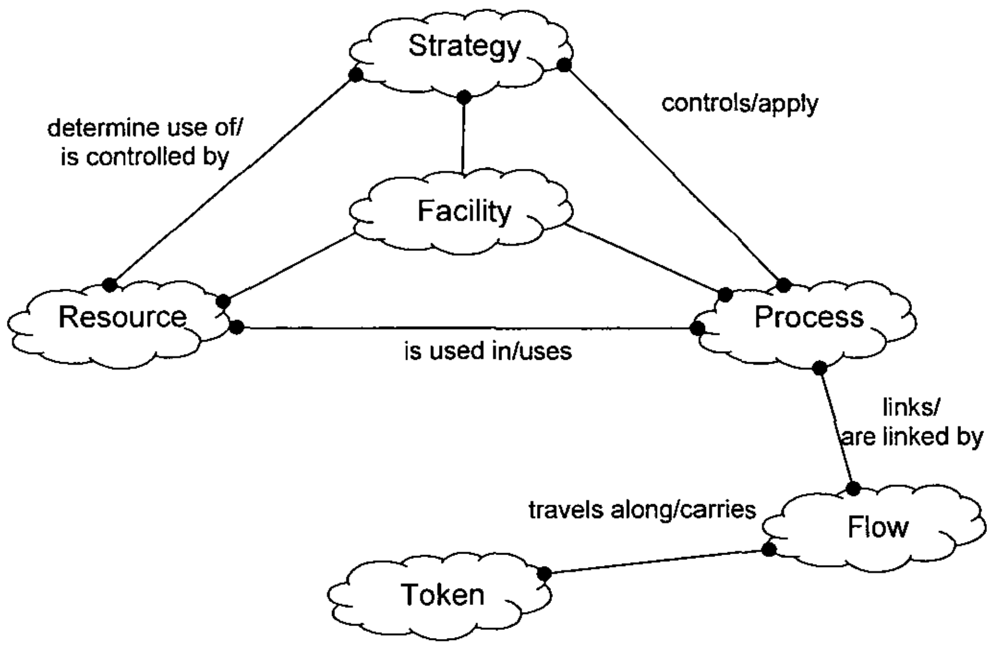

Figure 2: Key classes from factory data model [adopted from (Harding & Popplewell, 1999)]

Objects from the process class hierarchy capture functions, processes or activities within the business of the enterprise. Information describing and defining this class may include details of the process, other processes it may be a part of, duration, who/what is controlling it, its status, costs etc. The resource class hierarchy describes mechanisms capable of performing an action. Resource objects can range from human resources to machinery, tools, vehicles etc. the strategy class objects capture the knowledge and methods used to make decisions within different business levels. In real systems processes and resources are arranged into different facilities, related to business functions. Therefore objects from the facility class hierarchy have been included to help designers to view the organisation. The flow class objects connect independent processes and activities into a system with a purpose, while the objects from the token class represent the business objects that flow or move through the enterprise's system and processes. A detailed description of each of the main object classes can be found in (Harding & Popplewell, 1999) and (Yu, Harding, & Popplewell, 2000).

Implementation of the Modelling Approach

The implementation process is about the clarification of what is required, the generation of ideas, the analysis of the existing or possible systems, the comprehension of what already exists and how systems really work, the identification of possible design solutions and the evaluation of alternative solutions (Harding, Yu, & Popplewell, 1999). Different views of the system are presented so that the different perspectives of the design can be understood. Each view behaves in its own particular way and can support the design team at various different levels of abstraction.

The various viewpoints are represented with the aid of Unified Modelling Language (UML). UML is an object oriented modelling language containing a set of symbols. It also contains a group of syntactic, semantic and pragmatic rules (Noran, 1999). UML may be regarded the successor of the Object Oriented Analysis and Design methods that proliferated during '80s and '90s. In 1997, it became recognised and accepted as a potential notation standard by Object Management Group for modelling multiple perspectives of information systems (Booch, Rambaugh, & Jacobson, 1999). UML offers direct support for the design and implementation of each aspect of the information system and provides an integrated notation for their representation. In addition to supporting the main relationships between these representations, the application of the UML provides a natural migration process through the different development phases and perspective of the system, such as functionality, analysis and design, implementation, etc. (Costa, Harding, & Young, 2001)

The UML specification supports extensions and using which, (Eriksson & Penker, 1998) resent key business modelling concepts, including how to define business rules with UML's Object Constraint Language (OCL) and how to use business models with use cases. Using these extension, the business architects may add stereotypes and/or properties to the UML in order to suit their particular situations.

Strategic View

This view helps the management state their strategies as goals and objectives. It is used for validation as it states the business goals. Its helps the managers and designers by telling them what is required and how it should be performing. Then operational rules need to be determined and implemented. The strategic view should be revisited later in the design cycle, as the operational rules for defining priorities are required. The primary objective of every company generally relates to increasing the profit and growth of the company, however the way it is achieved differs from scenario to scenario. In product recovery, these opportunities come in the form of lowering procurement cost, establishing necessary assessment and inspection facilities, reducing the disposal cost, etc.

Figure 3 shows the strategic view of a typical product recovery company using a UML object diagram. The top level goal for the company is to increase market share, which is a common goal for any business. However, different businesses will adopt different routes and hence will have different "sub-goals" to achieve it. As discussed earlier, procurement of used product is a major activity for product recovery. Lowering the cost associated with procurement will significantly lead to high profits.

The customers for a product recovery company could be an OEM (which has contracted the company for recovery of its product returns) or an end user. In the case of product recovery, one of the things that need to be done is to campaign about the reuse and remanufacturing of product and make potential customers aware of the fact that these refurbished products are cheaper and more environment friendly. Apart from the individual end user, in some cases high volume consumers turn to be the perfect client for recovered product as they act as the source of used products as well as a destination for remanufactured products. On the other hand, while campaigning to attract new customers, it is necessary to maintain the satisfaction level of existing customers by quality assurance and timely delivery.

It can be noticed in figure 3 that some of the sub-goals are marked 'complete' while some are marked 'incomplete'. During the revisions, the state of the system changes according to situations and should help the managers understand the progress towards achieving particular goals. It should be noted that the enterprise under consideration is working in a collaborative environment, and therefore the interpretation of the goals can be different in various cases. If the company is an independent recovery company, it will aim to satisfy the end user, however a contract recovery company will try to meet the OEM's standards. In a collaborative environment, the performance of the company is quite influenced by the performance of other collaborators. So the enterprise needs to be aware of its collaborators' performance. This is shown in the next view.

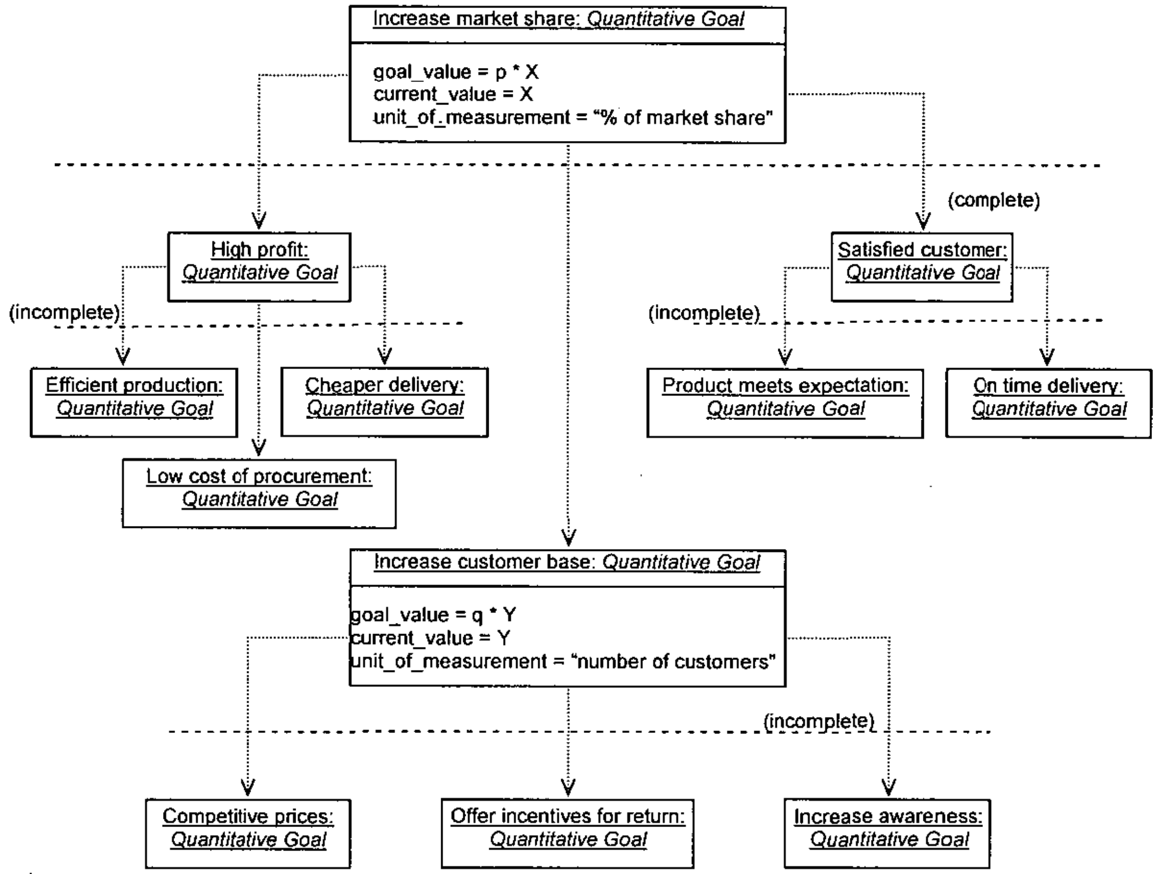

Figure 3: Strategic view of the product recovery enterprise

Function View

The business functions or activities which are essential to the operation of the enterprise are shown by the *function view*. The function view is primarily for information gathering and formulation. At the later stages of designing, when more detailed information is available, it can be replaced by a *business process view*.

