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A DUAL FACTOR DECISION MAKING MODEL IN GREEN MANUFACTURING

By

Bahador Jamshidy

B.Sc, Isfahan University of Technology, 1997

A thesis

Presented to Ryerson University

In partial fulfillment of the

Requirements for the degree of

Master of Applied Science

In the program of

Mechanical Engineering

Toronto, Ontario, Canada, 2011

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DECLARATION

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ABSTRACT

This study focuses on the evaluation of different methods of product recovery for GM. The evaluation is conducted through the application of a decision making model. The model evaluates product recovery options on the basis of two categories: optimization of objective factors and market demand.

The first category in the model focuses on optimization of five objective factors, including environmental impact (E), cost (C), quality (Q), resource consumption (R), and time (T). Goal programming is used to solve the optimization problem. The goal programming is supported by the construction of a decision making tree with three branches: remanufacturing, refurbishing**,** and current manufacturing. The solution of the decision tree helps determine the best method of product recovery for GM. The second category in the model focuses on the evaluation of market demand. This further supports the selection of the best method for product recovery. To evaluate market demand, a Bayesian forecasting model is used in the construction of a decision making tree. The study shows that the availability of product information including the objective factors and market demand, has a positive impact on making product recovery decisions. It also shows how recovery decisions can be modeled in decision making trees to represent the impact of product information on those decisions.

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ABBREVIATIONS

(C)	Cost
C_{RL}	Reverse Logistics Cost
CNC	Computer Numerical Control
DSP	Disassembly Sequence Planning
DRM	Disassembly Release Mechanism
(E)	Environmental Impact
EOL	End-of-life
EEC	European Economic Community
ECTEL	European Conference on Technology-Enhanced learning
EMV	Expected Monitory Value
GPP	Green Process Planning
GHG	Green House Gases
GM	Green Manufacturing
LCA	Life – Cycle Analysis
MRP	Manufacturing Resource Planning
MTBF	Mean Time before Failure
MTTR	Mean Time to Repair
MODM	Multiple objective decision making
OEM	Original equipment manufacturer
(Q)	Quality
QFD	Quality Function Deployment
(R)	Resource consumption
RPP	Remanufacturing Product profiles (RPP)

U_s	System Utility
(T)	Time
TAT	Turnaround time
WEEE	Waste Electrical and Electronic Equipment

NOMENCLATURE

F (t)	Probability function of failure
P (X_i)	Probability of occurrence of event X_i
C_S	Supply chain cost
C_{man}	Manufacturing cost
C_E	Environmental cost
C_P	Product cost
$C_{E\ new}$	Environmental cost for new product
$C_{E\ mat}$	Environmental cost for material phase
$C_{E\ man}$	Environmental cost for manufacturing phase
$C_{E\ reu}$	Environmental cost for reused product
$C_{E\ pro}$	Environmental cost for procurement activities
$C_{E\ rem}$	Environmental cost for remanufacturing phase
$C_{p\ reu}$	Product cost for reusing phase
C_{RL}	Reverse logistics cost
T	Time
X_i	Attribute
W_i	The weight related to each attribution
U_S	System utility
n_i	Number of revenue value in each category
X_i	The revenue value in each category
D_t	Documented sales during a period of time
K_t	Quantity of supplied products

(α)	The prior sales (demand)
(β)	The prior sales (demand)
t	Period
j	Decision alternatives
S_{ti}	State of nature in t which leads to decision node
D_{ti}	Decision node i in period t
S_{tj}	Chance node j in period t
P_{ti}	Probability that state of nature S_{ti} will occur
R_{ti}	Result node if the state of nature S_{ti} occur in period t
R_{tj}	Result node of a decision alternative j period t
$EMV(R_{tj})$	Expected value of result R_{tj}
μ^{*}_{t}	Maximum expected value of all decision alternative j in period t

Chapter 1: Introduction

1.1 Overview

Green manufacturing (GM) is a manufacturing strategy that is growing in importance. Its goal is to minimize the environmental impact and maximize the utilization of resources throughout a product's entire lifecycle, including design, production, packaging, use, and disposal, while simultaneously emphasizing sustained economic growth (Wang and Li, 2010). Green manufacturing is therefore concerned with developing methods for manufacturing products from the initial conceptual design to the end-of-life (EOL) disposal of the product. It emphasizes meeting and exceeding environmental requirements. In response to environmental legislation that is increasingly demanding, particularly in the automotive and electronic industries, many manufacturing organizations are developing end-of-life strategies for their products. For many reasons, such as lack of infrastructure and lack of necessary information, many products today are not recovered at their end-of-life in an efficient and environmentally friendly manner.

The purpose of this thesis is to help address this problem through the development of a model that highlights the opportunities and challenges associated with product end-of-life. The model focuses on the evaluation of two parameters: objective factors and market demand. The two parameters provide a basis for a methodology that provides guidance to product developers in specifying an end-of-life strategy, helps highlight environmentally friendly design options, and helps identify opportunities for developing new product recovery technologies. Product recovery aims to minimize the amount of waste sent to landfills by recovering materials from old products at their end-of-life through one of four approaches: repair, refurbishing, remanufacturing, and recycling. Product recovery includes collection, disassembly, cleaning, sorting, reprocessing, testing, reassembling and redistribution. Disposal is required for products and components that cannot be recovered for technical and economical reasons.

1.2 Parameter 1: Objective factors

Five objective factors are optimized in the model: environmental impact (E), cost (C), quality (Q), resource consumption (R) and time (T). These were selected based on the study of peer-reviewed literature.

All five objective factors are critical components of a GM strategy. The five objective factors may be efficiently evaluated through an optimization model. The objective factor quality (Q) should be maximized, while the other four objective factors should be minimized. As will be demonstrated in the model, different objective factors are more important for different end-of-life options (i.e. repair, refurbishing, remanufacturing, and recycling). It is also important to highlight that each objective factor has associated sub-factors. For example, sub-factors associated with resource consumption (R) include raw material and energy consumption. Further details on the sub-factors are provided later in the thesis. To enable manufacturers to select the optimal recovery option, a complex multi-objective decision-making model solved through goal programming will be developed.

1.3 Parameter 2: Market Demand

Market demand is the second parameter considered in the model. It will be demonstrated that the selection of the appropriate end-of-life recovery option is influenced by market demand. In this thesis, a Bayesian forecasting model is used for generating demand in a specific market. The Bayesian forecasting model will help manufacturers select the appropriate end-of-life recovery option.

It is noted that the uncertainty about market demand in the future makes forecasting difficult. Many manufacturers have used Bayesian forecasting model to manage demand commitment and to subsequently make a decision to accept or reject a customer order based on profitability and resource availability for both confirmed current orders and expected future orders. In this research, the Bayesian forecasting model is based on a dynamic linear demand model for specific products. The demand model incorporates information from multiple sources that include recorded sales, leading indicators and field knowledge.

1.4 Organization of the thesis

The remainder of the thesis is organized into five chapters. The next chapter provides a summary and discussion of the relevant literature. Details on the model are presented in the next two chapters. The end-of-life product options are discussed first in one chapter, followed by an evaluation of the objective factors and market demand in another chapter. A detailed example illustrating the application of the model is presented in the following chapter. The thesis finishes with a chapter on conclusions and recommendations for future research.

CHAPTER 2: Literature Review

Manufacturing organizations around the world are increasingly recognizing the need to address the environmental impacts of their products (Wang and Li, 2010). These environmental impacts must be addressed without compromising the economic viability of the organization. While the environmental impacts of particular products vary widely, the evaluation of those impacts can be broadly categorized according to the product's life cycle. Key stages in a product's life cycle include the extraction of raw materials, design, manufacturing, transportation, use, maintenance, reuse, recycling, and disposal (Ilgin and Gupta, 2010). Although these stages may be categorized in different ways, many manufacturing organization have recognized the importance of a holistic perspective in assessing the environmental impacts of their products.

To help structure their efforts to reduce the environmental impacts of their products, many organization have adopted "green manufacturing" (GM) strategies (Wang and Li, 2010). There are many definitions of GM in the literature. One representation definition is "A kind of modern manufacturing mode with the full consideration of resources consumption and environmental impacts. Its goal is to minimize the environmental impact and maximize the resource utilization during the whole product life cycle including design, production, packaging, using and disposal, and to make enterprises harmonize the economic benefits and environmental benefits (Ilgin and Gupta, 2010). Many definitions of GM emphasize the importance of moving to "closing the loop" in a product's life cycle. One key component of a closed product life cycle is product recovery through the repair, refurbishing, remanufacturing, and/or recycling of materials in manufacturing systems (Parlikad, 2007). While there has been much research on GM and product recovery, the published work is fragmented and there remain a need for research that focuses on the evaluation of the various methods of end-of-life product recovery for GM. This thesis contributes to this need.

In this chapter a review of recent relevant research is presented. The following subjects are covered: Facility layout alternatives for a remanufacturing environment, the remanufacturing domain, the importance of remanufacturing, active disassembly to extend profitable remanufacturing, life cycle costing for strategic evaluation of remanufacturing system, remanufacturing strategies to support product design and redesign, the effect of remanufacturing cost and demand uncertainties, and revenue and cost management for remanufactured product**.**

2.1 Facility layout alternatives for a remanufacturing environment

Facility layout alternatives for a remanufacturing environment have been explored by a number of authors. Gungor and Gupta (1999) illustrated a model for managing uncertainty in disassembly sequence planning (DSP). Clegg et al. (1997) described a model based on linear programming for determining the remanufacturing capability of a system. The model can be used to examine the effect of different cost structures on the long-term viability of remanufacturing operations, as well as short-term operations management issues. Van der Lann and Solomon (1997) introduced a general procedure to production and supply chain planning for a combination of newly manufactured and remanufactured components while leading a steady-state analysis of design for different sources of uncertainty. They also (1998) developed a technique to investigate a push control policy (products should be remanufactured very fast) and pull control policy (returned products should be remanufactured slowly but conveniently). Decision making between the push-disposal technique and the pull disposal technique essentially depend on the cost dominance relationship between various types of stock.

Guide and Jayaraman (1999) inspected the influence of proactive accelerating strategies in remanufacturing environments. They proved that product configuration can greatly influence the selection of the proactive accelerating strategy. Guide et al. (1999) investigated the use of a disassembly release mechanism (DRM). They also surveyed the effect of lead-time variability on flow times, mean square tardiness, and tardy percentage of different disassembly techniques in a remanufacturing environment. Dowlatshahi (2000) categorized the influential factors as including cost, quality, customer service, environmental impacts, and legislative concerns. Other factors associated with the operation included cost-benefit analysis, transportation, warehousing supply management, remanufacturing, and packaging.

2.2 The remanufacturing domain

Robert Lund (1984) defined remanufacturing as a process of bringing used products to a "like-new" functional state with warranty to match. Remanufacturing can be both profitable and less harmful to the environmental than conventional manufacturing as it reduces disposal to the landfill and the level of virgin material, energy and specialized labor used in production. Ijomah et al. (1999) described that remanufacturing typically begins with the arrival of a used product (called a core) at the remanufacturer, where it passes through a series of industrial stages including disassembly, cleaning, part remanufacture and replacing of unremanufacturable parts, reassembly and testing to produce the remanufactured product. Hormozi (1996), Haynesworth (1987) and Ferrer (1996) illustrated that the key remanufacturing drivers are environmental concerns (the need to reduce waste during the material extraction and manufacturing processes and throughout the remainder of the product lifecycle), legislation (international agreements to reduce the environmental impact of products and manufacturing processes) and economic, because remanufacture is often a quality and cost-effective option. Kerr and Ryan (2001) present a more thorough description of a generic remanufacturing process.

Stahel et al. (1994) illustrated that recycling is the sequence of activities for collection, arrangement and performance of discarded materials for use within new products. Amezquita et al. (1996) described that reuse is the particular process of using operative components from inactive assemblies. Ijomah (2002) described that remanufacturing is superior to recycling, because it adds value to destroyed products by taking them back to working condition, whereas recycling directly diminishes the retired product to its raw material value. Ijomah (2007) indicated that evidence of the environmental and economic advantages of remanufacturing is well documented in the literature.

2.3 Importance of remanufacturing

Lund (1984) illustrated that 85% of the load of a remanufactured product may come from used components. These products have equivalent quality with new products, but the energy consumed in their production is 50-80% less than a traditional manufacturing process and that they provide 20-80% production cost savings in comparison to traditional manufacturing. In large part due to the reduced energy consumption, remanufacturing processes have fewer CO_2 emissions than traditional manufacturing processes. Moreover, remanufacturing helps avert a considerable proportion of waste materials from landfill. Jacobs (1994) illustrated that converting recycled materials into manufactured products requires additional energy because the energy integrated in the materials in the early manufacture of the product is wasted during the recycling process. McCaskey (1994), Hormozi (1996) and Guide (1999) explained that remanufacturing is an essential reuse policy in waste material handling, wealth and employment creation, recovery of material and environmentally responsible manufacturing.

Ishii (1999) illustrated that although recycling has attracted more attention among design and manufacturing engineers, remanufacturing is superior to recycling from both an environmental and a financial point of view. Chick and Micklethwaite (2004) expressed that there are many designers and engineers who are unwilling to utilize recycled materials because of undesired quality or uncertain supply standards. It is important to consider products' potential for remanufacturing in the early level of design because the design level sets the product's capabilities. Ijomah (2002) explained that remanufacturing is a process of returning a used product to at least original equipment manufacturer (OEM) performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent. Since remanufacturing recovers a substantial fraction of the materials and value added to a product in its first manufacture, and because it can do this at low additional cost, the resulting products can be offered to the user at substantial saving.

2.4 Active disassembly to extend profitable remanufacturing guidelines

To increase a product's potential for remanufacturing developing design for remanufacturing guidelines has been an active area of research. Sundin (2001) analyzed household appliances to determine how to enhance remanufacturability designers. This work was continued by Sundin and Bras (2001) who proposed that cleaning and repairing are the most essential remanufacturing activities and that remanufacturability would be enhanced if designers focused on facilitating them. Amezquita et al. (1995) developed guidelines based on design features that assist remanufacturing and used these to identify design changes to improve automobile door remanufacturability. They also used surveys of independent practitioners in the automotive sector of the remanufacturing industry to identify and rank the factors influencing remanufacturability. Shu and Flower (1995) used case studies to analyze the impact of a range of fastening and joining methods on remanufacturing and other EOL options, concluding that joints facilitating recycling and assembly do not necessarily assist remanufacturability. Williams et al. (2001) analyzed toner-cartridge remanufacturers' waste streams to suggest design alternations to enhance toner-cartridge remanufacturability. Sherwood and Shu (2000) studied original equipment remanufacturers (OEM) waste streams to develop a modified failure mode and effects analysis to facilitate remanufacturing. Ijomah et al. (2007) and Ijomah (2010) addressed the lack of effective design for remanufacture guidelines.

2.5 Analysis of product end-of-life (EOL) strategy

Züst and Wagner (1992), Rose and Evans (1995) investigated the EOL value of individual materials, components, and joining elements outside the context of a specific product. This was done quantitatively through the development of systematic EOL value classification schemes or qualitatively (Navin- Chandra 1991, Beitz 1993), suggesting design principles and guidelines. While the benefits of the product-independent approach are easy evaluation and wide applicability, it is clearly an over-simplification, since the context in which an element is embedded often dominates its EOL value. In order to be able to evaluate or influence the EOL value of a complete product, one has to integrate product-independent information into a coherent product recovery plan that specifies in detail how to disassemble the product and what to do with each of the resulting subassemblies. Pnueli and Zussman (1997) suggested a recycling-oriented redesign approach, using the concept of a recovery plan based on a quantitative assessment of the EOL value of a product. It aims to further previous work by offering a set of tools for integrating EOL factors into product design. Shu and Flowers (1995) used case studies to analyze the impact of a range of fastening and joining methods on remanufacturing and other end-of-life options, concluding that joints facilitating recycling and assembly do not necessarily assist remanufacturability. Mangun and Thurston (2002) presented a decision tool to help decide when products should be taken back as well as the most appropriate component end-of-life options. The tool includes a model to help introduce redesign issues in product design.

2.6 End-of-Life Management

EOL management concerns the processing of products (with the objective of recovering maximum value out of them) after the initial user discards the product. Three important motives for well-organized EOL management are documented in the academic literature: environmental regulation, cost recovery from remanufacturing sales and "Green Image" marketing (Fleischmann et al., 2000; Hesselbach et al., 2001; Rogers & Tibben- Lembke, 1998, etc). In June 2000, DG XI of the European Commission (Directorate general for the environment is one of the more than 40 directorates general and services that make up the European commission. The objective of it is to protect, preserve and improve the environmental for present and future generations) issued a "proposal for a Directive on Waste from Electrical and Electronic Equipment (WEEE)" that makes the producers of electronic and electrical equipment responsible for take-back and recovery management of their products. The Directive also specified collection targets for local authorities as well as recovery and recycling targets for the producers to be met by specific deadlines. Guide, Jayaraman (1999) provide illustrations of how various companies have embraced recoverable manufacturing as a way to minimize waste disposal and ensure environmental sustainability. In addition to the "eco-motive", effective management of EOL products has a financial motive as well. There is an incentive of lower costs due to reuse of components from EOL products (Fleischmann et al., 2000). Returned products may enter the production process again as input resources, either in the original form or as components and modules after disassembly. Many companies have also reported increased profits by reselling returned products in secondary markets after refurbishment (Rogers & Tibben-Lembke, 1991). Besides ecological and economic factors, customer awareness is creating opportunities for "green marketing" and new markets for returned goods (Stock, 1998).

2.7 Life cycle costing for strategic evaluation of remanufacturing systems

Gungor and Gupta (1999) described possible business incentives for product take-back, such as market demand and acquiring unknown profitable contexts. Krikke et al. (1999) expressed that for handling of end-of-life product a recovery system is required to be implemented. The recovery system should be planned on the strategic and operational level. Guide and van Wassenhove (2001) illustrated that two systems can be considered for the take-back of end-of-life products from users: The waste stream and the market-driven system. The waste stream system is normally controlled by legislation motivating manufacturers to undertake the responsibility for their products throughout the total life cycle. Debo et al. (1995) delineated the role of decision support tools for helping decision makers investigate different alternatives for a remanufacturing process.

2.8 Analysis of the decision situations used in remanufacturing process

Zäpfel (2002) explored the (re-)manufacturing process based on establishing the structure and productivity of the process. According to that paper, the remanufacturing strategy can be classified according to the following sub strategies: technology strategy, strategy of vertical integrating, capacity strategy, and location strategy.

De Brito and Dekker (2002) illustrated that on a long-term planning level, decisions do not concern specific engineering topics. A choice has to be made on whether or not the strategy of design for remanufacturing should be pursued at all and how high the level of effort undertaken for this strategy should be. Implementation of each strategy in a remanufacturing system has effects on the cash flow situation of the products over the course of their life cycle. Tradeoffs can be distinguished between different life cycle phases in each production strategy. For example, by designing products to accommodate a remanufacturing process, costs may be increased at the production level but may be diminished at the recycling level. In relation to the strategy of vertical integration, Lee (2003) explained that the decision about the structure of the process should enable manufacturers to determine if the process should be handled with external sources or performed internally. The decision can be made based on a number of various quantitative (e.g. investment) and qualitative (e.g. core competence) criteria. In relation to the capacity strategy, Guide and Jayaraman (2000) argued that long-term capacity planning should be undertaken as a strategy. Creating an active take-back policy with encouragement of the user to return used products should be pursued.

