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VALUE OF QUALITY INFORMATION OF RETURNS IN PRODUCT RECOVERY MANAGEMENT

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

VALUE OF QUALITY INFORMATION OF RETURNS
IN PRODUCT RECOVERY MANAGEMENT

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Returned products of many industries are transported backwards through supply chains for recovery, thus forming "closed-loop supply chains". Benefits, forthcoming with more effective management of recovery of returns are gaining importance. However, some issues, such as lack of information required to assess the quality of the returned products, may translate into critical uncertainties in the product recovery decisions and prevent closed-loop supply chains from operating efficiently. Hence, it is envisaged that significant economies may be attained by increasing the quantity of information fed into the planning decisions related to returned products. Thus, the objective of this study is to test the hypothesis that ready availability of perfect quality grade information associated with returned products by means of "embedded systems", may lead to improved over all performance of recovery operations. To this end, in this thesis, linear programming models of generic multistage recovery processes are built. It is demonstrated by computational studies that significant gains may be obtained especially in environments where the prices of recovered products are decreasing in time.

Keywords: Reverse supply chain, product recovery management, quality grading, value of information

ÖZ

ÜRÜN GERİ KAZINIMI YÖNETİMİNDE
İADELERİN KALİTE BİLGİSİNİN DEĞERİ

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Birçok endüstri dalında iade edilen ürünler, geri kazanım amacı ile tedarik zincirinde geriye doğru taşınmakta ve böylece “kapalı döngü tedarik zincirleri”ni oluşturmaktadır. İadelerin geri kazanımının daha etkili yönetilmesinden sağlanabilecek yararlar giderek önem kazanmaktadır. Ne var ki, iadelerle ilgili ürün kalitesinin belirlenmesinde ortaya çıkabilecek veri yetersizliği gibi bazı sorunlar, geri kazanım süreçleriyle ilgili yönetim kararlarının alınmasında kritik belirsizliklere dönüşebilmekte ve kapalı döngü tedarik zincirlerinin daha etkin çalışabilmesinin önünde engeller oluşturmaktadır. Dolayısıyla, iadelerin geri kazanımıyla ilgili planlama kararlarının alınmasında kullanılacak bilginin niceliğinin artırılmasıyla kayda değer kazanımların sağlanabileceği düşünülmüştür. Bu nedenle, bu tezin amacı, iadelerin kalite derecelendirmesi ile ilgili olarak mükemmel düzeyde bilginin, “gömülü sistemler” yardımıyla elde edilebilmesi halinde, daha etkili geri kazanım kararlarıyla tedarik zinciri süreçlerinin performansının arttırılabileceğine dair hipotezi sınamaktır. Bu amaçla, tezde çok aşamalı geri kazanım süreçlerini genelleyen lineer programlama modelleri kurulmuştur. Özellikle fiyatların zamanla azaldığı piyasalarda, kayda değer kazanımların elde edilebileceği hesaplamalar ile gösterilmiştir.

Anahtar kelimeler: Tersine tedarik zinciri, ürün geri kazanım yönetimi, kalite derecelendirmesi, enformasyonun değeri

To My Parents

To My Teachers

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INTRODUCTION

Returned products of many industries, for example mobile phones, computers, electrical home appliances, peripherals and alike, can be treated as reusable assets and hence they are transported backwards through supply chains for recovery, forming “closed-loop supply chains” or “reverse supply chains”. Manufacturers have been increasingly becoming aware of the benefits that may be forthcoming with more effective management of recovery of returns, since they can generate multiple alternative revenue streams. However, some issues pertaining to collection and use of information about returned products prevent closed-loop supply chains from operating efficiently.

First of all, today’s product recovery operations are mainly driven by the products pushed into the reverse supply chain by the end users. Thus, most of the time, manufacturers have limited information and control over the rate of incoming product returns and their level of quality condition.

Further in the case of fluctuations of product demand, due to changes in fashion and technology level, it is hard to forecast the demand for different types of recovered products and the market prices of these products introduced to the second hand market.

The crucial point is the fact that information on the quality condition and residual life of returned products are often not available or inadequate. Lack of information required to asses the identity and certain other properties such as usage and maintenance history of the used products, in some industries, may translate into very high level of uncertainty in product recovery decisions. This situation of a returning party having the relevant quality condition information about the product returned and the receiver party having no or very little information is recalled as information asymmetry in the literature. Secondary hand markets for utility cars, returned electronics devices and even markets for financial derivatives are perfect exemplary environments where such an asymmetry exists. Asymmetric information may lead to a possible market failure according to “lemon product” perspective of Akerlof (1970) when returns’ quality is indiscernible beforehand by the manufacturer or buyer. Incentives exist for the customers to return low-quality goods as higher-quality ones.

In addition to such uncertainties, many recovery processes are entirely conducted manually which implies that these processes are slow, prone to error and are rather expensive. Also many recovered product returns’ prices are usually decreasing in time. Thus, delayed recovery decisions, long lead times in recovery operations and rapidly decreasing prices, may result in loss of asset value or potential revenues.

Based on these observations, it is envisaged that significant economies may be attained by increasing the amount of quality information fed into the planning decisions associated with recovery of returned products. Specifically, the focus of this study is on perfect quality grade information that can be provided upon reception at the retailer (or at the collection facility) by systems such as simple data loggers with radio frequency label implementations (RFID) that keep record of usage and condition statistics through the life time of a product.

The rest of this chapter aims to introduce the reader with general concepts, terminology and relevance of the subject: In Section 1.1 an operational definition of recovery management is made. In Section 1.2 importance of quality grading of time sensitive returns is introduced and in Section 1.3, legislative significance of the subject is elaborated. Finally in Section 1.4 an outline of the thesis is presented.

1.1. Supply Chain Management, Reverse Logistics and Recovery Management

Recovery management falls under the more general subject of reverse logistics which further goes under the title of supply chain management. Reverse logistics is a rather new area of research and practice which deals with the theory and problems of flow of products in the reverse direction, i.e. from customers to the producers, as compared to the product flows in the forward direction from the producers to the customers, which historically constitute the subject of traditional supply chains. When management of forward and reverse flows are combined (rather than being separated and managed individually) and the outputs of backwards flow processes are fed back into the forward supply chain, (thus increasing the general complexity of the supply chain), the underlying supply chain is usually referred to as a closed-loop supply chain (Clendenin (1997)). The term recovery management generally refers to the decisions related with returned products flowing in the closed-loop supply chains where these products are tested with respect to the level of quality condition, then if feasible processed to be recovered as second hand products, spare components, raw materials for manufacturing or as energy, dependent on their quality level.

To further enhance the introductory definition of recovery management, it will be appropriate here to provide a brief definition and classification of the term "returns" as it constitutes the fundamental element of recovery management. All kinds of returned products of different industries, including customer returns, commercial returns and packaging, can be considered as "returns". Traditionally, these returns have been regarded as possible raw material sources. However, in today's modern industries, returned products can be recovered also as spare parts, as components supply for the existing product lines or for use in brand new products if legislation permits. These returns can even be resold as well. In this study, essential concentration is on recovery of relatively sophisticated products like computers, cellular phones, brown goods and staple products like packaging materials are left out. With such emphasis, according to de Brito and Dekker (2003) returned products can be broadly categorized as;

i) Production sourced returns, occurring from scrap of semi-finished goods or from products that become obsolete during production.
ii) Distribution sourced returns from retailers due to wrong deliveries, product recalls or close outs, and
iii) Usage related returns, occurring when customers are allowed to return as a practice of sales policy, when used products are taken back in lieu of newer models via "take-back campaigns". "End-of-lease" returns

restored at the end of a rental period or “End-of-life” returns when the useful lives of products come to an end are in this class as well.

The focus of this study is on general usage related returns instead of manufacturing or distribution related returns.

To complement this introductory definition of recovery management, providing brief definitions of “recovery operations” and “recovery options” will be appropriate as well. Recovery operations can be defined as physical industrial operations such as collecting, transporting, accumulating, sorting, inspection, quality grading, repairing, remanufacturing, cannibalizing (i.e., disassembly of components to be used as spare parts), trimming, recycling or incineration for energy recovery. These operations are usually conducted in a network of warehouses, stock points, workstations and they are usually designed particular to the industry and the products. Whereas, recovery options are essentially marketable outputs of recovery operations such as trimmed, refurbished, remanufactured products, disassembled and reconditioned spare parts or recovered raw materials.

Finally, to conclude the definition, characteristics of decision problems encountered in recovery management needs to be elaborated: Basic management problems associated with recovery management can be classified broadly as;

i) Long term planning and design problems, where decisions associated with the nature and capacities of the recovery processes are determined in line with statutory requirements.
ii) Medium term problems, where decisions associated with the design of the product, production planning and information collection are made.
iii) Short term problems, where decisions related with quantity and timing of operations to run the recovery processes effectively and economically under various constrains and uncertainties are made.

The above three categories may be termed as “strategic decision problems”, “tactical decision problems” and “operational decision problems”, respectively as well.

1.2. Importance of Grading and Time Sensitive Returns

The concepts of “grading” and “time sensitive returns” have central importance in analyzing recovery management problems considered in this study. Grading, or more openly “quality grading of returned products” can be conceived as the processes where relative recoverable value of returns are measured in an ordinal scale so that, returned products may be routed more effectively through the supply chain. Fleischmann (2003) defines grading (or disposition or inspection) as the sorting of the product stream into fractions of different quality and their allocation to different reuse options.

Time sensitive returns may be defined as returned products which loose their value rapidly through time. Some perfect examples may be computers and cellular phones. Loss of value may be due to variations in demand for first hand products, changes in the technology and technical properties demanded on market for recovered products or steadily decreasing, seasonally fluctuating market prices. Consequently, importance of quality grading of time sensitive returns lies in the fact that rapid recovery management decisions supported by sufficient grading information may improve overall performance of the supply chain.

Effectiveness of grading depends on the availability of relevant data; and data collection is not costless. Usually collection of data to be used in grading of returned products needs to be designed beforehand and an overall balance needs to be made between the cost of grading information and expected gains from solving operational problems of recovery management with the availability of such information. Also data collection and grading can be done in several ways and can be complicated depending on the product. One straight forward option is inspecting returned products in a centralized work center. Other options that can be more instrumental are data collection techniques like utilizing barcodes, smart cards, radio frequency labels and embedded systems such as data loggers.

For a better visualization of grading issues, one may consider an example of a simple sticker placed in a laptop computer or a mobile phone, to test whether it is “liquid damaged” or not, when it is returned for some reason. When and if it will be advantageous to sort returns of such products and route them in to the network of recovery process according to the criteria of being “liquid damaged” or not, the information carried in the sticker, obviously will be instrumental in defining suitable grades operationally.

1.3. Legislative Aspects of Recovery Management

Statutory requirements related with environmental, energy conservation, fair competition and consumer protection aspects impose restrictions on recovery management decisions of manufacturers. Among many such restrictions one such legislation in the European Union is the "Directive for Waste Electrical and Electronic Equipment" (WEEE). Legislation imposes constraints, "returns to sales ratio" targets and directions to formally plan product recovery management operations over a horizon of at least one year for certain industries. In the directive these industries are cited as;

- i) Large home appliances
- ii) Small home appliances
- iii) Computers and telecommunication equipments
- iv) Consumer equipments
- v) Lighting equipments
- vi) Electrical and electronic tools
- vii) Toys
- viii) Entertainment and sports equipments
- ix) Medical devices
- x) Tracking and Control tools and
- xi) Vending machines.

1.4. Objective and Outline of the Thesis

As portrayed above, decision problems associated with product returns and recovery management, especially on consumer electronics, continue to gain both economic and statutory importance and this encourages further research on the subject.

The main objective of this study is to investigate economies that can be attained in recovery management processes, by increasing the amount of information regarding the quality condition of the returned products. Specifically, the focus in this thesis is to test the hypothesis that ready availability of perfect quality grade information associated with reusable returned products by means of embedded systems may lead to improved all over performance of recovery operations especially those involving product returns with time sensitive prices. To this end, in this study general aspects of a reverse supply chain, it's sequential quality testing and recovery processes are modeled as generic, multistage, multiperiod linear programming models with a time invariant returns quality distribution assumption. Extensive computational studies are conducted assuming forecasted return and demand values are determined as deterministic problem parameters to analyze and evaluate certain issues of product recovery management under different scenarios. Cost and revenues are determined bearing the consumer electronics market in mind.

A generic base case model is set up for mimicking returns testing; product recovery processes and some modified similar models for investigating effects of different testing configurations are developed. Then, all of the models are differentiated into two versions; versions with and without the availability of quality grade information upon issuing of returns. Models are compared in terms of profit and recovery levels and as a result of this study the significance of the economic value in implementing systems for gathering usage and related quality information is shown. A generalized recovery planning model is developed as a decision making tool and rough cut break even point for implementing embedded systems, given the return and demand forecasts, costs and revenues, is quantified using spreadsheet solvers.

The outline of the thesis in the sequel is as follows; in Chapter 2, general background of the subject is given with a survey of the relevant literature. In Chapter 3, a generic base case model of the multiperiod recovery management problem is constructed and formulated as a linear programming model. Afterwards some alternative versions of the generic model with different testing configurations are presented. In Chapter 4 various computational studies for comparing the generic base case model, alternative configurations and gatekeeping considered versions of these models are provided and discussed. Practical aspects of the use of the models are elaborated. Chapter 5 contains a conclusion and directions for further research.

CHAPTER 2

BACKGROUND, THE RELATED LITERATURE AND THE PROBLEM DEFINITION

In this chapter a summary of the relevant literature and the general background of the thesis are given. Since the subject of this thesis goes under a more general title of “reverse logistics”, Section 2.1 is devoted to the presentation of the concept of reverse logistics, its timely evolution with various definitions of the term and elaboration of some misleading notions close to this topic that appeared in the literature. In Section 2.2 the relevant literature related to product returns is investigated and manufacturers’ incentives for engaging in reverse logistics activities are discussed. In Section 2.3 returns are classified according to reasons of occurrences. Section 2.4 covers description of industrial recovery operations and recovery options and in Section 2.5 major challenges of recovery management are pointed out. In Section 2.6 current research literature is examined in view of generic decision making and engineering problems of the area and underexplored areas of the subject are identified. Finally in Section 2.7 a definition of the problems focused in this research is presented.

2.1. Evolution and Definitions of Reverse Logistics

Reverse logistics is a concept that spans immense series of activities associated with the efficient management of returned materials, components, products, packaging, equipments and sometimes entire technical systems with the objective of recovering some value. The reverse logistics issue has a history of no more than two decades of work.

In the 70’s the terms like “reverse distribution”, “reverse channels” or “reverse flows” began to appear in the literature however these terms and related research were essentially focused on materials recycling or disposal of products (Guiltinan and Nwokoye (1975), Ginter and Starling (1978)). In the first half of the 80’s, terms like, “resource reduction”, “environmentally conscious manufacturing”, “responsible manufacturing” and “green production” began to have general use, especially in Europe, which was triggered by the growing environmental consciousness from the late 70’s. Later, the first legal enforcements of materials recovery and proper disposal have come. At the time, used products in general were either accounted as waste or as a burden to be dealt with in order to comply with environmental legislations if raw material reclamation is not possible. According to Rogers and Tibben-Lembke (1998) the reason for this lack of interest in returned products has been that these products were perceived to have low economic and strategic importance.

In the late 80’s, other terms such as “backward flows” and “retro movements”, which were closer to reverse logistics idea came up (Murphy and Poist (1989)). Although these terms did not gain much recognition, it is important to mention that Murphy and Poist’s paper is one of the first papers considering traditional supply chain flows as forward, and reverse logistics as backward flows. In the end of 90’s the topic of reverse logistics has started to gain recognition in the academic community. Evidence from recent research suggested that returns can be used as a source of competitive advantage (Stock et al. (2002)). Latest real life examples like the remanufacturing of mobile phones, have pointed out the profitability of recovery activities and the relative importance of value creation from returns rather then their environmental aspects (Guide and Wassenhove (2001)). Since then the number of articles interested in reverse logistics research, which are published in academic journals, has grown exponentially as emphasized by Fleischmann et al. (2004). Figure 2.1 is composed by a rough keyword search in scientific articles published since the end of 1980’s up to date, through Google Scholar Search. Regarding data can be found in Table A.1 in Appendix A. This figure shows the trends in relevant literature as numbers of scientific publications containing keywords; “reverse logistics”, “closed loop supply chains”, “WEEE”, “reverse supply chains”, “returned product recovery”, either in their titles or in the abstracts. It should be noted that terms like reverse logistics and closed loop supply chains are sometimes confused with each other. With reverse logistics, European academicians imply the whole supply chain activities in reverse, while Americans imply only the logistics activities, transportation and warehousing.

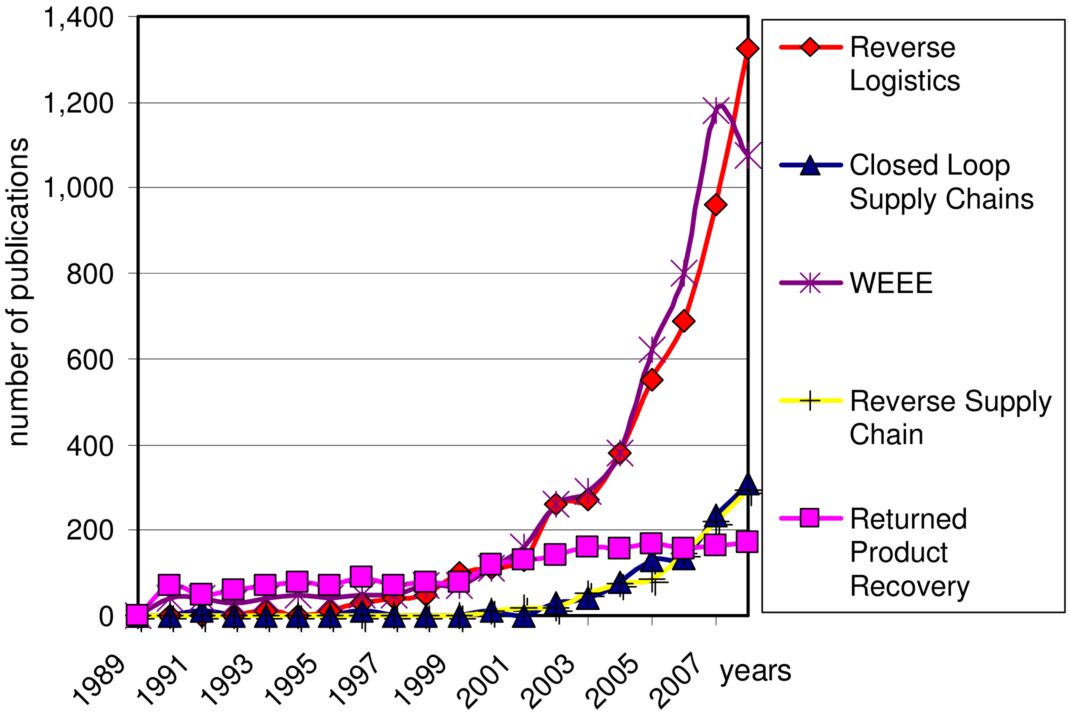

Figure 2.1. Numbers of scientific papers published annually in various areas of interest Source: Google Scholar Search

The first definition of Reverse Logistics was published in the early 90's by The Council of Logistics Management as: *"…all relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal."* (Stock (1992)). A contemporary definition was made by Pohlen and Farris (1992), which seems to be influenced from marketing perspectives; "*…the movement of goods from a consumer towards a producer in a channel of distribution."* Kopicky's (1993) definition is a little deranging, it bundles the waste management issue as if it is the foremost consideration, on the other hand emphasizes the direction of product and returns flows, namely forward and reverse, which is worth mentioning; *"Reverse Logistics is a broad term referring to the logistics management and disposing of hazardous or non-hazardous waste from packaging and products. It includes reverse distribution which causes goods and information to flow in the opposite direction of normal logistics activities"*. "The European Working Group on Reverse Logistics" (RevLog), improved the definition in 1998, suggesting; *"The process of planning, implementing and controlling flows of raw materials, in process inventory, and finished goods, from a manufacturing,* *distribution or use point to a point of recovery or point of proper disposal"* (Dekker et al. (2004)). And in the end of the 90's just after RevLog's proposition, Rogers and Tibben-Lembke (1999) made a comprehensive definition of Reverse Logistics, at last, as *"The process 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 or proper disposal."*

As a final remark on the definition of reverse logistics, it has to be pointed out that there exists several other terms and definitions somewhat related to reverse logistics like "closed-loop supply chains", "green logistics", "waste management", etc. and these competing terms should be dilated here in order to avoid misconception in both research and practice as stated by Melissen and de Ron (1999). Forward logistics indicate all logistic activities on "virgin" materials, components or products. Whereas reverse logistics indicate activities on returned most likely non-virgin materials, components or products. Because discrimination may become difficult in a holistic system in which both forward and reverse logistics activities exists, the term closed-loop supply chain (CLSC) has been introduced. This concept emphasizes that the recovery practices are in the frame of the entire supply chain. The closed-loop idea stresses that the forward and reverse logistics should be integrated and the design should consider both aspects at the same time.

Green logistics considers environmental impact of all logistics related activities and concentrates more on forward logistics. Long-run environmental impact of the overall logistics system, rather than economical or administrative motives, is taken into consideration until the end-of-life of the product (Gungor and Gupta (1999)).

Waste management is another important competing term, mainly refers to collection, sorting and processing waste effectively. The gray point here is on the definition of waste: Turkish Environmental Act (1983) defines waste as *"substances thrown or deserted by means of whatsoever activity…"* UK's Environmental Protection Act (1990) indicates waste as; *"Any substance which constitutes a scrap material, an effluent or other unwanted surplus arising from… any process or any substance or article which requires to be disposed of which has been broken, worn out, contaminated or otherwise spoiled, anything which is* *discarded otherwise dealt with as if it were waste". B*oth definitions are very broad, denoting that not only worn out or spoiled artifacts but also discarded ones can and do become wastes. However even a broken down or discarded "waste" may have a value when recovery is considered. Wastes are disposed products for which there is no possible use, on the other hand reverse logistics concentrates on streams where there is some value to be recovered.