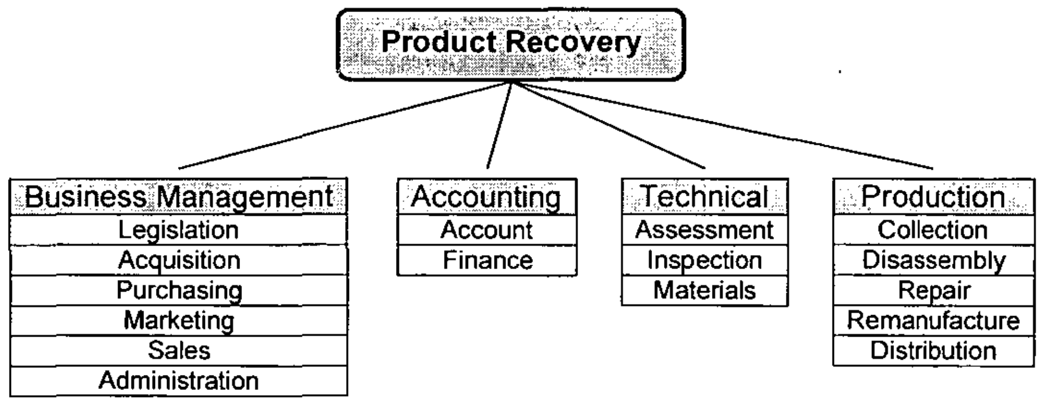

Figure 4: Organizational view of the product recovery enterprise

To better understand the requirements of the function view, it is useful to include an *organizational view*. This allows the designer to define the main functions and processes step by step. Later these can be refined and more details can be added when necessary. Figure 4 presents the organizational view of the product recovery company. Discussion of departmental responsibilities through the organizational view may facilitate the production of the function view. For example, one of the major influences in a product recovery company's strategy is the government legislation. The management needs to keep an eye on the changes on the legislation so that its products comply with the standards. On the other hand, the company must make use of any business opportunities arising due to such changes. Inclusion of a legal or legislation function in the organisational view will ensure that these considerations are taken care of when generating the function view.

Unlike a traditional manufacturing company, there are two distinct types of raw-materials sources, the major one being the user with used products at their end of life; hence the acquisition function is needed in the organisational view. In addition remanufacturing processes need other consumables or critical components which need to be purchased. In the case of a traditional company, the acquisition/purchasing and marketing/sales functions will always belong to different departments. However, in a product recovery company, they can stay with the same management group as in this context, the production is more driven by availability of used products than by the demand in the market. Administration is a common function for any department, however in figure 4 it has been included only in the business management function where it represents administering the whole company rather than the department itself.

After defining the top level functions within the departments in the organisational view, the functional view can be developed by the additional refinement of these functions. Figure 5 shows one such refinement. Modelling becomes useful when it enables the behaviour and performance capability of the factory design to be analysed and assessed before undertaking the implementation. The organisational and functional views described above help building an essential comprehension of the business elements and structure of the enterprise.

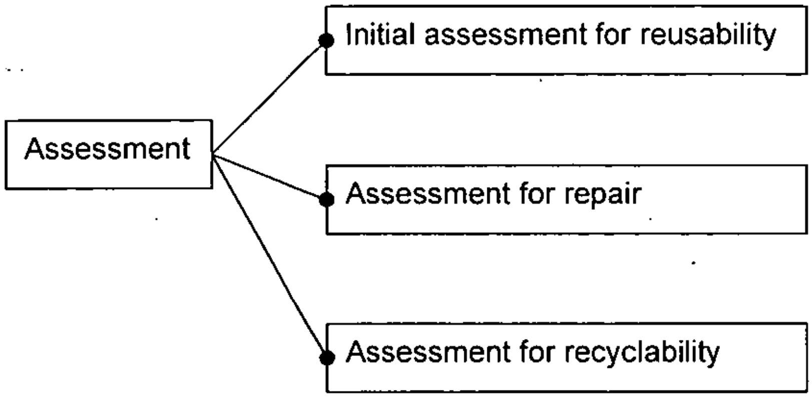

Figure 5: First phase of refinement of business functions

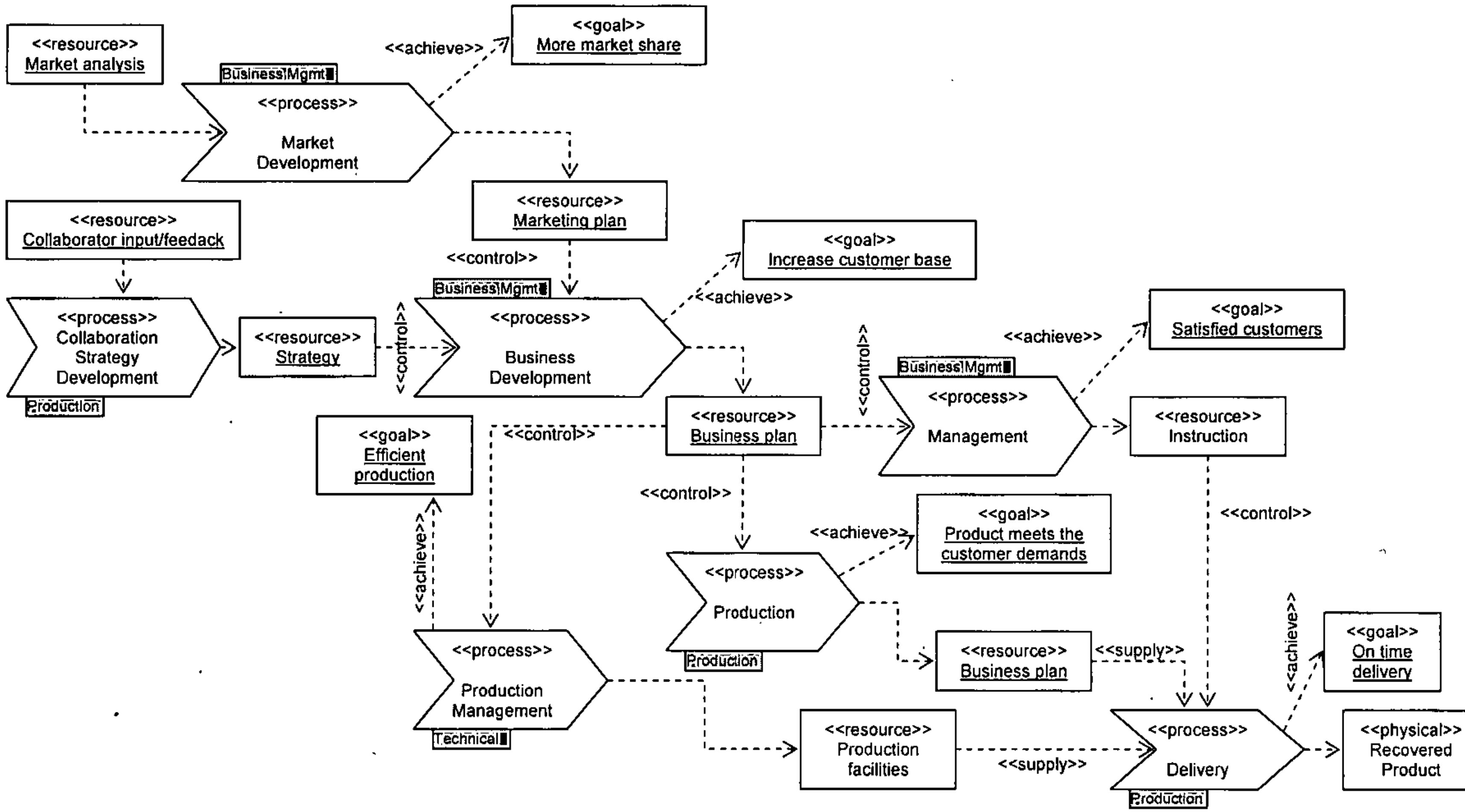

Figure 6: Business process view of the product recovery enterprise

The understanding of the business elements and enterprise structure leads to the understanding of the business behaviour by the application of the business process view. Based on the goals set in the strategic view, the business processes are identified and specific information associated with them are gathered. Figure 6 shows the business process view using UML activity diagram with the involvement of departments of the enterprise in it. It shows the activities, what it is controlled by, its goal and its output. The small grey boxes indicate the departments the activity belongs to. When the business process view is taken, the order of processes or activities so that the model captures the way in which the processes are linked. Once the structure of one or more business processes has been achieved, the relationship between the business functions and business processes can be examined. Business processes may be refined and details may be added as and when required.