2.9 Remanufacturing strategies to support product design and redesign

Kerr (2001) proposed that a designed product should be analyzed in aspects of remanufacturing and then the designer should develop the ability to remanufacture the product. Rose and Ishii (1999) illustrated that remanufacturing is an end of life model that decreases consumption of raw materials and saves energy while maintaining the product value added during the manufacturing process. Sundian (2001a) expressed that the remanufacturing process should be designed in such a way that it supports the current products for remanufacturing. William and Shu (2001) reported that two levels can be helpful for designers in decision making. First, considering a remanufacturing and reuse policy is very important in the product design process. Potential reuse and remanufacturing policies are evaluated by parameters including costs, competitors, policy, etc. to confirm their technological and profitable possibilities for improving the product. Secondly, designers should be assisted in the development of the remanufacturable product by highlighting product parameters linked to remanufacturability properties and advising on the target values of these criteria (Lagerstedt and Luttropp 2006). These two levels are necessary to better integrate the remanufacturing perspective during the design process.

Barker and King (2006), Franke et al. (2006), Sundian (2006) explained that if the remanufacturing process is not optimal, the cost of production will be increased. Brissaud and Zwolinski (2008) explained that an optimal remanufacturing and reuse policy must be developed for new products. Moreover, the scientific issue deals with developing design methods of remanufacturable products.

2.10 The effect of remanufacturing cost and demand uncertainties

Guide et al. (1999) studied the optimal acquisition and sales prices for a producer who obtained used product with different levels of quality and different remanufacturing costs. Dekker et al. (2004) expressed that there are two key features of closed loop supply chain management related to remanufacturing: The role of uncertainty in remanufacturing and investment in remanufacturing. The first feature is considered with uncertainty in the characteristics of returned products for a remanufacturing process. The characteristics of the product, such as quality, quantity and the time associated with product return, are not always recognized. Therefore, setting supply and demand is a significant challenge in reverse logistics.

Van der Laan (1997) described that uncertainty is considered as the most important parameter in decreasing the performance of reverse logistic operations. There is a vast amount of literature on managing uncertainty in quality and the timing of returns in the context of tactical-level decision making in product recovery. Aras et al. (2004) recognized a connection between manufacturing and remanufacturing systems in which there are diverse quality categories of returned products that leads to stochastic remanufacturing costs. They identify conditions under which quality-based categorization of returned products leads to cost savings in the hybrid manufacturing-remanufacturing system. Ray et al. (2005) evaluate the optimum prices for remanufactured products with good quality while considering the age of the returned product. Debo et al. (1995) evaluated the connection between pricing and the manufacturing technology selection problem. Selection of technology depends on the characteristics of the product, such as how durable the product will be and the quality level of the product. Zikopoulos and Tagaras (2008) evaluated a case where a used product with unknown quality can be obtained from two collection sources and determined the conditions for obtaining maximum used product. Ferguson and Toktay (2006) evaluated the difference between new and remanufactured products of a monopolist and determined the conditions under which the monopolist would prefer the remanufacturing method.

2.11 Revenue and cost management for remanufactured product

Fleischman et al. (2000) evaluated the design and performance of supply chains for reverse logistics. Guide et al. (2006), Ferguson and Toktay (2006), and Galbreth and Blackburn (2006) indicated that their works are inspired by the cell-phone industry, and collection is a decision rather than a constraint. Guide et al. (2006) wrote that the firm determines the price it will pay for a core of a certain tier, and thus the firm decides simultaneously on both the number and the quality of cores to acquire. The firm also determines the price of the manufactured product and maximizes profit. Galbreth and Blackburn (2006, 2010) show that their work is modeled as a cost minimization problem where market demand for remanufactured products is derived externally. Market division, competition and cannibalization have been analyzed from different point of views. For instance, Majumder and Groenevelt (2001), and Ferret and Swaminathan (2006) argued that reused products and new ones are indistinguishable from each other and thus concentrate on the external competition. Debo et al. (2005) illustrated that users have less regard for reused products and, consequently, used products are internal competitors for the new product. Moreover, some investigators consider a third-party remanufacturer as an external competitor who may collect the company's used products, refurbish them, and then present them in the market, thus cannibalizing the firm's sales of the new product externally. Ferguson and Koenigsberg (2007) address the management of deteriorating inventory. In their two-period model, the firm in the second period may face an inventory of leftover product, for which customers are willing to pay less than what they would pay for the new product, which is similar to the firm's putting a refurbished product on the market. They found out that the price of the new product is related to the quality of the leftover product (which in their strategy they realize the diversity of consumers' reluctance to pay for it).

2.12 Summary and motivations for research

Product recovery is the process of returning used products at their end-of-life to at least original performance specification from the customers' perspective and giving them warranties at least equal to that of equivalent new products. The practice is an important reuse strategy in waste management, material recovery and environmentally conscious manufacturing because it is simultaneously highly profitable and less environmentally harmful than conventional manufacturing.

Three main motives for efficient EOL management are documented in the academic literature: environmental regulation, more effective reverse logistics and new marketing opportunities.

Environmental degradation has become a big concern, and governments all around the world are formulating “producer responsibility” legislation to put pressure on businesses to manufacture products that minimize eco-burden. In addition to the “eco–motive”, effective management of EOL has a financial motive as well. There is an incentive of lower costs due to reuse of components from EOL products. Besides ecological factors, customer awareness is creating opportunities for “green marketing” and new markets for returned goods. Moreover, both the lack of natural resources, raw materials and energy, and the shortage of landfills force industry to consider ways to increase the amount of components and materials that can be reused in some fashion. Considering the many benefits of product recovery, this research presents a decision making model, integrates technical, economical and environmental considerations for the product’s evaluation. The goal of this contribution is to develop an instrument which supports decision makers in their consideration of a product’s EOL strategy. The model incorporates two key parameters that have not been combined in any of the existing models: objective factors and market demand.

It is clear that product recovery operations are characterized by their dependence on the availability of information associated with the product. Thus, by increasing the amount of information available, the uncertainty associated with the state of the system is expected to reduce, facilitating more effective product recovery decisions. The market demand as an economical criterion suffers from a lack of research in the field of recovery strategies. This is a critical gap given the influence it has on strategic decisions, and therefore needs to be quickly addressed. In this research, a demand modeling mechanism is proposed with a Bayesian update structure that incorporates both observed realizations and expert judgment into the production process. When it comes to evaluating the relevance of a strategy, the economic efficiency is tightly linked to the product itself, the coordination of the supply chain (suppliers, OEM, and distributers) and the final behavior of the customer (willingness to pay, reverse logistics, etc).

Hence, a making decision model that is constructed from product recovery can be used to analyze how ready availability of product information at the product's EOL leads to better product recovery decisions. In this study a Bayesian approach is also used to analyze the effect of enhanced information on product recovery decisions. The research shows qualitatively that the availability of product information has a positive impact on product recovery decisions. It also illustrates how recovery decisions can be modeled to represent the impact of product information on those decisions.

CHAPTER 3: Evaluation of Product End-Of-Life

End-of-life strategies may include a combination of reuse, remanufacturing, recycling, incineration and disposal options. Using a survey of current products and associated end-of-life strategies, it is importance to identify these relevant factors, focus on key significant product characteristics, and develop a methodology that guides product developers to an optimal end-of-life strategy (Masui and Mizuhara, 1999). End-of-life management concerns the processing of products after the initial user discards the product (Parlikad, 2007). It is defined as those options accessible to a product after its useful life (Parlikad, 2007). As illustrated in Figure 3.1, there are four recovery options available for recapturing value from products at their EOL: repair, refurbishing, remanufacturing, and recycling. Figure 3.1 shows that reuse can be considered a sub-set of repair and refurbishing. Each of the recovery options are discussed further in the following sub-sections. Prior to discussing the options in detail, however, the key information requirements for EOL decision-making are briefly reviewed.

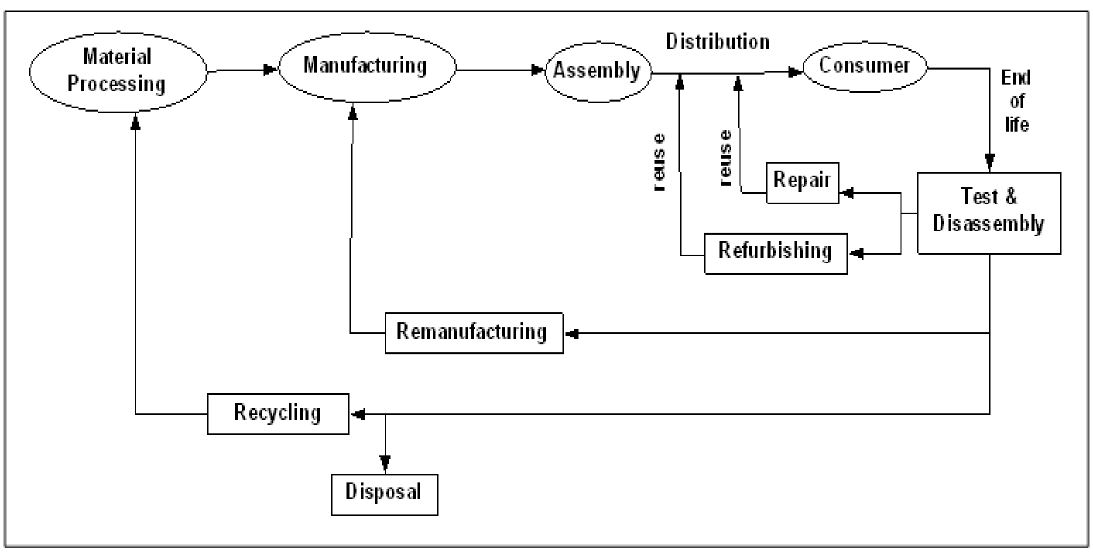

Figure 3.1 Different recovery options used in green manufacturing

It should be noted that if parts and materials obtained from products at their EOL cannot be recovered through any of those four strategies that they should be disposed of with consideration given to both safety and environmental regulations. The two primary options for disposing of products at their EOL are incineration and land filling.

3.1 Information requirements for end-of-life decision making

End-of-Life is typically defined as any processing of a product after the initial user discards the product. This processing includes steps taken to collect, reuse, remanufacture, recycle, incinerate or dispose of a product (Guide et al., 1997). Evaluation of environmental improvement and costs of these processes are important to identify the best life cycle strategy. Each manufactured product has specific functions, materials, parts, technology and proposed consumers. It is necessary to determine appropriate end-of-life strategies based on the product characteristics available to designers during the early steps of product development. To develop a model that addresses life-cycle impacts, it is important to first determine the information requirements for decision making at end-of-life. The product information required for end-of-life decision making can be categorized into two categories: (1) internal information, and (2) external information (Parlikad, 2003). The composition of each of these categories is shown in Figure 3.2 [adapted from (Parlikad, 2003)].

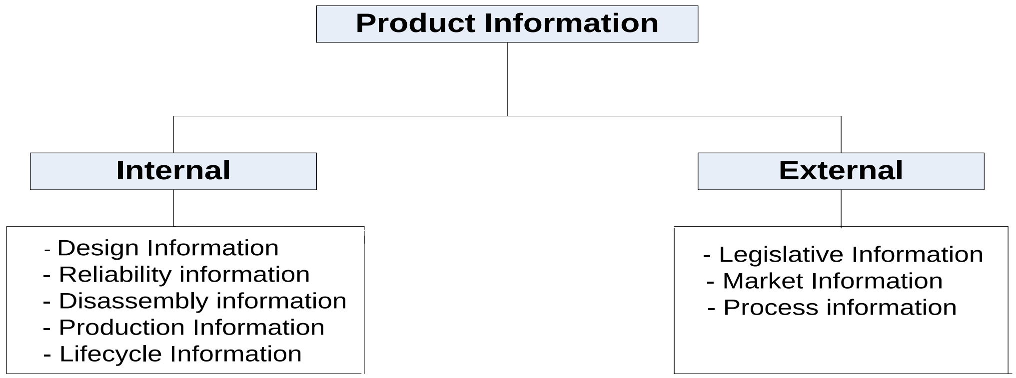

Figure 3.2 Information requirements for EOL decision making

3.1.1 Internal information and its impact on EOL decision

Internal information includes information required to maintain the identity of a product throughout its lifecycle. The different parameters that provide this information discussed below with an emphasis on their influence on end-of-life decisions.

3.1.1.1 Design information

Design information consists of information relating to the physical structure of the product including information on the location, size, shape and weight of components and modules within the product (Parlikad, 2003). Since many life-cycle impacts of a product are essentially determined in the design phase, this information is useful for identifying design strategies to improve the eco-efficiency of the product (Cramer, 1997). Eco-efficiency means not only ecological efficiency, but also economic efficiency, making a direct connection between environmental targets and market opportunities (Parlikad, 2003). The information related to the weight and volume of the product is often considered in the determination of the economic viability of various recovery methods.

Information related to material composition of the components is also needed for determining their recovery value. This information enables a recycler to make better decisions related to selecting the best options for recovering the product. Information regarding material composition is also important for identifying potentially hazardous materials used and determination of their disposal method.

3.1.1.2 Reliability information

Information regarding the reliability of the product helps to predict the time when it will reach its end-of-life and thus help in the planning of the recovery of the resources. Reliability itself is defined as the probability of an item to perform its initial functions successfully during a certain period of time (Anityasari and Kaebernick, 2008). Reliability information of components can be used for determining their reusability and residual value with more accuracy. To reduce the cost related to disassembly and cleaning activities, reliability evaluation should be performed before the disassembly process. In other word, reliability of the components must be measured at the end of the first life. In general, there are two different streams for estimation of reliability including statistical reliability analysis and Condition-Monitoring (CM) approaches (Anityasari and Kaebernick, 2008).

Statistical reliability analysis

This approach aims to represent a component's total functional life and to estimate the associated reliability parameters. The input for this analysis is failure data collected either from in-house testing or maintenance activities. In fact a limited number of items run to work simultaneously under standard operating conditions and a control environment until failure. Therefore, unless the life of a particular component is very long, all tested components will fail during the designated test period. Mean life or mean-time-to-failure (MTTF) is one of the most popular parameter used for estimation of remaining life (Anityasari and Kaebernick, 2008).

Condition-Monitoring (CM) approaches

This method predicts potential failure by using advanced data analysis techniques. The result of the CM method is an estimated used life of an item. The potential of reuse is then calculated by using the equation below:

$$RL = MTTF - t_1$$

Where RL is the remaining useful life, MTTF is the mean life and t_1 is the estimated used life or the age of the item (Anityasari and Kaebernick, 2008).

3.1.1.3 Disassembly information

Disassembly is one of the keys to any product recovery operation. It has been identified as the most important activity in EOL management. In an engineering context, disassembly may be defined as the organized process of taking apart a systematically assembled product (assembly of components) (Desai and Mital, 2003). As described in Figure 3.3 [adapted from (Parlikad, 2003)], a product may be disassembled to enable maintenance, enhance serviceability and/or to affect end-of-life (EOL) objectives such as component reuse (components from a retired product being used without up graduation in a new product), remanufacture (components from a retired product being used in a new product after technological up graduation) and recycling (reuse at the material level, e.g. recycling of plastics). These constitute some of the most important reasons for disassembling products (Desai and Mital, 2003). Because of its importance, researchers are getting more interested in the investigations on disassembly such as disassembly process planning, disassembly evaluation and design for disassembly (Desai and Mital, 2003; Masui and Mizuhara, 1999).

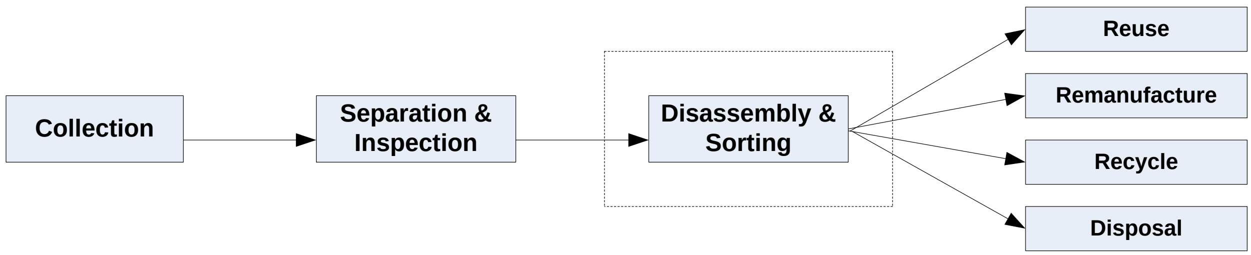

Figure 3.3 Schematic view of disassembly's role in product recovery at product's end-of-life

The concept of a product embedded disassembly process is useful to enhance the disassemblability of the products. Advantages of this concept include position insensitivity and simultaneous separation of plural connections, and thus, shortening disassembly time and enhancing automation potential (Masui and Mizuhara, 1999). In addition to design and reliability information, disassembly information should be made available at the product EOL. The availability of disassembly instruction, accompanied with other related information such as design, reliability, production and lifecycle information will enable automation of the product disassembly process, potentially leading to increasing cost efficiency and reduction of components disposed (Masui and Mizuhara, 1999). Disassembly planning can help to find optimal strategies for complex products, with quantitative evaluation of dismantling costs and with an optimal management of all information about the product and its previous use.

3.1.1.4 Production information

In the selection of materials, the designer requires production information for a number of reasons, including controlling the use of hazardous materials and making them easier to recycle (Ferguson and Browne, 2001). Every manufactured product undergoes different processes during production such as forging, painting, etc. which may change the fundamental properties of the material. Hence, design planning requires updated information associated with both the product's configuration and the product's composition (Ferguson and Browne, 2001). Proper design reduces unexpected changes during the disassembly processing. For example, a part coated with a hazardous chemical might need to experience particular treatment before it can be handled for disassembly. Thus, it is necessary for the designer to have the relevant knowledge about all the processes and materials that were used in the manufacture of the products (Parlikad, 2003).

Design modifications are often necessary to manufacture a product efficiently. For instance, the design of a product might have had a screw joint that had to be changed to a welded joint during production. This has implications for the disassembly process as well, since a welded joint cannot be separated in a non-destructive manner. Therefore, in the design of product components and materials the designer must facilitate the dismantling, reuse, recovery and recycling of end of life products (Ferguson and Browne, 2001).