2.2. Incentives for Reverse Logistics

According to Fleischmann (2001) and Brito and Dekker (2003) there are five drivers of reverse logistics in the aggregate, driving manufacturers to engage in reverse logistics activities. These are "corporate citizenship", "legislation" "marketing", "asset protection" and "economics" and will be briefly discussed below;

Corporate citizenship implies a set of principles that force an organization to become responsibly engaged with reverse logistics activities (Brito and Dekker (2003)). With the growing importance of environmental consciousness, green image of a company became a somewhat competitive edge. According to the survey carried out by Rogers and Tibben-Lembke (1999) 65.2% of 311 companies initiated product recovery activities as a competitive strategy.

Legislation, as a driver implies any statutory requirement pressuring a company to accept its sold products back. End-of-use and end-of-life take-back laws stress businesses such that effective management of the entire life of products becomes crucial. The most widely known regulation is the waste electrical and electronics equipment directive (WEEE) of the European Union Council (2003). The objective of the WEEE can be summarized as; *"the prevention of waste electrical and electronic equipment, and in addition the reuse, recycling, and other forms of recovery of such wastes so as to reduce the disposal of waste"*. Legislation also targets, "*improving the environmental performance of all operators involved in the life cycle of electrical and electronic equipment*". The WEEE directive requires that by weight 65% to 80% of electronics waste to be recovered. Recently a draft of a directive resembling WEEE legislation, inspired by the European Union, is introduced in Turkey recalled as "Atık Elektrik ve Elektronik Ekipmanlar Yönetmeliği Taslağı" (AEEE). This legislation is being prepared under the framework of European Union accession criteria. Both WEEE and AEEE legislations require all the electronics related industries to formally make recovery operations plans for the their product returns over a planning horizon of at least one year and to report quarterly for checking performance against enforced "returns to sales ratio" targets. Undershooting the committed recovery levels are expected to result in tightened obligations and financial consequences.

Marketing as a driver implies taking back end-of-use products with promotions and campaigns for an opportunity to sell brand new items to old customers, which in turn increases customer loyalty. It is worth mentioning that product take back for recovery eases second hand sales of end-of-use products because quality is more visible and this in turn increases confidence in brand, eases sales of brand new products. Also collecting end-of-life products can be seen as a service to take care of the customer's disposal needs (Fleischmann (2001)).

Asset protection is the third driver for companies to recall or get back the products from the market following end of use. If a company does not collect its products but someone else does, this may have an adverse effect on the brand reputation (Jacobsson (2000)). When reusable assets like packaging is collected by a rival, certain additional costs of buying or production of new assets may arise.

Economics is the final and latest noticed incentive. The amount of product returns can be very high, with some industries experiencing returns at over 50% of sales (Trebilcock (2002)). Since used products are low cost material and spare part resources, reverse flows are almost always considered economically attractive. Recovery is usually cheaper than manufacturing from scratch or buying new products with virgin materials and components. Fleischmann (2001) states that in view of low raw material prices, economic attractiveness often relies on the direct recovery of manufacturing value added, rather than on mere material recovery. Product recovery may be the only way to get certain functional spare items that are no longer produced, may also act as another source of supply when a supplier is incapable of fulfilling an order as stated by Flapper (2003), it may also take less time than purchasing, transporting, producing and distributing brand new products. Another interesting economic driver for reverse logistics is data collection from used products. Usage data from end-of-use products can be collected during the inspection phase and fed back into the design process (Klausner and Henricksson (1998), Krikke et al. (2003)).

It will be appropriate to comment on an “energy perspective” which does not deliberately mean the recovery of energy by means of incineration, although it is a possibility and has found some applications. The point is that energy is used in every possible operation of producing and remanufacturing a product; hence any operation skipped by reusing or reconditioning returns instead of full disassembly and materials recycling, saves energy. Williams and Sasaki (2003) indicate that reselling or upgrading 10% of end-of-life computers reduces life cycle energy use, which is the total energy used in production, distribution, maintenance and recovery if possible, by 8.6% and 5.2% respectively. In contrast, materials recycling 10% of end-of-life computers only save 0.43% of life cycle energy, suggesting that reselling as is or upgrading as a refurbished product are far more effective from an economic and environmental standpoint.

Among these incentives, focus of this thesis of research on benefits to be gained from better product recovery management, is chosen bearing the economical perspective and statutory obligations in mind.

2.3. Classification of Returns

In principle, returns may occur at any stage of a supply chain. There are simply two reasons for returns; either the product is no longer needed even it is in good condition in which case the returns are called end-of-use, end-of-lease returns or the product malfunctions due to rupture or ageing in which case it is called as end-of-life returns. But this classification is too broad. De Brito and Dekker (2003) use a classification based on returns’ origins as manufacturing returns, distribution returns and customer returns. The same classification is embraced through the thesis and these sources are elaborated as follows:

Products may return at the manufacturing phase for several reasons; final products sometimes fail quality checks, leftovers occur as by products of a manufacturing option, late emerging design errors may occur and lastly product may become obsolete while in production. In the distribution phase product recalls may be a reason for returns due to safety issues. Occasionally, commercial returns may occur from retailers in order to decrease risks of obsoleteness, damaged deliveries etc. Closeouts occur when retailer discontinues selling products and want to remove the entire inventory. There is also the "functional returns" case, where inherent function of the product under consideration is going back and forward in the manufacturing and distribution phases of a supply chain (de Brito and Dekker (2003)). Obvious examples are the pallets, packages, big bags etc. Manufacturing phase returns, distribution phase returns and functional returns will not be considered in the thesis. Focus of this study will be on customer returns.

Possibility of "customer returns" give customers either a "money-back guarantee"; an opportunity to change their minds about buying a product shortly after acquiring. Although money-back guarantee returns are items that are barely used by the customers, they are usually treated to be salvaged for they are taken out of the original package. Products discovered to be defective or incorrectly thought to be defective by customers or retailers are sources for returns where in some cases one may claim a product is defective when it is not, in order to return the item free of charge. These barely used non-defective returns can simply be put back to the shelves if the condition of the returned item is apparent, but they can not be sold as virgin any more. If the condition is not apparent some level of quality tests should be conducted to be on the safe side.

Amongst other types of customer returns; "Warranty Returns" are also very common when products fail and are returned for repairs or changes at service centers. Also there are the "take-back guarantees"; opportunities to exchange customers' older products with economy priced brand new products. End-of-use returns happen when users find opportunities to return an item at a certain life stage of the product for liquidation or to benefit from take-back incentives. Examples to note here are second-hand apparel and leasing returns of photocopiers etc. Although these products cannot be considered new, they are often in a reasonable state.

Finally, there are the end-of-life returns, products that reached the end of their usable lives. At this stage possible gains from recovery is usually limited thus in most cases things work with legislative force.

2.4. Recovery Operations and Options

"Recovery operations" can be defined as physical industrial operations, usually conducted in a setting of warehouses and workstations which are specially designed particular to the industry and the product. The term "recovery options" essentially refers to the possible ways of dispositioning outputs of recovery operations so as to realize the recovered value.

In general, recovery options are distinguished as "product recovery" options and "material recovery" options (Gungor and Gupta (1999)). It is suggested that "component recovery" and "energy recovery" options should also be added to this list. According to Prahinski and Kocabaşoğlu (2005) recovery operations can be organized mainly under five key steps namely "product acquisition", "sorting/grading", "disposal", "reconditioning" and "redistribution". Fleischmann (2001) provides a similar list. Figure 2.2 summarizes the relation between recovery operations and options. In this figure "returns acquisition" refers to bringing the products from the customers to a point of collection.

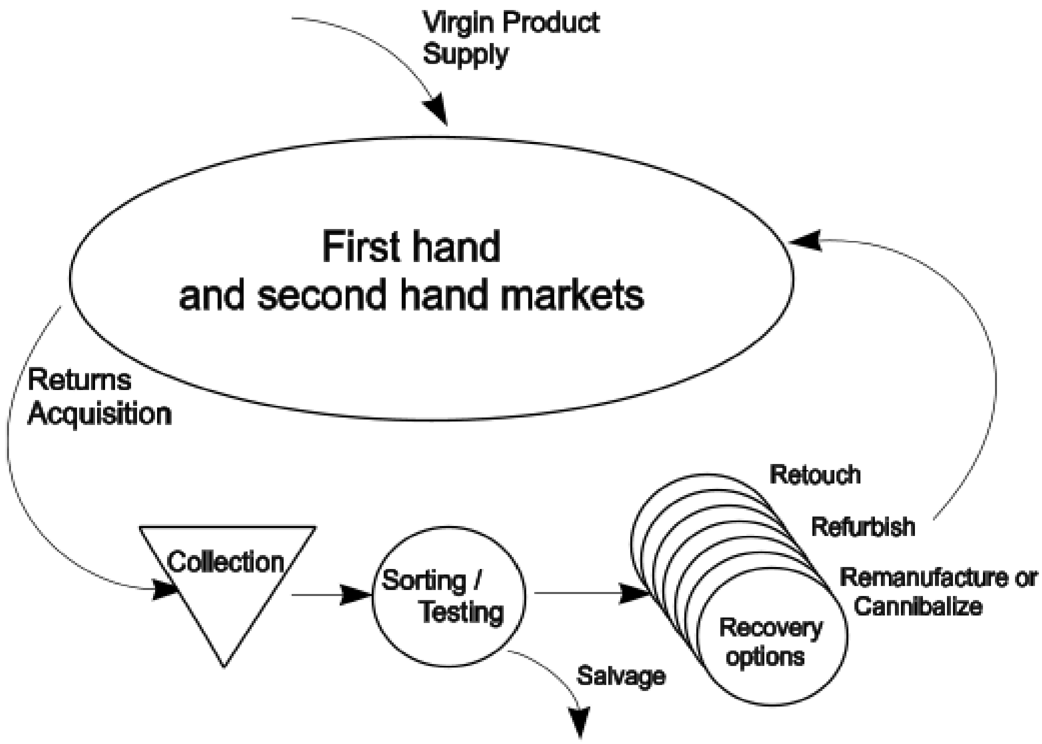

Figure 2.2 Recovery operations and options

Collected returns are sorted, tested and quality graded either in a distribution warehouse or in a recovery center. The condition of returned products may be derived from the return reasons if such information is readily available, since same type of products with similar return reasons will bear similar qualities. However the information will have an average value not specific to the returned product in concern thus testing is mandatory. The level of quality is assessed individually and a decision is made on the viable option for product recovery. For product returns where recovery is not possible or not feasible, salvaging or disposal is the final operation.

Returns feasible for recovery are sent to “reconditioning” according to their quality state, where the returned products are restored to a better state. Target for reconditioning may be reselling returns in their original market or in a secondary market by just retouching, ensuring that the returned products are in as good as new condition. This option is recalled as “direct recovery” in the literature as well. If returned products can be sold after a repair, refurbishing option is viable. In case of componentwise recovery, products are disassembled and worn out, obsolete components are replaced with a remanufacturing operation or modules or parts of a returned product are used in the manufacturing of the similar products or in repair of warranty claims with an operation that may be recalled as cannibalizing. In case of recycling, products are either grinded, ingredient materials are sorted out and treated in order to use as raw material supply or products are burned and the released energy is captured. These options may also be combined, for instance one may first retrieve spare parts from a peripheral and then recycle the residuals.

Finally, as stated in the figure, after reconditioning redistribution is the process of bringing the recovered goods to relevant markets, components, spare parts and materials to manufacturing and service centers and energy to the grid.

2.5. Challenges of Recovery Management

Recovery Management is essentially “decision making and control” associated with recovery operations and options and many of the challenges occur in this area. In fact definition, formulation, modeling, computation and solution of decision making and control problems of recovery management reflect similar challenges as faced in the design, planning and scheduling problems of traditional manufacturing management i.e. forward supply chains. However, operations and options in forward flows are relatively well defined, inputs and outputs are well controlled, whereas in reverse flows, characteristics of almost all recovery operations and options; arrival rate of returns, returns' conditions and usability, demand and prices of recovered products are highly uncertain and barely forecastable. Hence one of the biggest discrepancies in recovery management is lack of information. Due to this discrepancy most recovery systems face additional challenging engineering and management problems. Some of these challenges which are pertinent to the problems and models dealt with in this study are elaborated in the sequel with references to the current literature. A more detailed list of literature related to recovery management is classified by problem type and is given as Table A.2 in Appendix B.

Today, most recovery systems, where collected returns are quality tested and processed, are centralized in terms of location. In these recovery facilities, activities are monitored more loosely than regular forward flows. Once the returned products arrive at the center, usually a decision needs to be made for recovery. However, because of the uncertainty in returns quality, final recovery option is not as clear as it is in forward flows where materials flowing have relatively uniform quality. This situation of quality uncertainty presents a challenging problem which Tibben-Lembke et al. (2001) points out as "the gatekeeping problem": In many recovery management operations a large part of recovery cost is on transportation to and from the recovery center. It is best to discover the condition of a return first, if possible upon retrieval of the return, whether a returned product should be directly resold or sent to the central recycling facility, so as to prevent incurring unnecessary costs of testing evaluation and sorting.

Lag in time to return to market, is another challenging issue as the life cycle of the products shortens and products like consumer electronics lose their value both in first hand and second hand markets while management spends time and effort on deciding which option to take for recovery. Although end-of-use and end-of-life returns may be reconditionable, time value needs to be considered carefully for making the recovery decisions; depreciation limits recovery options very fast. Blackburn et al. (2004) mentions this discrepancy and states that evaluation, reconditioning decisions and operations must be made very rapidly and this is valid especially for markets with declining margins such as consumer electronics. They emphasize that poorly handled return streams and increasing returns volumes can quickly erode profits significantly. Also, Van Wassenhove (2002) states that the longer it takes to retrieve a returned product; the lower will be the likelihood of finding an economically viable recovery option for the product.

Designing and operating better systems for collecting the data and the information needed for increasing the effectiveness of reverse logistics in general is another big challenge in recovery management. It is a fact that every product is subject to a different set of conditions through its life, which means product information is unique to every individual product. Hence gathering (after point of sale) usage information may provide some idea on the quality condition of sales returns or end-of-use returns. Increasing the level of detail of the information available, uncertainties are expected to reduce, thus facilitating more effective recovery decisions. Such data may be used in order to generate a score for grading purposes and quality grade may be used for sorting the product in advance of a series of tests which may have a significant impact on the cost performance of the reverse supply chain by means of decreasing number unnecessary tests and increase in revenues by means of speeding recovery, which in turn may facilitate taking advantage of time sensitive disposition options.

Different tagging methodologies exist today which may be employed to provide the after point-of-sale quality condition information described above. In fact such methodologies edge into the market lately where they are used for identifying products individually for the purpose of tracking sales and inventories. Such systems may also be employed for collecting data about the use and maintenance history of products, thus enabling faster evaluation, testing, routing, inventory carrying and transshipment decisions in recovery management. Most of tagging systems, such as barcode systems in use today, are static systems where only the type of the item is stored on the tag while the current information about the item is stored not in the tag but in a database elsewhere. Today it is still found expensive to carry dynamic information on a tag for many products. But dynamic systems using radio frequency identification technology (RFID) are emerging rapidly. RFID technology uses an electronic data-carrying device, the transponder, of which communicates data by means of electromagnetic waves to a manual or portable read/write device dynamically and has several advantages over the use of barcodes such as the possibility of identifying items without line-of-sight, simultaneous reading of several tags to uniquely identify items; and operating automatically i.e. without human interaction. (Karkkainen, 2003).

Wilding and Delgado (2004) discuss further challenges of recovery management by pointing at the forthcoming needs for sensory data acquisition systems in order to log the usage data automatically. These types of systems are known to be "embedded systems" (ES). Embedded systems technology is also an emerging technology and it is defined in the embedded systems glossary (2002) as; "*A combination of computer hardware and software, and perhaps additional mechanical or other parts, (like sensors) designed to perform a dedicated function. In some cases, embedded systems are part of a larger system or product, as in the case of an antilock braking system in a car.*" Embedded systems can accumulate and conceal the usage data, sense the condition with some certainty, calculate expected residual life and can be instrumental in better recovery management decisions including pricing decisions. An example is provided by Klausner and Hendrickson (1998) for reusing electric motors in consumer products by making use of an electronic data log to gather the usage data and estimating the remaining life of the motor.

2.6. Review of Current Literature

Interest in Reverse Logistics from both academia and practitioners has increased during the last decade as stated by Fleischmann et al. (2003). Several comprehensive reviews of the reverse and closed loop supply chain research is published by Gungor and Gupta (1999), Guide (2000), Dowlatshahi (2000), Fleischmann (2001), Guide and Van Wassenhove (2003) and Prahinski and Kocabasoglu (2005). In the current literature most interest is diverted at various planning and decision making problems encountered in recovery management which are broadly classified under;

i) Strategic decision problems
ii) Tactical decision problems and,
iii) Operational decision problems.

Strategic decision problems receiving attention in the current literature are long term planning problems associated with the nature and capacity of the recovery processes. Reverse supply chain network design, supply-chain coordination and capacity planning problems as well as planning for green manufacturing, which are manufacturing systems designed with environmental considerations, fall into this category. Other current issues include deciding locations of components of a reverse supply chain to be centralized or decentralized. As Fisher (1997) points out; a centralized structure, where recovery operations are held at a central processing workshop, namely a recovery center, implies a cost efficient returns network whereas a decentralized structure, where every recovery process is held at different workshops implies a responsive network.

In terms of responsiveness there is another concept called delayed differentiation in forward supply chains where the manufacturing starts by making a generic product that is later differentiated into a specific end-product. This is a preferred method in environments with high demand uncertainty and helps to satisfy demand even if there is no room for forecast improvement. According to Blackburn (1999), in reverse supply chain design, early product differentiation yields high profitability, but not delayed differentiation as in forward supply chains. Blackburn recalls this early differentiation as “preponement” (as the opposite of postponement) such that product returns are sorted and differentiated in terms of quality and other aspects, before placing great strains on the costs. Unlike forward supply chains, design strategies for reverse supply chains are relatively underdeveloped. Key concepts of forward supply chain design like coordination, postponement, and the bullwhip effect, may be useful for the development of reverse supply chain design strategies and need more attention in the current literature.

Tactical decision problems analyzed in the current literature include, medium term problems where decisions are associated with the design of the products, returns forecasting, data and information collection designs, product returns handling, warehousing and aggregate production planning in terms of returns’ recovery. Production planning for recovery is the most popular issue; pointed out by several researchers, such as Guide and Srivastava (1998), Guide (2000), Souza et al. (2002), Ketzenberg et al. (2003). Increased uncertainties compared to that of traditional production planning activities complicate this recovery planning issue mainly as denoted by Guide (2000). Product recovery refers to the set of activities to reclaim value from a returned product. Various authors categorize and classify the recovery processes differently. Johnson and Wang (1995) define it as a combination of remanufacturing, reusing and recycling, whereas Thierry et al. (1995) divide recovery into repair, refurbishing, remanufacturing, cannibalization and recycling. Melissen and de Ron (1999) define recovery practices and provide relevant definitions and terminology.

Operational decision problems are short term problems, related with warehousing operations, dynamic control of product recovery operations, dynamic acquisitions, dynamic pricing, disassembly scheduling and lot sizing problems where both quantity and timing decisions are made to run the recovery processes effectively and economically under various constraints and uncertainties. Disassembly scheduling and product recovery operations control related decisions for reassembly operations are considered as short term. More detailed schemes to monitor, share and control information need to take place at this level also.

In this thesis, a tactical level problem, a rough-cut recovery production planning problem is considered with the possible benefits of aforementioned early differentiation of product returns on mind. In line with the focus of this thesis, recent and relevant contributions to the literature on the subject of sales returns, end-of-use and end-of-life product recovery decisions are reviewed next beginning with research highlighting time value and condition variability. Next, some papers on popular topics, information value and benefits of sorting before disassembly which are gaining ground lately, are reviewed and briefly discussed.

In the current literature, proper management of collecting, sorting, testing and recovery of end-of-use and end-of-life products is being analyzed under the title of product recovery management. A recent relevant study in this area is due to Willems et al. (2004). This work emphasizes the growing attention in WEEE directive and focuses mainly on end-of-life product recovery strategy selection for electrical and electronics equipment. More specifically, the sensitivity of the disassembly time and cost on the selection of the end-of-life strategy is investigated. A linear programming model for deciding which types of different disassembly operations to be chosen for recovery operations is formulated. The main features of the developed model are as follows;

- A profit maximization problem is modeled in contrast to similar research.
- Supply of discarded products from shops, collection center, second hand shops are considered as inputs.
- Demands for end-of-life items are assumed to be ample.
- Acquisition, transportation and recovery processing lead times are not taken into consideration.
- The disassembly time for recovery which is strongly correlated with the disassembly costs, is investigated.

Analysis on two products with different disassembly complexities and different second hand market potentials implies that low value products are not worthwhile the investment of implementing better disassembly techniques because no disassembly time reduction can influence the selection of the optimal end-of-life strategy. For high value products on the other hand, the investment results in a drastic change of the optimal end-of-life strategy from material recycling towards reuse. In general, delays caused by disassembly lead time and disassembly costs are barriers in front of enabling better reusing opportunities. The issues of quality testing lead time and costs focused in this thesis are very similar compared to the study of Willems et al (2004).

Souza et al. (2005) examine the impact of the time value on reverse supply chain design for commercial product returns and they find that returns are often time sensitive and firms frequently lose much of the value remaining by not making disposition decisions as quickly as possible. The main characteristics of their model are as follows;

- Single facilities and processes at every stage on the return path are considered.
- Operations corresponding to acquisition at retailers, evaluation of returns and remanufacturing are modeled as M/M/1 queues to capture the significant congestion effects.
- The processes on the forward network; manufacturing, distribution and retailer sales, which realize little congestion, are modeled as M/G/∞ queues.
- Transportation delays from acquisition to recovery facility are included.

- Authors present queuing network models focusing on profit maximization.

Three product return cycles are mentioned such as; the introduction cycle where returns occur after product is launched to market, maturity cycle where returns occur steadily and maturity cycle where quantity of returns diminish after product is taken off the market. Only the cycle, where returns occur steadily, is taken into consideration due to the high volumes involved and the long time duration of this state. Unfortunately the introduction cycle, where product prices decline aggressively and return levels change rapidly are not elaborated.

The idea behind solving analytical models is to be able to compute the value of time in a closed–loop supply chain and provide closed form expressions that allow a manager to quickly quantify the value of reducing delays. Solely this approach differentiates the study from many of the previous similar literature.