Informational View

Before moving to performance view, an additional view is presented to show the informational viewpoint of physical objects and entities in the system. UML object diagrams are used to show the information related to physical objects and entities. Figure 7 shows the details of different objects in the system. For example, the information regarding the product include its type, condition, serial etc. Product pr1 belongs to product class ABC123 and it is an electronic component. Its condition is the numeric value 2, which could mean it is in reusable, recyclable or disposable condition. If recovery is carried out, it will need parts s039 and c120. It also contains the serial number given by the OEM at the time of production, which actually can help in getting the technical details about it from the database. This information is passed across the enterprise when needed and used at different places according to the situation. Before discussing the flow of information in and across the enterprises, performance view is presented in next sub section.

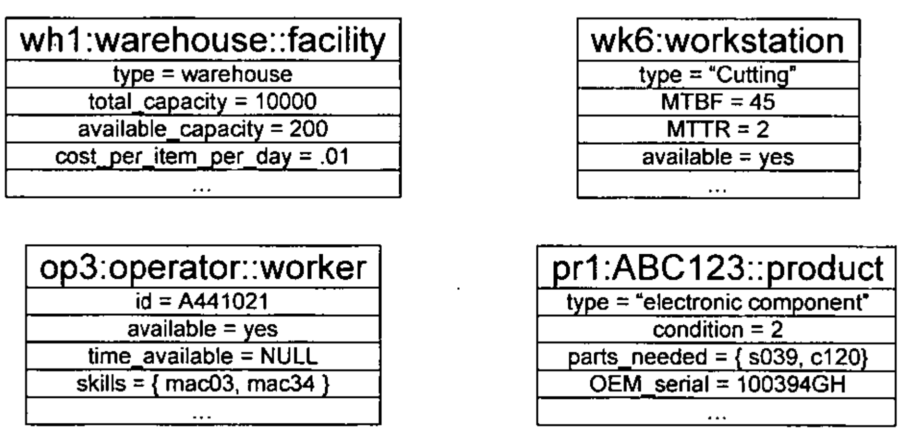

Figure 7: UML object diagrams used to show the entity/object information

Performance View

Once a sequence of processes and the resources they use have been identified, it is possible to look at the information from a *performance view*. The performance view helps the managers and designers to examine if the proposed enterprise can perform to its expectations and hence it provides them with valuable feedback at various stages of the design. There are several methods for performance measurement. The performance view proposed in this research uses two approaches for performance evaluation. Static evaluation uses performance metrics, like lead time, throughput or costs etc. On the other hand, dynamic evaluation uses simulation technology enabling 'what-if' experiments to be carried out. Dynamic evaluation gives the designer a better insight of how the proposed enterprise will work. This paper focuses on the assessment of dynamic performance of the system with the aid of simulation models. Following the simulation experiments, the designs can be refined further by revisiting the previous views.

For building the performance view, detailed information related to processes and resources is needed. A detailed simulation model will need data related to machine breakdown history, maintenance requirements, operational rules, etc. With the help of an informational view, the behaviour of real systems can be mimicked by building the performance view and using them to understand the utilization of different resources in the system and help making decision about capacity etc.

Simulation models were created using the Arena software (Kelton, Sadowski, & Sadowski, 1998) and the information required to build the simulation model was taken from the enterprise model. The simulation experiments were planned with the objective of deciding the location and capacities of different facilities of the system. It is a macro level design problem so the majority of the simulation decisions at micro level were based on assumptions and probability.

Informational Flow

Figure 8 shows the flow of information in typical product recovery activities. If all the activities are performed by one actor, the information flow will be simple to manage and access. However, the product recovery industry essentially works in a networked and collaborative environment, which complicates the situation further. In such scenarios, the enterprise should be provided with easy access to the information to relevant department while maintaining confidentiality of sensitive data when dealing with its collaborators.

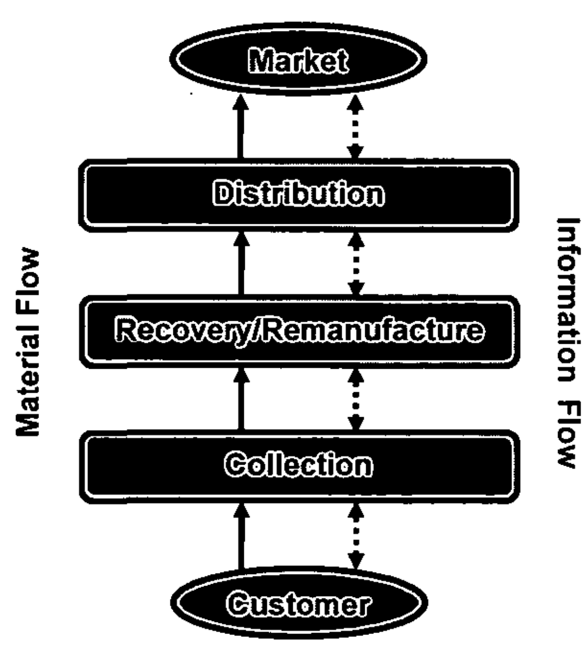

Figure 8: Material and information flow in product recovery

Figure 9 shows typical flow of information in and across two networked companies performing, the same activities as those in Figure 8, but in collaboration. One of the companies is involved in independent recovery while the other is a logistics provider. So the first job of collecting the used product from the user is the responsibility of the logistics provider while rest of the production work, viz. assessment, disassembly, repair, remanufacturing, etc. are done by the independent recoverer. The business management department of both the companies handle the job of communicating with the outer world, while the other departments can contact and exchange relevant information among themselves.

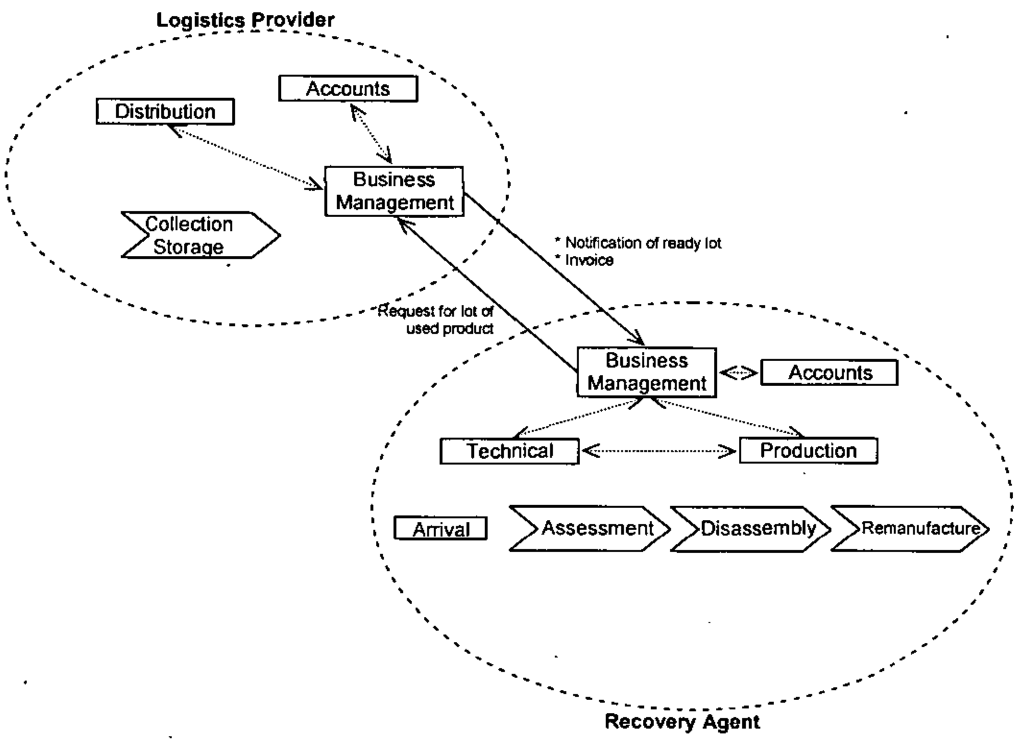

Figure 9: Typical information flow in a network of two collaborating enterprises

Based on this concept, the performance view of the proposed model can be extended to evaluate the enterprise in presence of "dummy" collaborators. Though it makes the simulation modelling part more complex, it brings the model closer to reality and hence results in higher confidence level of the evaluation. The authors are in process of building distributed simulations for networked enterprises. In order to achieve this, Arena has been used in conjunction with Visual Basic, and the communication between different simulations has been carried out though an agent based system.