3.1.1.5 Lifecycle information

This class of information is related to the use of a product over its entire life (Ferguson and Browne, 2001). This information may be available from the product user and perhaps the retailer of the product. The product lifecycle may be modeled as a sequence of processes. These processes are manufacturing, use, inspection, take-back, repair, overhaul, adjustment, recycling, processing, reuse, disposal, and so on (Ferguson, 2001). Products and materials are transferred from one process to another process. Each process has its own parameters such as energy consumption, processing cost and waste discharges (Hata et al., 2000). Information on product properties and the history of product use are essential for higher levels of product recovery. This is due to the fact that operating conditions and maintenance has a huge bearing on the structural composition of the product and quality of the components at its end-of-life (Klausner et al., 1998). Quality, in the context of product recovery, is defined as the functionality, reliability, and remaining lifetime of the product (Krikke et al., 1998).

In Figure 3.4 [adapted from (Gungor, 1999)], the four key phases of a product lifecycle are summarized as design, manufacturing, use and End-of-Life (EOL) (Gungor, 1999). In the EOL phase, a product is disassembled to retrieve the parts or subassemblies that are recycled, reused, or remanufactured.

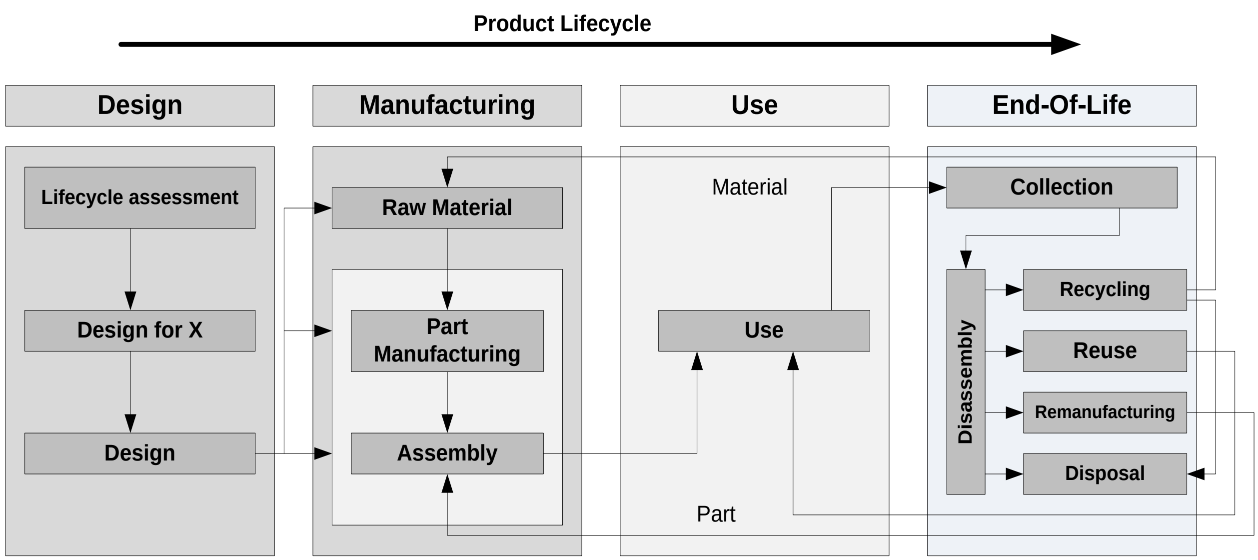

Figure 3.4 Product's lifecycle

Due to strict quality requirement for reuse and refurbishment, the reusability of components and modules depend on their quality at the time when the product is returned (Parlikad, 2003). A recently replaced component will have a longer residual life than those that were originally part of the product. Hence maintenance and replacement history will lead to greater chance of parts and modules being reused and may reduce the cost of lost opportunity due to the disposal of potentially reusable parts and modules. Lifecycle information could also be used by manufacturers to analyze their products and increase their durability.

3.1.2 External information and its impact on EOL decisions

External information pertains to those types of information that are not directly related to the product, but that impose pressure on the recovery option available. The different parameters that constitute this category of information are explained below.

3.1.2.1 Legislative information

In recent years, there has been growing recognition of mankind's impact on the environment and the need to adopt a more sustainable approach to our consumption pattern has begun to take on enhanced significance (Barba-Gutierrez et al., 2008). Different countries and governments impose different legal requirement for waste management and recycling. For example proposed European Union legislation sets targets for collection and recycling for a wide range of consumer products. The primary drivers in requiring take back and recycling of products are societal concerns about resources, landfill or incineration, and lack of control of hazardous substances at the end-of-life phase (Barba-Gutierrez et al., 2008).

Take back systems should be required to be eco-efficient to make sure that they are attaining environmental goals and the costs to achieve these are in proportions (Rose et al., 2000). Environmental directives often specify the maximum proportion of the product that can be land filled. For example, the Waste Electrical and Electronic Equipment (WEEE) directive requires that 70% by weight of EOL electronic products should be recovered and at least 50% of the recovery WEEE should be reused or recycled (Sabbas et al., 2003). In addition to this legislation, which directly addresses end-of-life issues, new legislation is also emerging in industrialized countries that will extend the focus of environmental impact over the entire product life cycle from design to end-of-life (Goosey, 2004). It is important to express a well-defined distinction between two possible definitions of lifecycle. One is relative to the life of a product in the market with respect to business/commercial costs and sales measures; and the other, which is the topic in this research, is relative to the material lifecycle from cradle to grave, by taking into account different end-of-life options (Barba-Gutierrez et al., 2008). As these rules and regulations change continuously, effective EOL decision depends on the ability of the information system to keep track of the most recent legal requirements. The availability of this information leads to product recovery processes that are compliant to government legislation and hence minimize the negative impact on the environment (Barba-Gutierrez et al., 2008).

3.1.2.2 Market information

In any logistic flow, one important objective is to obtain the highest value possible for the products in accordance with any legislation or constraints imposed by the government and/or the vendor respectively (Ferguson and Browne, 2001). In order to achieve this objective, the manufacturer must have timely and accurate access to market information regarding demand, price and availability of recovered (refurbished or remanufactured) components and modules (Ferguson and Browne, 2001). This information should be presented to the recycler before the sorting activity occurs. Since this information can be used for determining the economic reliability of product recovery operations, they are essential for deciding the optimum disassembly level and EOL strategy of products. For instance, having information about market demand and price for a particular component will help the manufacturer to decide whether it is economic to disassemble the end-of-life product for reuse or to recycle it for material recovery.

The product recovery network can be divided into three parts as shown in Figure 3.5 [adapted from (Fleischmann et al., 2000)].

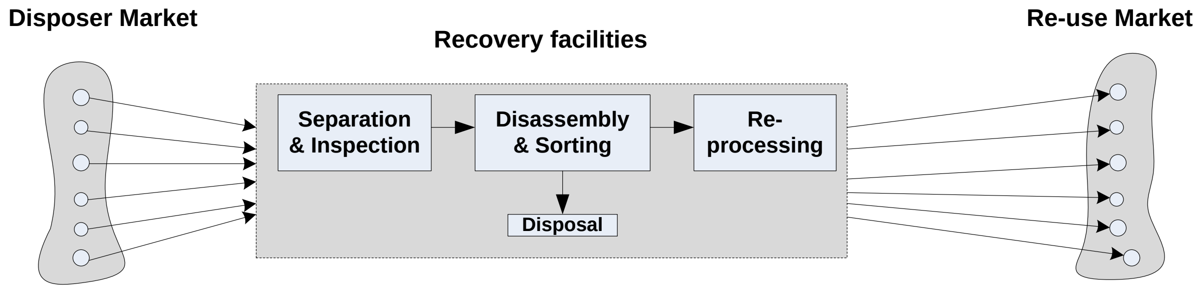

Figure 3.5 The market chain

In the first part, corresponding to the collection phase, flows are converging from the disposer market (typically involving a large number of used products) to recovery facilities. In the second part, corresponding to the recovery facilities, flows are considered for implementing an optimal disassembly sequence aimed at maximizing profit. In the last part, corresponding to re-distribution, the flow is diverging from recovery facilities to demand points in the re-use market. An optimal disassembly sequence considering both economic and environmentally aspects necessitates providing knowledge regarding the market demand and the price of the recovered product. In addition of demand and price constraints, the market can be affected along a number of parameters such as supply constraints, competitive pressure and marketing advertisement (Bijak, 2006).

3.1.2.3 Process information

Process information is the knowledge regarding a reverse logistics (RL) strategy that involves dismantling used products in order to provide required parts and materials for implementing different types of recovery processes (Parlikad 2003). Reverse logistics is defined as: “The processing of planning, implementing and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value of proper disposal" (Rogers and Tibben-Lembke, 1999). Strict environmental legislation and reducing raw material resources have intensified the importance of RL. Figure 3.6 [adapted from (Meade and Presley, 2007)] shows set of functions, activities, inputs, outputs, and mechanisms from the perspective of a reverse logistics channel.

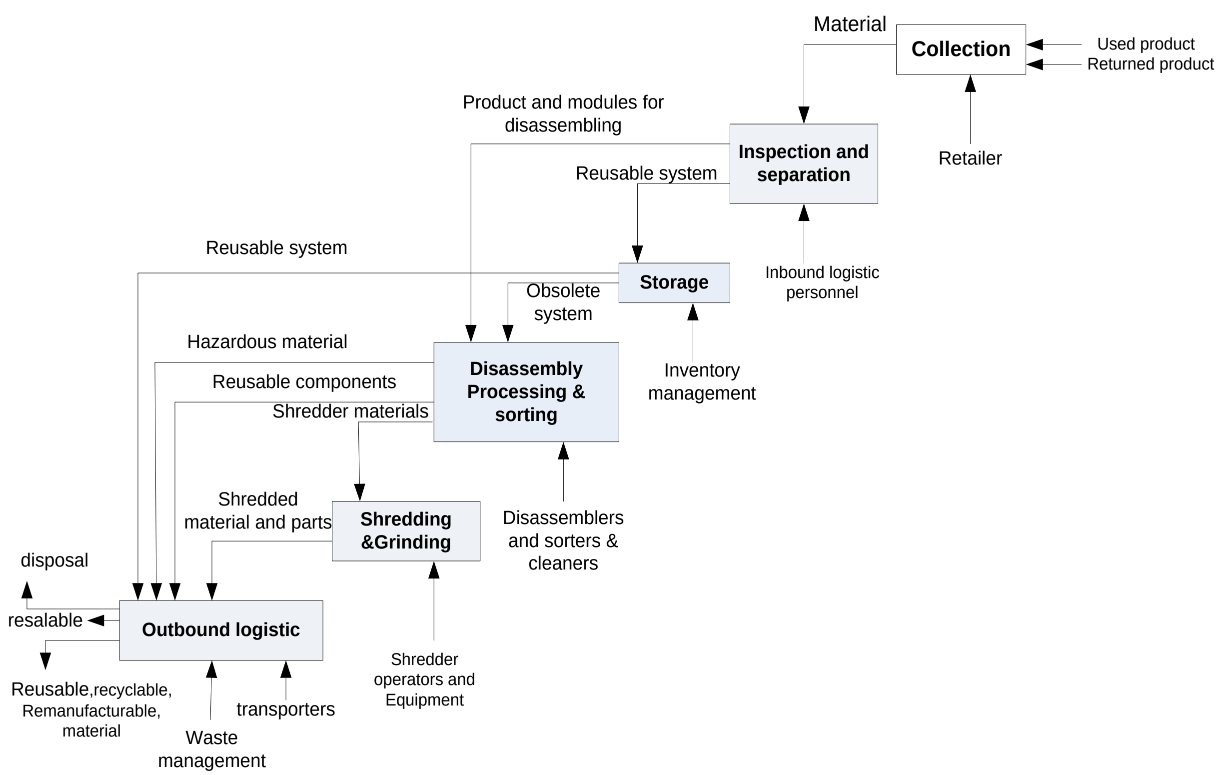

Figure 3.6 Systematic examples of mechanisms, input, output, functions and activities within a reverse logistics channel.

Collection refers to all activities related to the moving of used products and product at end-of-life to some point where further treatment is taken care of (Fleischmann et al., 2000). In general, collection may include purchasing, transportation and storage activities. Inspection/separation which is the starting point of the reverse logistics channel and refers to all activities determining whether a given product is in fact reusable and in which way (Fleischmann et al., 2000). Thus, in this stage, the flow of used products is dismantling based on distinct re-use and non re-use (disposal) options. Disposal is defined as: products that cannot be reused for technical and economical reasons (Parlikad, 2003). The non-reusable system is dismantled and then the products and components are transferred to the disassembling process stage. The reusable system is transferred to the storage stage for inventory assessment (Fleischmann et al., 2000). In addition to inventory activity, the reusable system (repairable) is selected from the obsolete system and it is carried to the outbound logistic stage as a resalable system while the obsolete system enters disassembly processing. In disassembly processing, the used products and obsolete systems are disassembled to obtain individual components and modules. Subsequently, disassembled components and modules would be sorted. Sorting activity is usually performed according to their condition, material and recycling requirements. The non reusable components would be shredded in one stage and then accompanied with reusable components and waste materials are removed to outbound logistics as the last stage of reverse logistics (Fleischmann et al., 2000). In this stage, all components and materials are selected according to repairable, resalable, recyclable, remanufacturable and disposal condition (Ferguson and Browne, 2001).

3.2 Evaluation of recovery options

The recovery process is a combination of material recovery (recycling) and product recovery (reusing and remanufacturing) (Gungor and Gupta, 1999). The main reasons for implementing material and product recovery include: 1) retrieving hidden economic value of solid waste 2) market requirements and 3) government legislation (Parlikad, 2003). Material recovery aims to minimize the amount of waste sent to the landfill or incinerator and to maximize the amount of the materials returned to the production cycle (William et al., 2001). This process mostly includes disassembly for separation and processing of materials of used products.

The main purpose of product recovery is to add value to used parts or products for re-using (Gungor and Gupta, 1999). Product recovery includes disassembly, cleaning, sorting, replacing or repairing bad components, testing, reassembling and inspecting (Gungor and Gupta, 1999). Collection of retired products is the essential stage for profitable performance of product recovery. The three product recovery options are: repairing, refurbishing, and remanufacturing. All options are suitable for both products and components. Each of the product recovery options involves collection of used products and components, reprocessing, and distribution. The main difference between the options is in reprocessing. Figure 3.7 [adapted from (Jacobsson, 2000)] describes an integrated supply chain where service, product recovery, and waste management activities are included.

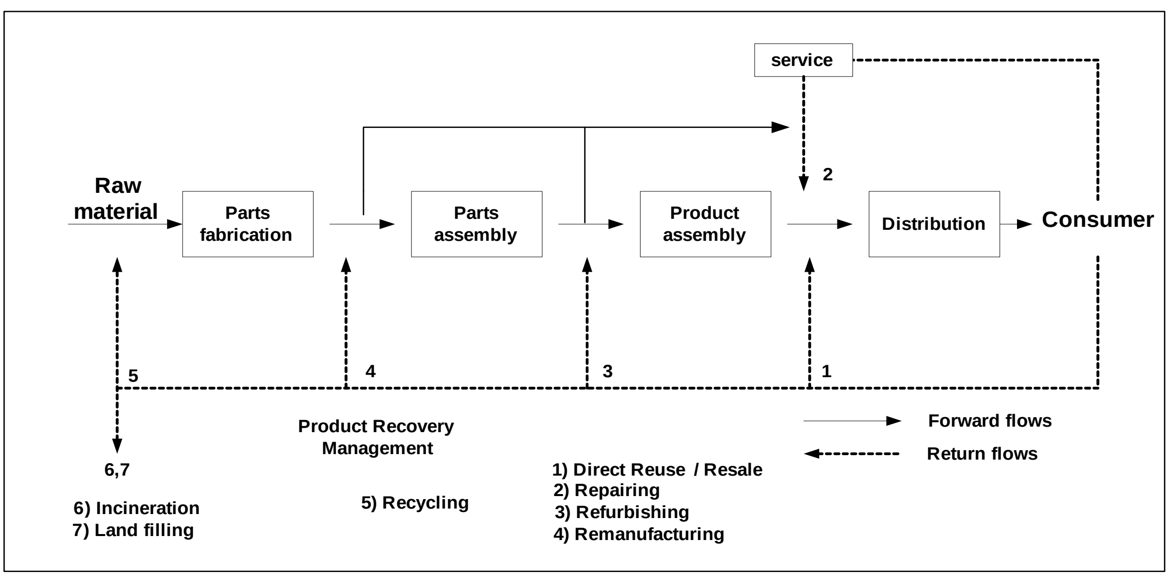

Figure 3.7 Management of different product recovery methods associated to product EOL

As Figure 3.7 illustrates, returned products and components can be resold directly (1), reused by repair or refurbish (2, 3), remanufactured (4), recycled (5) or disposed (6, 7).

3.2.1 Repair

Repair is the first product recovery option and is defined as the process of bringing damaged components back to a functional condition (King et al., 2006). It focuses on extending the life of the product with fixing and/or replacement of broken parts. Repairing can thus be viewed as a corrective function of particular faults in a product and it requires only limited product disassembly and reassembly. One key goal in the repair process is to reduce turnaround time (TAT) at the lowest cost while maintaining the needed level of quality (Kang et al., 1998). The quality of the repaired product is generally equal or less to the quality of a new or remanufactured product (Parlikad, 2003). Repair operations can be performed at the customer's location or at manufacturer – controlled repair centers.

3.2.2 Refurbishing

Refurbishing is defined as the process that brings the quality of used products up to a specified level by disassembly of the product, inspection and replacement of broken components (Parlikad, 2003). The purpose of this function is to increase the quality of the used product to a determined level. This is accomplished by disassembling the product, conducting a check-up, and replacing any faulty modules. Refurbishing can also incorporate the renewal of technology through the replacement of out of date modules or components. Since the refurbished product is not new, it usually has the same market as repaired products (Parlikad, 2003). One particular type of refurbishing is reconditioning. The reconditioning process is defined as the reconfiguration or replacement of major components of a product to a working condition that is expected to be inferior to that of the original model (King et al., 2006). Normally, reconditioned products supply a special market referred to as a “gray goods” market.

3.2.3 Remanufacturing

Remanufacturing is the third end-of-line recovery alternative. It is defined as the process of bringing broken assemblies (cores) to a “like new” functional state by rebuilding and replacing their component parts (King et al., 2006).

It has important economic and environmental implications. In remanufacturing a used product is completely disassembled. Usable parts are then cleaned, refurbished, and put into inventory. Subsequently, the new product is reassembled with both old and, where necessary, new parts to produce a product that is in all respects comparable, and sometimes superior, in achievement to the original new product (Gehin and Zwolinski, 2008). To support design for remanufacturing, the waste stream of remanufacturers should be studied. The remanufacturing strategy has some advantages. Reusing parts or modules not only result in lower energy consumption, but also cut raw material consumption (Gehin, 2008). Moreover, remanufacturing, decreases prices of products and reduces cost of disposal. Implementation of remanufacturing strategy improves product value and develops compliance with regulation (Gehin, 2008). The main problems that remanufacturers face are associated with high uncertainty and high risk since it is usually impossible to determine in advance the quantity and quality of the incoming products (Ijomah et al., 1999). The uncertainties involve variability in demand volume, core quality, core quantity, product type and availability of technical knowledge (Ijomah et al., 1999). The term “core” is used for typical remanufactured parts which are the largest items of the product. Such uncertainty has significant implications for scheduling, capacity planning and shop floor control. In addition, remanufacturing operations require cost and time effective systems that facilitate easy and accurate information accumulation and processing. Remanufacturing is specifically applicable to complex electro-mechanical and mechanical products which have cores that, when recovered, have sufficient value added to them that is high relative to their market value and to their original cost (Ijomah et al., 1999). Cleaning and lubricating ability are other important factors associated with remanufacturing ability and ultimately with disassembling abilility which must be considered for quality of production. In the refurbishing process, some usable components from failed products are reused, but before reuse, they should be cleaned and then lubricated. Considering these parameters leads to higher recovery levels and lower disposal of reusable components.