A case study and analysis of reverse logistics activities of Hewlett-Packard Company by Guide et al. (2005) suggests that instead of focusing on cost minimization and technical quality, returns should be recognized as a value stream and revenue should be maximized by fast disposition, proper refurbishment and resale through appropriate channels. An end-of-use remanufacturing planning network flow linear programming model is used in order to evaluate new design and policy options for the reverse supply chain. The model has the following properties;

- A multiperiod setting is discussed.
- Benefit in sorting of only two quality levels of returns by a single testing operation is highlighted.
- Authors recognize the impact of value of time on profitability. However, they only investigate aging of returns and linear decline of prices given the age of the returned product. They do not consider the rapid fall off of prices due to changes in technology and fashion.
- Demand is assumed to be ample in the models and experimentation. A limited example is provided where demand is finite.
- Quality of returns and outcome of the test is assumed to be constant over time.

Typical centralized returns evaluation network designs are chosen for cost minimization purposes and to enjoy economies of scale. However, sorting returns at the retailer and restocking them immediately within a decentralized setting is an idea that may increase revenues by decreasing effects time sensitivity caused by rapidly declining prices as well as reducing transportation costs, utilization at the central evaluation facility and delay of other returned products.

Sensitivity to time may be due to several reasons: One well known reason is that technology advances at an exponential rate as explained by Moore's law (1965). This implies that products also get outdated and similarly their prices fall at an exponential rate as in Figure 2.3. There may be other reason of time sensitivity such as physical properties, wear and tear and changes in cost components associated with collecting, transporting, handling and stocking of product returns.

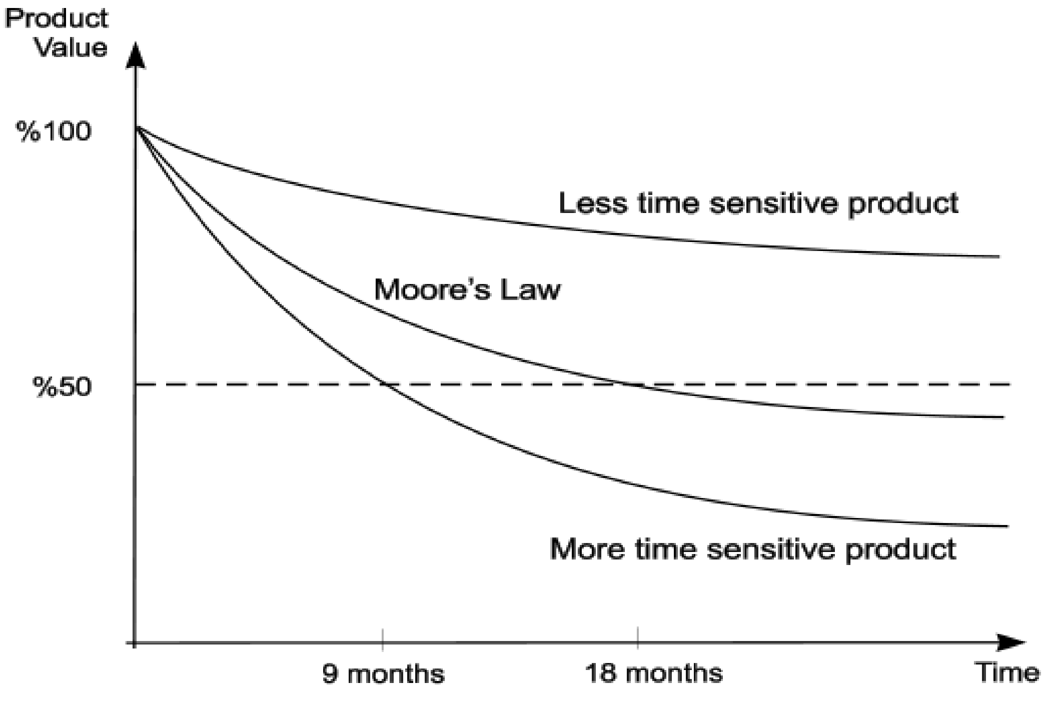

Figure 2.3 Time sensitivity of virgin product prices

In the current literature, most of the research in remanufacturing planning area considers a single-period problem or a case where there exists only good and bad quality returned products. Multi-period production planning problems have been addressed by Guide et al. (2001) and Ferguson et al. (2006). Ferguson also addressed the planning issue where different quality levels are considered. This problem as well is formulated as a linear programming model with a network-like structure, given demand forecasts over a planning horizon. Several analytic properties of the optimal solution is presented such as the firm always remanufactures the exact quantity demanded in each period if the holding cost for remanufactured products is higher than that of returned units. This condition holds in most of the remanufacturing cases since remanufacturing is a value-added operation.

Although some research started to consider multiple quality grade models, quality of incoming returns are considered as known and steady through every stage of the product life cycle in many cases. However, decision making under condition of uncertain quality of returns issue is arousing interest lately. The earliest study to mention is due to Krikke et al. (1998) where the optimal product recovery and disposal is determined considering the uncertainty in technical and the quality level of the product with a stochastic dynamic programming approach. This model is further modified and updated by Fleischmann et al. (2001), Goldsby and Closs (2000), Inderfurth et al. (2001) and again by Krikke et al. (2003).

In one contemporary study, Guide and Wassenhove (2007) investigate the optimal disposition decision of product returns. Authors provide an analytic model with a two-step policy showing that high congestion levels in the remanufacturing facility delay the sale of the remanufactured product at the secondary market, decreasing the value at which it can be sold. In the first step, the returned product's random processing time is observed. In the second step, a disposition decision is made. They conclude that salvaging a higher proportion of products is financially attractive as remanufacturing costs and the value decay rate increases.

A recent paper worth mentioning is a study by Denizel et al. (2007) considering both multi-period and stochastic structure of recovery management in terms of quality, a typical situation seen in most of the product recovery and remanufacturing environments. The main assumptions of the study are as follows;

- A remanufacturing planning problem for end-of-lease returns in a finite planning horizon is considered.

- Quantities of incoming returns are assumed to be known exactly. however there exists uncertainty in quality levels.
- Aggregate capacity constraints are considered.
- Demand is assumed to be deterministic as well.

The problem is formulated as a stochastic linear programming model, maximizing the total expected profit over the planning horizon. The numerical study showed that uncertainty in the quality levels of returns create problems for the planning of remanufacturing. Quality grading and better returns' recovery management results in higher quality cores remanufactured at a lower cost and with lower capacity usage. Profit is most heavily influenced by the shape of the production cost curve, convex increasing, linear, or concave increasing in the lower quality of the core, the salvage value of an unprocessed core, and the cost of grading. On the other hand, per unit holding cost of returns, as well as unit backlogging cost, has a smaller impact on the optimal solution.

Although the investigation spans an underexplored section of the recovery management subject, the solution method chosen is overcapitalized. Such an exponentially growing model becomes unreasonable to solve for a realistic planning horizon and for the size of problems found in practice.

Galbreth (2006) considers uncertainty in the remanufacturing yield associated with a given sorting policy, analyzing both the dichotomous condition case, either returned products in good or bad conditions exist, and the case where used product condition is defined along a continuum. The acquisition and sorting decisions using both heuristic approaches based on deterministic estimates of yield and stochastic yield models is analyzed. Under a wide range of situations, the stochastic yield model is found to provide very limited cost benefits over the simpler deterministic yield model.

Aras et al. (2004) points out the significant variability in the condition of the returns and consider the effect of categorizing returned products, especially the impact of quality-based categorization. Authors show, through extensive numerical studies on a continuous-time Markov Chain model, that there is significant cost savings. Savings are amplified as the return quality decreases, and as the return rate increases. Quality-based categorization increases these cost savings because it makes use of the additional quality information in the system.

Zikopoulos and Tagaras (2006) investigate location of sorting operations. Authors state that the location where returns are sorted may have substantial impact on the profitability. The paper contributes to the quantification of the trade-offs related with this decision by examining and comparing two alternative options which can be considered as the two extremes with respect to the physical distance and the time delay between sorting and recovery procedures. The setting of the study is as follows;

- A recovery system consisting of a single collection center and a single recovery site is considered.
- A single period remanufacturing setting is focused on.
- The system faces uncertainty due to two factors: uncertainty in the quality of returns and uncertainty in the demand for recovered products.

Numerical investigation shows that sorting at the collection center becomes more favorable compared to sorting at the remanufacturing facility as yield decreases, transportation cost increases and as higher revenues and lower costs make remanufacturing more profitable. There are some interesting extensions of the present single-period model that are worth studying, such as the generalization to the case of multiple collection sites, the case of imperfect sorting and the consideration of a larger number of possible quality states of the returns.

Zikopoulos et al. (2008) examine the attractiveness of simple sorting procedures characterized by limited accuracy just before disassembly and remanufacturing of used products. That type of quick sorting is often made possible through the installation of simple electronic devices in new products, which record basic usage data and provide information about the remanufacturability of the product without the need for its disassembly. There is uncertainty about the remanufacturability of used products and authors derive the conditions under which quick sorting is economically justifiable. The model’s considerations are as follows;

- A recovery system consisting of a single collection center and a single remanufacturing facility is focused on.

- Used products are in one of two possible quality condition states, either remanufacturable or not.
- Sorting is used to classify items into remanufacturable and non-remanufacturable items but it is subject to two types of misclassification error. Returns can be incorrectly classified as non-remanufacturable (type I error), or can be incorrectly classified as remanufacturable (type II error).

It is shown that the economic attractiveness of sorting depends on the costs of transportation, disposal, disassembly, the cost and accuracy of the sorting procedure and the quality distribution of the returned items. the specification of the sorting criterion may have a significant impact on the profitability of the remanufacturing operations.

Parlikad et al. (2004) investigate the role of product information in end-of-life decision making. Authors point out that loss of information associated with the product after the point-of-sale is a fundamental obstacle in making efficient product recovery decisions and show qualitatively that the availability of product information has a positive impact on product recovery decisions. An in depth discussion is given on possible benefits of radio-frequency identification technologies to provide the necessary information. The paper also elaborates how recovery decisions with uncertain quality can be modelled by using utility theory and Bayesian probabilities to represent the impact of product information. A pioneering implementation of a similar idea can be found in the literature by Klausner et al. (1998) where authors discuss reusing used motors based on the data acquired by equipping new motors with Electronic Data Loggers, a type of embedded system for collecting usage information. Authors state that cost savings due to less testing may improve the economic efficiency of product take back programs making take back a source of positive profits. Another paper worth mentioning on products with data acquisition features is due to Simon et al. (2000), where authors try to evaluate benefits of usage data acquisition in a very similar manner.

2.7. Problem Definition

Basic deficiency of the common approaches for reverse supply chain management seem to lie in the fact that combined treatment of quality grading of multilateral quality returns and cases with time sensitivity in the sense that prices diminish rapidly, are rather underexplored and remain as a challenge for further research. Indeed it is not hard to visualize that at many manufacturing companies, such problems of recovery management are still considered as trivial. Economic benefits to be gained from better product recovery management are yet undervalued and forward supply chains are considered stand-alone. While the challenge of running a distribution system in forward is already difficult; it is considered even more difficult to allocate resources to manage the system in reverse. However, as shown in Figure 2.2, it may be more important to manage inventory well at the end of a product's life cycle than at the beginning.

A recent business research by Accenture (2008) on consumer electronics suggests that more than %68 of volume associated with product returns are characterized as "no trouble found", where customers believed the products had failure, yet no problem founded upon testing by the manufacturer and turned out that these returns can be resold as is. Thus, rewards of additional effort for better managing time sensitive returns can be more promising than believed. Anticipated gains can be classified as; faster returns to markets, finding higher selling prices as refurbished products, fewer amounts of time and money spent on testing, less need for labor, more reusability as intended by WEEE and eventually less amount of disposal as wastes. Further, emerging technologies are bringing sophisticated tagging and grading systems well within the reach of even small sized manufacturing companies. These technological systems bring the opportunity to increase the quantity of information which reduces uncertainties in the product recovery decisions.

Hence, the main objective of this research can be worded as to investigate and quantify the significant economies that can be attained in recovery management processes by increasing the quantity of information regarding the quality condition, residual life of the returned products by means of embedded systems. There exists a lack of quantitative research on the evaluation of the benefits of such systems. Quantifying the benefits of enhanced recovery systems with early product differentiation in terms of quality will emphasize the economic attractiveness of reverse logistics operations, especially those involving high level of good quality product returns within a time sensitive price environment.

CHAPTER 3

MATHEMATICAL MODELS

The main objective of this study is to evaluate the benefits of recovery systems with early product differentiation in terms of quality. This study points out the existing deficiency in quantitative research. Quantifying the benefits will emphasize the economic attractiveness of reverse logistics operations, especially those involving high level of good quality product returns within a time sensitive price environment. Also the goal is to develop a rough-cut recovery planning model for deciding on allocations of returns to different recovery options which in turn can satisfy the planning and reporting obligations of the forthcoming returns recovery management legislation. Investigation is expected to feature the difficulties in managing recovery systems and effects of different testing configurations in terms of profit and recovery levels. The different testing configurations in consideration are a base case generic recovery system, modified testing configurations and the versions of these models with gatekeeping possibility added such that the benefit of implementing a gatekeeping operation can be quantified given the parameters.

The organization of this chapter is as follows; first in Section 3.1 the environment of the problem is discussed. Then in Section 3.2 the model developed for the generic base case is presented such that material flows between collection, sorting, testing/inspection and recovery operations of a generic recovery system are modelled as a linear programming model. In Section 3.3 possible testing configurations are discussed. In Section 3.4 the generic base case model is modified in order to analyze the case of gatekeeping process at the retailer side with aforementioned embedded systems for early quality discrimination. In Section 3.5 another quality discrimination alternative, pre-sorting is mentioned. Discriminating product returns given the information on their return reasons is discussed. Finally in Section 3.6 some discussions on developed models are stated.

3.1. The Environment

A generic recovery system is considered with a central product returns recovery facility, where a single type of returned product is processed. Returned products are tested with respect to quality conditions and reconditioned at the recovery facility by taking viable recovery decisions to satisfy demands for different types of recovered products and to maximize profits. Thus, the focus is a rough-cut production planning problem for returned products' recovery.

The source for satisfying the demand is the supply of products returning from the customers with different return reasons such as “sales returns”, “warranty returns” or “end-of-use returns”. There exists classification of return qualities under which each class defines the recovery option that each return can be converted. These return classes are referred to as “quality grades”. Each return may be in a quality state, where it is reusable, can be refurbished, can be remanufactured, cannibalized or in a condition where only recycling is viable. In order to discover the incoming products' quality, a sequence of tests should be conducted where each test will be termed as a stage form now on.

The types of recovered products in demand are “reusable products”, “refurbished second hand products”, “spare parts” and items that are recyclable in terms of material and energy, so called “scrap”. Returns, eligible for a certain level of recovery, are processed accordingly by being assigned to different recovery options. The options available for recovery decisions may be termed as “retouching”, “refurbishing” and “remanufacturing”. Remaining recyclable items are salvaged for recycling. Each recovery option corresponds to a recovered product. Thus there is one to one relationship between recovery options and type of recovered products.

It is possible to downward substitute a superior quality returned product as an inferior quality returned product for recovery, for instance reusable items, superior to all types of recovered products in terms of quality and value, are processed by retouching to be reused as is. However, they can be utilized as refurbished products, spare parts and even as scrap if it is rational to do so. Refurbishable items are inferior to reusable products, superior to returns to be cannibalized and to be salvaged. These items can be utilized as refurbished second hand products, spare parts or scrap. Lastly, spare parts are inferior to retouched reusable and refurbished products, superior to scrap only and can be utilized as is or salvaged as scrap for recycling.

Rate of collection for returns, rate of demand for recovered products, cost of operations, for example transportation costs, handling and holding costs at the facility, costs of product recovery in different workstations and market prices corresponding to different types of recovered products may assumed to be either dependent or independent of each other. Parameters reflecting success rates of the quality grading tests are assumed to be stationary for the sake of simplicity both in description of the environment and in mathematical formulation. These values account for the inputs of the model.

Under the simplifying assumptions of steady state quality distributions and flow rates, the models developed for the recovery system in consideration are only good for analyzing effects of changes in relative prices, supply, demand and the configuration of the network.

For our generic model the objective is to maximize net present value of total profit over a finite planning horizon, T . Revenue is gained from sales of different types of recovered products of O many different product recovery options or from salvaging as scrap for recycling. It is assumed that;

i) The firm does not have a power to manipulate prices.
ii) The firm does not have a power to manipulate returns and demands.
iii) The prices for recovered products are time dependent.

It is assumed that the forecasts for available number of returns in period t is R_t and in the models developed these values are treated as deterministic, independent of recovered product demand and may be non-stationary in time. For studies on forecasting of returns, one may refer to the book by Fleischmann et al. (2004), “Reverse Logistics: Quantitative Models for Closed-loop Supply Chains”, Chapter 3.

Returns that are either stored at the collection facility or transported to the recovery facility, waiting in raw returns stock points to be tested or they can be salvaged as scrap to be recycled at any time. For items to be salvaged, unit price for scrap is independent of the testing stage that the item has passed and is assumed to be constant over all periods.

Demand in period t for a certain type of recovered product processed according to recovery option o, D_{ot} is assumed to be deterministic and may be non-stationary in time. Forecasts are to be used as inputs. It is assumed that;

i) The demand for different types of recovered products is independent from demand for other types of recovered products.
ii) It is not possible to substitute a demand for a recovered by any other type.
iii) The demand for cannibalized items is assumed to be ample which implies there is no need to consider explicitly.
iv) Unsatisfied demand will be lost.

In general, returned products to be recovered in centralized facilities (often outsourced), are shipped in bulks in order to minimize transportation costs. According to Blackburn (2004), the supply chains are designed to minimize processing costs, often at the expense of long delays. To reflect the general effects of aforementioned lead times, which are encountered in almost any reverse supply chain, a constant time lag during transportation from collection center to the recovery facility is considered as a part of the modeling environment, which is presented in Figure 3.1. It is a fact that returns from acquisition linger in the pipeline moving from the collection facility to testing. The main reason for loss of time is the retailers or collection centers waiting for economies of scale to arise.

Because many recovery processes like testing and recovery operations are entirely conducted manually, these processes are labor intensive, slow, error prone and are rather expensive. Skilled labor availability is considered in order to investigate the behavior of the recovery systems under capacity constraints.

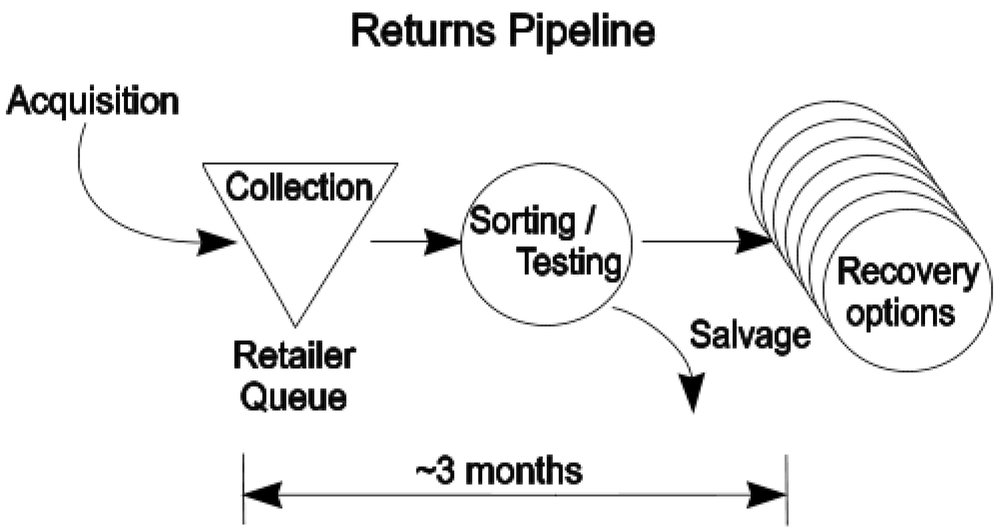

Figure 3.1 Time Lag in Returns Pipeline (adapted from Blackburn (2004))

Capacity is defined as available labor hours for the entire recovery facility. Deterministic capacity requirements are assumed. Let l_g^x and l_o^y be the unit capacity requirements for testing operation $g \in G$ and recovery operation $o \in O$, respectively. Note that l_g^x and l_o^y can be treated as standard times for g grade testing operations and standard times for option o recovery operations. Calculated labor requirements, constrained by the total man-hours available, added more realism to the recovery models in consideration.

Costs are incurred for variable processing at each step of recovery operations; collection, transportation, testing and recovery operations as TL/unit, and for inventory holding as TL/unit/period. The relevant assumptions employed are;

i) All cost parameters assumed to be non-stationary, i.e. depends on time t

ii) Possible economies or diseconomies of scale situations are ignored

iii) For inventory related costs, an end-of-period accounting scheme is considered

iv) For the holding costs of work-in-process, due to the lead times, it is assumed that the holding cost rate at the previous stock point is used.

In any stock point, unit inventory holding cost of an item will be computed as the cost of capital tied up in the inventory, a function of the value of the item, where all processing costs that have been incurred up to that point are multiplied with an inventory carrying charge e. Because an item may get through from different routes of testing and recovery operations, for holding costs, items are assumed to follow the longest and the most costly route.

Our assumptions on testing and recovery operations are as follows;

Incoming product returns are held in the initial raw returns stock point. Returned items are ordinally sorted according to their quality grades, with a sequence of testing operations. If there are $G+1$ quality grades including the condition of being scrap, there exist G many testing operations to reveal the quality condition of a returned product. Skipping of some tests and instead entering tests for inferior quality items is possible for the generic base case.

All items passing any test g enter the associated work-in-process (WIP) inventory, WIP-grade g. All items failing any test g, enter the associated raw returns stock point i, where $i = g+1$. At the raw returns stock point i, items are either continued to testing operations or salvaged. If an item fails in the terminal stage, the final test of the sequence, test G, the condition of the items is obvious and there will not be a need for further testing. These items will be salvaged directly.