Conclusion

In order to survive in the ever changing recovery market, small and medium enterprises involved in product recovery must be ready to redesign and adapt to the requirements of new products in an effective and competitive manner. This paper presents an information centric formal model for product recovery enterprises. The aim of the model is to aid the designers with modelling and evaluation tools to enable the progressive design of the enterprise. A variety of views of the model and their functionality have been discussed. The model can be evaluated using one of the viewpoints designed for this purpose. The views are presented in unified modelling language, which is an industry standard. The model is generic in nature and takes care of the networked and collaborative nature of the industry.

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Appendix C: Submitted Paper

Modelling and Optimization of a Single–Product Recovery Network

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Modelling and Optimization of a Single–Product Recovery Network

Abstract

An appropriate logistics network is an important element of the infrastructure of any product recovery company. Small and medium enterprises (SMEs) constitute a major fraction of the product recovery industry with a different business objective and scale of operation from those of original equipment manufacturers. This paper addresses the network design issues for SMEs involved in product recovery activities. A mathematical formulation is presented in an SME context and a subsequent simulation model is developed. A genetic algorithm approach is presented for optimizing the network for single product scenario.

Keywords: Product recovery, reverse logistics, simulation, optimization, genetic algorithm, Arena

1 Introduction

Recovery of used products and materials has attracted researchers' attention for many years. However in the recent years, the enforcement of environment friendly policies by different governments and customer enthusiasm towards greener production has encouraged companies to start product take–back activities. The products are collected after their end of life with the aim of recovery or safe disposal.

Product recovery is the transformation of used and discarded products into useful condition through reuse, remanufacture and recycling. Implementation of product recovery requires setting up an appropriate logistics infrastructure for the arising flows of used and recovered products. Physical locations, facilities, and transportation links need to be chosen to convey used products from their former users to a producer and to future markets again. Reverse logistics encompasses the logistics activities all the way from used products no longer required by the user to recovered products that are again usable in a market. The study of reverse logistics can be broadly divided into three areas: *distribution planning*, which involves the physical transportation of used products from the end user back to the producer; *inventory management*, which is the process of managing the timing and the quantities of goods to be ordered and stocked, so that demands can be met satisfactorily and economically; and finally *production planning*, which despite not being a logistics activity, influences the other two greatly. One of the initial publications addressing distribution issues was by Gottinger (Gottinger. 1988). Thereafter, several models have been proposed which focus on aspects such as product recycling and planning/distribution (Caruso, et al. 1993, Fleischmann, et al. 2001, Giannikos. 1998).

The main activities in reverse logistics are the collection of the products to be recovered and the redistribution of the reprocessed goods. The reverse logistics problem looks quite similar to the normal forward distribution problem; however there are some differences too. Reverse flow of goods is convergent in nature, so the products need to be collected from many points. Therefore cooperation of the senders becomes important as product packaging is generally problematic. Products flowing in the network tend to have low value. On the other hand, time is not so important an issue as it is in forward distribution. Taking these issues into consideration, reverse logistics need new networks to be constructed. The major issues concerning design of a recovery network are the determination of the number of tiers in the network, the number and location of collection/drop–off and intermediate depots and the interaction of the reverse chain with the forward chain.

Recently, a number of case studies have been reported in the literature addressing the design of logistic networks in the product recovery context. Kroon and Vrijens (Kroon and Gaby Vrijens. 1995) address the design of a logistics system for reusable transportation packaging. They discuss the role of the different actors in the system, economy, cost allocation, amount of containers and locations of the depots. Del Castillo and Cochran (Del Castillo and J. K. Cochran. 1996) discuss the distribution and collection of reusable bottles for a soft drink company while Duhaime *et al.* (Duhaime, et al. 2001) address the same issues for reusable containers for Canada Post. Alshamrani *et al.* (Alshamrani, et al. 2007) develop a heuristic procedure for route design and pickup strategy for a network inspired by blood distribution by the American Red Cross. Krikke *et al.* (Krikke, et al. 1998) address the remanufacture of photocopiers and as remanufacturing is a labour intensive process they compare two remanufacturing options for the company; one coinciding with the existing manufacturing network and the other in another country where labour is cheap. Barros *et al.* (Barros, et al. 1998) report a case study discussing the design of a logistics network for recycling sand coming from construction sites as waste. Recycling of carpet waste is addressed by Louwers *et al.* (Louwers, et al. 1999) and Realff *et al.* (Realff, et al. 2000) and a mixed integer linear programming (MILP) model for the recycling of industrial by–products in German steel industry has been developed by Spengler *et al.* (Spengler, et al. 1997).

The above examples highlight the fact that most research in the area of reverse logistics network design has been case specific. The most generic model for the design of a reverse logistic network is the one proposed by Fleischmann *et al.* (Fleischmann, et al. 2001). This model considers the impact of inclusion of product recovery on the forward network and the model is optimized taking into account both the flows. A MILP formulation is proposed extending the traditional warehouse location problem and integrating the forward chain with the reverse chain. This work has subsequently been extended by Salema *et al.* (Salema, et al. 2007) where capacity constraints, multi–product scenario and uncertainty were added.

In the present literature, much of the published work addresses problems involving big market players like Hewlett Packard, Canon, Dell and other original equipment manufacturers (OEMs) in the electronics industry. Similarly, the published research work dealing with other types of industries focuses on the original manufacturers' point of view. However, the recovery industry largely consists of smaller, independent recovery companies. These companies are not OEMs, so for them merging their procurement process with the distribution is not of great importance as their markets are quite different from those of OEMs. As these companies are small and medium enterprises (SMEs) and recovery is their main job, design of an efficient recovery network is extremely important as the damage caused by network inefficiency can not be compensated from other means. This paper presents a mathematical model for the design of the network of a third party recovery firm. The formulation is based on Fleischmann *et al.* (Fleischmann, et al. 2001) however the context is quite different as Fleischmann *et al.* (Fleischmann, et al. 2001) present a generic model for companies wanting to integrate reverse logistics into their existing supply chain. In contrast the formulation presented in the next section addresses the network design issues for SMEs dealing with remanufacturing of returned items. The proposed model also takes into account the capacity limits of the facilities. The model is optimized using a genetic algorithm in conjunction with a simulation approach. The use of simulation helps in incorporating the uncertainty associated with the product returns. The computational setup is discussed in later sections of this paper and the proposed mathematical model is described below.

2 Recovery Network Model

This section presents a mathematical formulation for a product recovery network design. The motivation for the model comes from our experience with industry. Three facility levels are considered, i.e. collection points which are responsible for collecting the used products, warehouses where returned products are stored and plants which finally reprocess them (Figure 1).

While establishing a distribution network, it should be taken into account that facilities have limitations on the number of products they can store or process. These limitations are due to various factors like availability of space, number of workers and workstations etc. The network model addresses this limitation by incorporating capacity constraints for each facility.

Take in Figure 1

2.1 Mathematical model

The proposed recovery network model involves the following index sets, variables and parameters:

Index Sets

$i \in I$; where $I = \{1, \ldots, N_c\}$ fixed locations for collection points

$j \in J$; where $J = \{1, \ldots, N_w\}$ potential locations for warehouses

$k \in K$; where $K = \{1, \ldots, N_p\}$ potential locations for plants

Costs

F_i^c Fixed cost for enabling collection point i for inspection

F_j^w Fixed cost of opening warehouse j

F_k^p Fixed cost of opening plant k for disassembly and reprocessing

T Collective cost of storage at collection points, warehouses and plants

t^{cw} Unit transportation cost from collection point to warehouse

t^{wp} Unit transportation cost from warehouse to processing plant

C_{ijk} Cost of reprocessing returned product from collection point i coming through warehouse j at plant k

$C_{ijk} = t^{cw} l_{ij} + t^{wp} l_{jk} + c^{p} + T$ where l_{pq} is the distance between p and q; and c^{p} is unit cost of reprocessing

D_{ijk} Cost of disposing of the returned product coming from collection point i through warehouse j and plant k

$D_{ijk} = t^{cw} l_{ij} + t^{wp} l_{jk} + c^{d} + T$ where l_{pq} is the distance between p and q; and c^{d} is unit cost of disposal

S_{ijk} Cost saving by disposing the discarded returned product at inspection enabled collection point i (and not traverse it through warehouse j and plant k)

$S_{ijk} = t^{cw} l_{ij} + t^{wp} l_{jk} + T$ where l_{pq} is the distance between p and q

P Unit penalty cost for not processing returned product

Variables

$$x_i^c = \begin{cases} 1; & \text{if collection point } i \text{ is enabled with inspection facility} \\ 0; & \text{otherwise} \end{cases}$$

$$x_j^w = \begin{cases} 1; & \text{if warehouse } j \text{ is opened} \\ 0; & \text{otherwise} \end{cases}$$

$$x_k^p = \begin{cases} 1; & \text{if plant } k \text{ is opened} \\ 0; & \text{otherwise} \end{cases}$$

y_{ijk} return fraction served by collection point i, warehouse j and plant k

z_i fraction of the returned product at collection point i which can not be reused (chosen with a random distribution)