3.2.4 Recycling

The recycling process is defined as the series of activities applied to discarded materials (King et al., 2006). The series of activities includes collection, sorting, processing, and the production of the new product (Anityasari and Kaebernick, 2008). The recycling process typically requires more energy than remanufacturing and refurbishing processes (Gehin et al., 2008). Recycling can be applied to an assembly as well as its materials. If an assembly comprises mono or compatible materials it can be recycled right away, without separation of materials, but if an assembly consists of multiple incompatible materials, then separation should take place. Chemical processes that separate mixed materials, are seen as transformation processes and the remaining mixture of materials (not separated) is disposed of (Krikke et al., 1998). Separation is defined as the physical or mechanical isolation of materials from an assembly or mixture of materials (Krikke et al., 1998). Separation of material functions increase the value of the materials recycled by removing material contaminates, hazardous materials, or high value components. In assembly transformation, the assembly loses its identity and is broken down into a mixture of materials (e.g. shredding). The purpose of shredding is to reduce material size to facilitate sorting. The shredded material is separated using methods based on magnetic, density or other properties of the materials. Material transformation is the process in which materials are recycled into either the original or entirely new materials (e.g. iron recycling) (Krikke et al., 1998).

The potential recyclability of a product is determined at the design stage, and thus it can be improved by changes in materials, structural layout, and interpart connections (Chen and Navin-Chandra, 1994). The key is to consider the main engineering requirements of the product and simultaneously design their components and materials for easy and economical recycling (Sabbas et al., 2003). An optimal recycling strategy is of major importance in order to show the most efficient treatment at their end-of-life.

3.2.5 Disposal

Disposal of a product is required when reuse or recycling is not viable from an economic or technical perspective. Disposal can be achieved by means of two options including incineration and landfill (Parlikad, 2003). Often there are quality requirements for the input of disposal processes. This is particularly the case when assemblies contain hazardous substances, which requires sophisticated processing, because different tariffs are charged for toxic materials. Note that regulation can prohibit the use of certain disposal options (Krikke, 1998).

3.3 Reusability

Reuse is any operation by which a component of the end of life product is used for the same purpose for which it was conceived (Parlikad, 2003). As previously noted reuse can be viewed as a sub-set of repair and refurbishing. Direct implemention of the reuse method without repairing or refurbishing has a number of economic and environmental advantages. The reusability of a product may be assessed in a number of ways, including assessment based on the check-up of a product or its components and assessment based on its time of use (Anityasari et al., 2005). The most important problem regarding to the reuse method is uncertainty of the product's quality after it has been used (Murayama and Shu, 2001). Other issues could be associated with the design of the product, if, for example, it was not designed for efficient disassembly. In any case, the purpose of reuse is to have an item with acceptable quality. Reuse of a used item for a second time is mainly affected by two important factors. The first factor is related to the technological life of products. If the pace of technology development for a specific item is fast, then the technological life of that item is short, the reusability of the item will be reduced. The second factor is associated with the quality of the product. An item with good quality means that its functions are well during its life time. Quality is a broad term including availability and reliability aspects (Mazhar et al., 2007). Availability is considerable only if its reliability is acceptable. Therefore if an item starts to function well but can not continue over a reasonable period of time, it is not suitable for reusability. In this condition assessment of its reliability is essential.

3.4 Evaluation of remanufacturing vs. different reuse processes

Assessment of remanufacturing, refurbishing, and repairing indicates that, these processes can be differentiated in four key ways. Figure 3.8 [adapted from (King et al., 2006)] presents the three processes of remanufacturing, refurbishing and repair on an axes based on the typical value of warranty, performance (reliability) of their products and the work content that they normally require.

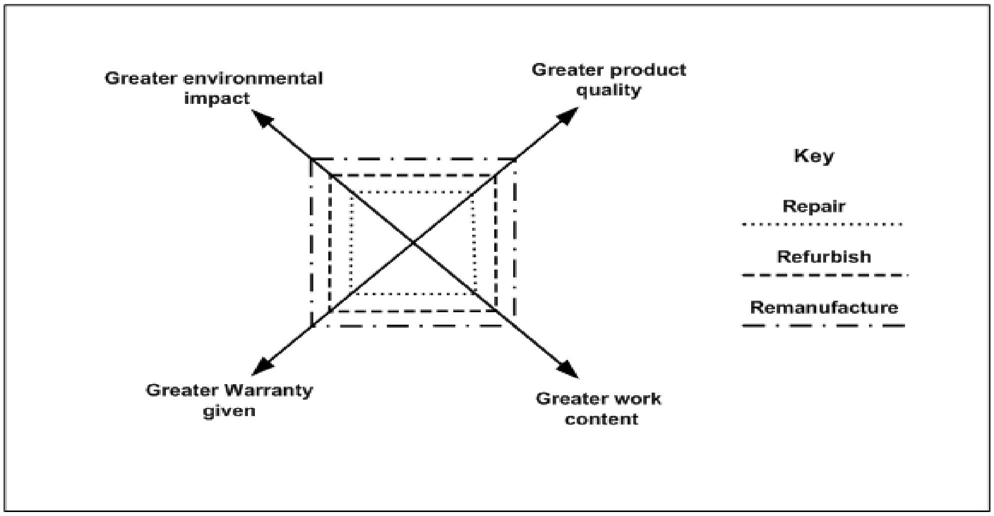

Figure 3.8 The hierarchy of secondary market production process.

Repaired or refurbished product have inferior warranties in comparison with a new product while remanufactured products have warranties equal to that of new alternatives. Typically, the warranty that stems from the refurbishing process encompasses all major wearing parts while for repair it applies only to the repaired component. Secondly, remanufacturing generally encompasses greater work content than the other two processes leading to products that generally have superior quality (reliability) and performance. Thirdly, remanufactured products lose their identity while being repaired and refurbished products retain theirs. Fourthly, in reusing processes (repair and refurbish); functional components from retired products are used, while remanufacture may involve the upgrade of used product further than the original specification. Environmentally, remanufacturing is preferable in comparison with recycling processes, because it adds value to waste products by returning them to working order, whereas recycling simply reduces the used product to its raw material value (Ijomah, 2010).

CHAPTER 4: Evaluation of Objective Factors and Market Demand

4.1 Introduction

The manufacturing industry is a key contributor to environmental pollution. Therefore, the issue of how to minimize the environmental impact of the manufacturing industry is critical for all manufacturers. As previously discussed, GM can help minimize environmental impact and resource consumption during a product's lifetime. However, further research is necessary on all aspects of GM, particularly in selecting appropriate options for products at their EOL. In this chapter, a decision making model for reverse back processing is presented to help address this need. The two key parameters considered in the model are objective factors and market demand.

4.2 Parameter 1: Objective Factors

The decision making model for green manufacturing (GM) involves five objective factors: Quality (Q), Cost (C), Environmental Impact (E), Resource Consumption(R) and Time (T). The Table 3.1 indicates the rationale for the five objective factors.

Table 1: The rationale for the five objective factors

Objective Factor	Characteristics
1) Quality (Q)	Quality, in the context of product recovery is the functionality, reliability and remaining lifetime of the product.
2) Cost (C)	Product life cycle cost represents all costs that occur during the product's life cycle phases (PLCC) including product cost (C_P) and environmental cost (C_E). PLCC = $C_p + C_E$
3) Environmental Impact (E)	Different methods of GM have different influence on the environment and can be classified to ecological impact and impact of occupational health and safety issues.
4) Resource Consumption (R)	Raw materials accompanied with energy (electricity, fossil fuels) and labor resources are consumed in each step of different GM strategies.
5) Time (T)	The complexity of each product recovery method is different. Thus, each method has a different time requirement. The most important parameters in the product recovery time schedule are quantity and material property.

The three objectives of Quality (Q), Cost (C), Environmental impact (E) are particularly critical in reverse back processing (RBP), Quality (Q) should be maximized, while Environmental Impact (E) and Cost (C) should be minimized. Figure 4.1 presents the structure of the decision making objective system for GM.

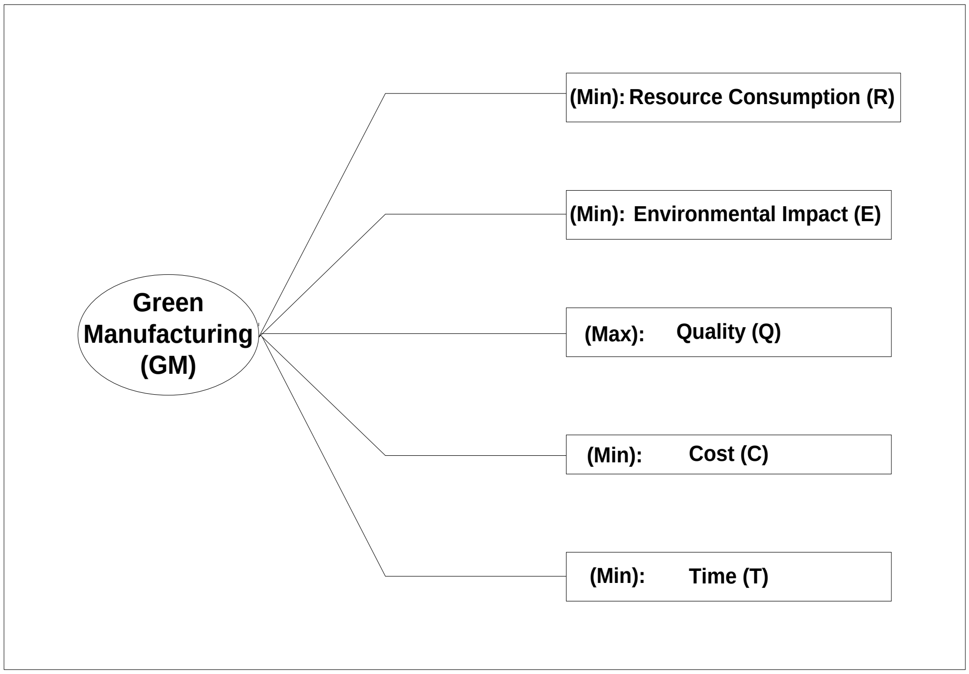

Figure 4.1 Decision making objective model for green manufacturing optimization

4.2.1 Environmental Impacts (E)

Rapid development of manufacturing activities in the world have lead to many environmental impacts, including consumption of energy and natural resources, air and water pollution, soil deterioration, and waste disposal, among other issues. These issues must be addressed now and in the future. In many cases, addressing environmental issues requires the implementation of new or revised manufacturing processes. For the purposes of this thesis, the environmental impacts of manufacturing are categorized into the two categories. They include:

1) **Ecological issues**:

   Manufacturing processes produce a number of environmental discharges, including (but not limited to) solid waste (e.g. left over material, reject, scrap iron), liquid waste (e.g. waste lubricant, waste water), and gaseous emission [e.g. Green House Gases (GHG)].

2) **Health and safety issues**:

Manufacturing processes have a number of health and safety issues. Although these vary depending on the process, some examples include moving equipment, noise, and the use of hazardous chemicals. Many functions associated with machine processing cause insecurity. For example, a variety of injuries or accidents might happen, such as injury by the splashing of scraps, scalding by hot work pieces, and being pricked by the scraps on the ground.

4.2.2 Cost (C)

Product life cycle cost (PLCC), represents all costs that occur during the product's life cycle phases which are product cost (C_p) and environmental cost (C_E) (Anityasari et al., 2005).The cost of a new product and an old product are illustrated below. It is supposed that the life cycle phases of usage and end-of-life are assumed to be equal for a new and old component. Therefore they do not appear in the cost calculation.

4.2.2.1 Cost of new product

The cost of new product can be divided into three categories, including the cost of materials, manufacturing, and the supply chain.

$$C_{pnew} = C_{mat} + C_{man} + C_S \quad (4.1)$$

$$C_{Enew} = C_{Emat} + C_{Eman} \quad (4.2)$$

C_{pnew} = Product cost for new option

C_{Enew} = Environmental cost for new option

C_{mat} = Material cost

C_{man} = Manufacturing cost

C_S = Supply chain cost

C_{Emat} = Environmental cost for material phase

C_{Eman} = Environmental cost for manufacturing phase

Manufacturing cost involves two key categories:

1) Direct labor cost is related to the workers who are associated with the unit of production.

2) Manufacturing overhead captures other costs not related to direct material cost and direct labor cost. Manufacturing overhead includes such things as the machines and the buildings needed to produce the product, property insurance, electricity used to operate the factory equipment, indirect material cost such as lubricants, grease and water which are not used as raw materials, and indirect labor costs such as supervisors and administrative staff.

The supply chain connects suppliers, manufacturers and distribution companies to ultimately deliver products that cover customer requirements. The supply chain cost covers a number of categories, including: transportation costs, warehouse cost, shipping costs, packing and packaging costs, insurance costs and marketing cost. Given the many costs that can be included in this category, consistency is very important.

4.2.2.2 Cost of old product

There are costs associated with repairing, refurbishing, and remanufacturing products. As shown below, these include procurement and reprocessing costs.

$$C_{Pold} = C_{pro} + C_{rep} \qquad (4.3)$$

$$C_{Eold} = C_{Epro} + C_{Erep} \qquad (4.4)$$

C_{pro} = Procurement cost (including collection, take back, transport, and storage)

C_{rep} = Cost of reprocessing options such as repairing, refurbishing, remanufacturing, recycling (including disassembly, cleaning, sorting, testing and reprocessing)

4.2.3 Quality (Q)

Product quality evaluation is required for making decisions related to the life cycle design of a product. The quality of the product is related to several parameters, including reliability, functionality, and remanufacturability, which itself consists of disassembly / assemblability, cleaning ability, lubricating ability, etc.

The quality control and reliability problem of recovered products are quite different from the original ones. It is necessary to ensure the stability of the recovered products qualification in order to eliminate the public bias that recovered products are second hand products, and enhance their acceptance and market occupancy. The reliability of recovered products is one of the most important evaluation indexes of product quality, especially for remanufactured products. Reliability is the probability that an item will perform a required function under stated conditions for a stated period of time (Zhang, 2010). Statistical quality control concerns mainly reliability and manufacturing errors. The recovering equipment, production technology and production environment, and even the operation ability of workers will affect the final quality and reliability of recovered products. A product with high reliability should work properly during a normal usage time. The reliability information of components is an essential tool for determination of reusability and residual value. The most common reliability parameters that are used for quality evaluation are MTBF (mean time before failure) and MTTR (mean time to repair).

Functionality of the product expresses what the product is for and how well it can achieve its planned function at the beginning of the life. Quality of a product is related to functional behavior, and can be evaluated by analyzing the behavior (Noble and Lim, 1998). In Quality Function Deployment (QFD), function is related to parameters that represent performance of a product. Then function of the product is measured and evaluated quantitatively (Hata et al., 2000). Therefore there is a direct relation between quality and functionality parameters in such a way that increasing one of them increases the other one.

The efficiency of the disassembly sequence is an important factor in the selection of the product recovery options such as repairing and remanufacturing. Quality and economic help drive this sequence. Disassembly instructions and disassembly process plans are important factors in the evaluation of the quality of both product and processing strategies.

4.2.4 Resource consumption (R)

Manufacturing systems operate like an input – output system, in which the raw material resources enter to the system from one side and, after passing through different processes, exit from another side of the system as a final or semi product. Transformation of the raw materials is accompanied with consumption of energy and labor resources in each step of manufacturing processing. Each of these processes can have vital results for the environment and for the sustainability. The transformation of raw material and energy is illustrated in Figure 4.2.

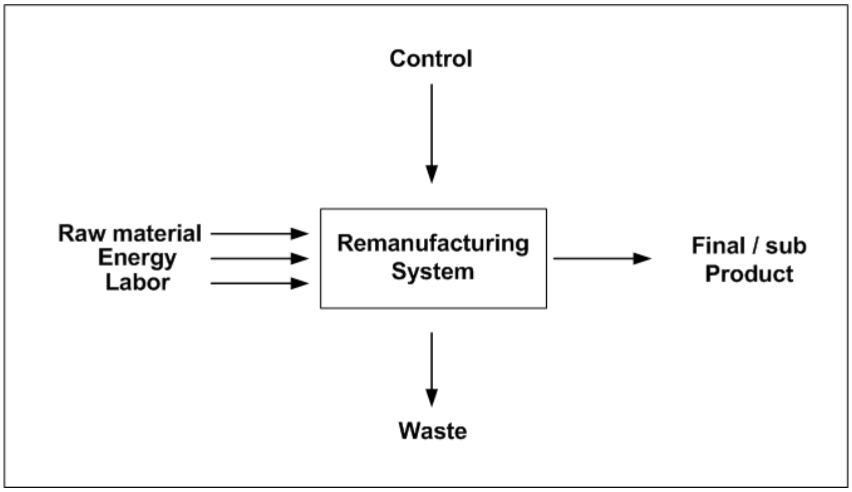

Figure 4.2 The machining system process

In both remanufacturing and manufacturing processes, energy is used in several ways. In addition to raw material, auxiliary materials can be added to products or processes in any step of manufacturing. An example is the material that is used to service cooling or heating equipment (lubricating or cleaning material).

4.2.5 Time (T)

There are several parameters which are influential in the product recovery schedule. The complexity of each product recovery method is different and, thus, each method has a different time requirement. By analyzing the product recovery process in each step, a flow chart can be drawn and the important influencing parameters of processing rate can be determined. The most two influential parameters in the product recovery time schedule are quantity and material property.