The fraction of items that can pass test g, incoming from raw returns stock point i is θ_{ig}. At any test g, one does not obtain any further information on the success of further tests, i.e. it is an operation revealing only if the quality of the returned products is satisfactory for the given quality grade g or not. This success ratio can be computed from the quality distribution of collected returns, which can be represented by a set of parameters $\alpha_g \in \{\alpha_1, \alpha_2, ..., \alpha_G\}$ where $\sum_{g=1}^{G} \alpha_g = 1$ and α_g

stands for the proportion of grade g returns that can be recovered from the inbound flow of collected returns when they are submitted to all tests sequentially without any exception.

It is assumed that;

i) Quality distribution of incoming returns, defined by $\alpha_1, \alpha_2, ..., \alpha_G$, is an input that is to be forecasted.

ii) And this distribution is time invariant.

Probability or rate of success, θ_{ig} for issued flows from raw returns stock point i at the testing workstation g in any period can be calculated with conditional probabilities. The probability that an item is in quality condition grade g, given that it is unsuccessful, U, form a previous test i can be represented as:

$$\theta_{ig} = P\left(grade = g \,|test_i = U\right), \text{ where } i \le g \text{ and } i, g \in \{1, ..., G\} \tag{3.1}$$

when expanded with Bayes' theorem:

$$\theta_{ig} = \frac{P\left(test_i = U | grade = g\right) P\left(grade = g\right)}{P\left(test_i = U | grade = g\right) P\left(grade = g\right) + \sum_{i \ne g}^{G} P\left(test_i = U | grade = i\right) P\left(grade = i\right)} \tag{3.2}$$

The rate of success can be expressed briefly as:

$$\theta_{ig} = \frac{\sum_{g=i}^{G=g} \alpha_g}{\sum_{g=i}^{G} \alpha_g} = \frac{\left(\alpha_i + ... + \alpha_g\right)}{\left(\alpha_i + ... + \alpha_G\right)} \tag{3.3}$$

Note that this derivation is not valid, when quality grade distribution of the incoming returns is varying in time. Changes in the quality of incoming returns from period to period, present some difficulties when mixing of different quality items occur in the stock points. Raw returns arriving in different time periods with different quality grade distributions should be stored in the designated, separate raw returns stock points to differentiate items, which is unlikely. The variability on the time dependent success probabilities of inflows from various raw returns stock points, together with the flexibility of being able to issue materials from a raw returns stock point to the choice of several testing workstations, requires cumbersome formulations for finding success probabilities of testing operations in period t, which can be denoted as θ_{igt} instead of θ_{ig}, alternatively. Calculation of the rate of success in every transaction by means of either simple averaging or weighted averaging of incoming quality of returns with the quality of revolving inventory, results in a non-linearity of the model. Thus time invariance of quality distributions is a key assumption of the models developed. Although we considered time invariant quality distributions, from a practical point of view this problem may be overcome by making some simplifications like not allowing inventory holding prior to the graded products' work-in process inventories.

The sequence of events together with costs incurred in each period can be summarized as follows; for each returned product, an unavoidable unit acquisition cost is incurred. For the returns decided to be salvaged directly, unit revenue is obtained from salvaging. Quantities of returns to be transported to the central recovery facility are determined, unit cost of transportation and inventory holding costs due to lead time are incurred. These items become available in "raw returns" stock point, $i = 1$ after associated lead time passes. For each available raw returns inventory, $i = \{1, ..., G\}$, the quantity to be pushed to any testing workstation g, to be salvaged or to be held in the inventory are determined. Relevant testing and inventory holding costs are incurred.

The consequences associated with these decisions are;

i) θ_{ig} fraction of the items sent to test g, pass the test successfully, and they are placed in WIP-grade-g inventory. The fraction $1 - \theta_{ig}$ of the items sent to test g fail the test and they are placed in the next raw returns inventory $i + 1$.

ii) Unit testing costs are incurred from the quantities sent to tests g where $g \geq i$.

iii) Unit revenue for recycling is obtained from the quantity sent to recycling.

For items in WIP-grade-g inventories, where $g = \{1,...,G\}$, quantities for holding in the inventory and quantities for dispositioning according to economically relevant recovery options o are determined. Items flowing into the recovery option o became available in recovered-product-g inventory and recovery operation costs are incurred. From available recovered-product o inventory, according to the corresponding occurrence, demands are satisfied and revenues are gained.

In order to clarify there exist G many testing operations to classify returns between $G+1$ quality grades, there exists an equal number of stock points I prior to testing and an equal number of recovery options O.

Since a generalized representation of the generic base case is quite complicated, we provide an example with $G = 3$, in Figure 3.2. In this figure triangles represent stock points and circles represent workstations where operations such as transportation, testing and recovery processes are performed. Directed arcs represent possible flows of items between workstations and stock points. As it can be seen from the figure, customer returns from various sources with various reasons are acquired in the collection center. These are transported to a central product recovery facility where they are routed through a sequence of testing / grading workstations and processes, such that those returns filtered trough the testing operations are said to be quality graded and successful items are stocked at relevant grade work-in-process stock points to be further processed in recovery workstations. Failed products in each testing stage either continue to further inferior quality tests or sold as scrap for recycling directly.

Because the quality distribution of the flows change after every testing stage, it is essential to define an inventory per stage. This structure enables us to investigate the make to order or make to stock behavior of the recovery system as well. Items succeeding form tests are stored in graded work-in-process stock points and then recovered in a viable recovery process so as to satisfy respective demands for different types of recovered products. Note that there is always the option of disposing raw returns directly to recycling.

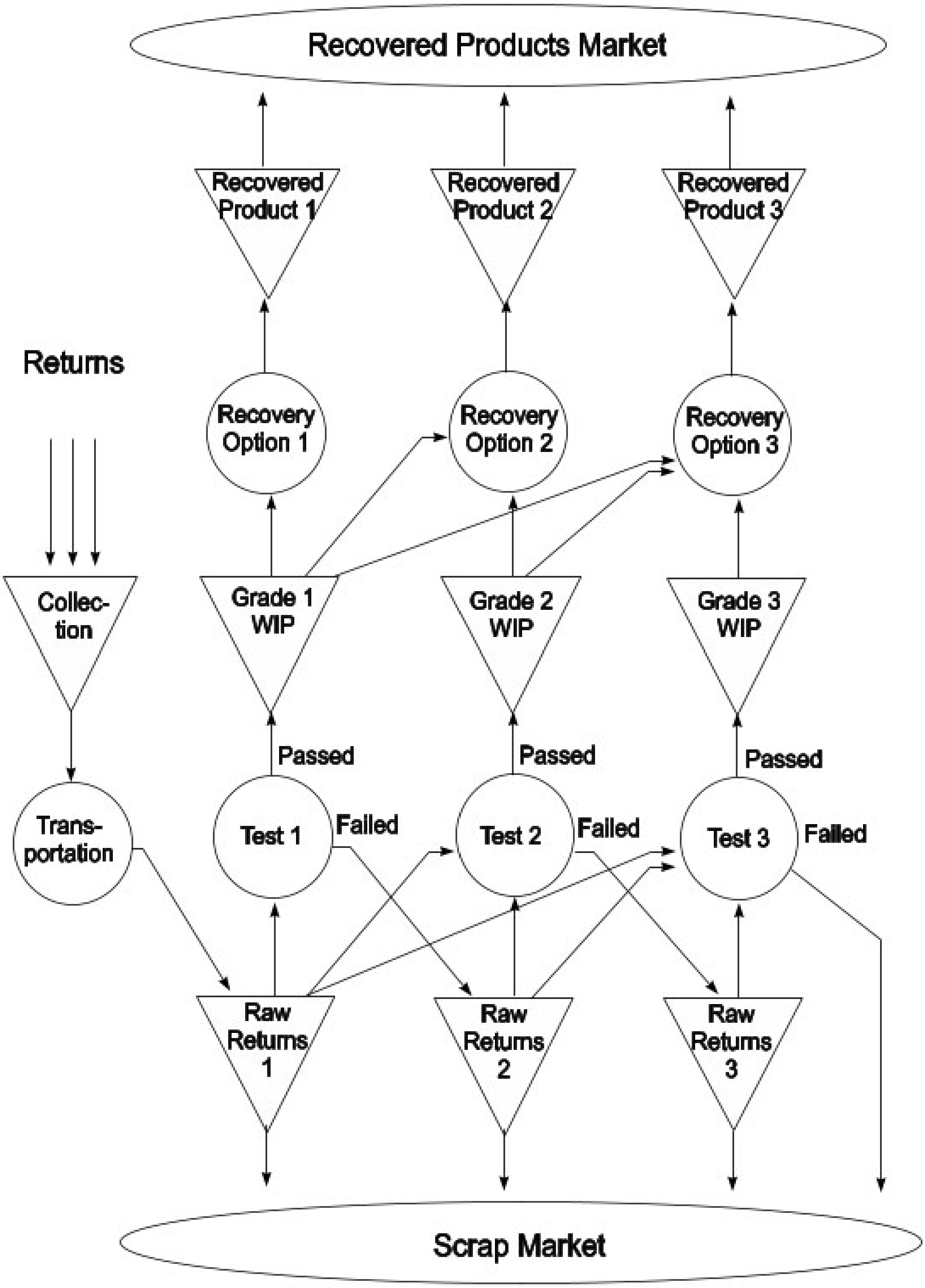

Figure 3.2 Graphical representation of the generic base case

The testing operations of the generic case are assumed to be arranged in a way that flow of items in the forward direction is possible only and it is allowed to skip some of the testing operations, issuing relatively good quality items in the raw returns and work-in-process stock points to testing and recovery operations essentially installed for inferior quality returns. The drawing of the generic base case is presented as a descriptive tool for reference in constructing mathematical formulation of the multi-period model in the next section.

3.2. The Generic Base Case Linear Programming Model

In this section firstly the parameters, the decision variables and the regarding notation used for the generic base case model of the product recovery system in consideration are explained. Afterwards, a multi-period linear programming model to obtain an optimal solution to the rough-cut product recovery planning problem is provided. Finally, objective function and constraints are described. Notations for the proposed generic model starting with the parameters are;

T	:	Planning horizon.
t	:	Index for time periods $t = \{1,...,T\}$
G	:	Number of quality grades.
g	:	Index for quality grades $g = \{1,...,G\}$.
I	:	Number of raw returns stock points, (stock before testing).
i	:	Index for stock points $i = \{1,...,I\}$.
O	:	Number of possible recovery options.
o	:	Index for recovery options $o = \{1,...,O\}$.
R_t	:	Returns collected at the acquisition warehouse in period t.
D_{ot}	:	Demand for option o recovered products in period t.
p_{ot}	:	Unit price of option o recovered products in period t.
p_s	:	Unit price for salvaged products.
β_t	:	Discount rate in period t for calculating net present value.
e	:	Inventory carrying charge TL/TL/period.
α_g	:	Proportion of quality grade g items that can be recovered

from the incoming stream of returns.

θ_{ig} : Probability (or rate of success) that an item issued from raw returns stock point i passes the test at testing workstation g.

c^a : Unit acquisition cost for returned products (where a stands for "acquisition").

c^h : Unit transportation cost to the central recovery facility in period t, (where h stands for "hauling").

c^{hc} : Unit inventory holding value at collection center, (where hc are the initials for "holding" and "collection").

c_i^{hr} : Unit inventory holding value at raw returns' stock point i, (where hr are the initials for "holding" and "raw returns").

c_g^{hw} : Unit inventory holding value at g grade work-in-process stock point, (where hw are the initials for "holding" and "work-in-process").

c_o^{hp} : Unit inventory holding value at stock point of recovered option o products, (where hp are the initials for "holding" and "processed").

c_g^x : Unit cost of testing at testing workstation g in period t.

c_o^y : Unit cost of recovery as option o at the relevant recovery workstation.

l_g^x : Standard times for grade g testing operations.

l_o^y : Standard times for option o recovery operations.

L_t : Labor availability in period t.

Notations employed for the decision variables are;

B_t : Number of returned products transported from collection center to the recovery facility in period t.

S_{gt} : Number of items salvaged as scrap from raw returns stock point g in period t.

X_{igt} : Number of returned items issued from raw returns stock point i to be tested at workstation g in period t.

Y_{got} : Number of returned items issued from work-in-process warehouse g to be recovered as option o in period t.

Q_{ot} : Number of option o recovered products sold to the customers in period t.

I_t^c : End of period t inventory at collected returns warehouse

I_{gt}^w : End of period t inventory at the WIP-grade g stock point.

I_{it}^r : End of period t inventory at the raw returns stock point i.

I_{ot}^p : End of period t inventory at the stock point for recovered products of option o.

Definition of the proposed generic model:

At the beginning of every period t, where $t \in \{1,...,T\}$, customer returns, R_t are collected at the product acquisition warehouse. An acquisition cost of c^a is incurred. Acquisition is an obligation and when returns occur denying acquisition is not possible. Thus, although acquisition has no effect on the outcome of the problem, in order to quantify the full value of the information it's not neglected.

Afterwards, a quantity of product returns, B_t from the acquisition warehouse is transferred to the central recovery facility with a unit transportation cost of c^h. These returns are stocked at "raw returns stock point" as shown in the Figure 3.1. Returns are then released to the testing workstations and magnitudes of such flows are represented by X_{igt} where i represents issuing warehouse and g represents receiving workstation in period t respectively.

Testing inspection and sorting operations' unit costs c_g^x are assumed to be stationary. Returns stocked at raw returns stock point i are issued to testing workstation g and items successfully passing the test with a probability of θ_{ig} are delivered to the work-in-process stock point g. In other words of all items tested at a relevant workstation, θ_{ig} percent of those are delivered to stock points to be recovered accordingly. On the other hand, items failing the test g are delivered to stock points $g+1$ with a probability of $\left(1-\theta_{ig}\right)$, either to be further tested or to be salvaged as scrap. Again it can be put another way such that of the items tested in workstation g coming from raw returns stock point i, $\left(1-\theta_{ig}\right)$ fraction of those tested can not pass the test and are sent to the next stock point for further testing or to be salvaged as scrap. In practice, testing is not necessarily to be conducted in a strict sequence. Depending on changes in demands, costs, revenues and production capacities some tests may be skipped and items may be issued from one stocking point i to a testing operation g where $g>i$ and $g \neq i+1$. Returns successfully passing tests are stored in respective work-in-process stock points, where they may be issued to a respective recovery work center o in quantities, Y_{got} in each period t, where $o \in \{1,...,O\}$.

Unit cost of recovery operations, c_o^y are assumed to be stationary for simplicity. Inventory holding costs at all warehouses in period t are computed by multiplying end of period inventories I_t^c, I_{gt}^r, I_{gt}^w and I_{gt}^p of warehouses by respective unit inventory holding values of c^{hc}, c_g^{hr}, c_g^{hw}, c_g^{hp} and the interest rate e. Inventory holding costs are defined as the sum of collection, transportation and other operational costs incurred until the product reaches the respective warehouse; for example for the collected returns warehouse inventory holding value, c^{hc} is equal to acquisition cost of returns, c^a. Inventory holding value at raw returns warehouse is $c^{hr}=c^a+c^h$ i.e. sum of acquisition and transportation costs etc. When lead times are desired to be introduced in to the model for transportation, testing and recovery operations, then the holding costs to be incurred during such lead times can be assumed equal to holding cost at issuing warehouses.

Prices of recovered products for different recovery options, p_{ot} are variable over time periods and they are independent of sales quantities, Q_{ot}. In reality salvaging as scrap for recycling may be initiated from any node of the network but for the sake of simplicity this option of selling scrap will be confined to the raw returns stock points at central recovery facility only. Also the returns failing final testing operations are assumed to be salvaged as scrap as an end condition and for convenience in formulations. Based on the assumptions made and conditions stipulated above, a generic linear programming formulation of the model may be given in closed form as in the sequel.

The linear programming model of the generic base case can be stated as follows;

$$Max \quad \sum_{t=1}^{T} \beta_t \left\{ \sum_{g=1}^{G} (p_{ot} Q_{ot} + p_s S_{gt}) - c^a R_t - c^b B_t \right.$$

$$- \sum_{g=1}^{G} \sum_{i=1}^{g} c_g^x X_{igt} - \sum_{g=1}^{G} \sum_{i=1}^{g} c_g^y Y_{igt} - e \ c^{hc} I_t^c$$

$$\left. - \sum_{g=1}^{G} e(c_g^{hr} I_{gt}^r + c_g^{hw} I_{gt}^w + c_g^{hp} I_{gt}^p) \right\} \tag{3.4}$$

Subject to

$$I_t^c = I_{t-1}^c + R_t - B_t \qquad \forall t = \{1, ..., T\} \tag{3.5}$$

$$I_{1t}^r = I_{1t-1}^r + B_{t-1} - \sum_{g=1}^{G} X_{1gt} - S_{1t} \qquad \forall t = \{1, ..., T\} \tag{3.6}$$

$$I_{gt}^r = I_{gt-1}^r + \sum_{i=1}^{g-1} \left(1 - \theta_{ig-1}\right) X_{igt} - \sum_{i=g}^{G} X_{igt} - S_{gt}$$

$$\forall g = \{2, \ldots, G\}, t = \{1, \ldots, T\} \tag{3.7}$$

$$I_{gt}^w = I_{gt-1}^w + \sum_{i=1}^{g} \theta_{ig} X_{igt} - \sum_{o=g}^{G} Y_{got} \qquad \forall g \in \{1, \ldots, G\}, t \in \{1, \ldots, T\} \tag{3.8}$$

$$I_{ot}^p = I_{ot-1}^p + \sum_{o=g}^{G} Y_{got} - Q_{ot} \qquad \forall o \in \{1, \ldots, O\}, t \in \{1, \ldots, T\} \tag{3.9}$$

$$\sum_{i=1}^{G} \sum_{g=i}^{G} l_g^x X_{igt} + \sum_{g=1}^{G} \sum_{o=g}^{O} l_o^y Y_{got} \le L_t \qquad \forall t \in \{1, \ldots, T\} \tag{3.10}$$

$$Q_{ot} \le D_{ot} \qquad \forall o \in \{1, \ldots, O\}, t \in \{1, \ldots, T\} \tag{3.11}$$

$$0 \le I_t^c, I_{gt}^r, I_{gt}^w \qquad \forall g \in \{1, \ldots, G\}, t \in \{1, \ldots, T\} \tag{3.12}$$

$$0 \le X_{igt}, Y_{got}, S_{gt}, Q_{ot}, I_{ot}^p \qquad \forall g \in \{1, \ldots, G\}, i \in \{1, \ldots, G\}, o \in \{1, \ldots, O\}, t \in \{1, \ldots, T\} \tag{3.13}$$

Objective function in (3.4) aims to maximize net present value of profit over the planning horizon T. Costs of collection, transportation, testing, recovery and inventory holding costs at all stock points from each period are subtracted from sales revenues of recovered products and scrap in total. β_t is the multiplier for computing the net present value. Note that the double summation term with X's represents cost of testing operations, and the double summation with Y's represent cost of recovery operations.

Constraint (3.5) ensures the inventory balance at the customer returns collection center, reflecting the fact that collected returns may only be received by this warehouse. Returns can be stored at the collection, can be transported to the central recovery facility or can be salvaged. Constraint (3.6) ensures the inventory balance at the initial raw returns warehouse determining the balance of inflows from acquisition and outflows to either possible testing operations or salvaging as scrap for recycling. Constraint (3.7) ensures the inventory balance at the other raw returns stock points, unsuccessful items are released to either further testing operations or salvaged as scrap for recycling. Constraint (3.8) ensures the balance at the work-in-process stock points. Here the amount of items successfully passing tests to be recovered is determined.

Tested and graded items are either stored or sent to relevant recovered product inventories after processing. Constraint (3.9) ensures the balance at the recovery processed items stocking points by determining the balance of inflows from the recovery processes and outflows to relevant markets for satisfying demands. Constraint (3.10) introduces an over all labor availability constraint L_t per period with the assumption that there is flexibility in skilled labor substitution between workstations. l_{gt}^{x} and l_{ot}^{y} are standard operation times for g grade testing and option o recovery operations, respectively. The forecasted demands are introduced in constraint (3.11). Finally the constraints (3.12) and (3.13) ensure the non-negativity conditions.

Time dependent physical work-center capacity constraints for testing and recovery may be stipulated as;

$$\sum_{i=1}^{g} X_{igt} \leq f_{gt}^{x} \qquad \forall g \in \{1,\ldots,G\}, t \in \{1,\ldots,T\} \qquad (3.14)$$

$$\sum_{g=1}^{o} Y_{got} \leq f_{ot}^{y} \qquad \forall o \in \{1,\ldots,O\}, t \in \{1,\ldots,T\} \qquad (3.15)$$

where f_{gt}^{x} and f_{ot}^{y} are production capacities of testing and recovery processing workstations respectively.

Warehouse capacity constraints based on availability of space may also be stipulated if needed as follows:

$$I_{t}^{c} \leq f^{c} \qquad \forall t \in \{1,\ldots,T\} \qquad (3.16)$$

$$I_{gt}^{r} \leq f_{g}^{r} \qquad \forall g \in \{1,\ldots,G\}, t \in \{1,\ldots,T\} \qquad (3.17)$$

$$I_{gt}^{w} \leq f_{g}^{w} \qquad \forall g \in \{1,\ldots,G\}, t \in \{1,\ldots,T\} \qquad (3.18)$$

$$I_{ot}^{p} \leq f_{o}^{p} \qquad \forall g \in \{1,\ldots,G\}, t \in \{1,\ldots,T\} \qquad (3.19)$$

where f^{c}, f_{g}^{r}, f_{g}^{w} and f_{o}^{p} are collection, raw returns, work-in-process, production stock point capacities respectively.

3.3. Some Alternative Testing Configurations

In this section some alternative testing configurations such as a parallel testing environment and a serial testing environment generated with modifications on the base case model, are mentioned. These configurations may seem to be easier to model, setup and manage in practice. However, we will discuss the similar problems encountered in both generic base case and alternative cases. In computational studies, these models are used for specific instances in order to compare the generic base case and alternative configurations in terms of level of profit sub-optimality.