Parameters

R_i return from collection point $i; i \in I$

M_i^c maximum capacity of collection points $i; i \in I$

M_j^w maximum capacity of warehouse $j; j \in J$

M_k^p maximum capacity of plant $k; k \in K$

Using the above notation, the mathematical formulation to minimise the sum of the fixed, variable and penalty costs is as follows:

$$\min FC + VC + PC \tag{1}$$

Where,

$$FC = \sum_{i \in I} F_i^c x_i^c + \sum_{j \in J} F_j^w x_j^w + \sum_{k \in K} F_k^p x_k^p \tag{2}$$

$$VC = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} R_i C_{ijk} y_{ijk} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} R_i z_i \left(D_{ijk} - S_{ijk} x_i^c\right) \tag{3}$$

$$PC = \sum_{i \in I} R_i \left(1 - \sum_{j \in J} \sum_{k \in K} y_{ijk}\right) P \tag{4}$$

Subject to:

$$\sum_{j \in J} \sum_{l \in K} y_{ijk} + z_i = 1, \quad \forall i \in I \tag{5}$$

$$\sum_{j \in J} \sum_{k \in K} R_i y_{ijk} \le M_i^c x_i^c \quad \forall i \in I \tag{6}$$

$$\sum_{k \in K} \sum_{i \in I} R_i y_{ijk} \le M_j^w x_j^w \quad \forall j \in J \tag{7}$$

$$\sum_{i \in I} \sum_{j \in J} R_i y_{ijk} \le M_k^p x_k^p \quad \forall k \in K \tag{8}$$

$$0 \le y_{ijk}, z_i \le 1 \tag{9}$$

$$x_i^c, x_j^w, x_k^p \in \{0,1\} \tag{10}$$

The above formulation minimizes fixed cost for the set up of facilities and costs involved in the recovery/disposal processes. The three terms in equation (2) represents the cost of installing inspection facilities at collection/drop–off points and setup cost for warehouses and reprocessing plants. The first term in equation (3) maps transportation costs and reprocessing/disposing costs for the reprocessing/disposing of product, while the second term in this equation involves cost savings for the product if the collection point it is coming from has inspection facilities installed. The returned products which are not processed due to the capacity constraints pose a loss and are mapped by equation (4). Constraint (5) ensures that all the returns are taken into consideration. Equations (6–8) make sure that the capacities of the facilities are not exceeded.

The formulation is generic in nature and can reflect recovery scenarios for various kinds of products. The disposal of unusable products from collection points as well as from plants may involve sending them to a third party recycler/disposer or to the remanufacturer's own facility and the associated transportation cost. This model just requires the flow of such items to leave the network after sorting.

2.2 Optimization of the model

Solution Methodology

One of the major characteristics of problems concerning reverse logistics activities is the uncertainty associated with the return of products. The stochastic nature of these problems means that most of the analytical models become either too simplistic or exceptionally complex. Discrete event simulation is regarded as the most suitable analysis tool for such situations and is largely used to evaluate "what-if" scenarios.

A general simulation based optimisation method consists of two essential components: an optimisation module that guides the search direction and a simulation module for evaluating the performance of candidate solutions. The decision variables create the environment in which the simulation is run while the output of the simulation runs is used by the optimizer to progress the search for optimal solution (Figure 2).

Take in Figure 2

In the existing literature, a number of simulation–based optimization methods have been reported, which include gradient based search, stochastic approximation, sample path optimization, response surface and heuristic search methods (Andradóttir 1998, Azadivar 1999). Several evolutionary algorithms have been linked with simulation for industrial application. According to an empirical comparison of search algorithms by Lacksonen (Lacksonen. 2001), genetic algorithm (GA) appears to be the most robust to solve large problems though it requires a large number of replications. In this paper, GA has been adopted to perform stochastic search for solutions. The details of the algorithm are discussed in later subsections.

Simulation Model

A simulation–based optimization method has been developed for the optimization of a network design problem, keeping the constraints within the model logic. The simulation model has been created in Arena 10.0, which was selected over other available simulation software because of its seamless integration with other software supporting Microsoft technologies. Arena exploits two Windows technologies that are designed to enhance the integration of desktop applications. The first, ActiveX Automation allows applications to control each other and themselves via a programming interface. The second technology exploited by Arena for application integration addresses the programming interface issue. Visual Basic for Applications (VBA) is a Visual Basic programming environment for inclusion in desktop applications that support ActiveX Automation. The combination of these two technologies allows Arena to integrate with other programs that support ActiveX Automation. Visual Basic code can be written directly in Arena (via the Visual Basic Editor) for the model logic as well as to automate other programs. In this research, the code for the optimisation algorithm has been written in Visual Basic and uses the Arena model for the evaluation of candidate solutions.

In the simulation model, the entities representing returned products in the model are generated on a daily basis and the number of products is decided by normal distribution with a mean proportional to the population of the customer zone. Each entity carries attributes of its origin customer zone, warehouse and plant locations and reusability. The decision whether a facility is open or not is coded in the candidate solution sent over by the GA code while Arena VBA blocks decide what alternative facilities are available for the entity to use.

Genetic algorithm representation and operations

One of the most important aspects of genetic optimization is the chromosome encoding for representation of a typical solution. The encoding depends largely on the nature of the problem. In this case, the chromosome is an array of binary variables as shown in Figure 3. The individual binary arrays for facilities at all the tiers are concatenated to form chromosomes for binary representation of the solution. As the chromosome consists of variables of uniform nature, the genetic operations are performed on the whole of the chromosome at once. Each binary variable in the chromosome represents the installation of the associated facility.

Take in Figure 3

Crossover and *mutation* are two basic genetic operations for the optimization search. The crossover method applied in this work is Single Point Crossover illustrated in Figure 4. In this method, a position is selected randomly. The binary string from the beginning of the chromosome to the crossover point is taken from one parent and the rest is copied from the other parent. As shown in Figure 4, this operation can produce two offspring chromosomes using one crossover point. In this paper, the parents are selected by roulette wheel selection and both the produced offspring chromosomes are included in the new population. To maintain the diversity of the population, and save the search from getting trapped in local optima, GA uses another operation called mutation. Based on the mutation probability, the produced offspring is subjected to mutation operation. Out of the several methods, the one used in this paper is Bit Inversion Mutation. In this method, the binary bits of the chromosome are inverted (applied a NOT binary operation) as shown in Figure 4. Motivated by previous experience, the probabilities of crossover and mutation operations for the problems have been chosen to be 0.9 and 0.1 respectively. Later, with the help of a small example of similar nature and complexity, it was determined that the choice of probabilities was near to the best combinations.

Take in Figure 4

3 Example

3.1 Problem description

A hypothetical example of single product recovery has been used to analyse the model. The structure and functionality of the hypothetical company is based on our experience gained from product recovery industry. The design of the reverse logistic network for an SME dealing with printer cartridge remanufacture is considered. It is assumed that the SME procures used cartridges from certain customer zones through its collection points spread in the UK (Figure 5). The collection points procure used cartridges from independent retailers and high volume users irrespective of their condition (reusable/unusable). The returns coming from the customer zones are assumed to be proportional to their population. The collection points may or may not have facilities to sieve out unusable products. If the products are found to be unusable in an inspection enabled collection point they are sent directly to the disposal site.

This saves costs of storage and transportation of the unusable product at different tiers of the network. From the collection points, the cartridges are sent to warehouses for storage. Plants have facilities to inspect and reprocess the products.

The design problem poses several questions for the decision maker for the SME. Depending on the location of collection points, the nature of the returned product will vary. Some collection points with large volumes of returns might actually have benefits if they are enabled with inspection facilities. The location of the warehouses and plants is another strategic issue to save transportation and handling cost. The complexity of the problem multiplies as the numbers of tiers and products increase.

Take in Figure 5

3.2 Computational experience

Figure 6 shows the screenshot of the optimization tool developed in Visual Basic. When the basic data has been entered, the tool invokes Arena to generate the simulation model specific to the problem scenario. A screenshot of an Arena model created by this tool is shown in Figure 7. The model shown has 10 collection points generating a number of entities (representing returned products) on every working day based on a uniform distribution. Attributes representing origin, destination warehouse and reprocessing plant and inspection tags are created for each entity. The entity travels through the various VBA logic blocks and decision modules, which determine the destination warehouses and plants of the entity and assign it to the respective attributes. These decisions are based on the model constraints and input in the form of candidate chromosomes. Associated costs are calculated as the entity travels through process blocks before being disposed (representing products being sent to market or recycled/disposed due to infeasibility of remanufacture).