The time of recovery process strongly depends on the quantity of components. The amount of material available for return to production through each of the product recovery options is directly proportional to the number of products currently in use, the rate of obsolescence or failure, and the fraction of these products which return to the recovery processes. In addition, the processing time will be increased with the complexity of product disassembly. The other factor that affects disassembling time and that ultimately has an influence on recovery processing time is related to product material. For example, disassembly of some products which contain hazardous substances or toxic material might need to undergo special treatment that takes extra time. The product recovery time schedule, (t_i), is a function of these two main parameters. If *a* and *b* represents the quantity and material property respectively, then (t_i) can be defined as in Equation (4.5):

$$(t_i) = f_i\,(a, b) \qquad \& \qquad i = 1, 2 \ldots n \tag{4.5}$$

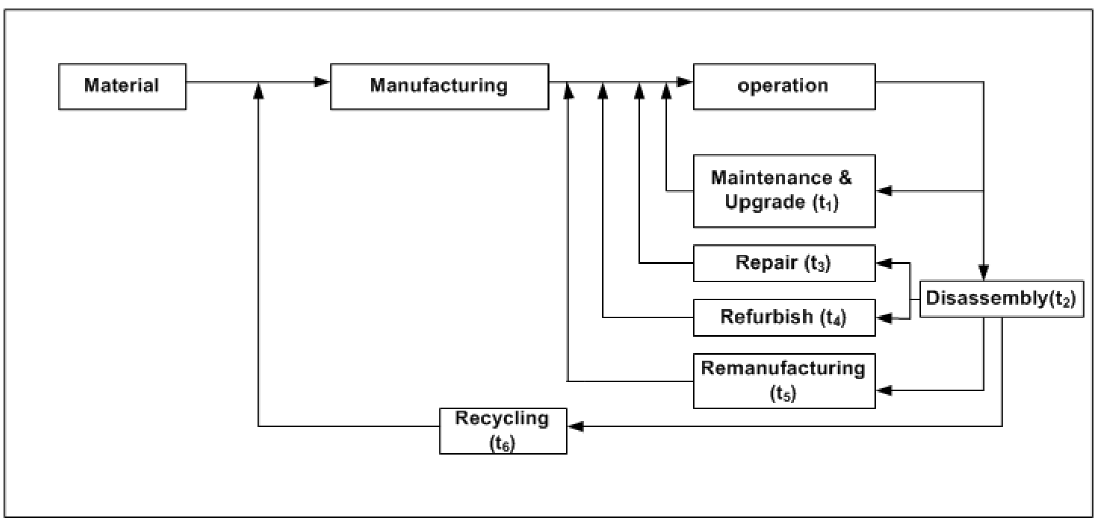

Figure 4.3 The product recovery time schedules associated with each processing step

As shown in Figure 4.3 the proper product recovery time schedules for each processing method can be estimated by summing the times of each step as (4.6).

$$t_i = \sum_{j=1}^{n} (t_j) \tag{4.6}$$

t_i= time of each process (i=1, 2, 3… 6)

t_j= time of each step in each process

4.3 Optimization of objective factors

Each decision-making problem in GM is related to some or all of the five objective factors. Depending on the type of product (for example, appliance, automobile, electronic, etc.) the manufacturers will need to determine which objective factors are the most relevant for the product recovery decision. In any case, from the viewpoint of GM, an environmental impact (E) will need to be one of the essential factors considered. To demonstrate how the objective factors may be optimized, consider the factors of environmental impact (E), cost (C), and quality (Q) as show in Figure 4.4. As previously discussed, environmental impact and cost must be minimized, while quality should be maximized. Furthermore, in this model increasing the value of quality (Q) will increase the values of the cost (C) and environmental impact (E). The relative values of the three objective factors may be solved using optimization techniques.

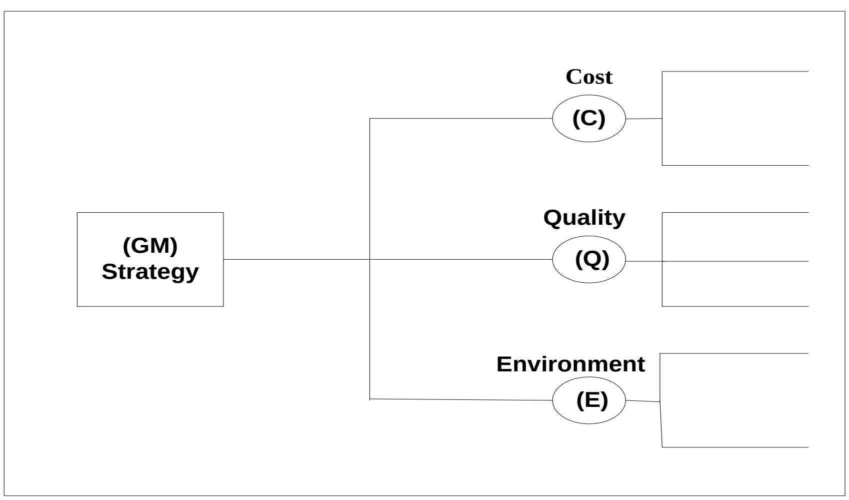

Figure 4.4 The objective factors of C, Q, and E in a GM strategy

Optimizing the objective factors in a decision making model can lead to the selection of product recovery options that result in products of high quality with relatively low environmental impacts and costs. In order to apply optimization techniques, information about the process, including design, processing control, packaging, and transportation, among other issues, is required.

The easiest way to optimize the objective factors is through goal programming. Implementing goal programming requires a system utility function which can be created by listing the attributes of the system and incorporating these by forming a weighted sum of measures of the attributes. The objective factors including environmental impact (E), cost (C), quality (Q), resource consumption (R), and time (T) are indicated by attributes X_1, X_2, X_3, X_4, and X_5 respectively which are obtained in quantities of $x_1, x_2, \ldots, x_n$. The weight associated to each attribute is as the following:

w_1: The weight related to X_1 (environmental discharges)

w_2: The weight related to X_2 (cost)

w_3: The weight related to X_3 (quality)

w_4: The weight related to X_4 (resource consumption)

w_5: The weight related to X_5 (time)

The weights are normalized as described by equation (4.7) and the weighted average is calculated by equation (4.8)

$$\sum_{i=1}^{5} w_i = 1 \tag{4.7}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i \cdot x_i}{\sum_{i=1}^{n} w_i} \tag{4.8}$$

Optimizing the integrated attributes in the system, maximizes the manufacturing profit and minimizes its environmental discharges. It will be appropriate to treat the attributes of a system as utility independent. The multi attribute utility function is a valid form for utility measure. The functional forms work only when the system utility (U_s), can be separated into component utilities indicating the utilities of the different attributes as in equation (4.9).

$$U_s = f\,[u_1(x_1), u_2(x_2), u_3(x_3), u_4(x_4), u(x_5)] \qquad (4.9)$$

where u_1, u_2, u_3 … are the utilities of attributes X_1, X_2, X_3,… obtained in quantities x_1, x_2, x_3, …x_5. The attributes are considered as independent attributes. The additive utility function form is the most regularly used utility for solving engineering problems. The utility-independent system is described in terms of 'n' attributes as given by equation (4.10).

$$U_s = \sum_{i=1}^{n} w_i \,.\, u_i(x_i) \qquad (n=1, 2 \ldots 5) \qquad (4.10)$$

Where U_i = the utility of attribute i occurring in quantity x_i and w_i = a weighting factor. Extending the objective factors framework for different methods of GM strategy can be considered as a valuable method for decision making and can be used for the selection of the best recovery option. Based on the above explanation, the framework for the decision making model involves different methods of GM as depicted in Figure 4.5.

It is supposed that four decision variable vector $x_i = (v_1, v_2 \ldots v_n)^T$ is used to indicate different methods of GM which are applied to manufacturing, and v_1, v_2, v_3, v_4 are the decision variables which represent each method of GM strategy as in equation (4.11):

$$v_i = \begin{cases} 0 & \text{unadopted method} \\ 1 & \text{adopted method} \end{cases} \qquad (i= 1, 2 \ldots n), \quad (n=4) \qquad (4.11)$$

Based on above illustration, the decision making framework model of different methods of GM can be considered as described in equation (4.12).

Minimizing $U_s = w_1u_1(x_1) + w_2u_2(x_2) + w_3u_3(x_3) + w_4u_4(x_4) + w_5u_5(x_5)$ (4.12)

Subject to: $\sum_{i=1}^{n} x_i = 1$ $(n = 1, 2 \ldots 5)$

$x_i = 0$ or $x_i = 1$

The presented optimization model can also be solved through goal programming.

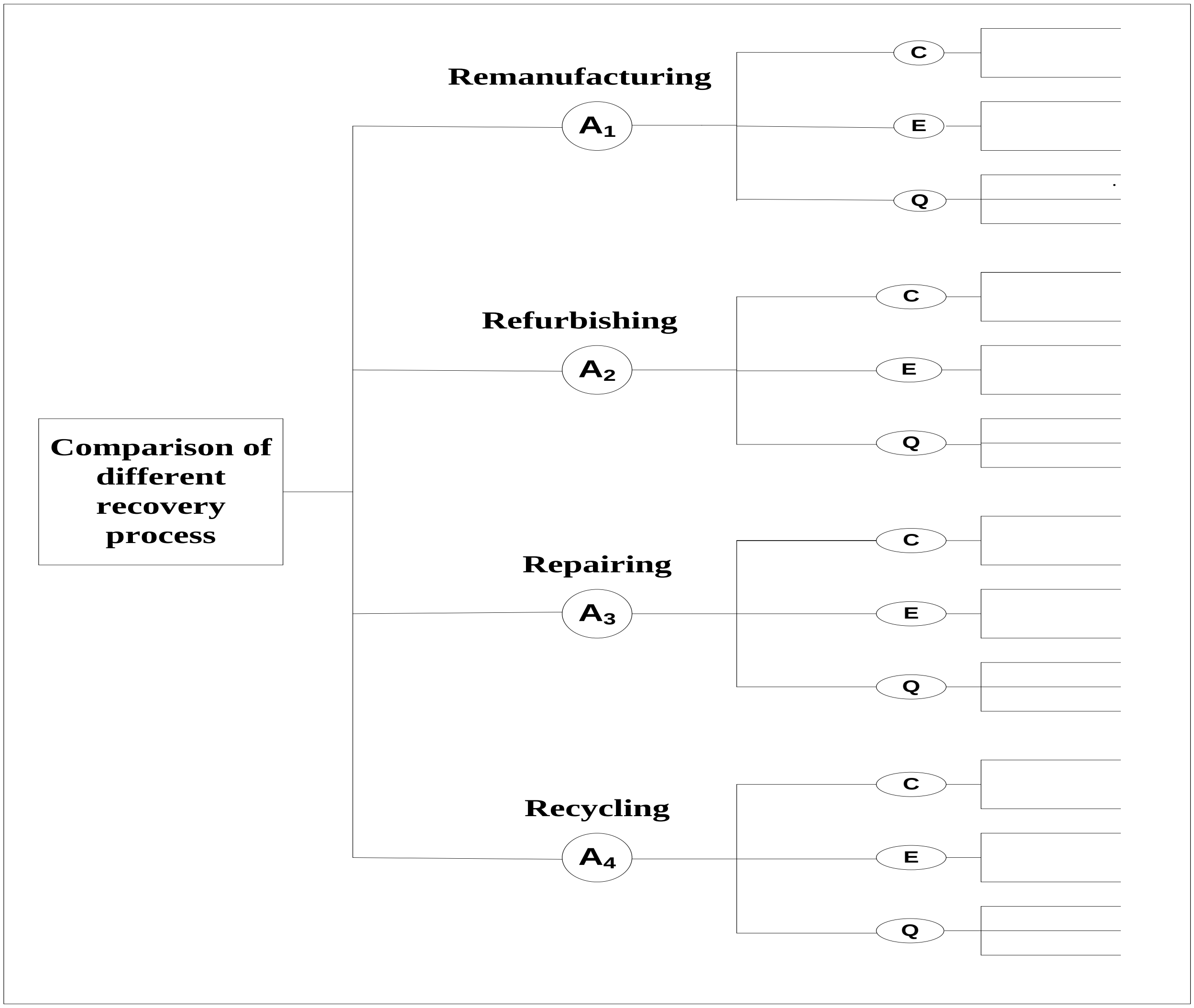

Figure 4.5 The comparison making model for selecting the best recovery option for the production process.

4.4 Parameter 2: Market Demand

Market information includes knowledge regarding the demand and price of recovered components and modules that constitute the end-of-life product. Since this determines the economic viability of product recovery operations, they are essential for deciding the optimum disassembly level and EOL strategy of products (Parlikad, 2007). For instance, knowledge regarding market demand and price for a particular component will help the remanufacturer to decide whether it is economical to disassemble the end-of-life product and retrieve that particular component for reuse, for remanufacture, or to recycle it for material recovery.

Sales information focuses on the sales history of parts and materials. Sales history contains information on the quality, quantity, and price of parts sold in a specified period of time. This information is important to the manufacturer in the collection and sorting activities, as the manufacturer needs to assess the potential demand and hence purchasing cost of end-of-life parts / materials. Without this information, the product might end-up being recycled for material recovery or even disposed, when it could have been potentially reused.

In economic terms demand can be defined as the quantity of a product or service which consumers are willing and able to buy during a given period of time. As a consequence, demand forecasting is the art of predicting the level of demand which might occur at some future point or period of time. In other words, demand forecasting is a function of the assessment of service or the quantity of a product which will be purchased by consumers. The development of a demand forecast is performed by two techniques, including informal methods, such as educated predictions, and quantitative methods, such as consideration of documented sales data or current (present) data from the market. The reasons for using demand forecasting is to make decisions on pricing and future capacity as well as to make decisions on whether to participate in a new market or leave the current market. Demand forecast modeling also considers market size and the dynamics of market share over a period of time. Demand forecasting is not 100% accurate, but the use of forecasts, such as reference class forecasting, can improve accuracy of estimates and help reduce the probability of large errors.

4.4.1 Reference class forecasting

This method predicts the result of a tentative project action according to real results in a reference class of similar actions to that being forecast (Flyvbjerg, B, 2007). Reflecting reference class forecasting on a particular project involves three steps:

1) Distinguish a reference class of past and a similar class.
2) Organize a probability distribution for the variables that is being forecast in the selected reference class.
3) Comparison between the reference class distribution and the specific project should be performed in order to find the most likely result for the particular project.

4.4.2 Factors affecting demand

The essential factors that affect the demand for a good or service include:

1) **Price of product:** According to the law of demand, there is a reverse relationship between price and quantity demanded. That is, when one of them increases; the other one will be decreased.

   $$\text{Demand} \propto \frac{1}{\text{Price}}$$

2) **Income of the consumer / buyer:** The effect of income on market demand depends on the type of product. In other words, for typical products, when income is increased the

demand for the product will be increased and when income falls, the demand for the product will be decreased.

3) **Advertising and marketing:** Many manufacturers use aggressive selling techniques including ads in newspapers, magazines, TV, and radio in order to induce people to buy their products.
4) **Availability of product:** The availability of the product has an important role for enhancement of demands. The greater the distribution of the product, the greater the chance of sale will be increased.
5) **Export of product:** Exporting of products can increase market share in other markets and therefore lead to increased demand.

To be competitive in a market, it is also very important to present a product with high quality. Below a model is developed for efficiently integrating the uncertainty about future demand in the market, so that demand parameters with correlated probability distributions may be established and continually revised. A demand modeling mechanism is proposed with a Bayesian update structure that incorporates both documented demand and expert determination into the methodology generation process.

The uncertainty about market demand makes it complicated for manufacturers to select a manufacturing procedure that is both responsive to customers and profitable for the company. Beyond the traditional approach to supply of products, a manufacturer can have a higher profit if they adopt a revenue management approach by delaying the delivery of current less profitable supply of products and wait for favorable market. Applying this strategy can cause manufacturers to save a certain amount of products for the future where the supply is more profitable. It would not be possible to achieve this strategy without effective prediction of future market demand and a mechanism for integrating uncertainty into decision making.

Development of a procedure for estimating market demand which is compatible with the decision making model can be very important for manufacturers in selecting the appropriate method for product recovery. The procedure must reduce the complexity of the demand assessment process sufficiently, so as to enable the use of the documented demand and Bayesian updated demand model for generating the parameter estimates for the plan structure. With that in mind, the next subsection describes the problem of generating demand category. In the following subsections a method for a minimum set of attributes for specifying demand values is described that serves as the basis for the decision making structure. A Bayesian forecasting based on linear demand model is proposed for individual recovery options. The demand model incorporates information from multiple sources that include documented sales, field knowledge, etc.

4.4.3 Creating demand category

Categorization of market demand and the set of categories for a decision making model is essential for manufacturers to select the best method for product recovery. The procedure reduces numerous demands which may be documented during a specified period of time to the relatively few categories that are required as inputs to the decision making tree model.

To represent the numerous demands, the decision tree illustrated in Figure 4.6 is proposed. The first sets of branches of the decision tree structure are related to the different methods of GM for the specific product. The second sets of branches are allocated to the three possible categories of demand, including large, medium and small. This categorization is performed based on the manner described below:

(n_3) Revenue $< Y_1$ → related to "Small Demand"

$Y_1 \leq (n_2)$ Revenue $< Y_2$ → related to "Medium Demand"

$Y_2 \leq (n_1)$ Revenue → related to "Large Demand"

Y_1, and Y_2, indicate two different revenue values related to the categorization border which are arranged from the minimum to maximum values ($Y_1 < Y_2$). The categories of small, medium and large are chosen in terms of expectation of sales. (n_1), (n_2) and (n_3) indicate the number of revenue values in each categorized demand. For example if 10 records from a total of 60 records have revenues between Y_1 and Y_2, then the probability of the demand is 10/60 and the average revenue is calculated within the 10 records.

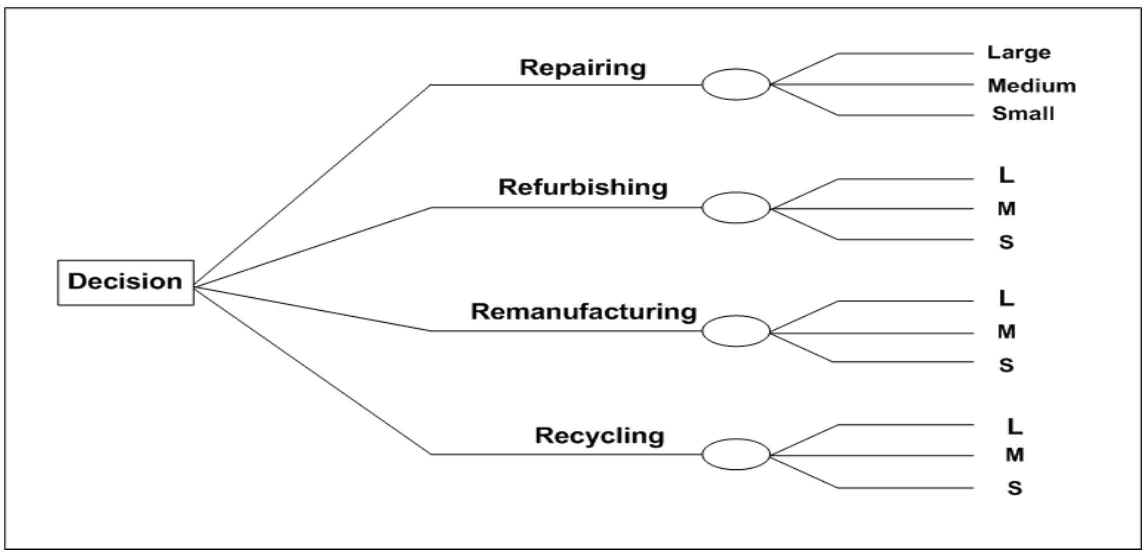

Figure 4.6 Demand categorizations for different demand values

With evaluation of different levels of demand, the manufacturer has flexibility in planning production quantitatively and has sufficient information for determining the most appropriate method of product recovery. The decision tree tool is a valuable procedure for constraining demand so that the best method is recognized for production.