In the parallel case, returns incoming to the recovery center are sent to viable quality tests only once. Items successfully passing tests are sent to relevant grade work-in-process stock points. Failed ones, on the other hand, are salvaged as scrap for recycling. This situation is shown as a network flow diagram in Figure 3.3. Although for a lucid presentation a simplified diagram has been supplied, this model is actually a subset of the generic case and can be modelled by adding the following constraint:

$$X_{igt} = 0 \qquad \forall t = \{1,\ldots,T\}, \forall i = \{2,\ldots,G\}, \forall g \geq i \qquad (3.20)$$

Constraints defined in (3.20) forces that no returns from a raw returns stock point (except the first one, accepting returns from collection), can be sent to the other quality testing workstations. Thus, items failed at any testing operation can only be salvaged as scrap for recycling as shown in the figure. Note that the network configuration utilizes a single stock point for raw returns. Other stock points are become antiquated because there would be no incentive to keep, will be scraped items in the inventory.

But restrictions made in the network configuration, the flexibility in issuing returns failing some test i for further testing at another testing workstation is suppressed. Obviously this result in sub-optimal solutions compared to the generic case i.e. reduced profits, as will be shown computationally, due to added constraints and decreased solution space of the linear programming model.

In the serial case, returns incoming to the recovery center are sent to viable quality tests in a sequential manner. This situation is shown diagrammatically in Figure 3.4. Items successfully passing a test are sent to relevant work-in-process stock points. Failed ones on the other hand, are either sent to the next inferior quality grade testing workstation or salvaged as scrap for recycling. Equations of the linear programming formulation of this serial testing case take the following form:

$$X_{igt} = 0 \qquad \forall t = \{1,\ldots,T\}, \forall i = \{1,\ldots,G\}, \forall g > i \qquad (3.21)$$

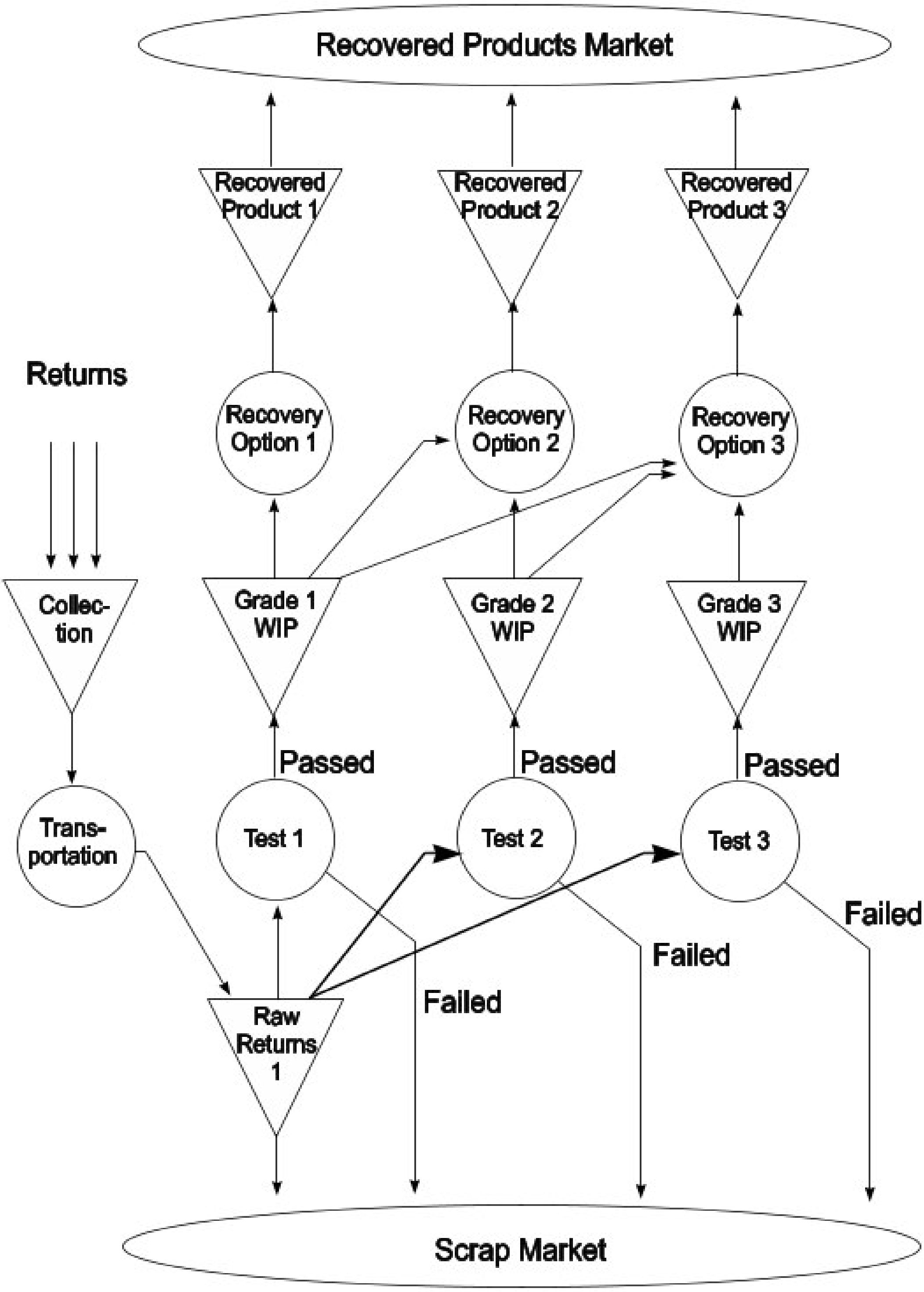

Figure 3.3 Graphical representation of parallel testing case

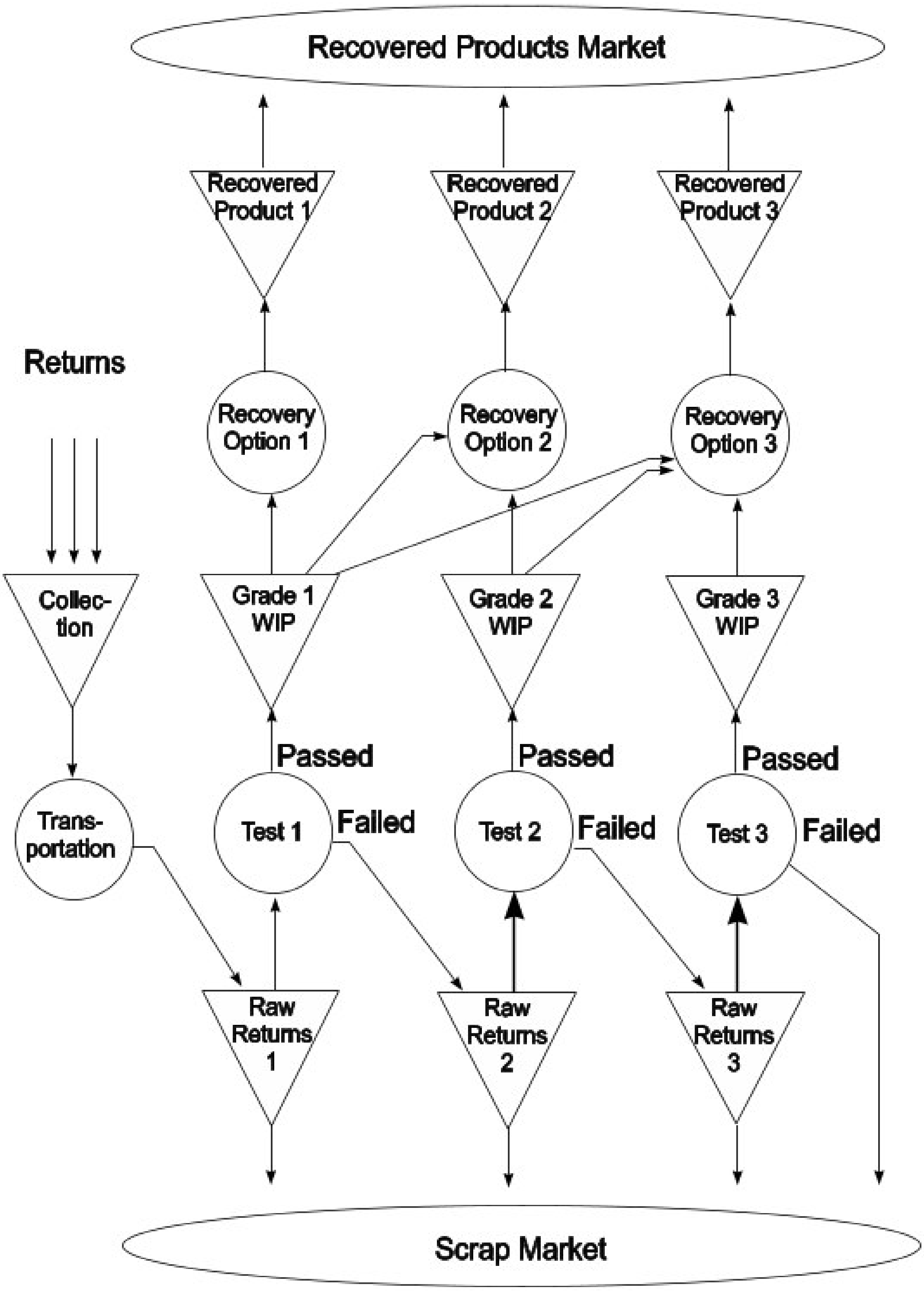

Figure 3.4 Graphical representation of serial testing case

Constraints defined in (3.21) forces that no returns from a raw returns stock point can be sent to an inferior grade quality testing workstations. Note that the possibility of skipping unnecessary tests to economize is not possible in this configuration. It may be a technical necessity to setup such a configuration or it may be chosen due to easier record keeping. However, again restrictions made in the network configuration obviously results in sub-optimal solutions compared to generic base case due to added constraints and decreased the solution space of the linear programming model. However, closing this profit performance gap with help of extra information will be elaborated with simple cases in the next chapter.

3.4. The Case of Gatekeeping

Apparent from the above discussion, it is possible to make many variants of the generic base case, depending on the industry, type of returned products and pertinent parameters that may appear in the setting under consideration. In this study, the case of gate keeping will be covered mainly and will be compared to the generic base case model.

The gatekeeping modification to the generic base case is presented diagramatically in Figure 3.5. As can be seen from the figure, the difference between the generic base case is the introduction of "Gate keeping station(s)" at the source(s) of the light touch returned products, eg. retail stores.

This gate keeping process may be envisaged as some simple identification facility which does not require any additional labor and special training, but supported by the information provided from embedded systems installed in the products, for example, for guiding store workers to decide whether to send a sales rerturn directly to the shelves or to the central recovery station. Some fraction of returns incoming to the collection center are considered as resellable and sent back to shelves. If demand for resellables is satisfied, residual resellable items may either be stored in the inventory or sent to the recovery center with similar transportation costs and lead time. Because the quality grade is known beforehand these items are introduced to the WIP-grade 1 inventory to derive benefit from alternative recovery options. It is expected that in such a case overall performance of the recovery operations will be improved. A new parameter, γ, is introduced as the proportion of resellable quality grade items that can be sold as is from the incoming stream of returns and three decision variables; I_t^s, as the end of period t inventory of collected resellable returns at the store or collection center, B_t^r, as the number of resellable returned products transported from collection center to the recovery facility in period t, Q_t^r, as the sales quantities of resellable items in period t.

Equations of the linear programming formulation of this gate keeping case take the following form:

$$Max \quad \sum_{t=1}^{T} \beta_t \Bigg\{ \sum_{g=1}^{G} \left(p_{ot} Q_{ot} + p_{1t} Q_t^r + s S_{gt} \right) - c_t^a R_t - c_t^b B_t$$
$$- c_t^b B_t^r - \sum_{g=1}^{G} \sum_{i=1}^{g} \left(c^x{}_g X_{igt} \right) - \sum_{g=1}^{G} \sum_{i=1}^{g} \left(c_g^y Y_{igt} \right) - e c^{hc} I_t^c$$
$$- e c^{hc} I_t^s - \sum_{g=1}^{G} e \left(c^{hr}{}_g I^r{}_{gt} + c^{hw}{}_g I^w{}_{gt} + c^{hp}{}_g I^p{}_{gt} \right) \Bigg\} \qquad (3.22)$$

Subject to

$$I_t^s = I_{t-1}^s + \gamma R_t - B_t^r \qquad \forall t = \{1, ..., T\} \qquad (3.23)$$

$$I_t^c = I_{t-1}^c + (1-\gamma) R_t - B_t \qquad \forall t = \{1, ..., T\} \qquad (3.24)$$

$$I_{1t}^r = I_{1t-1}^r + B_{t-1} - \sum_{g=1}^{G} X_{1gt} - S_{1t} \qquad \forall t = \{1, ..., T\} \qquad (3.25)$$

$$I_{gt}^r = I_{gt-1}^r + \sum_{i=1}^{g-1} \left(1 - \theta_{ig-1}\right) X_{igt} - \sum_{i=g}^{G} X_{igt} - S_{gt}$$
$$\forall g = \{2, \ldots, G\}, t = \{1, \ldots, T\} \qquad (3.26)$$

$$I_{1t}^w = I_{1t-1}^w + B_{t-1}^r + \theta_{11} X_{11t} - \sum_{o=1}^{G} Y_{1ot} \qquad t \in \{1, \ldots, T\} \qquad (3.27)$$

$$I_{gt}^w = I_{gt-1}^w + \sum_{i=1}^{g} \theta_{ig} X_{igt} - \sum_{o=g}^{G} Y_{got} \qquad \forall g \in \{2, \ldots, G\}, t \in \{1, \ldots, T\} \qquad (3.28)$$

$$I_{gt}^p = I_{gt-1}^p + \sum_{o=g}^{G} Y_{got} - Q_{ot} \qquad \forall g \in \{1, \ldots, G\}, t \in \{1, \ldots, T\} \qquad (3.29)$$

$$\sum_{i=1}^{G}\sum_{g=i}^{G} l_g^x X_{igt} + \sum_{g=1}^{G}\sum_{o=g}^{O} l_o^y Y_{got} \le L_t \qquad \forall t \in \{1,\ldots,T\} \qquad (3.30)$$

$$Q_{1t} + Q_t^r \le D_{1t} \qquad t \in \{1,\ldots,T\} \qquad (3.31)$$

$$Q_{ot} \le D_{ot} \qquad \forall o \in \{2,\ldots,O\}, t \in \{1,\ldots,T\} \qquad (3.32)$$

$$0 \le I_t^c, I_t^s, I_{gt}^r, I_{gt}^w, I_{gt}^p \qquad \forall g \in \{1,\ldots,G\}, t \in \{1,\ldots,T\} \qquad (3.33)$$

$$0 \le X_{igt}, Y_{got}, S_{gt}, Q_{ot}, Q_t^r, B_t, B_t^r \qquad \begin{array}{c}\forall g \in \{1,\ldots,G\}, i \in \{1,\ldots,G\}, \\ o \in \{1,\ldots,O\}, t \in \{1,\ldots,T\}\end{array} \qquad (3.34)$$

Revenue from direct selling resellable returns, cost of transporting resellable items to the central recovery center and inventory holding at the collection are added to the generic base case objective function as in (3.22).

Constraint (3.23) ensures the inventory balance at the newly introduced resellables stock point. Constraint (3.24) ensures the inventory balance at the collection center. Constraint (3.25) ensures the inventory balance at the initial raw returns stock point, unsuccessful items are either released to further testing operations or salvaged as scrap for recycling. Constraint (3.26) ensures the inventory balance at the remaining raw returns stock points and is the same with the generic base case model. Constraint (3.27) ensures the balance at the work-in-process stock points. Inflows from the newly introduced resellables stock point are introduced here. Constraint (3.28) maintains the balance at the remaining work-in-process stock points.

Constraint (3.29) ensuring the balance at the recovery processed items stocking points and constraint (3.30) introducing an over all manpower availability, are the same as it is in the generic base case model. The forecasted demands for to be resold items are satisfied from both items returning to shelf at the gate keeping station and items coming from the recovery center as stated in (3.31). General demand constraint is in (3.32) and finally the constraints (3.33) and (3.34) ensure the non-negativity conditions.

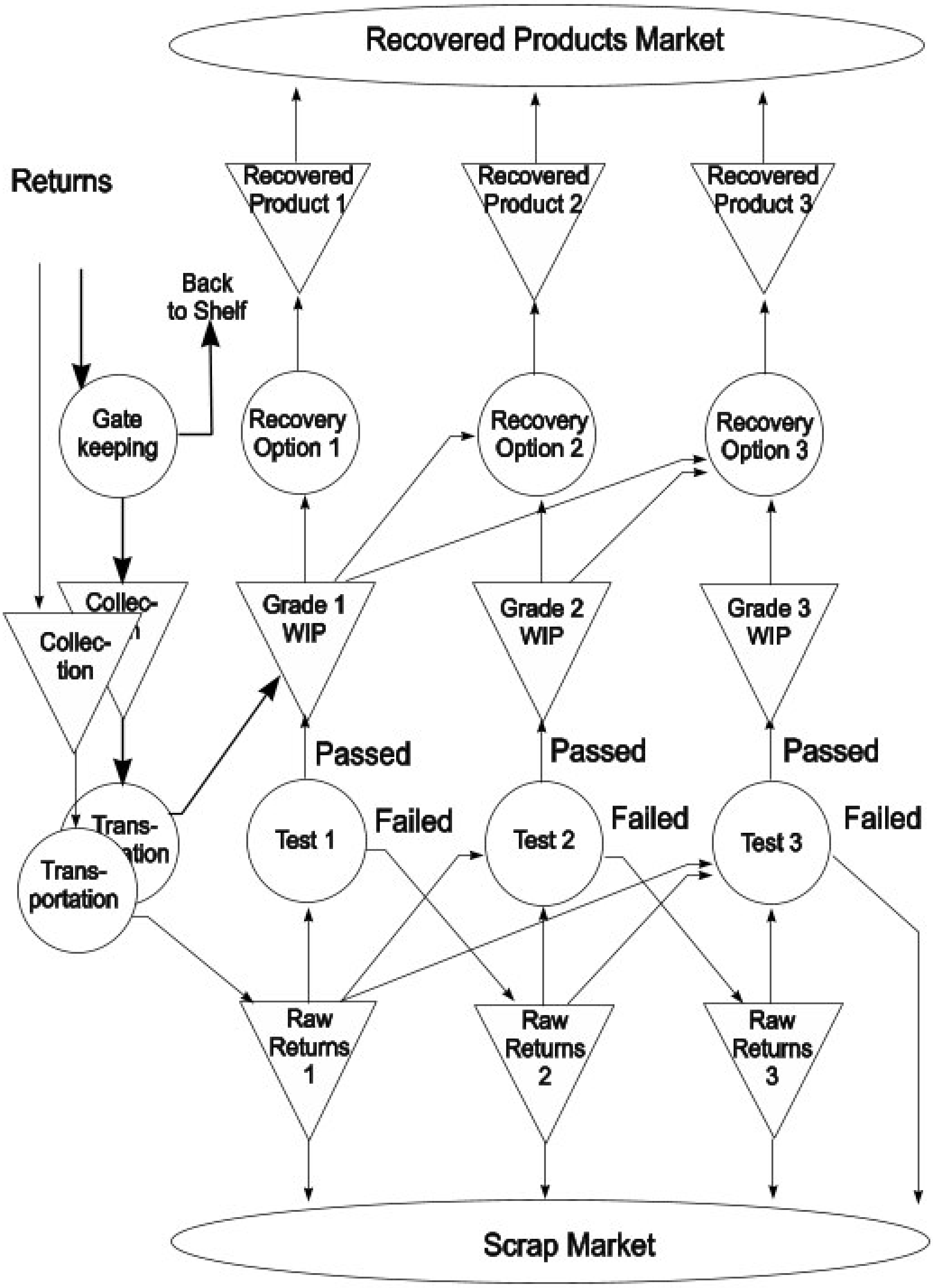

Figure 3.5 Graphical representation of gatekeeping case

3.5. The Case of Pre-Sorted Returns

In the above formulations quality of incoming returns were represented by a set of parameters $\alpha_1, \alpha_2, ..., \alpha_G$ which may be interpreted as the probabilities or fractions of a single return stream belonging to a certain grade. It is assumed that quantities received each period R_t at the collection center may vary in time but qualities remain invariant. However, if some more information about the quality of incoming returns can be supplied; for example if returns can be designated as “sales returns which essentially require a light touch of trimming” and as “warranty returns which require repair and refurbishment” etc. than a different configuration of the recovery facility may be arranged to take advantage of this additional information by splitting these into two different return streams, recalled as pre-sorting. Here, a possible approach is proposed for modifying our current generic base case model to span this recovery configuration as well.

If pre-sorting is possible, base case may be modified as in Figure 3.6. According to this figure returns are collected and pre-sorted into two different streams, namely sales returns and warranty returns, then received by their respective raw returns stock points. Pre-sorting does not mean getting rid of all the uncertainties associated with the quality of the pre-sorted returns. But in this case instead of an aggregate set of quality parameters, each stream of pre-sorted returns stored at separated raw returns stock points (or storage locations in the warehouse) may have their individual sets of quality parameters $\alpha_{k1}, \alpha_{k2}, ..., \alpha_{kG}$, where $k \in \{1, ..., K\}$ and $g \in \{1, ..., G\}$.

Such ready information may be obtained in several ways ranging from simply good record keeping and/or wise pre-sorting to sophisticated embedded systems applications depending on the product. Consider for example the returns collection process of end-of-use glass bottles. Usually at the disposal stations, two containers, one for colored glass and one for transparent is employed, grading and sorting is accomplished at the source of the recovery network at practically no cost. However not all product returns are suitable for pre-sorting. It depends on the product and design is usually not costless.