Once the model is created, run parameters and optimization parameters are fed in and the optimization starts. The optimization is run on 10 randomly generated examples with values uniformly distributed in the ranges as shown in Table I. These ranges are decided upon the understanding built from the survey of the available literature. The simulation horizon is set to 1 year. The warm–up period, required for the simulation model to reach the steady state is set to 1 month. For each candidate solution, ten replications of simulation were run to smooth out residual randomness. The GA population size is set to 25. While generating the initial population, 1 solution is predefined with all the facilities setup and the rest of the solutions in the population are randomly generated. At each generation, solutions are selected for crossover or mutation operations based on their respective probabilities. The optimization tool is run on a Pentium 4HT Dual Processor PC running Windows XP at a clock speed of 3.06 GHz on 2 GB of RAM and took around 1-2 minutes per generation of GA.

Take in Figure 6

Take in Figure 7

Take in Table I

3.3 Discussions

Simulation model

The simulation model built for the optimization is generic in nature and is modified according to the data provided by the optimization tool and hence the model run for each problem is unique. The simulation model built for the optimization is quite flexible in nature and the decisions with multiple influencing parameters/variables such as determination of destination facilities are taken by the VBA blocks built within it. The logic of these blocks can be slightly modified to give a competitive edge to certain facilities according to the problem scenario. Such tweaks in the logic are useful in the cases where facilities at geographically dispersed locations have different overall cost and time for processing products. Once the optimization is finished, the models can be simulated without the help of the optimization tool with the optimum or other set of configuration for further investigations.

Optimization approach

To test the genetic algorithm based optimization approach, a small example of 10 candidate collection points (CP), 5 warehouses (WH) and 2 plants (PL) was considered as shown in Figure 5. The generated model was optimized with the developed tool giving out reasonably good solution at around 300th generation. Figure 8 shows the plot of best solutions obtained in generations for the first test set. The continuous plot in the figure shows the convergence of solution Figure 9, Figure 10 and Figure 11 show different configuration of the network as obtained by iterative optimization process and associated costs. Note that the cost associated with the network in Figure 10 is not much higher than that in Figure 11 despite the longer traverse paths. This is due to the fact that the latter involved fixed cost for setup of additional facilities.

Take in Figure 8

Take in Figure 9

Take in Figure 10

Take in Figure 11

The crossover probability of 0.9, mutation probability of 0.1 and population size of 25 seem to be working the best for this example considering solution quality and computational time. However, in later runs of bigger problems, the number of simulation replications was reduced to 5 to save some computational time as it was noticed that the randomness was significantly smoothed with only 5 replications.

Reverse logistics network

The optimization was run on 10 examples generated using the values in Table I. Figure 12 shows costs associated with initial and optimal configurations for the various example problems. It is observed that most of the configurations came out with only a few collection points enabled with inspection facilities. This is due to the fact that printer cartridges are one of the most 'remanufacturable' products, so the probability of being reusable is high (hence the parameter settings in the model). Cartridges have very short life cycle and are generally handled with care. Short life span helps in two ways: the cartridges don't get much time to be mishandled and they don't become obsolete by the time they are returned. Hence they have a high probability of being in a reusable condition when they reach the remanufacturer. However, for a more complex product, the case is different. For example, a mobile device (phone or laptop) becomes obsolete within half of its lifespan! In such cases, having intermediate inspection sites will be helpful for channelling the product to disposal or other type of reuse/recycle site. The above observation is also backed by Table II. Table II shows the variation in number of inspection enabled collection points obtained from simulation runs with different values of reusability of the returned product.

Take in Figure 12

Take in Table II

4 Conclusions and ongoing extensions

To successfully implement the product recovery activities, an appropriate logistics network needs to be established for the flow of returned products. This paper presents a MILP formulation addressing the network design issues for SMEs involved in independent product recovery activities. The formulation takes care of the inspection and separation stages. Based on the formulation, a simulation model is created. The network configuration is optimized using GA with fitness functions calculation done by the simulation model. The optimum configurations obtained from the optimization are then utilised to perform further investigations.

The formulation presented in this paper addresses the network issues for a SME dealing with single product. However, the SMEs in the independent recovery business essentially deal with multiple products. The presence of multiple products makes the problem much more complex and has great impact on the output. Moreover, the data was generated for the models keeping in mind a simple product like a toner cartridge. Consideration of other products like computer peripherals or white goods will add to complexity of the model and make it closer to the real life problems.

The work presented in this paper is a part of ongoing research and further efforts are currently being put into addressing the shortcomings mentioned above. The future work includes formulation for multiple products and associated simulation/optimization considerations for more complex products. It has been observed that the recovery activities are generally carried out in a collaborative environment where different parties perform different activities like logistics, remanufacture and recycling. Work is being carried out in order to address such scenarios by means of distributed simulation.

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List of figures and tables

Table I: Parameters and Costs (in GBP) for the SME example

Description	*Parameter*	*Value*
Fixed installation cost per collection point	F_i^c	[4000, 8000]
Fixed setup cost per warehouse	F_j^w	[8000, 11000]
Fixed setup cost per plant	F_k^p	[32000, 40000]
Transportation costs per mile	t^{cw}	0.008
Transportation costs per mile	t^{wp}	0.005
Reprocessing cost per product	c^p	10.0
Disposal cost per product	c^d	2.5
Return per 1000 resident	R_i	0.1

Table II: Reusability vs Inspection Enabled Facilities

Probability of being reusable	0.90	0.80	0.75	0.70
Percentage of inspection enabled collection points in optimal configuration	0	9	61	83