4.4.4 Demand assessment for different manufacturing options

To allocate values and probabilities for each of the branches of the decision tree, demand as a random variable must be defined and then evaluate some of parameters such as α and β and its distribution. This evaluation is required for determination of the uncertainty associated with demand. Moreover with consideration of this distribution based on expected value, the probability associated with each category of demand can be estimated. A separate demand model is developed for each GM option and manufacturing method. In this assessment, the number of branches depends on the different types of methods that are considered by the manufacturer. These critical configurations along with their associated numerical distributions form a set of distributions for the decision making problem.

4.4.5 Bayesian forecasting model

Bayesian forecasting is the particular method used for predicting the quantity of the market demand as a probability distribution. This permits the regulated integration of subjective information and experienced demand into the decision making model. Bayesian forecasting can also be used for a diversity of applications, including reliability of production, market demand, manufacturing cycle time, etc. For example, having information about the demand, revenue, and supplier preference for specific product is crucial for making this prediction. Equation (4.13) describes Bayesian Theorem (Bijak, 2006):

$$P\,(A \mid B) = \frac{P\,(B \mid A)\,.\,P\,(A)}{P\,(B)} \tag{4.13}$$

If the equation can be extended to parameter estimation in such a way that the likelihoods are equal to P (data | hypothesis), it is necessary to find the P (hypothesis | data). Therefore, the Bayesian theorem can be used for determining the probability as shown in equation (4.14):

$$P\ (\text{hypothesis} \mid \text{data}) = \frac{P\ (\text{data} \mid \text{hypothesis})\ .\ P\ (\text{hypothesis})}{P(\text{data})} \quad (4.14)$$

P (hypothesis) is called the prior probability because it represents former beliefs about the probability of a given hypothesis. P (hypothesis | data) is called the posterior probability, meaning that it represents the belief about the hypothesis after collection of the data (Bijak, J, 2006).

4.4.6 Assessment of parameter values for each manufacturing type

The forecast Bayesian model is evaluated as a prior probability based on documented sales (D_t) during a period time, and the quantity of supplied products (K_t). An example is, if a sales representative knows that a large order is going to be placed in a market that will affect the demand for a specific product. At any time during the forecast assessment, the prior probability distribution illustrates the state of discernment about demand and involves both data of information related to future manufacturing method. These priors (demand and orders) can be represented as conditional probabilities as follows:

$P\ (\alpha \mid D_t, K_t)$ and $P\ (\beta \mid D_t, K_t)$ where:

D_t: Sales data received in time period t

K_t: Supplied products information in specific period time

α, β: Market knowledge

The prior distribution for the parameters α and β (market knowledge) can be used for deriving a model of demand in the context of the decision making tree.

The probabilities related to the parameters (α and β) are reevaluated based on Bayesian formulas. The result of this is the posterior probabilities for the parameter values of the demand model.

The probability distribution related to these parameters can be performed at each performance cycle as long as the new sales information has been received at the point the parameters α *and* β are renewed by use of the Bayesian rule as equation (4.15):

$$P\ (D_t \mid \alpha) = \frac{P\ (\alpha|D_t)\ .\ P(D_t)}{P(\alpha)} \tag{4.15}$$

The parameter of the demand can be generated by a transformation process where a prior distribution for parameters is initially demonstrated and then a posterior probability for the parameters of the demand is resulted (Meixell and Chen, 2004).

4.4.7 Summary

Decision making models are becoming increasingly important in controlling the number of manufactured products and production management particularly in competitive environments. Even though decision making models have been used in practice for decades, there continues to be research challenges relative to advanced methods that explicitly incorporate demand uncertainty into the decision making process. This study extends research on decision making for determining product recovery strategy where new sales observation and field knowledge of impending different methods are available for use in developing a view of future demand. The Bayesian updated demand model and illustration demonstrate that the complexity and the uncertainty in this problem class may indeed be well managed to provide a useful basis for modeling demand for each type of manufacturing strategy.

CHAPTER 5: Example Studies

In this section two example studies are discussed to show how to select a suitable recovery process among four types of product recovery options and current manufacturing methods. The product recovery options include repairing, refurbishing, remanufacturing and recycling. The first example study is related to objective factors. The second example study focuses on market demand.

5.1 Overview of decision making model

In recognition of legal demands and the need to recover products in an economic manner, a manufacturer must systematically consider EOL options to remain competitive. In addition to internal factors there are several external influencing factors which should be considered in balancing decision alternatives. These external factors include improvement of technology, development of legal regulations, market competition and the condition of returned products. It is important to mention that the subjective probabilities associated with these factors can be obtained by questioning experts to gain the needed data. An approach to multi-stage dynamic decision making is a decision tree which represents the possible decisions and the influential external events. The basic structure of the decision tree is illustrated in Figure 5.1.

t : Period, t = 1, 2… n

j : Decision alternatives

S_{ti} : State of nature in t which leads to decision node

D_{ti} : Decision node i in period t

S_{tj} : Chance node j in period t

P_{ti} : Probability that state of nature S_{ti} will occur

R_{ti} : Result node if the state of nature S_{ti} occurs in period t

R_{tj} : Result node of a decision alternative j period t; R_{tj}= R_{ti}

EMV {R_{tj}}: Expected value of result R_{tj}

μ*t*:* Maximum expected value of all decision alternatives j in period t

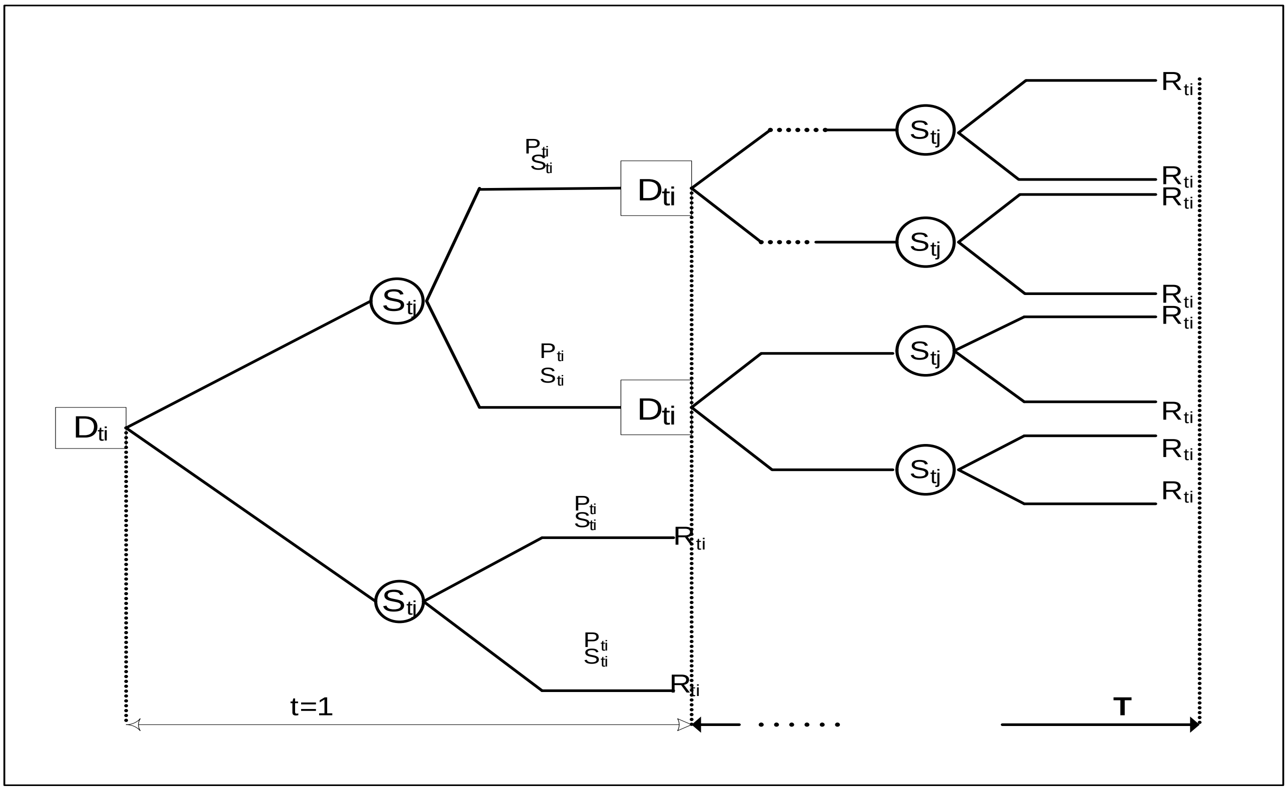

Figure 5.1 Basic structure of a decision tree

In Figure 5.1 squares show decision nodes (D_{ti}) and circles indicate chance nodes (S_{tj}), which represent states of nature characterized by the external influencing parameters mentioned above. For evaluating of stochastic situations, the expected monetary value is required to identify the best decision option (j). The expected monetary value of the result R_{tj} is the sum of the weighted result R_{ti} for the decision options calculated by equation (5.1)

$$\text{EMV}\ (R_{tj}) = \sum (P_{ti}\ .\ R_{ti}) \tag{5.1}$$

In all decision options j, the maximum (EMV) must be detected and the sum of probabilities related to the states of nature for one chance node is equal to one, μ_t*= max (EMV (R_{tj})) and $\sum P_{ti}$=1.

An optimal solution must be found from the last stage of the problem and will be continued step by step by moving backwards until every stage including the first is covered and the optimal procedure for the entire decision problem has been found.

5.2 Example 1: Objective factors

The first example focuses on the objective factors and how they can help the manufacturer to select a product recovery options in the context of a GM strategy. The objective factors include environmental impacts, quality, resource consumption, cost and time. It is important to acknowledge that the number of objective factors selected in decision making problems vary differently. Manufacturers may focus on some or all of the objective factors. The decision makers depend on condition of production to determine the objective factors that are effective for their particular decision making problems. For example, if the manufacturers realize that the quality of product is the most important parameter, it is possible that they won't consider the factors of time and resource consumption in their decision making problem. Therefore, each decision-making problem in GM is related to some or all of the five objective factors.

5.2.1 Overview of example

In this example, three objective factors including quality (Q), cost (C) and environmental impact (E) are considered in the decision making model. It is supposed that the objective factors are optimized by goal programming to obtain the required weights, expert judging may be applied in the decision making process.

The uncertainty associated with the example is related to the weights of the objective factors and different indexes. Availability of information such as expert judging facilitates the product recovery decision. Moreover, if the data of indexes is in form of a fuzzy matrix, it could be solved by multi fuzzy assessment theory in order to find single data for every index. Subsequently, the objective function for optimization would be a linear equation.

5.2.2 Example 1

Table 5.1 includes the required information for decision making about recovery option. In this example A_1, A_2 and A_3 are represented as refurbishing, remanufacturing and recycling methods respectively.

Table 5.1 The assessment data of the example study related to objective factors

Objective	(w_i)	indexes	(w_i)	method	index value
Quality	0.4	Reliability	0.5	A_1	0.45
				A_2	0.7
				A_3	0.8
		Functionality	0.3	A_1	0.50
				A_2	0.64
				A_3	0.82
		Recycling ability	0.2	A_1	0.60
				A_2	0.72
				A_3	0.79

Environmental Impact (E)	0.3	Ecological issues	0.6	A_1	0.35
				A_2	0.69
				A_3	0.80
		Safety issues	0.4	A_1	0.7
				A_2	0.61
				A_3	0.78
Cost (C)	0.3	product Cost	0.7	A_1	0.55
				A_2	0.71
				A_3	0.82
		Environmental Cost	0.3	A_1	0.5
				A_2	0.65
				A_3	0.9

In the example, it is supposed that three options, including refurbishing, remanufacturing and recycling methods, are considered for product recovery by the manufacturer. In addition, it is supposed that at first the required objective factors are optimized by goal programming and then the decision making model is applied for selecting the best recovery option. Furthermore, all weights related to the factors and indexes (sub-factors) are obtained through the subjective judgment of experts with experience in traditional comprehensive evaluation methods, which are used in evaluation analysis. The three objectives of quality (Q), cost (C) and environmental impact (E) are the critical factors considered to cause impact on the selection of the appropriate product recovery option in this example.

The indexs have variable values and constant weights. For example, the value of reliability in refurbishing, remanufacturing and recycling is 0.45, 0.7 and 0.8 respectively, but its weight is constant and equal to 0.5 in all methods. The quality, environmental impact and cost as the objective factors have values equal to 0.4, 0.3 and 0.3 respectively, which are constant in all three recovery methods. Weights are obtained through the subjective judge of experts in traditional evaluation methods, which are used in evaluation analysis.

Figures 5.2 and 5.3 provide an overview of the decision making model based on information in Table 5.1.

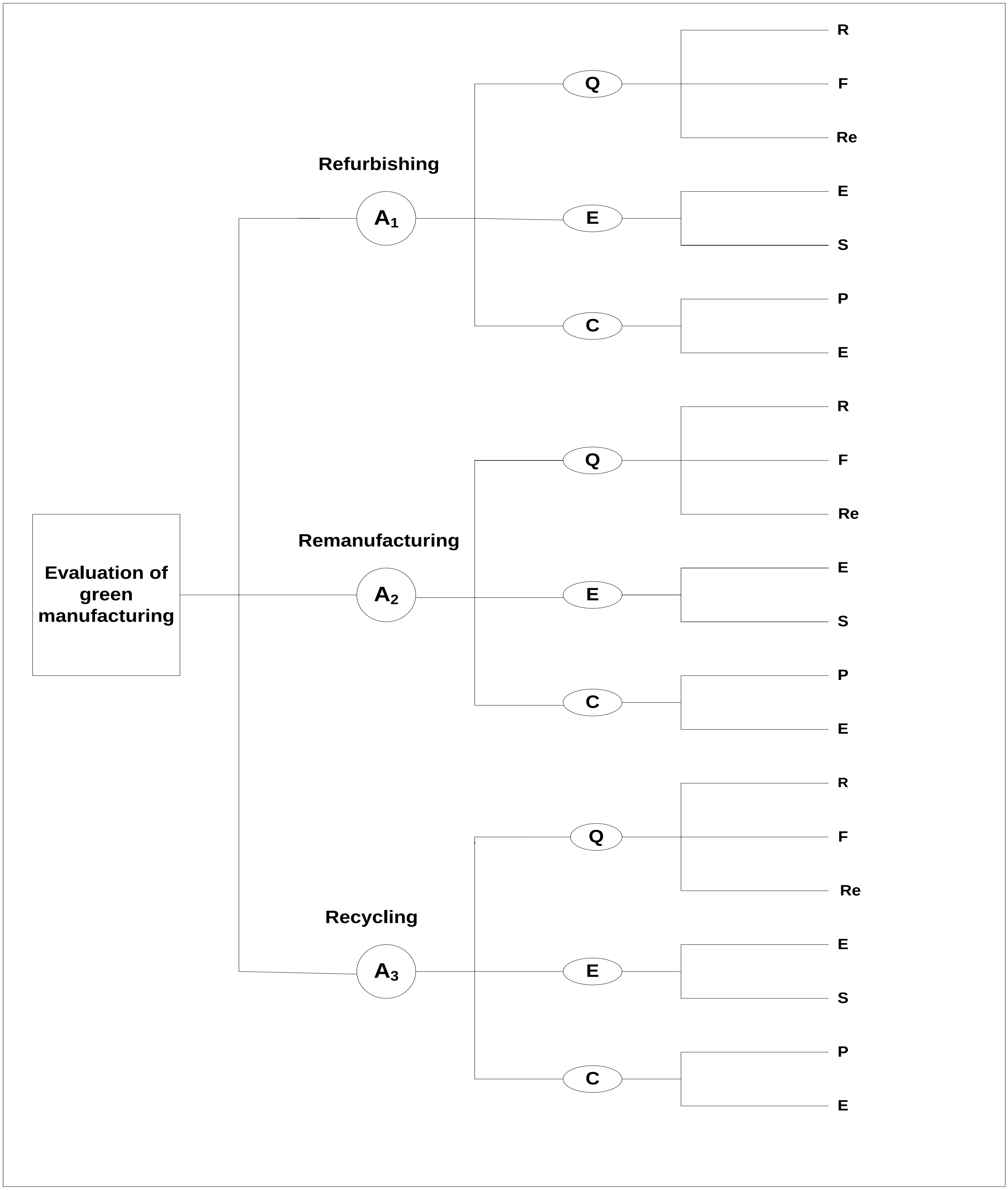

Fig 5.2 The comparison making tree related to the example of objective factors (without value)

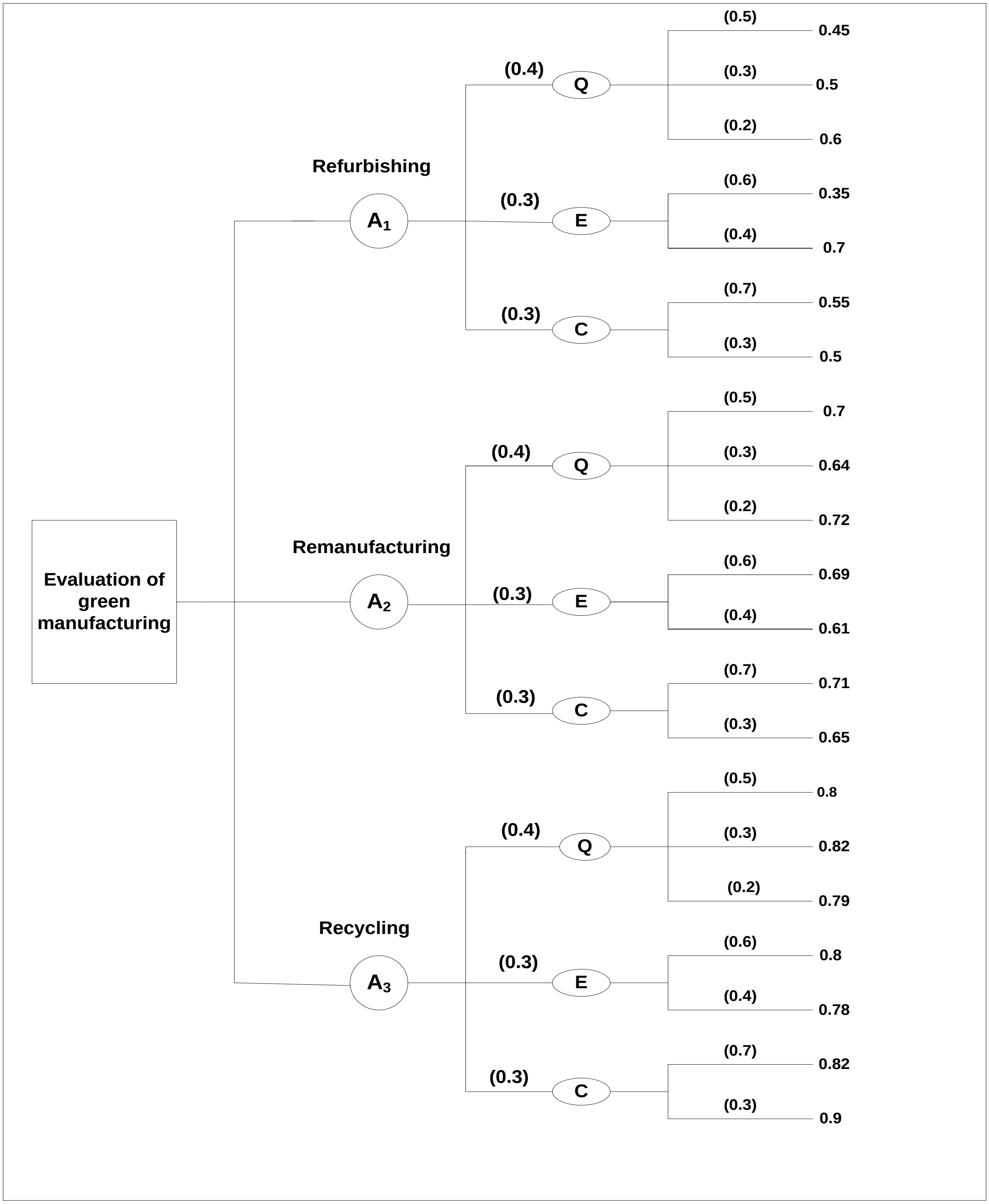

Figure 5.3 The comparison making tree related to the example of objective factors (with value)

5.2.3 Solution:

As Figure 5.2 shows, there are three main branches associated with refurbishing, remanufacturing and recycling methods. Detection of the maximum expected monetary values is required for identification of the best recovery option. Thus, for the first step, expected monetary value of each branch must be calculated. EMV of all branches is estimated by equation 5.1.