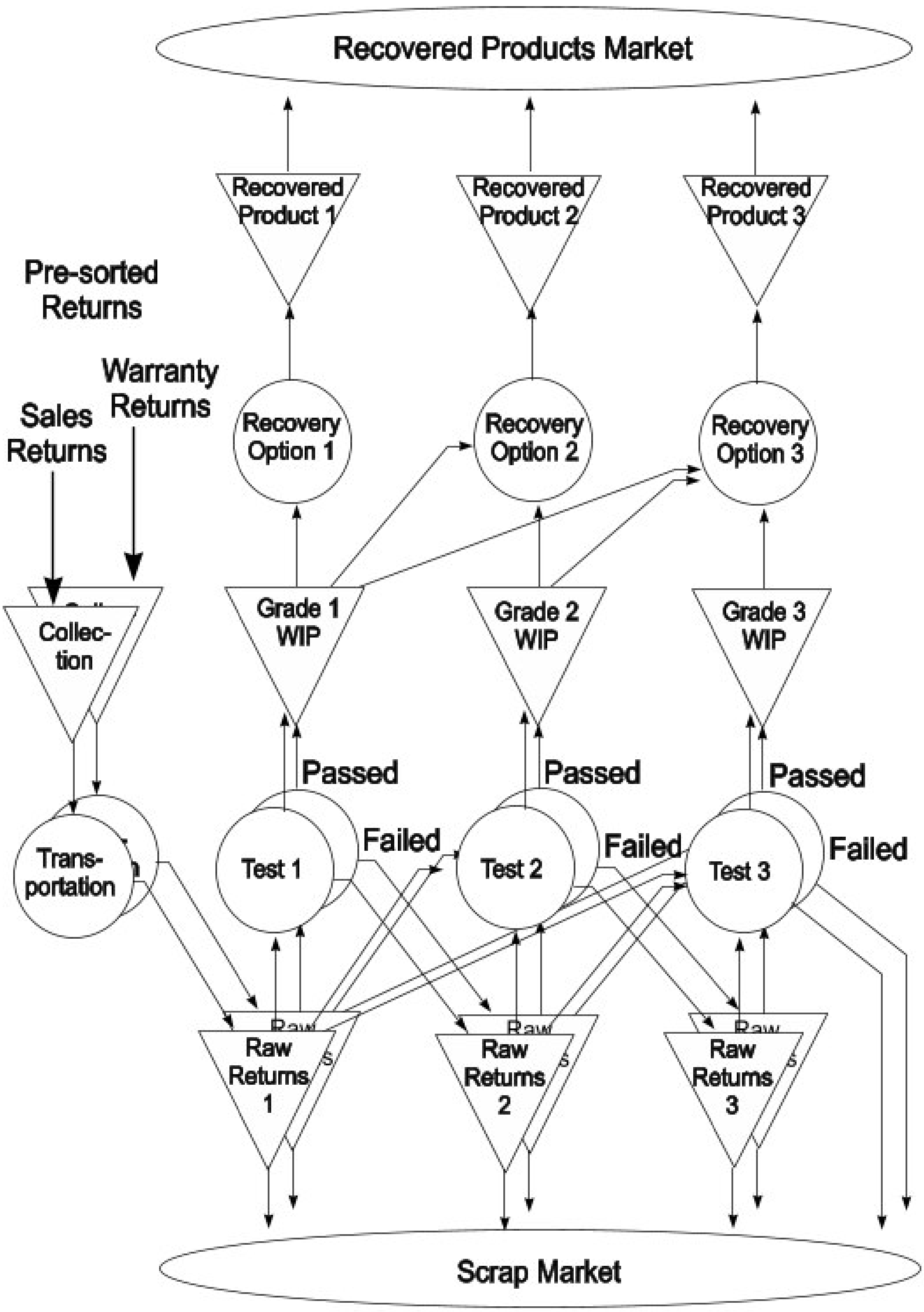

Figure 3.6 Graphic representation of pre-sorted raw returns case

The objective function and balance equations of the linear programming formulation of pre-sorted raw returns case are rather cumbersome and difficult to follow for the number of subscripts, which are now increased to four. Hence they are not explicitly given here. Nevertheless it has to be noted that the structure of the equations of the presorted case are the same as that of the generic base case, actually it is the same as solving several generic base case models in parallel with different inputs, bound with same demand and labor resource constraints. It is possible to compare a pre-sorted acquisition case with the generic base case and it's alternative configurations by submitting an aggragation of the quantity and quality data of the pre-sorted case into these models.

3.6. Discussion of the developed models

In this section the applicability of the proposed models, benefits and drawbacks are discussed explicitly. In general the above linear programming model of the base case does not reflect any problems of computational difficulty in terms of complexity or solution time. However, the uncertainties in the amount of incoming returns to the collection center, R_t, demands for different types of recovered products, d_{ot} and their prices, p_{ot} in every period cannot be put into consideration. Although this model can be converted into a stochastic programming model, it is believed that in real life cases settling forecasts and continuing with rolling basis planning approach will produce satisfactory results especially in tactical problems. In the short term, rolling basis planning approach, in fact is both practical and inevitable, where one solves a problem for a long planning horizon but implements the solutions obtained for only the immediate time frame during the course of which new and more reliable information may be obtained to solve the problem again and so on in this fashion.

The models developed can be used as tools for solving tactical decision problems at different levels of product recovery management. However, it should be accepted that for a complete production planning, these models have limiting simplifications and assumptions. Reverse supply chain structure is simplified such that a single retailer, single collection center and a single recovery center are considered only. Locations, returns allocations, recovery operation scheduling problems and similar problems are neglected. Also assumptions such as steady quality grade distributions for returns and deterministic amounts of supply and demand divert from real life conditions slightly.

Models developed in this thesis can be used to satisfy the obligations arising from the WEEE and AEEE legislations to prepare rough-cut product recovery plans, to set targets on aggregated recovery levels or can be used to take general recovery policy decisions, quality tagging or sorting investment decisions. Models appropriate for such a rough cut plan may not be employed as a full operational production planning system due to lack in detail.

As stated previously, differences in the quality distribution of returns incoming each period present a difficulty in modeling the product recovery management network. In detail, the complexity arises from the difficulty to formulate computation of time dependent success probabilities of inflows to inspection processes from various raw returns stocking points each period. The flexibility of being able to stock returns at any stage before recovery operations and to issue these materials from the raw returns warehouse or any stocking point to a choice of several testing work-centers requires cumbersome formulations for finding success probabilities of dynamically blending materials. Thus the prior models are modelled bearing in mind a time invariant structure for returns quality distribution. The work around of this problem proposed is to model the multi-period setting as separated LP's which are bind with a common resource constraint. Each multi-period network LP, handles the product recovery management problem of a certain period's incoming batch of returns with time invariant quality distribution assumption maintained through the planning horizon as it has been already modelled. Bind with the same demand and labor constraints however a single large LP model and a single planning problem will have been solved in the end.

It is believed that the alternative configurations or testing policies are computationally more practical especially in a rolling basis planning approach. Uncertainties and difficulties associated with the quality of collected returns both in computation and record keeping are brought to a minimum. But restrictions made in the configurations suppressed flexibility of the generic case. Obviously this result in sub-optimal solutions compared to generic case i.e. reduced profits, as will be shown computationally, due to added constraints and decreased solution space of the linear program.

CHAPTER 4

COMPUTATIONAL STUDY

The purpose of this study is to evaluate the benefits of extra information gathered by implementing tagging systems, which enable early product differentiation in terms of quality. Data for resembling, most likely to happen situations, is generated to investigate the value of increased quantity of quality information. Quantifying benefits will emphasize the economic attractiveness, especially those involving high level of good quality product returns within a time sensitive price environment in the sense that items lose value rapidly.

Firstly, general experimental design and relevant parameter value settings are given with reference to a hypothetical case. Next, the setting for the computational study and the results are presented with sensitivity analysis. Lastly benefits of nearly perfect information tagging with respect to different recovery system configurations are discussed. Performance measure comparison of the proposed generic base case recovery system and the proposed gatekeeping modification to the generic case is intended in this study. For each experiment, the linear programming model given in Section 3.2 is solved to obtain the profit of the generic base case recovery system. Also the linear programming model extension in Section 3.3 is solved with same parameters to obtain profit of the system with gatekeeping opportunity. In general an existing system under similar or different conditions and a proposed gatekeeping option can be compared in terms of different performance measures by implementing this approach.

The performance measures used in comparison are determined as follows:

- The absolute benefit of using the gatekeeping alternative in terms of profit is defined as;

$$\Delta\ \Pi = profit\left(gatekeeping\right)\ - profit\left(base\ case\right)$$

where $profit\left(basecase\right)$ is the optimal objective function value of the generic base case model given the parameters and $profit\left(gatekeeping\right)$ is the optimal objective function value of the generic case with gatekeeping opportunity under same conditions.

Ratio of the absolute gain to the gatekeeping gross profit may be considered as a good performance measure of gatekeeping policy but this measure takes negative values when gate keeping and/or base case profit take negative values, and may be misleading. This situation occurs especially when the level of quality of returns is low. Hence, in the analysis below relative gain figures are used as performance measures of implementing gate keeping policy.

- Relative benefit of using the gatekeeping alternative is defined as;

$$\%\Delta\ \Pi = \frac{profit\left(gatekeeping\right) - profit\left(base\ case\right)}{NetSales\left(base\ case\right)}$$

where $NetSales\left(genericcase\right)$ is the revenue from sales in TL reported on a company's financial statements after deductions. Net sales give an accurate picture of the actual sales generated by the company, the revenue to be received from the generic configuration without gatekeeping, and is chosen because it is always a non-negative number to be used in comparison without any confusion.

Lastly, in order to quantify the impact of proposed gatekeeping system on the level of recovery in terms of quantities;

- Relative quantity of different types of recovered items in proportion to the incoming total quantity of different quality returns are defined as a performance measure given the instances;

$$\%\Delta\ \text{recovered} = \frac{\text{recovered}\left(gatekeeping\right) - \text{recovered}\left(base\ case\right)}{Returns}$$

where $\text{recovered}(gatekeeping)$ and $\text{recovered}(base\ case)$ are the quantities of items recovered as option o under gatekeeping and base case settings respectively. $Returns$ denote the total quantity of product returns incoming through the cycle.

These performance measures are computed for each and every instance in the experimental study. The computations have been executed on an Intel(R) Pentium(R) M processor of 1.50GHz, 512 MB RAM, with Frontline's Excel Risk solver.

4.1. Parameter Settings and Experimental Design

An extensive computational study is carried out in order to investigate the behavior of the proposed product recovery system models under different circumstances. Alternative testing and recovery configurations and different instances are compared to quantify the level of gains from increasing the quantity of information fed into the planning decisions related to returned products.

A hypothetical case, where a new series of a certain consumer electronics product line will be introduced into the market, is considered. The manufacturer is in the process of making plans for a returned product recovery system. This product may be imagined as a desktop computer, cell phone, refrigerator, or any similar consumer durable.

A 3g cellular phone is taken into account to generate the data for the cases. Life of the product is estimated to be 6 years, equivalently 24 quarters, from introduction to pulling off from the market. It is envisaged that retail price of the product will be 600 TL at product's launching, which is chosen to be a resemblance to the average prices of any high-end retail consumer electronics product that may be in consideration. The virgin product prices are expected to decline at a rate of 50% every 18 months due to Moore's law.

As denoted by Souza et al. (2006), rate of incoming commercial returns follows a curve similar to the product life cycle, shifted to the right in the time axis as shown in Figure 4.1. After the introduction of the product to the market, product returns which are mainly due to sales guarantee and failure warranty based reasons, rapidly reach a stable level. At the beginning of steady return rate time periods, refurbished and remanufactured products became available, After the steady state, product enters the phase out or decline cycle where large numbers of stock adjustments from retailers, end-of-use and end-of-life product returns dominate the distribution of inflows.

Sales promotion policy traditionally accepts returns from unsatisfied customers if product is returned with packaging material within 30 days, It is a statutory obligation in many countries and is recalled as money-back guarantee returns. These “sales returns” are then channeled to a central recovery facility together with other vendor returned products which usually need a simple “trimming” or “light touching”, before they find their place on the shelves of some sales point again but this time at a lower price.

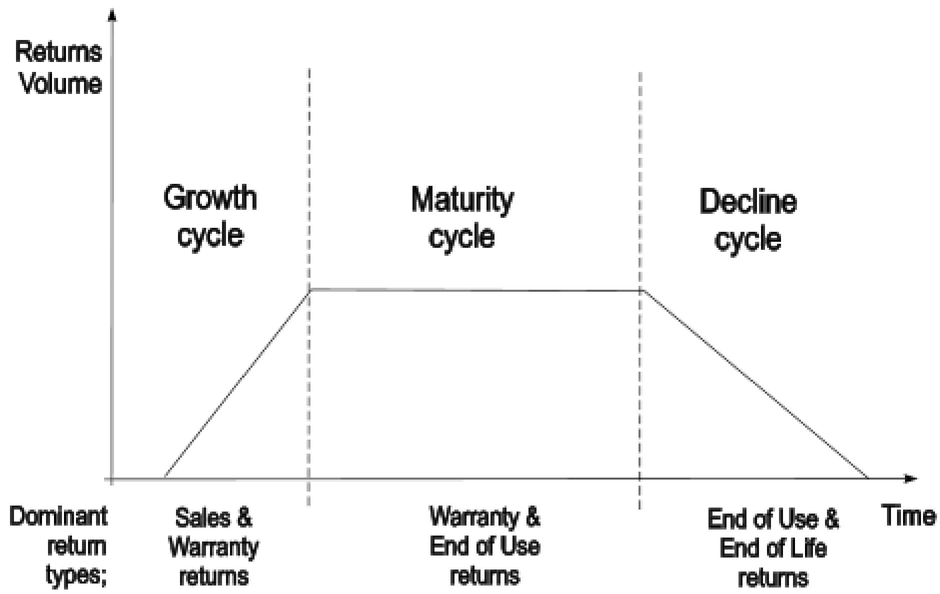

Figure 4.1 Product Returns Volume in Growth, Maturity and Decline Periods (adapted from Souza et al. (2005))

Sales returns sometimes may also require a “refurbishment” or a serious repair before heading for the market. Although rather rare, they may even be in worse condition in which case they are either “cannibalized” i.e. disassembled and the components are sold to be used in other production operations or recycled i.e. salvaged as scrap for recycling. In this study four different recovery options are considered. These are; reselling/ reusing, refurbishing, cannibalization and salvaging as scrap for recycling.

The products of the company are sold with 24 months of warranty and sales points of the company are also authorized to accept warranty claims. If malfunctioning products cannot be repaired at a sales point they are then exchanged with a new product and the returned products are again channeled back to the recovery center as “warranty returns”. Experience shows that some of the warranty returns can again be “refurbished”, can be “cannibalized” and some can be “salvaged” based on their quality state.

Due to statutory obligation of meeting a certain target of product recovery, suppose that the company has ongoing policy of accepting end-of-use returns for 30 TL rebate on newer models of the same line of products and these returns are again channeled back to the recovery facility to be resold, refurbished, cannibalized or salvaged.

In order to investigate benefits of proposed embedded systems at different stages of the life span of the product in consideration, time is separated into three sub cycles, corresponding to growth, maturity and decline. The planning horizon for each life cycle is fixed at 8 periods, each time bucket t, where $t = 1,...,T$, represents a quarter of a year. So the whole life cycle is assumed to be 24 quarters.

Anticipated return patterns are generally assumed to be following the demand for the virgin product in the market, these are;

- Linearly rapid increasing returns for resembling products’ market introduction.
- Stationary returns for resembling maturity period,
- Linearly decreasing returns resembling the phase out period of the product life cycle.

The demands for different types of recovered products, processed according to different recovery options, such as retouching, refurbishing, cannibalizing and salvaging are assumed to be some constant percentages of mean demand rate. Total demand for recovered products is;

- 75% of total quantity of returns for investigating demand as a constraint,
- 125% of total quantity of returns for ample demand consideration.

The price pattern contemplated for virgin products are shown in Figure 4.2, such as;

- Prices decline at a rate of 50% in 12 months for faster value fall off,
- Prices decline at a rate of 50% in 18 months as inspired by Moore's law,
- Prices decline at a rate of 50% in 36 months for slower value fall off.

Note that prices are assumed to become stable at some 40% level of the introduction price, corresponding to salvage value approximately.

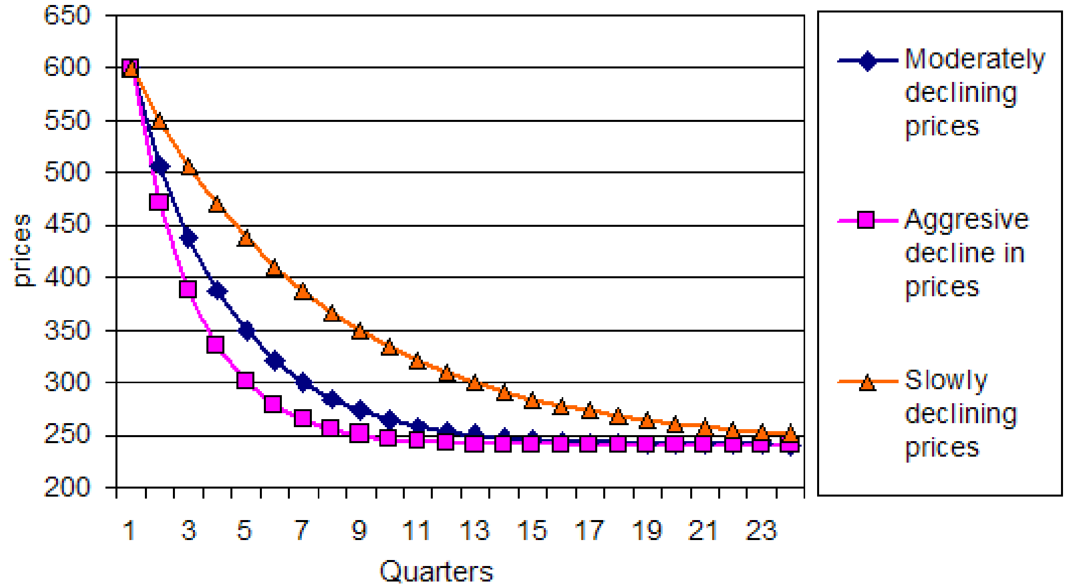

Figure 4.2 Time Sensitivity of Virgin Product Prices

The regarding periodic price discount rates, calculated with Excel's goal seek function, are $\{63.89\%, 74.18\%, 86.13\%\}$ for faster, medium and slower value fall off respectively. For example for a price decline at a rate of 50% in 18 months a discount rate of 74,18% should be effective each quarter.

Recovered products i.e. light touched products, to be resold as is, refurbished products and sum of cannibalized components of a single product will have a lower price tag as compared to the virgin product prices such as;

i) Each recovered product price is determined to be a ratio of the virgin product price. The ratio of virgin product price to certain recovered product price is assumed to be constant in time.

ii) Unit revenue from selling spare parts and unit revenue from salvaging is assumed to be constant over all periods.

The recovered product prices are assumed to be dependent on the first hand sales price of the virgin product, and this fraction is invariant in time for the sake of simplicity in calculations. Resellable light touched products are assumed to find a 10% lower than the price of virgin products on shelf, while refurbished products will be able to find a 35% lower the price than that of the virgin product.

Prices of cannibalized products and salvaged returns are assumed to be fixed. This assumption is rational because there is no dependency left in terms of demand, fashion or functionality between the virgin product and its salvage. Remaining value is due to material or energy composition only. For the calculation 90 TL and 35 TL price is assumed for cannibalized parts and salvaging as scrap respectively. Price data over the first cycle ,8 periods of the planning horizon, is given as in Table 4.1. There are no acquisition costs other than a rebate of 30 TL for end-of-life returns and the unit transportation cost by ground express is on the average 12 TL/unit.

Costs and relative prices of recovered products compared to the virgin product price are set intuitively based on our experience where two water damaged cellular phones are quality tested, repaired and sold as second hand. Price and cost relations are chosen to resemble a similar relation. There exist companies like RefurbIT and Recellular solely working on similar products' recovery. Similar values can be gathered form related auction sites as well....

Table 4.1 Price Estimates (in TL)

Period	1	2	3	4	5	6	7	8
Year	1	1	1	1	2	2	2	2
Quarter	1	2	3	4	1	2	3	4
Virgin Product Price	600	550	507	470	438	411	387	367
Light Touched Product Price	540	495	456	423	394	370	348	330
Refurbished Product Price	390	358	330	306	285	267	252	238
Cannibalized Price	90	90	90	90	90	90	90	90
Scrap Price	35	35	35	35	35	35	35	35

Operation cost data associated with the workstations derived from assumed unit testing and recovery operation times is summarized in Table 4.2. Inventory carrying charge throughout the whole planning horizon is assumed to be 12%.

Table 4.2 Operations' Unit Costs (in TL)

	Testing Operation Times	Unit Cost of Testing	Recovery Operation Times	Unit Cost of Recovery
Light-touching	17 min	4 TL	30 min	7 TL
Refurbishing	21 min	5 TL	38 min	9 TL
Cannibalization	25 min	6 TL	45 min	11 TL

Wage rate for skilled labor employed in testing and recovery operations is assumed to be 2.500TL per man for a month with 22 work days, each day constituting of 8 hours. Unit costs of testing and recovery operations are calculated by dividing monthly wage to total labor minutes available for a month, multiplied by the assumed standard operation times for each operation as mentioned in Table 4.2. Total available skilled labor, considered as the common resource constraint, is assumed to vary between 25 and 55 workers, numbers are chosen lower than required and strictly higher than required at peak return and demand cycles implicitly.

Recovery probabilities associated with different recovery options of each class of returns are estimated based on past experience with similar products, these inputs can be forecasts based on similar data or can be expert opinions. The input data for quality distribution estimates are shown in Table 4.2. In order to use the models for operational planning problems these quality distributions may be gathered by sampling or by making a full sequence testing of a batch of returns as well.

Table 4.3 Returned Product Qualities

		Probability of Recovery by Option			
Pre-sorted Returns	Returns Distribution	Light Touchable	Refurbish-able	Can be cannibalized	Can be salvaged
Sales Returns	30%	80%	15%	3%	2%
Warranty Returns	40%	5%	65%	15%	15%
EoU EoL Returns	30%	0%	10%	40%	50%
Aggregate Quality	**100%**	**27%**	**39%**	**21%**	**13%**

The aggregate qualities from the Table 4.3 are used as inputs for quality distribution of returns in our generic base case model, estimated from the different sources of returns such as, sales returns, warranty returns, end-of-use or end-of-life returns. These different sources of returns and regarding conditions may be used as inputs to the proposed pre-sorting case for comparison between generic base case, gatekeeping modified version of the base case and pre-sorted case. While considering the gatekeeping case however, the sales returns brought to the retail store at large are discriminated from the overall returns to the system. In the analysis, fraction of light touched sales returns are altered only, cannibalized or salvaged options are kept fixed paying attention in the and sum of fractions adds up to 100% as can be seen in Table 4.4. Three different return patterns based on life cycle consideration, first second and last 8 period cycles, three different quality distributions, three different price time sensitivity patterns (slower, moderate, faster fall off of prices) and two demand patterns, lower than or higher than current returns, are considered. A full factorial design is applied, so that the total number of problem instances is $3*3*3*4*3*2=648$. Table 4.4 below summarizes the experimental setting with the parameters of life cycle, quality of returns, transportation cost, recovery facility labor capacity and time sensitivity of prices.