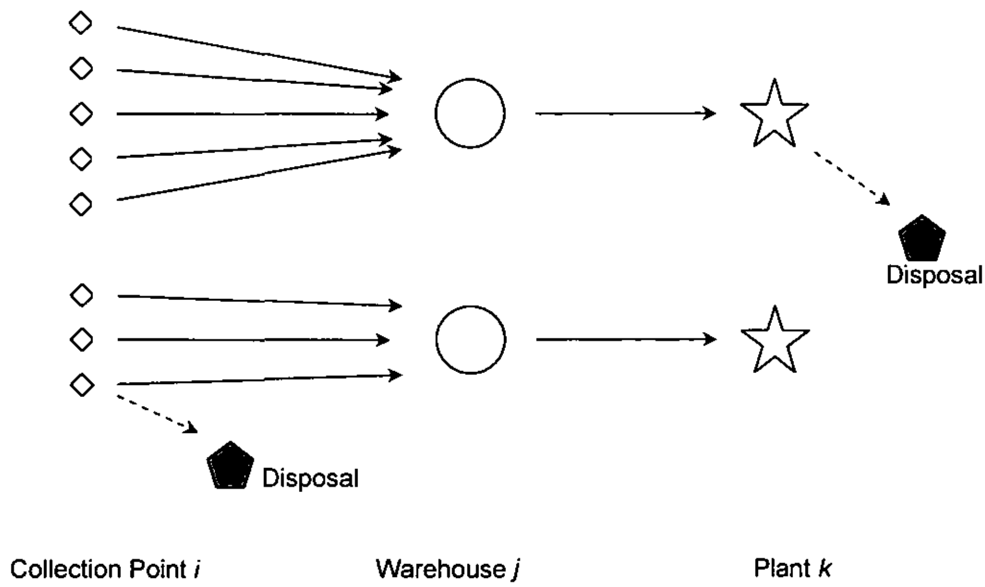

Figure 1: Recovery Network

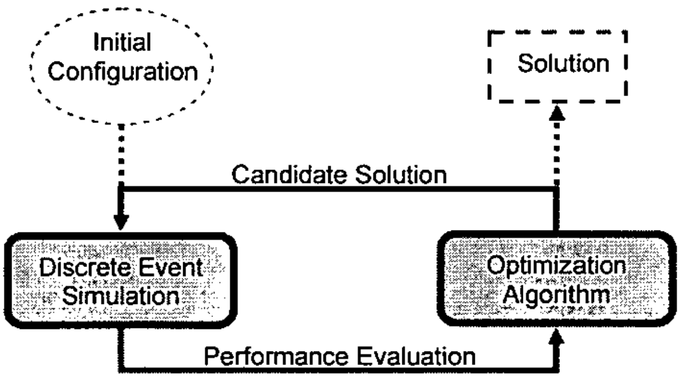

Figure 2: Simulation based optimization approach

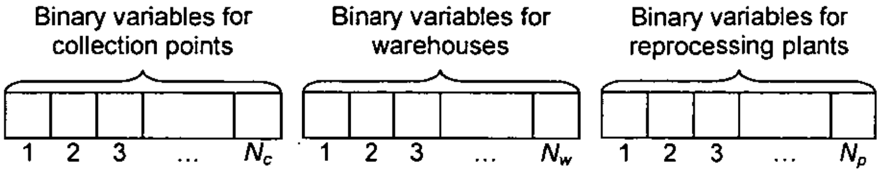

Figure 3: Genetic representation of the chromosomes

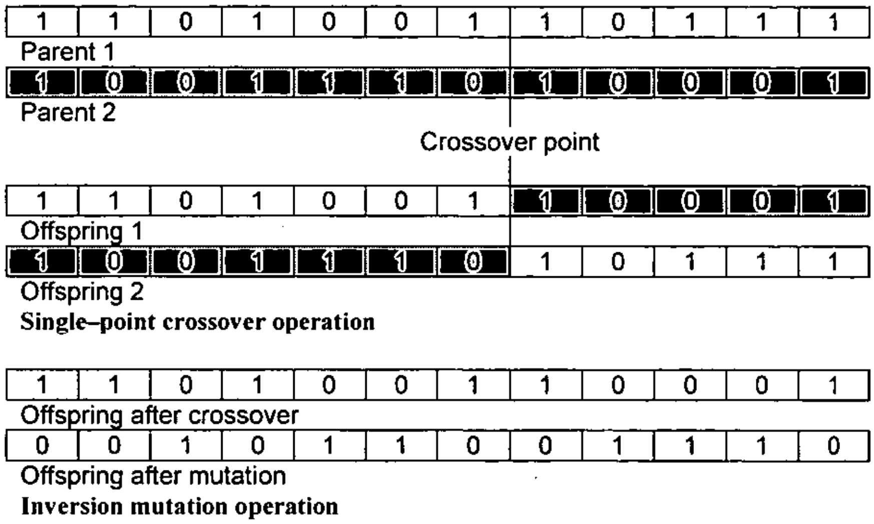

Figure 4: Genetic operations

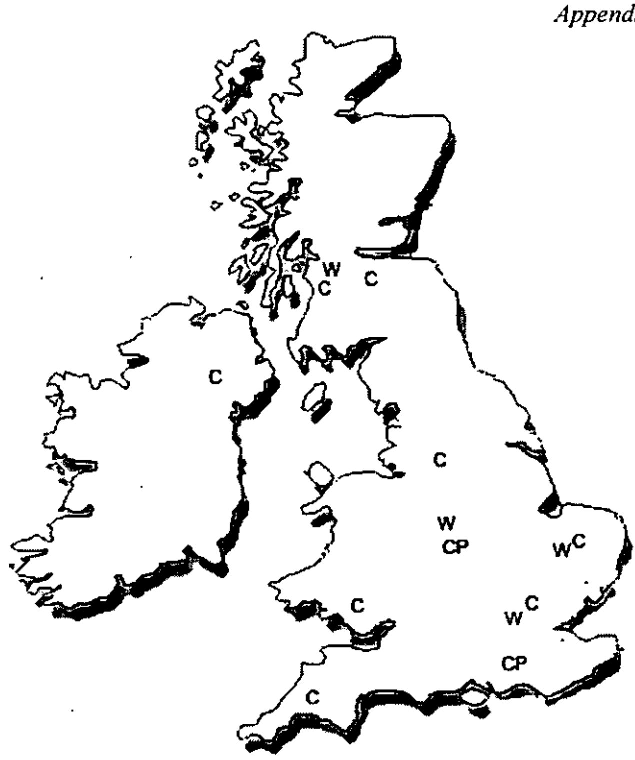

Figure 5: Location of candidate facilities (C: Collection Points, W: Warehouse, P: Plant)