The first set of branches of the decision making tree are related to the refurbishing method.

Evaluation of EMV (A_1) related to "Refurbishing" method:

(Q) Value: $[(0.5 \times 0.45) + (0.5 \times 0.3) + (0.6 \times 0.2)] = 0.495$

(E) Value: $[(0.35 \times 0.6) + (0.7 \times 0.4)] = 0.49$

(C) Value: $[(0.55 \times 0.7) + (0.5 \times 0.3)] = 0.535$

$EMV\ (A_1) = [(0.495 \times 0.4) + (0.49 \times 0.3) + (0.535 \times 0.3)] = 0.505 \approx 0.5$

The second set of branches of the decision tree is related to the remanufacturing method.

Evaluation of EMV (A_2) related to "Remanufacturing" method:

(Q) Value: $[(0.7 \times 0.5) + (0.64 \times 0.3) + (0.72 \times 0.2)] = 0.686$

(E) Value: $[(0.69 \times 0.6) + (0.61 \times 0.4)] = 0.658$

(C) Value: $[(0.71 \times 0.7) + (0.66 \times 0.3)] = 0.692$

$EMV\ (A_2) = [(0.686 \times 0.4) + (0.658 \times 0.3) + (0.692 \times 0.3)] = 0.679 \approx 0.68$

The third set of branches of the decision tree are related to the recycling method.

Evaluation of EMV (A_3) related to "Recycling" method:

(Q) Value: $[(0.8 \times 0.5) + (0.82 \times 0.3) + (0.79 \times 0.2)] = 0.804$

(E) Value: $[(0.8 \times 0.6) + (0.78 \times 0.4)] = 0.792$

(C) Value: $[(0.82 \times 0.7) + (0.9 \times 0.3)] = 0.844$

$EMV\ (A_3) = [(0.804 \times 0.4) + (0.792 \times 0.3) + (0.844 \times 0.3)] = 0.812$

After calculation of EMV related to each branch, as the second step the maximum (EMV) must be detected.

$$\mu^* = Max\ \{EMV\ (A_1) = 0.5, EMV\ (A_2) = 0.68, EMV\ (A_3) = 0.812\} = EMV\ (A_3) = 0.812$$

Comparison of these three values indicates that the EMV (A_3) has the biggest value. Thus the recycling process should be selected as the product's recovery method. This example shows qualitatively how availability of product information has a positive impact on product recovery decision. Moreover, it indicates that green manufacturing problems in product recovery have an application perspective and the decision making model is practical.

5.3 Example 2: Market demand

The second example study is related to market demand. It shows how external information can be considered for selecting the best recovery option. In this example, the parameter of demand is classified in three categories: large, medium and small.

Depending on different types of products supplied to markets, different types of recovery processes are considered in the decision making model. For example, the products supplied to markets may be produced by only two methods, such as refurbishing and remanufacturing. Thus, these mentioned methods would be considered in the decision making model. Assessment of market demand associated with each product helps the manufacturer determine the most appropriate method to consider.

5.3.1 Overview of example

In this example, it is proposed that two types of one product related to the automobile industry are supplied to the market. One is a refurbished motor pump and the other is remanufactured motor pump. Five years of sales history for both products were obtained from a major Middle East automobile manufacturing. The data is available in appendix 1.

In this example it is supposed that the company is going to extend another type of motor pump through a new remanufacturing method. The decision making model implies that assessment of market demand should be done by the company before it applies the new method. Bayesian forecasting may be used for predicting the quantity of the market demand as a probability distribution allowing for the disciplined integration of subjective knowledge and historic sales into the model. The company wants to find out which of the following production methods is the most profitable approach: the new remanufacturing method, refurbishing method and current manufacturing method.

5.3.1.1 Remanufacturing method

The total cost of the remanufactured product is about $80,000, including processing, material and marketing, and the revenues are $300,000 and $50,000 for large and small demand in a favorable market, respectively. The revenues for large and small demand in an unfavorable market are $200,000 and $30,000 respectively.

The market demand is predicted to be 30% for large demand and 70% for small demand by the company. According to market research, if the market demand is large, the probability of the market to be favorable is 0.9. Also if the market demand is small; the probability of the market to be unfavorable is 0.9. In the remanufacturing method, the appropriate probability of favorable and unfavorable market is calculated based on "Bayesian Rules" shown in Figure 5.4.

5.3.1.2 Refurbishing method

The refurbishment method is the second possible production method that the company may adopt based on the output of the decision making model. In this approach, the supply of products to the market depends on “Wait” and “Act now” policies. The company for supplying the products can wait for a favorable market with the probability of 0.6 or it can supply the products immediately (Act now) with the probability of 0.4. It is supposed that the probability values are obtained from expert judging. The information necessary to evaluate the refurbishing method is provided in Tables 5.3 and 5.4. The revenue and probability of each of demands have been obtained from real data in the market.

5.3.1.3 Current manufacturing method

In this method, similar to the refurbishing method, the “Wait” and “Act now” policies were adopted for the decision making model. However, the information to evaluate current manufacturing is obtained from Tables 5.5 and 5.6. In further details on the mentioned data and evaluation procedure in the example are provided in the following section. The schematic diagram of the proposed decision making model for current manufactured production is shown in Figure 5.7.

5.3.2 Solution:

According to the above explanation, there are three main branches associated with remanufacturing, refurbishing and current manufacturing methods. Detection of maximum (EMV) is aimed for determining the best method for production process.

The first set of branches is related to the remanufacturing method which is constructed based on the Bayesian forecasting.

Calculating (S_{11}) value of remanufacturing method

To estimate the value of (S_{11}), the first step is to calculate the particular probability based on Figure 5.4.

Probability Analysis

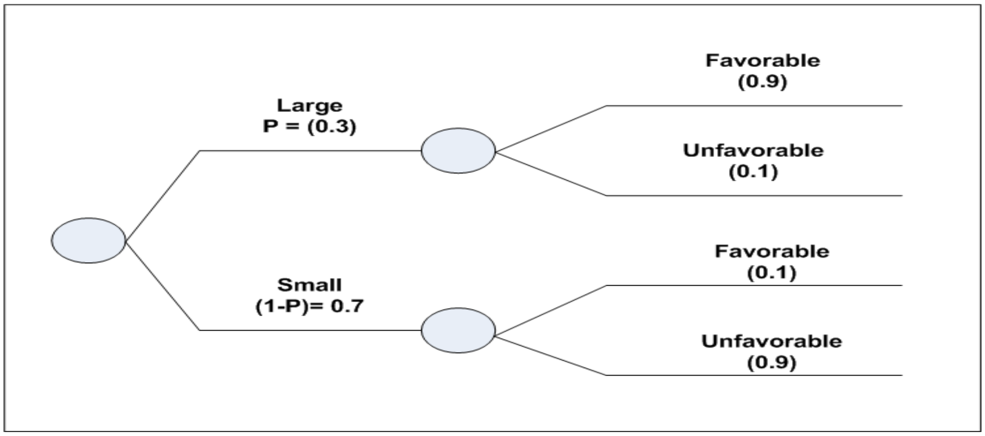

Figure 5.4 The probabilities related to predicted market

The formulas used in below calculation are as the following:

$P\ (A|B)\ P\ (B) = P\ (B|A)\ P\ (A)$

$P\ (A) = P\ (A|B)\ P\ (B) + P\ (A|\bar{B})\ P\ (\bar{B})$

$P\ (A|B) = 1 - P\ (\bar{A}|B)$

$P\ (favorable) = (0.9 \times 0.3) + (0.1 \times 0.7) = 0.34$

$P\ (unfavorable) = 1 - P\ (favorable) = 1 - 0.34 = 0.66$

$P\ (large) = 0.3$, $P\ (Small) = 0.7$

$P\ (favorable \mid large) = 0.9 ====> P\ (unfavorable \mid large) = 1 - P\ (favorable \mid large) = 1 - 0.9 = 0.1$

P (unfavorable | small) = 0.9 ====> P (favorable| small) =1-P (unfavorable | small) =1-0.9= 0.1

$$P\ (large \mid unfavorable) = \frac{P(unfavorable \mid large)\ P(large)}{P(unfavorable)} = \frac{0.1\times 0.3}{0.66} = 0.045$$

P (small | unfavorable) = 1- p (large| unfavorable) = 1- 0.045=0.955

$$P\ (large \mid favorable) = \frac{P(favorable|large)\ P(large)}{P(favorable)} = \frac{0.9\times 0.3}{0.34} = 0.794$$

P (small |favorable) = 1- P (large |favorable) = 1 - 0.794=0.206

P (small | unfavorable) =1-P (large | unfavorable) = 1- 0.045 = 0.955

The revenue values related to large and small demand in both favorable and unfavorable markets are shown in Table 5.2.

Table 5.2 The market status corresponding to remanufacturing process

Market status	Demand	Revenue	Cost
Favorable	Large Demand	300000	80000
	Small Demand	50000	80000
Unfavorable	Large Demand	200000	80000
	Small Demand	30000	80000

The skeleton of the remanufacturing method is the first branch of the decision making tree that has been shown in Figure 5.5. The interest value equal to zero indicates that the company doesn't supply any product to the market, so there is not any revenue.

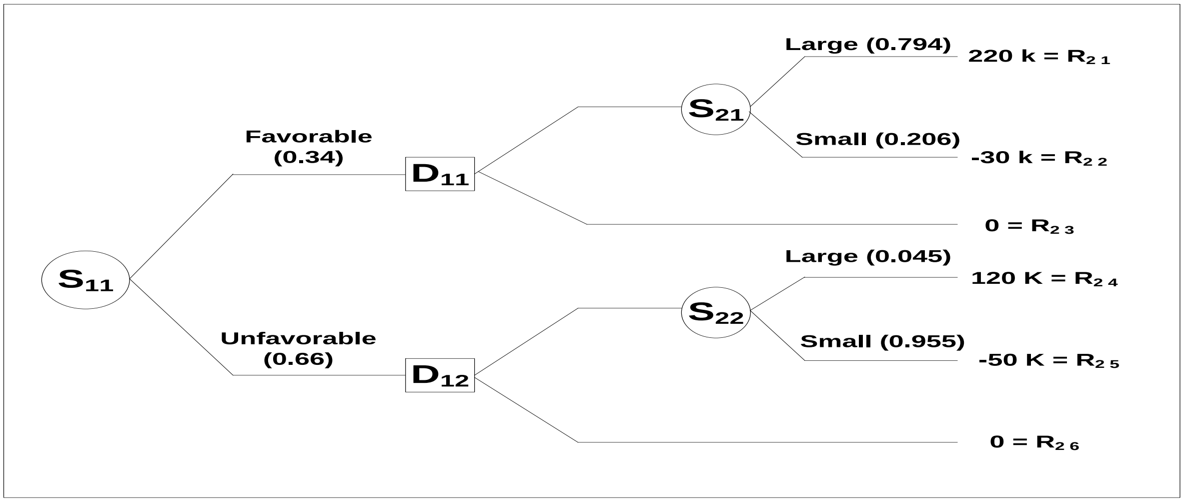

Figure 5.5 The decision tree related to the remanufacturing process

For estimation of the (S_{11}) value, the profit values corresponding to large and small demands in both favorable and unfavorable markets should be calculated as the following:

Profit = (Revenue - Cost)

Profit of large demand in favorable market= *300000 – 80000 = 220000*

Profit of small demand in favorable market= *50000 - 80000= -30000*

$EMV\ (S_{21}) = \{(220000 \times 0.794) + (-30000 \times 0.206)\} = 168529.41$

For making decision $D_{11,}$ the max (EMV) between (S_{21}) and (R_{23}) must be chosen:

$\mu_{11}^{*} = max\ \{EMV\ (S_{21}), (R_{23})\} = max\ \{168529.41, 0\} = 168529.41$

Profit of large demand in unfavorable market = *200000 – 80000 = 120000*

Profit of small demand in unfavorable market = *30000 – 80000 = -50000*

$EMV\ (S_{22}) = \{(120000 \times 0.045) + (-\ 50000 \times 0.955)\} = -\ 42350$

For making decision of $D_{12,}$ we compute similar to the above calculation. Therefore

$\mu_{12}^{*} = max\{EMV(S_{22}), (R_{26})\} = max\{-42350, 0\} = 0 = (R_{26})$

$EMV(S_{11}) = \{(168529.41 \times 0.34) + (0 \times 0.66)\} = 57300$

The EMV (S_{11}) which is related to the first set of branches in decision tree, should be compared with the EMV of (S_{12}) and (S_{13}) from the second and third branches associated with refurbishing and current manufacturing methods. For the next steps, the EMV of (S_{12}) and (S_{13}) must be calculated.

Calculating (S_{12}) value of refurbishing method

In this section we explain how to calculate the EMV (S_{12}) value of the refurbishment method. The EMV (S_{12}) value is calculated based on real data obtained from the market as shown in Tables 5.3 and 5.4. The revenues shown in the Tables 5.3 and 5.4 are the average of the revenues data collected over the past 5 years (60 months).

Table 5.3 Consumer reactions related to "wait" status in refurbishing method

No. of Revenue	Demand	Revenue	Cost	Probability(Pr)
n_1=32	Large Demand	192812.50	90000	0.54
n_2=14	Medium Demand	122857.14	90000	0.23
n_3=14	Small Demand	38571.42	90000	0.23

Table 5.4 Consumer reaction related to "Act now" status in refurbishing method

No. of Revenue	Demand	Revenue	Cost	Probability(Pr)
n_1=29	Large Demand	196896.55	90000	0.48
n_2=12	Medium Demand	108333.33	90000	0.20
n_3=19	Small Demand	55263.15	90000	0.32

It is necessary to mention that the values of the revenues shown in Tables 5.3 and 5.4 are the average of the all revenues related to each categorized demand. Each demand was determined based on each month during the last five years (Appendix 1). In addition, each record of the demand is classified in three categories of demands: Large, Medium and Small. This categorization is performed according to the value of revenue as follows:

(n_3) Revenue < 100,000 → related to "Small Demand"

100,000 ≤ (n_2) Revenue < 150,000 → related to "Medium Demand"

150,000 ≤ (n_1) Revenue → related to "Large Demand"

(n_1), (n_2) and (n_3) indicate the number of revenue values in each categorized demand. For example for Large demand in "wait status" related to the refurbishing method n_1=32 means that 32 records are equal or more than 150,000 and the average of the records is (192812.50) and its probability is calculated as following: $(32) \div (60) = 0.533 \approx 0.54$

All probabilities are calculated with following above manner. For example the probabilities of Medium and Small demands of refurbishing method in "Act now" status are calculated as following:

$(12) \div (60) = 0.2$

$(19) \div (60) = 0.32$

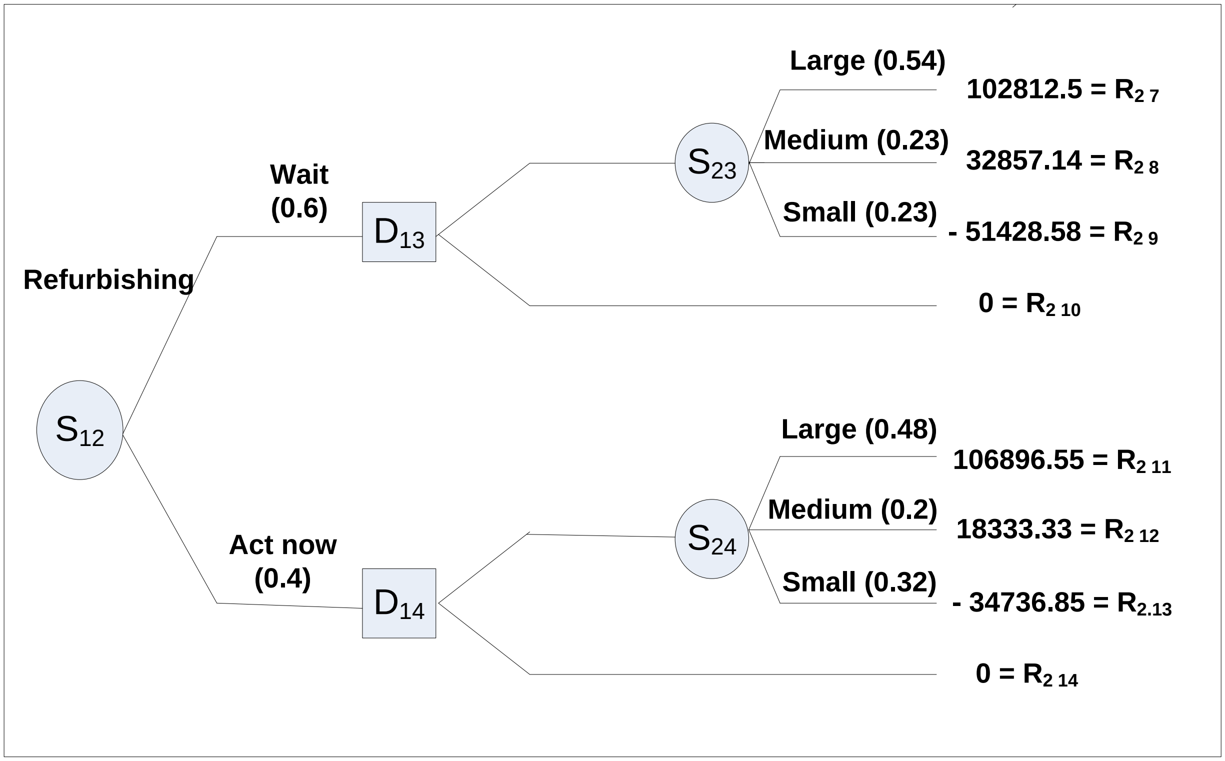

Figure 5.6 The decision tree related to the refurbishing process

Calculation of profit values of different demands corresponds to the following "wait" status in the refurbishing process:

Profit of large demand = *192812.50 – 90000 = 102812.5*

Profit of medium demand = *122857.14 – 90000 = 32857.14*

Profit of small demand = *38571.42 – 90000 = - 51428.58*

$EMV\ (S_{23}) = \{(102812.5 \times 0.54) + (32857.14 \times 0.23) + (-\ 51428.58 \times 0.23)\} = 50219.19$

For making decision $D_{13,}$ the max (EMV) between (S_{23}) and ($R_{2\ 10}$) must be chosen, so:

$\mu_{13}{}^{*} = max\ \{EMV\ (S_{23}),\ (R_{2\ 10})\} = max\ \{50219.19,\ 0\} = 50219.19$

Calculation of interest values of different demands corresponds to the following “Act now” status in the refurbishing process:

Profit of large demand = *196896.55 - 90000 = 106896.55*

Profit of medium demand = *108333.33 – 90000 = 18333.33*

Profit of small demand = *55263.15 – 90000 = - 34736.85*

$EMV\ (S_{2\,4}) = \{(106896.55 \times 0.48) + (18333.33 \times 0.2) + (-34736.85 \times 0.32)\} = 43861.22$

For making decision D_{14}, the max value between EMV (S_{24}) and ($R_{2\,14}$) must be chosen, so:

$\mu_{14}^{*} = max\ \{EMV\ (S_{24}), (R_{2\,14})\} = max\ \{43861.22, 0\} = 43861.22$

$EMV\ (S_{12}) = \{(50219.19 \times 0.6) + (43861.22 \times 0.4)\} = 47676$

The EMV (S_{12}) is related to the second set of branches which is associated with refurbishing method. In the next step, EMV (S_{13}) must be calculated in order to determination of max (EMV).