Table 4.4 Experimental Setting

Factor	Levels
Time sensitivity of prices	$\{63.89\%, 74.18\%, 86.13\%\}$
Life Cycles	$\{\text{growth, maturity, decline}\}$
Transportation cost in TL (c_t^h)	$\{4,\ 12,\ 36\}$
Capacity of recovery facility (L_t)	$\{25,\ 35,\ 45,\ 55\}$
Quality of sales returns (α_1)	$\{50\%,\ 70\%,\ 90\%\}$
Light Touched Product Demand (D_{1t})	$\{75\%,\ 125\%\}$

4.2. Results of The Computational Study

In this section the results and interpretations of the solutions obtained by solving the proposed linear programming models formulated in Chapter 3 are presented. The performance of the gate keeping model is measured by the percentage increase in the total profit compared to the generic base case as stated in the beginning of Chapter 4. For the tests, a generic data set presented in Section 4.1 above, is used. For each example, the optimal solutions for the generic base case and the gate keeping case are determined.

Models are solved by utilizing the Frontline Solver for MS Excel. A copy of the worksheet where the decision making tool is developed for the analysis is given in

Appendix C. In this worksheet, data extends for 8 quarters, spanning growth, maturity or decline phases of the complete lifecycle of a product under consideration. Numerous solutions are obtained by experimenting with the solver and most characteristic results obtained are summarized below in tables and graphs with interpretations.

In Table 4.5 optimal solution of the base case model with sample data for the complete product life cycle is summarized in an income statement format. Input parameters for that specific case were 40 units of labor capacity constraint and prices halving in 18 months with returns incoming with high return quality, %90 resellable. The 8 quarter output of the linear programming solution is believed to be satisfactory for use in regulatory reporting for WEEE or AEEE and as well for discussing the results obtained. As is apparent from the pattern of the sales figures in Table 4.5 the first two years of the time scale can be considered as the growth phase, the next two as the maturity phase and the final two the decline phase of the product life cycle. Interpretations of these results are given in the sequel by varying the parameters step by step. First note that the recovery facility modeled acquires greatest revenue from light touched product recovery option.

Table 4.5 Results of one instance of the Generic base case

					(TL X 1000)	
Years	**1**	**2**	**3**	**4**	**5**	**6**
Net Sales (Base Case)	4.582	8.768	8.708	7.479	6.090	3.337
Light Touched Product Sales Amount	3.022	5.431	4.610	4.336	2.264	614
Refurbished Product Sales Amount	866	1.556	1.794	1.685	751	836
Cannibalized Product Sales Amount	446	1.118	739	739	1.913	1.174
Scrap Sales Amount	250	663	1.566	718	1.161	713
Cost of Sale (Base Case)	1.823	4.727	6.228	6.250	5.008	1.772
Acquisition Costs	1.338	3.478	4.660	4.660	3.465	945
Transportation Costs	95	247	368	368	297	81
Testing Costs	256	660	866	866	838	516
Recovery Operation Costs	134	343	334	334	362	221
Inventory Holding Costs	0	0	0	22	46	9
Gross Margin (Base Case)	2.760	4.041	2.480	1.229	1.082	1.564

In Table 4.6 the results under gatekeeping policy is reported for the same problem instance. As expected the gate keeping case yields higher gross profits than the base case.

Table 4.6 Results of one instance of the Gatekeeping case

					(TL X 1000)	
Years	**1**	**2**	**3**	**4**	**5**	**6**
Net Sales (Gatekeeping)	4.540	8.720	9.439	9.064	6.238	1.696
Light Touched Product Sales Amount	2.870	5.160	4.336	4.079	2.151	583
Refurbished Product Sales Amount	975	1.752	1.983	1.865	1.326	360
Cannibalized Product Sales Amount	446	1.158	1.962	1.962	1.718	468
Scrap Sales Amount	250	649	1.158	1.158	1.043	284
Cost of Sales (Gatekeeping)	1.651	4.294	6.033	6.033	4.662	1.271
Acquisition Costs	1.338	3.478	4.660	4.660	3.465	945
Transportation Costs	67	173	292	292	255	70
Testing Costs	163	423	727	727	642	175
Recovery Operation Costs	85	220	353	353	300	82
Inventory Holding Costs	0	0	0	0	0	0
Profit (Gatekeeping)	2.889	4.426	3.406	3.032	1.576	424

The statistics for $\%\Delta\Pi$, relative benefit of using the gatekeeping alternative in contrast to the generic base case are shown in Table 4.7, across the experimental setting (i.e., across 648 problem instances) and for each step of the life cycle, namely growth, the first 8 quarters of the life cycle, maturity, the second 8 quarters of the life cycle and decline period, the last eight quarters of the life cycle.

It is found that, for the given experimental instances, the gatekeeping policy of implementing embedded systems into manufactured products for estimating condition of returns if they are resellable or not, is better 17.59% on average when compared to the generic base case recovery configuration, where products are transported back to the central recovery facility for grading and recovery processes, with a minimum of 6.55% and a maximum of 30.46% on rare instances. Statistics for $\%\Delta\Pi$, relative benefit of gatekeeping, changes across different life cycles in consideration such that, higher benefits are gained in the growth cycle, when prices are more time sensitive at the beginning and sensitivity decreases rapidly through time. Also there is the effect of resource constraints which gets tighter in the maturity cycle.

Table 4.7 Summary Statistics Relative Gain in Profit Fragmented Over The Life Cycle

Statistics	Overall	Growth	Maturity	Decline
Minimum	6.55%	18.27%	10.25%	6.55%
25th Quartile	11.89%	20.77%	14.79%	8.48%
50th Quartile	18.27%	22.83%	18.45%	10.41%
75th Quartile	22.98%	24.59%	23.26%	13.00%
Maximum	30.46%	30.46%	29.70%	17.41%
Mean	17.59%	22.89%	19.00%	10.87%
Std. deviation	6.26%	2.59%	5.25%	2.86%

The statistics for $\%\Delta resold$, where relative amount of resold items to the incoming amount of different quality returns estimated from the quality distributions are defined are shown in Table 4.8, over all cycles. It should be noted that the gatekeeping policy increases direct reusability by 1.81% when compared to the base case, with a minimum of -0.81% and a maximum of 7.71%. Higher benefits are gained in the growth cycle as well. Negative values are due to low level of quality in sales returns at the decline cycle where recovery as resellable units has lowest impact on profits, such that system prefers to send the returns to inferior testing work centers instead of testing for reusability.

The statistics for $\%\Delta refurbished$, where relative amount of refurbished items to the incoming amount of different quality returns estimated from the quality distributions are shown in Table 4.9, over all cycles. Note that the gatekeeping policy increases high level recovery by refurbishing, on the average, 1.58% when compared to the generic case, with a minimum of -6.35% and a maximum of 8.18%. Level of refurbishment varies drastically due to trade offs between cannibalizing. Negative values are due to low level of quality in sales returns at the maturity cycle and constrained recovery capacity where recovery for reselling and cannibalizing produces the best results. On the other hand refurbishing results in loss of some opportunity to recover items as resellables or results in higher costs due to excess and unnecessary testing operations.

Table 4.8 Summary Statistics for Relative Quantity of Resold Items Fragmented Over The Life Cycle

Statistics	Overall	Growth	Maturity	Decline
Minimum	-0.81%	1.58%	0.22%	-0.81%
25^{th} Quartile	0.22%	2.28%	0.62%	-0.54%
50^{th} Quartile	1.58%	2.98%	0.95%	0.08%
75^{th} Quartile	2.78%	3.68%	1.49%	2.04%
Maximum	7.71%	5.09%	7.71%	3.12%
Mean	1.81%	3.10%	1.54%	0.79%
Std. deviation	1.82%	1.18%	1.96%	1.39%

Table 4.9 Summary Statistics for Relative Gain in Quantity of Refurbished Items Fragmented Over The Life Cycle

Statistics	Overall	Growth	Maturity	Decline
Minimum	-6.35%	1.23%	-6.35%	-1.86%
25^{th} Quartile	0.95%	1.23%	0.95%	-0.32%
50^{th} Quartile	1.23%	1.23%	1.14%	1.04%
75^{th} Quartile	1.76%	1.23%	1.14%	3.04%
Maximum	8.18%	4.41%	6.28%	8.18%
Mean	1.58%	1.76%	1.29%	1.68%
Std. deviation	2.44%	1.19%	2.92%	2.79%

The statistics for $\%\Delta cannibalized$, where relative amount of cannibalized items to the incoming amount of different quality returns estimated from the quality distributions are shown in Table 4.10, over all cycles. Gatekeeping policy increases cannibalizing, on the average, 2.91% when compared to the generic case, with a minimum of -7.38% and a maximum of 16.63%.

The statistics for $\%\Delta salvaged$, where relative amount of salvaged items for recycling to the incoming amount of different quality returns estimated from the quality distributions are shown in Table 4.11, over all cycles. Gatekeeping policy decreases salvaging, on the average, -3.62% when compared to the generic case, with a minimum of -16.63% and a maximum of 1.89%. Increase in salvaging occurs when only very limited labor availability is at the point of issue.

Table 4.10 Summary Statistics for Relative Gain in Quantity of Cannibalized Items Fragmented Over The Life Cycle

Statistic	Overall	Growth	Maturity	Decline
Minimum	-7.38%	0.00%	0.00%	-7.38%
25th Quartile	0.00%	0.00%	0.84%	-1.45%
50th Quartile	0.75%	0.63%	7.94%	-0.26%
75th Quartile	6.54%	2.51%	9.62%	1.24%
Maximum	16.63%	6.54%	16.63%	7.82%
Mean	2.91%	1.80%	7.33%	-0.38%
Std. deviation	5.05%	1.18%	1.96%	1.39%

Table 4.11 Summary Statistics for Relative Gain in Quantity of Salvaged Items Fragmented Over The Life Cycle

Statistics	Overall	Growth	Maturity	Decline
Minimum	-16.63%	-6.11%	-16.63%	-11.08%
25th Quartile	-6.54%	-1.46%	-12.84%	-5.14%
50th Quartile	-0.50%	0.00%	-8.05%	0.00%
75th Quartile	0.00%	0.00%	-3.40%	0.00%
Maximum	1.89%	1.89%	1.53%	1.22%
Mean	-3.62%	-1.30%	-7.85%	-1.72%
Std. deviation	4.97%	2.59%	5.62%	3.03%

A comparison of cumulative profits of the gatekeeping and base cases is presented in Figure 4.3. This graph reveals that, as expected, gatekeeping policy has a higher gross profit than base case and hence must be preferred to base case. Of course this result is shown for a single instance of 40 units of available (labor) capacity and a pattern with prices halving in 18 months, the statistics of the experimental setting validates significance of the difference in profit. The NPV of gross profit difference between the two cases at the end of the product life cycle can be interpreted as the break even investment in an embedded system to facilitate the implementation of a gatekeeping policy.

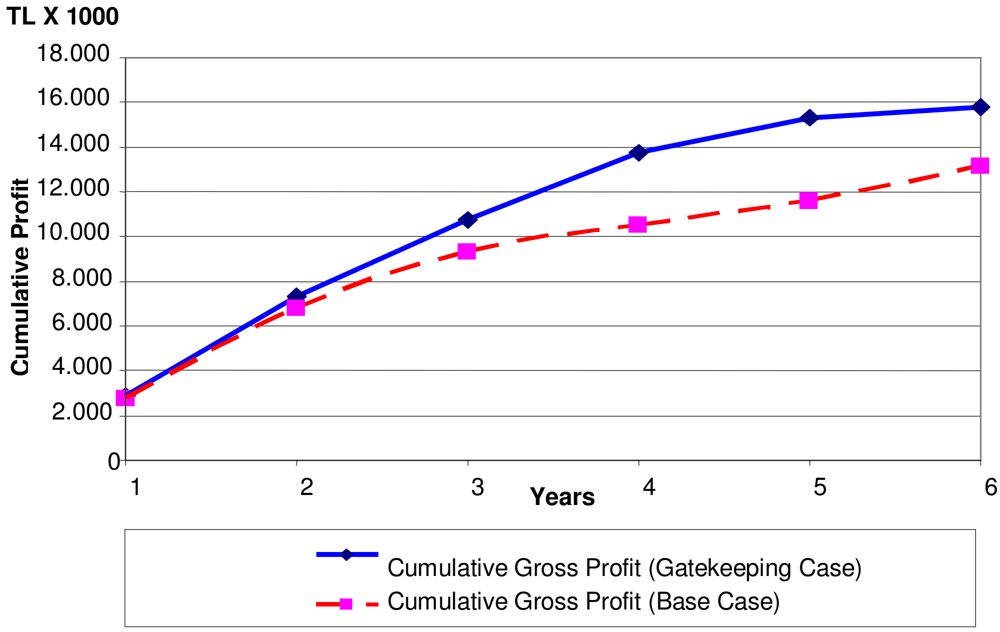

Figure 4.3 Comparison of cumulative profit of Generic Base Case and Gatekeeping Case

As a best practice benchmarking consideration, existing base case model with gatekeeping is modified as if perfect information on the quality condition of returns is available such that there is no need for testing. The goal of this benchmark analysis is to compare the gatekeeping implementation with a perfect information case to measure the remaining room for improvement. For computations, the existing model is run with zero unit testing costs. This way returns in reusable conditions are sent to shelves directly. Returns incoming to the central recovery facility are carried through testing workstations without any costs being incurred. Obviously these items will be allocated to testing and recovery operations that will be most fruitful.

The results of the study are presented below. According to Table 4.12 Gatekeeping has improved relative gross profits more than half the possible room for improvement, when compared to base case. While perfect information on whole quality condition of the returns would improve profits by 33% on average, gatekeeping has done approximately %20 improvement stand-alone.

Table 4.13 points to the change in relative recovery levels, where perfect information case, the benchmark, is compared to the base case with gatekeeping added. As it can be seen clearly, most of the improvement on better recovery diversification has been handled by early quality discrimination and tagging systems already. Perfect information case can divert approximately 1% more resold items only and decrease on salvaged items is at most 1.46% on the average.

Table 4.12 Benchmark Summary Statistics of prefect information case profit margin improvement overall cycles

Statistics	Compared to Base Case	Compared to Gatekeeping
Minimum	23.68%	5.72%
25th Quartile	28.16%	9.08%
50th Quartile	31.79%	14.77%
75th Quartile	36.52%	17.99%
Maximum	54.81%	24.68%
Mean	33.34%	14.07%
Std. deviation	6.83%	4.92%

Table 4.13 Benchmark Summary Statistics on recovery options overall cycles

Statistics	Resold	Refurbished	Cannibalized	Salvage
Minimum	0.00%	-1.23%	-6.38%	-14.07%
25th Quartile	0.95%	-1.23%	0.00%	0.004%
50th Quartile	1.11%	-1.11%	0.11%	0.00%
75th Quartile	1.23%	-0.56%	0.26%	0.00%
Maximum	1.23%	5.59%	14.07%	0.00%
Mean	0.92%	-0.06%	1.14%	-1.46%
Std. deviation	0.44%	1.40%	3.99%	2.86%

It can be interpreted from the experiment data analysis and regarding tables, Table 4.14, Table 4.15 and Table 4.16, that time sensitivity has the greatest impact on profits. Capacity restrictions have the second highest influence. Successively reusable returns majority has the third highest influence. Transportation has a lower impact compared to those.

Table 4.14 Relative Profit Gains Fragmented to Life Cycles and Capacity

Average of Delta %	Life Cycle			
Capacity of recovery facility	Growth	Maturity	Decline	Grand Total
25	24.71%	26.10%	14.85%	21.88%
35	22.45%	20.81%	11.17%	18.14%
45	22.20%	16.50%	9.06%	15.92%
55	22.20%	12.58%	8.43%	14.40%
Grand Total	22.89%	19.00%	10.87%	17.59%

Table 4.15 Relative Profit Gains Fragmented to Life Cycles and Quality

Average of Delta %	Life Cycle			
Reusable Quality	Growth	Maturity	Decline	Grand Total
50%	20.38%	17.38%	9.53%	15.76%
70%	23.79%	19.27%	11.04%	18.03%
90%	24.50%	20.35%	12.05%	18.97%
Grand Total	22.89%	19.00%	10.87%	17.59%

Table 4.16 Relative Profit Gains Fragmented to Life Cycles and Transportation Costs

Average of Delta %	Life Cycle			
Transportation cost(TL)	Growth	Maturity	Decline	Grand Total
4	22.23%	18.27%	10.30%	16.93%
8	22.89%	19.00%	10.88%	17.59%
12	23.55%	19.72%	11.45%	18.24%
Grand Total	22.89%	19.00%	10.87%	17.59%

Before continuing, the comparison of the profits of some variations of the returns recovery system namely the parallel and serial cases, both with and without gatekeeping policy are made. For a specific instance, with 40 unit capacity, prices halving in 18 months and with high return quality of 90% reusable sales returns, Table 4.14 shows these results. As expected, it is found out that the parallel case with no gatekeeping policy results in significantly inferior profits as compared to all other cases and the base case with gatekeeping policy yields greatest profit.

This result is interpreted such that the routing of the returns between testing operations at a recovery facility should not be restricted in any way beforehand as serial routing or parallel routing and material flows should be analyzed in detail for it pays to do so. Also it should be noted that the drawback of restricted networks can be gained on quickly when gatekeeping is considered.

Base case is a configuration where all returned products can be freely allocated to different quality test. Being free of constraints, it gives more profitable solutions in different situations with different returns quality distributions.

Table 4.17 Comparative financial results of Base Case, Serial and Parallel Case configuration with and without gatekeeping.

	Without Gatekeeping	Gatekeeping
Generic Base Case (TLx1000)		
Net Sales	28.016	28.737
Cost of Sale	18.057	16.798
Profit (Gross Margin)	9.959	11.939
Serial Case (TLx1000)		
Net Sales	27.997	28.681
Cost of Sale	18.043	17.493
Profit	9.954	11.188
Parallel Case (TLx1000)		
Net Sales	21.009	26.416
Cost of Sale	15.521	15.848
Profit	5.487	10.568

Serial case is generated out of the base case by adding constrains which in turn implies that the base case gives similarly profitable solution when this testing allocation constraints are non binding. These are cases where better quality returns are in majority. Thus, there will be no need to skip the good quality tests for lowering testing costs. Otherwise this configuration is always worse than the base case. The lower the incoming returns qualities, higher the inevitable testing costs are incurred such that the serial case becomes more disadvantageous.

In the parallel case returns can be tested only once due to company policy, due to diverse geographical positions of facilities or due to technical considerations, for instance when there exist cases with destructive testing or high level of disassemblies. Parallel case is generated out of the base case by adding constrains as well which results in lower outcomes in terms of profit generally, compared to both base and serial cases. In rare situations, where a specific quality condition is surpassing other possible quality returns, the parallel case approaches the results of the base case but parallel case solution is always worse than or equal to the base case.. On particular occasions where return quality is lower than reusable category the parallel case becomes superior to the serial case given the intense specific quality of returns. However, due to different usage conditions, use frequency, failure severities and uncertainty in customer returns it is unlikely to encounter such an instance. One circumstance that may recur to the mind is a recall situation where the possible issue is predicted before hand and sold items are

Pre-sorted case has the same configuration as the base case actually. Difference occurs from the view that the same base case model is solved for distinct buckets previously sorted according to some other consideration like return reason, returning customer types, retailers etc. but not according to a quality classification which can not be known beforehand testing. Because this thesis focuses on classification dependent on the returns' qualities the pre-sorted case is not investigated with extensive quantitative test. However current base case models are modified and intuitive results are tested and interpreted. Because each distinct bucket of returns may be composed of different quality distributed returns, testing sequence and recovery processing decisions on a relatively good quality returns bucket will be different form a worse quality returns bucket in a pre-sorted setting, which results in better profits with regards to the base case. Better results are gained dependent on the level classification obtained such that it is expected to result in the more dissimilar quality distributions are observed, the superior the pre-sorted case will be with regards to the base case and other cases.

4.3. Sensitivity Analysis of the Generic Model

In order to point the most influencing parameters, some sensitivity analyses are performed. The effects of the demand, the return pattern, capacity constraints, time sensitivity of prices and cost parameters on the performance of the models are determined. In the sequel results obtained by varying time sensitivity of prices, by parameterizing the labor constraint from tight to slack and changing the quality of incoming returns as low level, medium level and high are presented and interpreted. The results plotted by varying the time sensitivity of prices and percentage improvement over base case results obtained by implementing gate keeping policy are plotted in Figure 4.4.

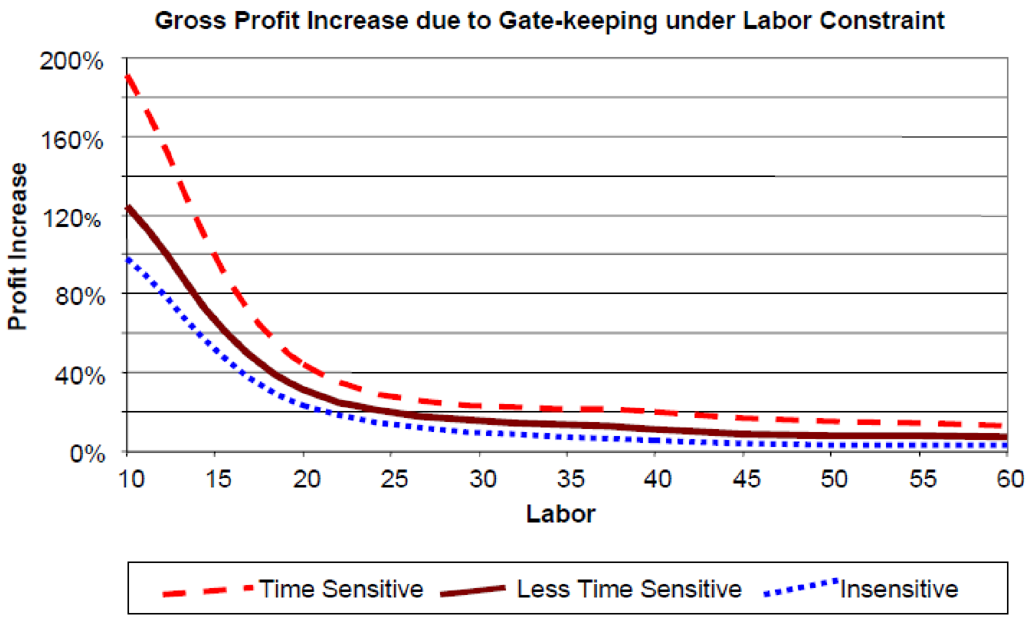

Figure 4.4 Effect of varying time sensitive prices and labor capacity on gross profit differential between gatekeeping and base case solutions

As it can be seen in this figure, the more time sensitive the prices, the more it is justifiable to invest in gatekeeping policy implementation. Note that "time sensitive prices" in this figure reflects 50% decline in virgin product's price just under 18 months, light touched product and refurbished product prices are dependent on the virgin product prices as assumed. Insensitive prices on the other hand decline %50 in over 36 months. The analysis further shows that as capacity allocated to the recovery operations of this specific product at a central recovery facility is decreased, there is more profit differential to justify investment into gatekeeping.