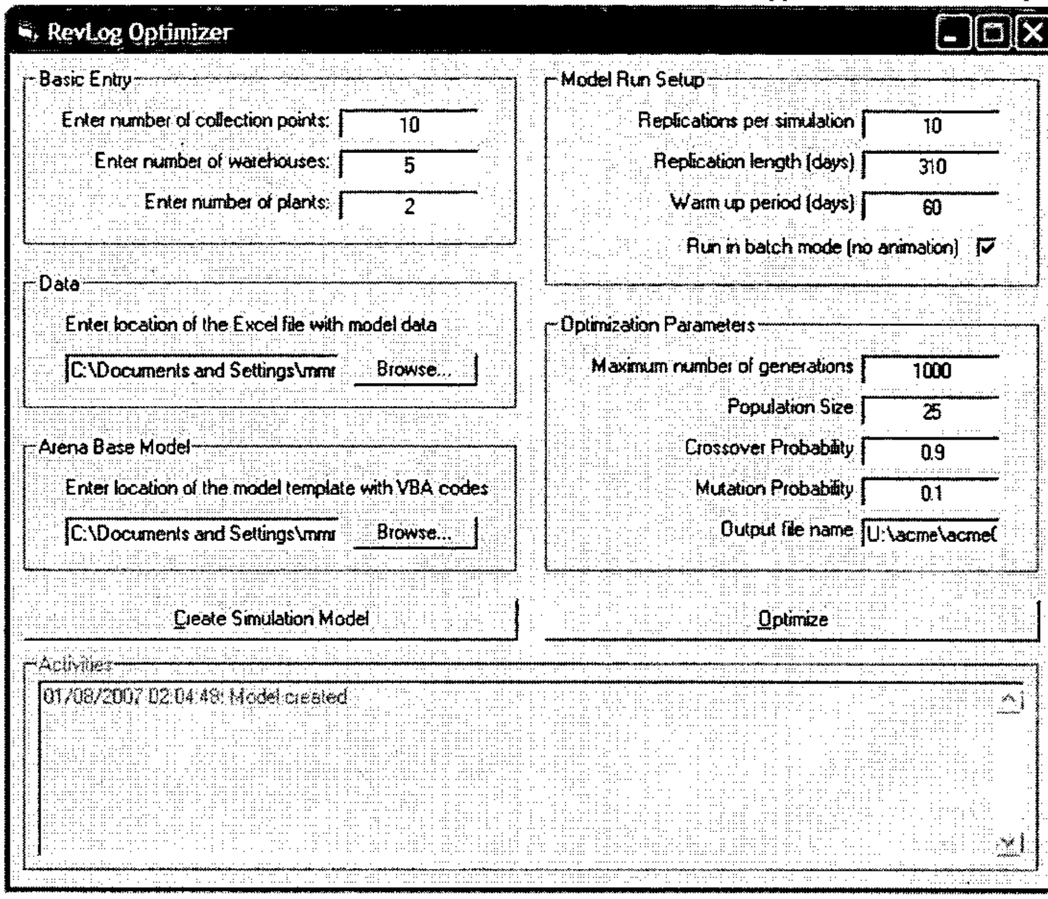

Figure 6: Screenshot of the optimisation tool developed

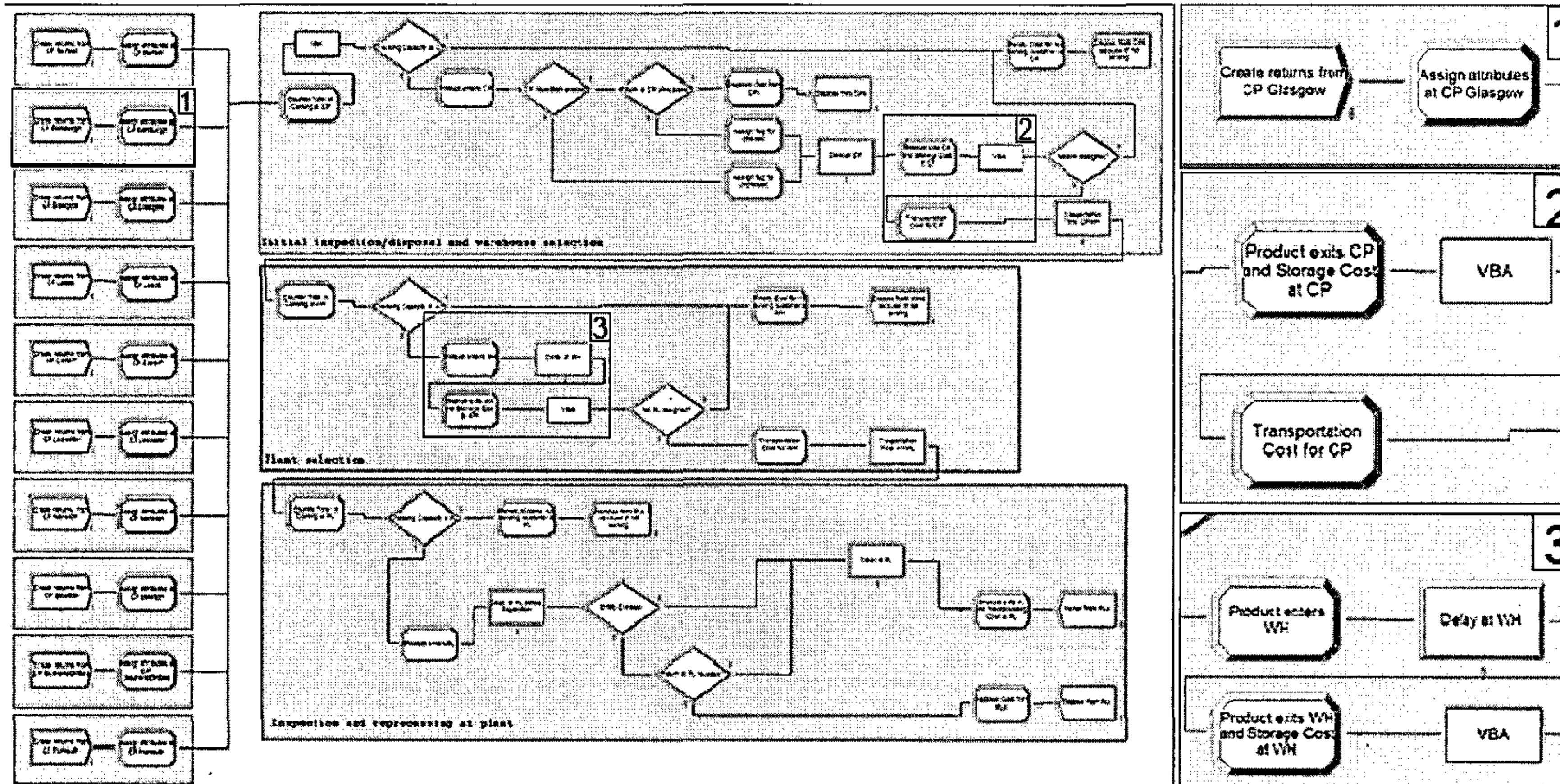

Figure 7: Screenshot of a model created by the optimization tool (1. Creation of entities and attribute assignment; 2. Assignments of various costs and VBA block for decisions and 3. Entities entering warehouse and process delays)

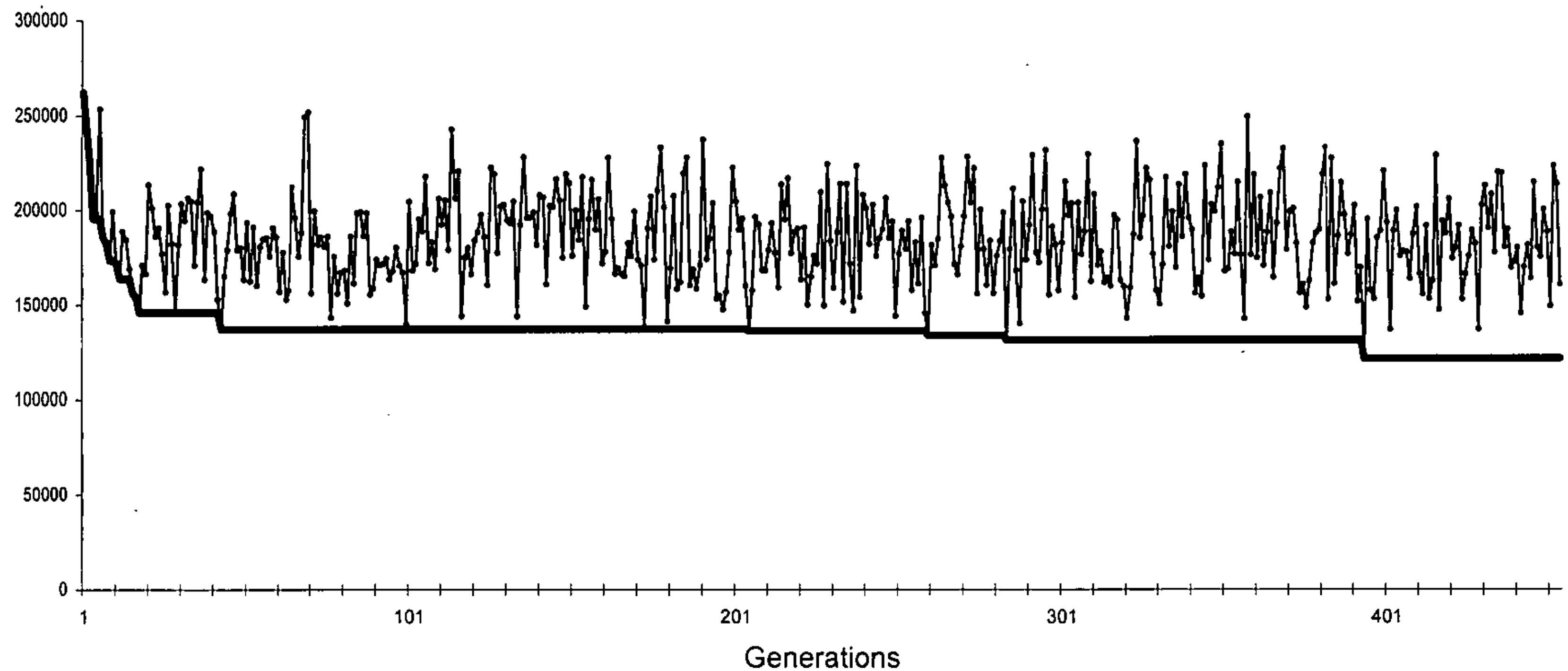

Figure 8: Costs of best solution in the populations and the convergance of solution over increasing generations

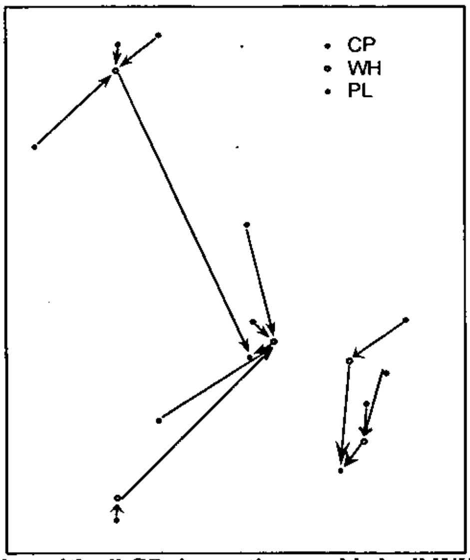

Figure 9: Initial configuration with all CPs inspection–enabled, all WHs working, all PLs working; cost: £233187

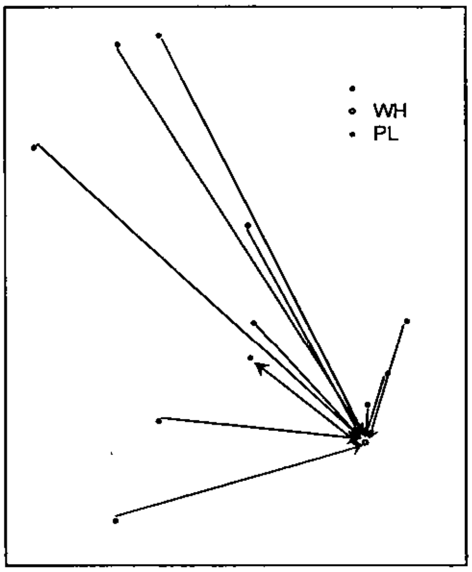

Figure 10: 284th generation; 2 inspection–enabled CPs, one WH working, and one WH working; cost: £131394

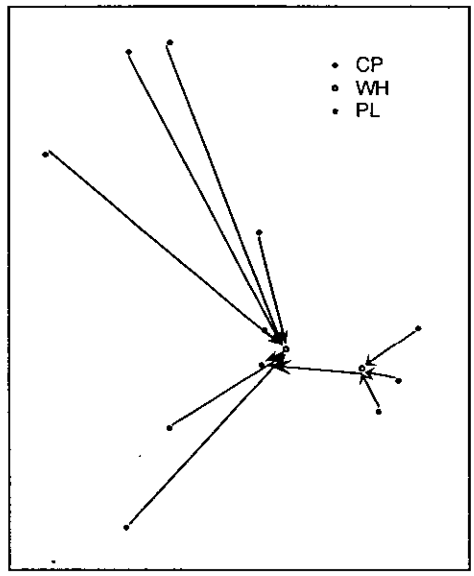

Figure 11: 394th generation; three inspection–enabled CPs, 2 WHs working, and one PL working; cost: £121564

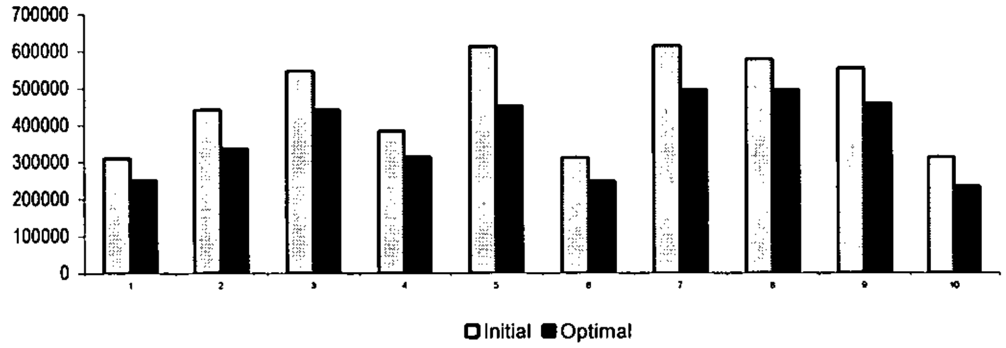

Figure 12: Costs associated with initial and optimal solutions