Calculating (S_{13}) value in current production method

In this section, the calculation procedure for the estimation of the (S_{13}) value is similar to the calculation of the (S_{13}) value in the refurbishing method. However the information shown in Tables 5.5, 5.6 was obtained from the dataset related to the company’s current production method and the manner of estimating the revenue values of each categorized demand is as same as the remanufactured method. It is necessary to mention that the calculation procedure for determination of the probabilities of all categorized demand including large, medium and small in current production method are exactly as same as the calculation procedure in the refurbishing method. For example the probability of large demand related to “wait” status in current production is calculated as follow: $(23) \div (60) \cong 0.38$

All probabilities of other categorized demand related to "wait" and "Act now" statuses are calculated as same as above manner.

Table 5.5 Consumer reactions related to "wait" status in the current production method

No. of Revenue	Demand	Revenue	Cost	Probability(Pr)
n_1 =23	Large Demand	195652.17	95000	0.38
n_2 =13	Medium Demand	125384.61	95000	0.22
n_3 =24	Small Demand	48333.33	95000	0.4

Table 5.6 Consumer reaction related to "Act now" status in the current production method

No. of Revenues	Demand	Revenue	Cost	Probability(Pr)
n_1= 24	Large Demand	203750.00	95000	0.4
n_2=10	Medium Demand	119000.00	95000	0.17
n_3= 26	Small Demand	46153.84	95000	0.43

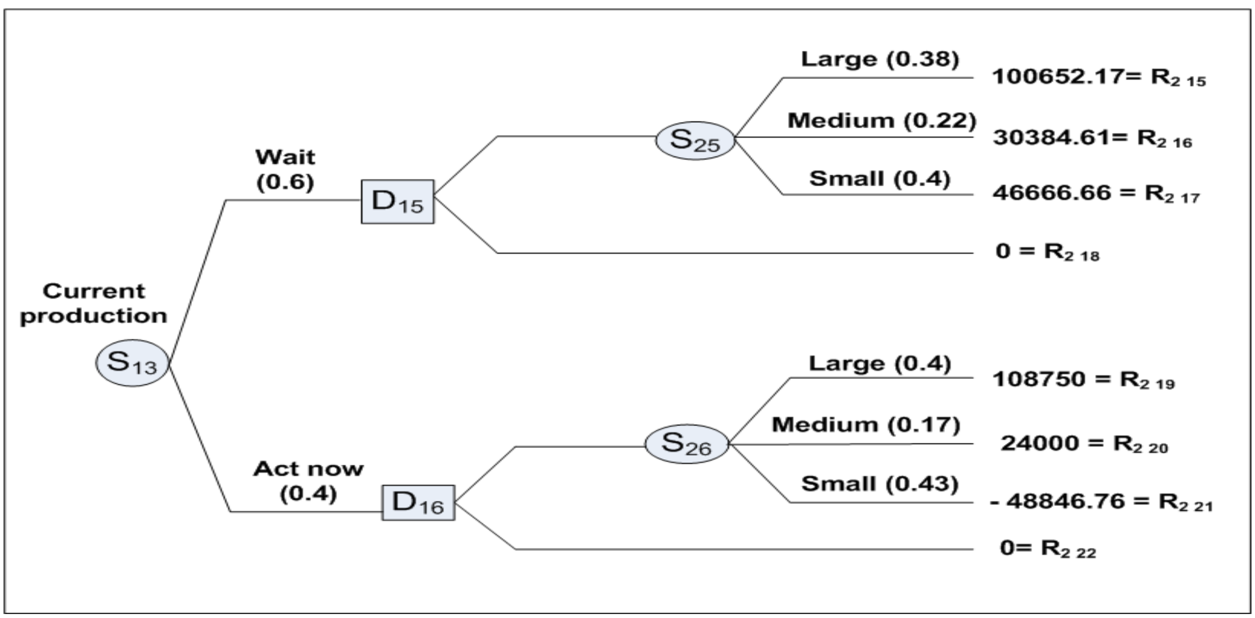

Figure 5.7 Structure of the current production processing

Calculations of interest values related to "wait" status in the current production method are as follows:

Profit of large demand = $195652.17 – 95000 = 100652.17$

Profit of medium demand = $125384.61 – 95000 = 30384.61$

Profit of small demand = $48333.33 – 95000 = - 46666.66$

$EMV (S_{25}) = \{(100652.17 \times 0.38) + (30384.61 \times 0.22) + (- 46666.66 \times 0.4)\} = 26265.77$

For making decision D_{15} the max {EMV (S_{25}), ($R_{2\ 18}$)} must be chosen, so:

$\mu_{15}^{*} = max \{EMV (S_{25}), (R_{2\ 18})\} = max \{26265.77, 0\} = 26265.77$

Calculation of interest values related to "Act now" status in current production process:

Profit of large demand = $203750 – 95000 = 108750$

Profit of medium demand =$119000 – 95000 = 24000$

Profit of small demand = $46153.84 – 95000 = - 48846.76$

$EMV (S_{26}) = \{(108750 \times 0.4) + (24000 \times 0.17) + (- 48846.75 \times 0.43) = 26576.15$

For making decision D_{16} the max {EMV (S_{26}), ($R_{2\ 22}$)} must be chosen, so:

$\mu_{16}^{*} = max \{EMV (S_{26}), (R_{2\ 22})\} = max \{26576.15, 0\} = 26576.15$

$EMV (S_{13}) = \{(26265.77 \times 0.6) + (26576.15 \times 0.4)\} = 26389.92$

$\mu_{2}^{*} = max \{EMV (S_{11}), EMV (S_{12}), EMV (S_{13})\} = max \{57300, 47676, 26389.92\} = 57300$

The comparison of these three values indicates that the EMV (S_{11}) has the biggest value; therefore the remanufacturing process is the best choice among recovery options for production process. Attention to the result of example motivates the company for setting the production process based on the remanufacturing strategy in order to recapture hidden economic value. The Figure 5.8 shows that how evaluation of alternative decisions by developing a decision making model can be considered for implementing the best option of GM in production process.

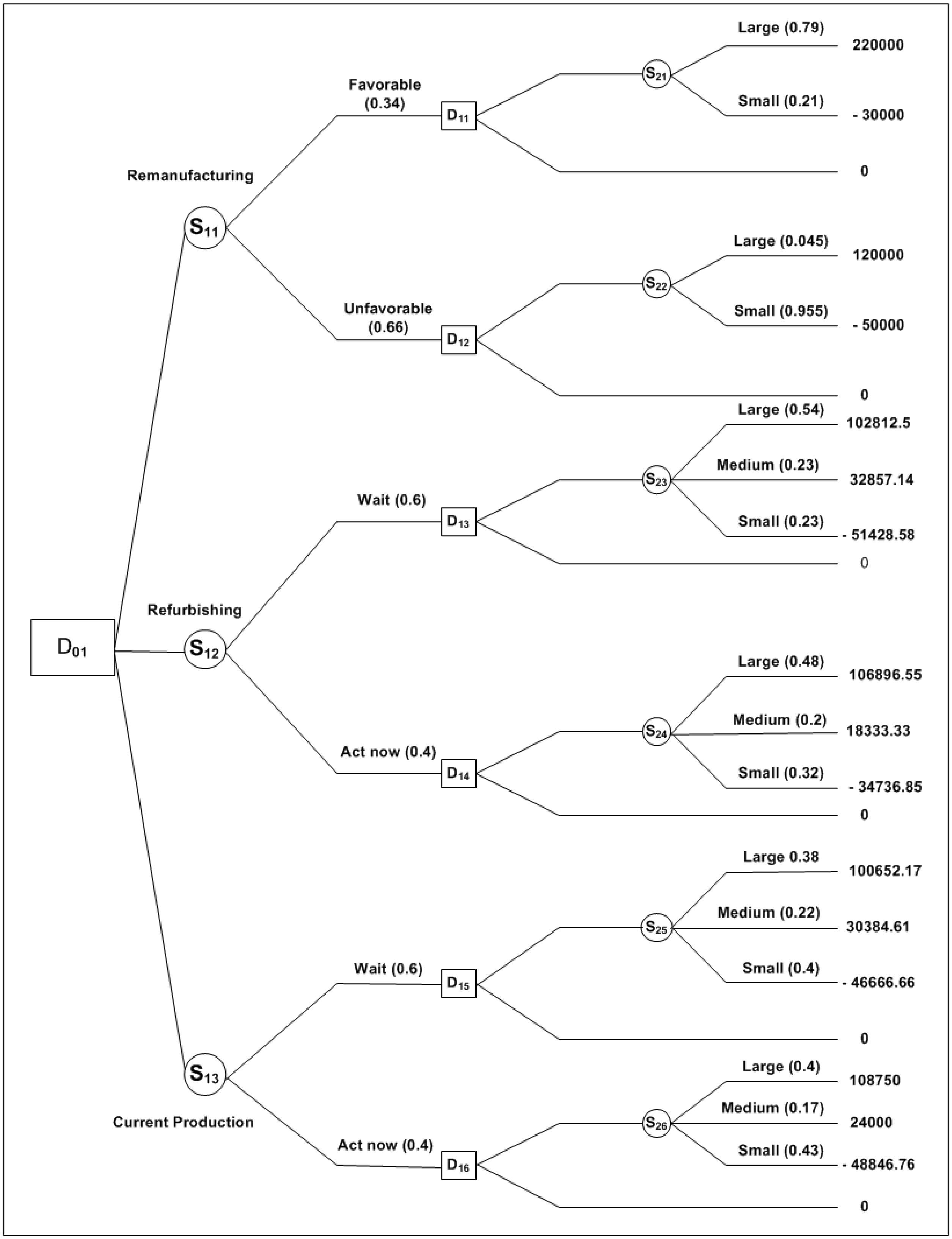

Figure 5.8 Making decision tree related to recovery option

5.3.3 Summary and Discussion

The two example studies have been analyzed in order to address the importance of the two key parameters, objective factors and market demand, in the selection of the appropriate recovery options for products at their end-of-life. The examples show qualitatively that the availability of product information has a positive impact on the product recovery decision. It also investigates how recovery decisions can be modeled to represent the impact of product information on those decisions.

The examples show that the decision making model will help a manufacturer to decide whether it is economical to disassemble the EOL product and which method is the most appropriate option for the product's recovery economically and environmentally. In the other words, the examples show the ability of such a model to automate product recovery processes should result in increased cost-efficiency as well as a reduction in environmental damage due to disposal. Moreover, the proposed model can enable manufacturers to obtain feedback on the lifecycle performance of products, thus providing crucial input for better product and process designs.

Chapter 6: Conclusions

6.1 Summary

Increased environmental awareness and legislative development enhance the need for manufacturers to address the product end-of-life phase. It is essential to determine on a product level if an intended end-of-life system is technically and economically feasible.

In this thesis, different methods of green manufacturing strategy as a product recovery processing were evaluated. The evaluation was based on two essential parameters: including optimization of objective factors and market demand. Analysis of each parameter was performed through the use of a decision making model. By evaluating differing levels of demand, the manufacturer can maintain flexibility in planning production quantity and will have access to information needed for determining what method is profitable for remanufacturing and when it should be implemented.

The objective factors which should be optimized include: Environmental Impact (E), Cost (C), Quality (Q), Resource Consumption (R) and Time (T). Each objective has a number of influential sub-objectives. The thesis argued that the easiest way for optimizing the objective factors is through the use of goal programming (GP), which is one of the most powerful multiple objective decision making (MODM) tools in practical decision making problems. Implementing goal programming requires a system utility function which can be created by listing the attributes of the system and then incorporating these by forming a weighted sum of measures of the attributes. It is appropriate to treat the attributes of a system as utility independent. When applying GP to decision making problems, such as project selection and resource allocation many problems may be formulated as GP with 0-1 decision variables. Minimizing the objective factors of environmental impact, cost, resource consumption and time, and maximizing the quality of the product, will help manufacturer make an optimal selection for product recovery.

The second parameter, evaluation of market demand is also considered in the selection of the best product recovery option. The thesis proposed the development of a procedure for evaluation of market demand which was compatible with the decision making model. For allocating value and probability related to each branch of a decision tree, the type of demand was defined according to three categories and it was demonstrated that the probability and value of average revenue related to each demand could be estimated**.** The procedure was designed to help reduce the complexity of the market demand assessment through the use of documented demand and a Bayesian updated demand model. It also planned a demand modeling mechanism with a Bayesian update structure that incorporated documented demand into the methodology generation process. The rational in using Bayesian forecasting was that it helped in correct decisions on pricing, used for evaluation of future demand and making decisions on whether to participate in new markets or not. It was shown that estimation of demand can be performed by two techniques: informal methods such as educated predictions and quantitative methods such as consideration of documented sales data or current data from the market.

6.2 Contribution

It is clear that product recovery operations are characterized by their dependence on the availability of information associated with the product and is hampered by its unavailability. In this study by increasing the amount of information available, the uncertainty associated with the state of the system is expected to reduce, facilitating more effective product recovery decisions. There are two essential differences between this thesis and the existing literature. First, the thesis investigates how recovery decisions can be modeled through decision making trees to represent the impact of product information on those decisions. Second, in the thesis, the model proposes using one specific type of Bayesian approach to analyze the effect of enhancing information on product recovery decisions.

6.3 Future research

A possible next step in this stream of research could be to evaluate this Bayesian forecasting compared to simulated bills of material and manufacturing data using principal component analysis. Then, the accuracy of the Bayesian forecast in concert with the decision making model implementation, leading to an evaluation of the utility of the overall methodology. Furthermore, product recovery systems are often analyzed by considering only one specific operations management issue (e.g. production planning or inventory management). In order to have a more realistic analysis of these systems, integrated methodologies should be developed. There is a need to develop strategic models for the analysis of product recovery systems with respect to technological and organizational dynamics.

As a possible future study, it could be developed into the integration model for incorporating all decision-making levels, including objective factors and market demand information, and need to develop a practical and efficient heuristics for solving the large-scale problems. The technical and ecological impacts of ready information availability will have to be measured by a different set of performance indicators, and thus would require a different modeling approach for analysis. A product-oriented information model can provide a logical way for presenting the information required for EOL decision making. Furthermore, the model can provide increased flexibility for an information system to be able to adapt according to the changing requirements imposed by different products. Obtaining the necessary information for EOL decision making has a cost attached to it. Hence, it is required to make a quantitative assessment of the impact of product information availability on the performance of product recovery decisions. In order to facilitate this, in this thesis a modeling approach for analyzing the impact of product information on product recovery decisions was presented.

Appendix 1: (Revenues Table)

The table represents sixty month revenues related to refurbishing and current production based on “wait” and “act now” decisions obtained from an automobile company in Middle East.

Month	Refurbishing		Current production	
	Wait	Act now	Wait	Act now
1	10000	150000	50000	210000
2	150000	120000	90000	230000
3	210000	190000	50000	220000
4	180000	130000	80000	10000
5	30000	100000	40000	50000
6	250000	120000	30000	10000
7	10000	100000	140000	150000
8	160000	160000	50000	170000
9	120000	90000	20000	160000
10	200000	210000	130000	80000
11	220000	190000	240000	240000
12	140000	40000	120000	60000
13	220000	60000	200000	220000
14	250000	250000	160000	100000
15	70000	80000	220000	10000
16	100000	30000	170000	20000
17	10000	230000	70000	70000
18	150000	180000	210000	190000
19	130000	60000	190000	120000
20	120000	240000	190000	30000
21	150000	100000	190000	160000
22	150000	100000	40000	60000
23	110000	210000	130000	250000
24	190000	90000	50000	170000
25	130000	20000	180000	130000
26	40000	240000	40000	230000
27	180000	80000	110000	20000
28	250000	180000	40000	220000
29	210000	150000	50000	50000
30	210000	120000	40000	130000
31	190000	110000	70000	150000
32	180000	190000	190000	120000
33	40000	100000	210000	10000
34	130000	170000	110000	30000
35	240000	240000	140000	90000
36	120000	100000	220000	80000
37	120000	70000	250000	80000
38	190000	150000	50000	200000
39	210000	100000	130000	230000
40	10000	250000	150000	20000
41	140000	50000	220000	160000
42	170000	50000	220000	40000
43	30000	190000	80000	240000
44	80000	90000	40000	190000

Month	Refurbishing		Current production	
	wait	Act now	wait	Act now
45	210000	180000	160000	190000
46	70000	40000	10000	20000
47	210000	220000	60000	30000
48	140000	10000	30000	120000
49	190000	180000	140000	20000
50	110000	60000	180000	80000
51	110000	60000	150000	140000
52	160000	50000	130000	250000
53	180000	240000	50000	90000
54	50000	250000	120000	250000
55	30000	160000	30000	110000
56	240000	20000	230000	80000
57	60000	200000	110000	60000
58	160000	160000	120000	120000
59	150000	160000	220000	210000
60	160000	190000	150000	100000

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