To investigate the advantages of gatekeeping policy in various conditions, comparative solutions are obtained by changing the quality level of the incoming returns. The light touched product yield in the sales returns is set to 90%, 70% and 50%, respectively. These conditions may be termed as high, medium and low return qualities respectively and the solutions obtained are plotted in the graph in Figure 4.5.

It is apparent from this figure that as the return quality increases advantages of implementing gate keeping policy also increases.

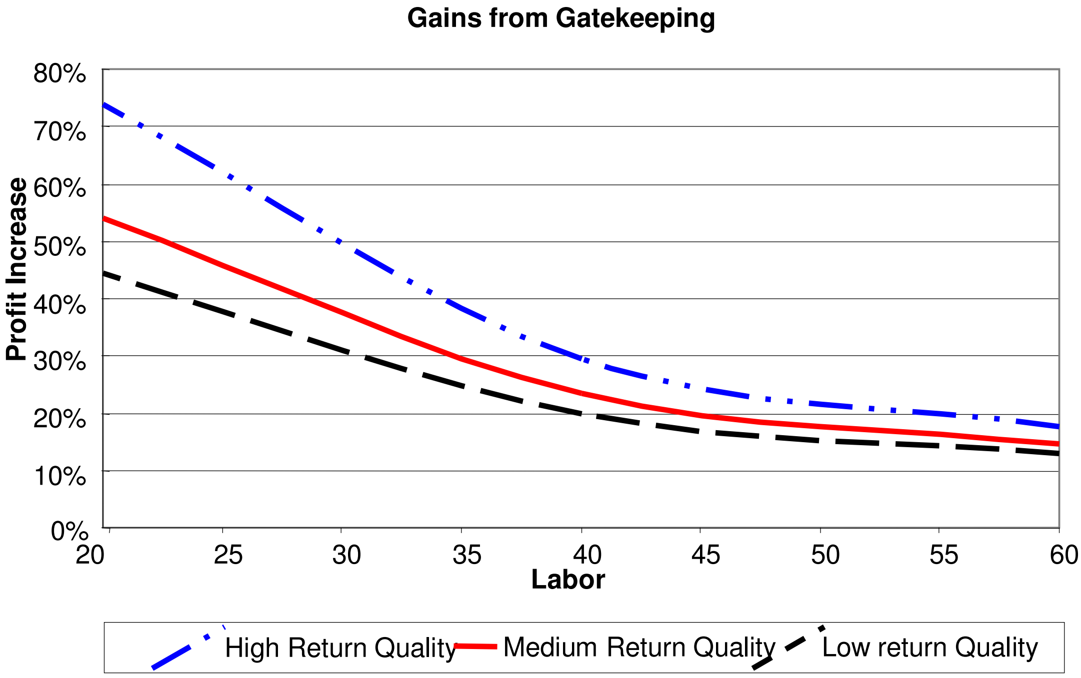

Figure 4.5 Effect of return quality on gross profit differential between gate keeping and base case solutions.

As a further test, inventory holding behavior of the recovery system under consideration is investigated. The results are interpreted such that the recovery system under time sensitive prices tends not to hold inventories as long as there is ample capacity. Plotting physical end of period (quarter) inventories revealed that, when the resources are scarce and binding, before the beginning of decline period of the life cycle, system tends not to dispose of returns as scrap at low prices knowing that capacity will be available in the future and may find it advantageous to stock raw returns, test and recover in the future. Results regarding this issue are presented in Figure 4.6. The system may also show inventory holding tendency depending on the assumptions about variations in demand constraint. But this has not been experimented in this study not to open the door for speculative reasons to hold inventory.

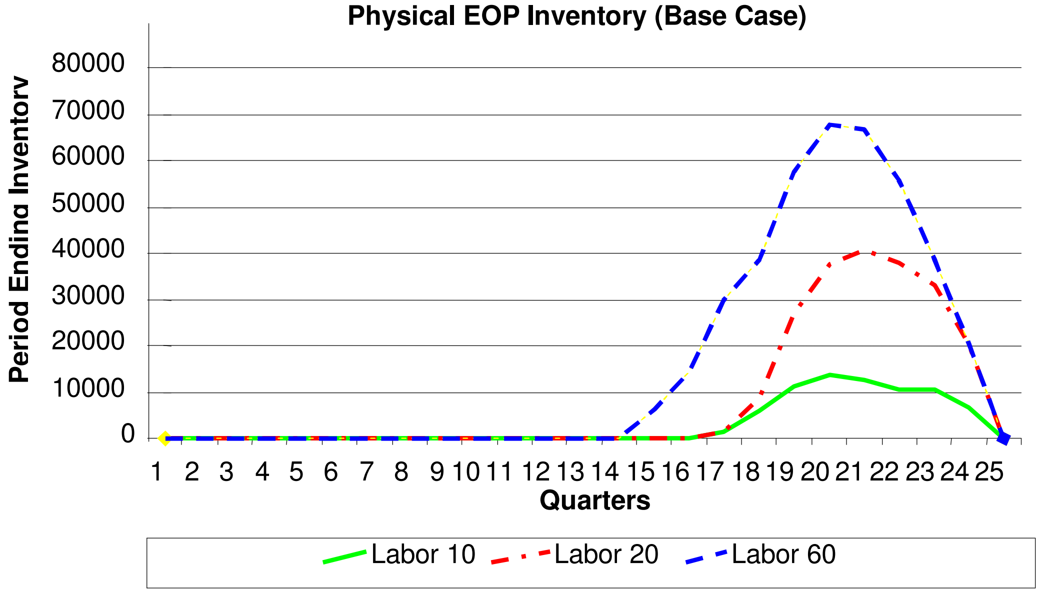

Figure 4.6 Inventory holding behavior of the recovery system Under changing capacity constraints

In the experimental setting it is assumed that the prices of a virgin product would be declining at a rate of 50% in 18 months as inspired by Moore's Law. Some experimentations are conducted with the base case model over a planning horizon of 8 quarters by delaying the commencing of the recovery operations by one or two quarters and observed respective gross profits and peak labor requirements, it is concluded that whether the prices are declining or constant over the planning horizon the model achieves diminishing gross profits and increasing peak labor requirements. Hence as long as there is no evidence that the prices of recovered products will increase through time there is no point in delaying recovery operations or allowing capacity constraints to be binding.

In order to verify that introduction of embedded systems will indeed improve overall efficiency of the recovery operations, the base case and the gate keeping case models are solved with chosen problem instances and compared. With this study net present values of the respective gross profits are obtained. Additional cost that may be justified for the introduction of an embedded system in to the product in consideration is shown below;

Table 4.18 Rough Cut Break-even Investment Analysis of a Gatekeeping Tag per Unit Manufactured

	All cycles considered	Growth	Maturity	Decline
Min	0.33 TL	2.99 TL	1.64 TL	0.98 TL
Mean	1.27 TL	4.48 TL	3.08 TL	1.13 TL
Max	3.08 TL	6.84 TL	5.23 TL	2.65 TL

It is apparent that the economy of gatekeeping has the greatest impact at the beginning of the cycle where returns occur. The systems enabling such gatekeeping operations are embedded to products at the manufacturing phase. Thus planning of embedded systems implementation should be made keeping in mind the rapid decline in benefits from early differentiation of returns.

CHAPTER 5

CONCLUSIONS AND FUTURE DIRECTIONS

In this study, the focus was on the tactical management problems in reverse logistics. The topics cover acquisition management, returns sorting, gatekeeping applications, dispositioning by means of testing, inspections, combined with multilateral recovery options, which are problems barely encountered in forward flow supply chains. Although underexplored in the literature, these topics are gaining attraction recently. One of the reasons for this attraction is the forthcoming legislative obligations like WEEE and its Turkish counterpart AEEE.

The testing and inspection issues are discussed in order to obtain a better understanding of the reverse supply chains and to establish improved recovery management policies. A novel approach, namely the implementation of embedded systems, which started to gain ground in the academic circles as well as in several industries is stressed. Embedded systems can be miniature sensory devices, auto-id applications or software, used to collect the bill of materials, product usage statistics and/or residual life information regarding the components of a product. This information is though to be a good representative of the current condition of a product. Thus, implementation of such systems may bring economic benefits by means of discriminating good and bad quality returns. However, there exists a lack of quantitative research on the evaluation of the benefits of such systems.

Bearing these in mind the main objective was to investigate and quantify the significant economies that can be attained in recovery management processes by increasing the amount of information regarding the quality condition of the returned products by means of embedded systems. In order to quantifying the benefits of enhanced recovery systems with early product differentiation in terms of quality, linear programming models are formulated for rough-cut planning of returned product recovery management.

A generic base case model is developed as a conceptual model of the reverse supply chain, which captures all the activities from acquisition to product recovery and redistribution in order to mimic a general recovery environment. Models developed included inventories at every stage to figure out if the system is working as a pull or push system. In relation to recovery processes being value added operations, almost all the time recovery processes behave as pull systems not to bear the opportunity costs of added value. Next, some alternative testing configurations are formulated by modifying the base case in order to analyze the effect of the alternative settings and policies on the performance measures determined. Improved management policies to be adapted have been tried to find. Finally, a nearly perfect information gatekeeping process is added to dispatch returns incoming at the retailer side, directly to shelves if the quality condition is viable.

An experimental setting is designed to investigate the effects of rapid decline in prices, return, demand conditions, life cycle and different quality distributions of returns. Analysis is conducted under the assumption of invariant returned product acquisition and level of quality.

A summary of the findings and interpretations can be found below;

On overall performance;

- If returns are classified beforehand incurring different operational costs, reusable items can be resold without encountering lengthy transportation, warehousing processes and expensive, labor intensive sorting, testing operations.
- When higher quality items are discriminated from the bulk returns, unnecessary testing costs carried with the expectation of recovery of good quality items will be avoided as well. Also the capacities previously allocated to higher quality items will be available for other returns testing and recovery operations resulting in higher recovery potential.

On inventory holding behavior;

- Due to rapidly declining market prices, returned products are dispositioned as fast as it could be. When capacities are not binding, inventory holding is inappropriate thus the recovery system works as a pull system. As long as demand is higher than returns, all returning units are classified and recovered to satisfy recovered products' demand within a stream of operations where no, or very little (due to lead times) inventory holding costs are incurred.
- If there is a possibility of increase in demand in the future or there exists returns' supply, demand seasonality, system may tend to hold inventory. However, these speculative reasons for inventory holding are not investigated.
- It is examined that when capacity constraints are binding, all different cases that are considered tend to hold some inventory to be able to use freeing capacity at the decline phase of the life cycle.

On the value of information;

- Under cases where higher quality, generally higher profit margin products are returned in majority, the value of information for classifying reusable and directly resellable units is higher.
- Gatekeeping and base case comparison results show that as the time sensitivity of prices of the returned products increase, benefits of implementing a gatekeeping policy becomes more significant.
- The amount of improvement by means of implementing embedded systems or alike, enabling instant classification if returns are reusable or not, constitute approximately the half of the room for improvement than can be gained from full testing and grading of items for recovery.
- The benefit of extra information does not only improve profits but also increases the level of reusing and refurbishing instead of recycling or energy recovery as current and upcoming legislations also intend. The notion is that importance in recovery operations should be given at most to reusing then refurbishing, refurbishing and remanufacturing successively instead of directly recycling. Early differentiation is an enabler to this notion and definitely increases amount of reused, refurnished items relatively.

- When the demand for different recovery options are lower than the supply, especially for the reusable items, benefits from discriminating good quality returns decay.
- Experiments on several policies indicate that supply chain's performance can be improved by adopting some basic policies.
    - Intuitively, testing operations should not be restricted. Evident result is that forcing testing operations to a strict sequence result in outstandingly lower profits.
    - Extra information that enables discrimination, improves recovery performance thus other than quality classifications, pre-sorting in terms of other parameters like return reasons etc. improves over all performance as well.

On the parameters that effect the performance of the models;

- Every value adding process is thought to have an impact on the outcome of the model. Thus, acquisition price paid outright to every return regardless of quality, afterwards transportation cost incurred for every return sent to recovery, then quality grading operational costs if it is feasible to test and lastly recovery costs if it is rational, are incurred which have decreasing weight of influence on the objective.
- Greatest influence belongs to the time sensitivity of prices, where rapid decrease in prices is dependent on the sub cycle of the life of a product.

Gathering usage information provides an idea on the quality condition of returns. With a gatekeeping implementation, it has been shown that greater quantities of returns are recovered as higher quality products in accordance with the targets of the forthcoming legislations. Also uncertainties are reduced and scarce resources like skilled labor are utilized more efficiently.

It will be appropriate to mention some discussions around the recovery management research literature before continuing to further research issues; The main issue that is discounted from contemporary research is the high level of uncertainty in quality of returns. Although some reverse logistics cases, like OCE printer, HP computers and Recellular, considers different quality grades, very few researchers show attention to this level of grading in their papers. Most of the returns are considered either good or bad in condition. This is the case why multilateral quality grades and recovery options are pointed out in this study. Many researches consider a predetermined percentage of the total sales as a static return rate, which is not the real case obviously. Forecasting is an important issue and needs more attention. The most desirable case may be leased item returns where accurate forecast for the timing of returns is possible.

Recovery activities are simplified such that a return in any condition can be transformed into a product as good as new. However, recovery options have a wide range of opportunities. Linearly escalating prices of first and second hand products are considered in some cases if the prices are not static at all. At large, both brand new products and recovered product returns loose their value increasingly. Thus time-value of recovery activities should be considered very important in all decision making activities from strategic perspectives to operational.

Further research issues are discussed below;

The area seems to be fruitful for future research. Legislations are tightening every year in order to force environmentally sustainability. Economical significance and competitive edges of reverse logistics are gaining ground every day. Reverse flows involve more uncertainty than the forward flow counterparts. Thus, deterministic models like the ones developed in this study with on the average values as inputs may not answer the decision specific questions accurately. Integrated solution approaches of simulation and linear/non-linear optimization methodologies can be proposed for many different questions. A case, including multiple collection centers, sorting inspection facilities, recovery centers and a diverse redistribution network can be considered. This modeling approach can be merged with pricing and take-back campaign decisions. Possible advantages of leasing based business models in plain reverse logistics or in a holistic closed-loop supply chain approach may be analyzed and the benefits may be quantified with this approach also. Further work is required to cover the “bathtub graph” shaped acquisitions and time variant return quality.

The level of testing and recovery activities can be analyzed with facility locations and equipment investment planning on mind. Perfect vs. certain levels of imperfect testing can be discussed and the benefits of such systems can be quantified. Multiple sensory device implementations with perfect vs. imperfect classification levels can be analyzed.

Concluding comments and suggestions may be summarized as follows:

1. The analysis in this study is conducted with make up data and in our opinion is generally good for rough-cut production planning purposes (in the sense that how much investment needs to be done in embedded systems) and for recovery facility design (i.e. how much labor and/or physical capacity to allocate in general).
2. The developed models can fulfill some of the reporting and requirements of forthcoming AEEE directive.
3. The developed generic base case model is good for making myopic decision making with rolling basis approach in the sense of adjusting capacity allocations when detailed and more realistic demand, price and quality data becomes available through practice.
4. The developed model differentiates from the available models in literature on the focus and on the generality of the model. The generic model used can be individualized according to different types of product testing and recovery processes.
5. The transportation, testing, recovery operation costs are separated within the model which brings easiness in terms of investigating the sensitivity of related parameters.
6. The analysis may also be repeated for the pre-sorted case with increased complexity in modeling in order to compare gatekeeping with better business processes.
7. By experimenting with the models and observations in the market as a consumer, it can be said that the above analysis and results may be representative of many electrical and electronic equipment such as cell phones, computers, refrigerators and the like which have similar price ranges, sales return and warranty policies. Quantifying benefits of embedded systems for these products individually should be elaborated.

REFERENCES

Accenture Communications and High-tech Research, 2008, “Big Trouble with No Trouble Found: How Consumer Electronics Firms Confront the High Cost of Customer Returns”

Akerlof, G. A., 1970, “The Market for 'Lemons': Quality Uncertainty and the Market Mechanism”, The Quarterly Journal of Economics, vol. 84, issue 3, pp. 488-500

Blackburn, J., Guide, D., Souza, G. and Van Wassenhove, L., 2004, “Reverse supply chains for commercial returns”, California Management Review, Vol. 46, No. 2, pp.7-21

Bottani, E., and Rizzi, A., 2008, “Economical assessment of the impact of RFID technology and EPC system on the fast-moving consumer goods supply chain”, International Journal of Production Economics, vol. 112, issue 2, pp. 548-569.

CLM, 1992, “What it’s all about”, Oak Brook, IL, Council of Logistics Management

De Brito, M.P., Flapper, S.D.P. and Dekker, R., 2002, “Reverse Logistics: a review of case studies”, Econometric Institute Report EI2002-21, Erasmus University Rotterdam, the Netherlands

De Brito, M.P. and Dekker, R., 2002, “Reverse Logistics – a framework”, Econometric Institute Report EI 2002-38

Denizel, M., Ferguson, M. and Souza, G., 2007, “Multi-Period Remanufacturing Planning with Uncertain Quality of Inputs”, under review at IEEE Transactions

Embedded systems glossary, http://www.netrino.com/Embedded-Systems/Glossary, last visited on 11th of November, 2008

Ferguson, M., Guide, D. and G. Souza, 2006, “Remanufacturing Planning with Different Quality Levels for Product Returns”, INFORMS, Pittsburgh, PA

Ferguson, Mark, V. Daniel Guide, Jr., Eylem Koca, and Gilvan C. Souza, 2008, "The Value of Quality Grading in Remanufacturing", Production and Operations Management, forthcoming

Fleischmann, M., Van Nunen, J., Gräve, B., and Gapp, R., 2004, “Reverse Logistics – Capturing Value in the Extended Supply Chain”

Fleischmann, M., 2003, “Reverse logistics network structures and design, in: Guide, Jr. V.D.R., Van Wassenhove, L.N. (eds.), “*Business Aspects of Closed-Loop Supply Chains”,* Carnegie Mellon University Press

Ginter, P.M., Starling, J.M., 1978, “Reverse distribution channels for recycling”, California Management Review, vol. 20, pp. 72-82.

Guide, V.D.R., Muyldermans L, Van Wassenhove L.N., 2005, “Hewlett-Packard Company Unlocks the Value Potential from Time-Sensitive Returns”, Interfaces 35(4), pp. 281–293.

Guide, V. D.R., Neeraj, K., Newman, C. and Van Wassenhove, L, 2001, “Cellular telephone reuse: the ReCellular Inc. case”, Managing Closed-Loop Supply Chains, Springer Berlin Heidelberg, 156 Pages.

Guide, V.D.R. and Van Wassenhove, L., 2003, “Business aspects of closed loop supply chains”, Carnegie Mellon University Press, Pittsburgh, 380 pages

Guiltinan, J.P., Nwokoye, N.G., 1975, ”Developing Distribution Channels and Systems in the Emerging Recycling Industries”, International Journal of Physical Distribution & Logistics, Vol. 6 No.1, pp.28-38

Gungor A. and Gupta, S.M., 1998, “Issues in environmentally conscious manufacturing and product recovery: a survey”, Computers & Industrial Engineering, 36:811-853.

Karkkainen, M., Holmstrom, J., 2002, “Wireless product identification: Enabler for handling efficiency, customization and information sharing”, Supply Chain Management: An International Journal 7 (4), pp. 242–252

Klausner, M. and Hendrickson, C., 1998, “Reuse of electronic motors in consumer products, design and analysis of an electronic data log”, Journal of Industrial Ecology, Vol. 2, Issue 2, pp. 89-102

Kopicky R.J., M.J. Berg, L. Legg, V. Dasappa and C. Maggioni, 1993, “Reuse and recycling: reverse logistics opportunities”, Council of Logistics Management, Oak Brook, IL, 324 Pages.

Klausner, M., Grimm, W.M., Hendrickson, C., 1998, “Reuse of Electric Motors in Consumer Products; Design and Analysis of an Electronic Data Log”, *Journal of Industrial Ecology,* Volume 2, Number 2, pp. 89-102.

Krikke, H., van Harten, A. und Schuur, P., 1999, “Business Case Océ: Reverse Logistic Network Re-Design for Copiers”, OR Spektrum, Vol. 21, Issue 3, pp. 381–409.

Melissen, F.W., Ron, A.J. de, 1999, “Defining Recovery Practices: Definitions and Terminology”, International Journal of Environmentally Conscious Design & Manufacturing, Volume 8, Number 2, pp. 1-18.

Murphy, P.R., Poist, R.F., 1989, “Management of Logistical Retromovements: An Empirical Analysis of Literature Suggestions”, Transportation Research Forum, pp.177-84.

Parlikad, A.K.N., McFarlane, D., 2004, "Investigating the role of product information in end-of-life decision making", Proc. 11th IFAC Symposium on Information Control Problems in Manufacturing INCOM'04, Brazil.

Prater, E., Frazier, G.V., Reyes, P.M., 2005, “Future impacts of RFID on e-supply chains in grocery retailing”, Supply Chain Management: An International Journal, 10 (2), pp. 134–142.

Pohlen, T. L., Farris, M. T., 1992, “Reverse Logistics in Plastics Recycling”, International Journal of Physical Distribution & Logistics Management, Vol. 22 No.7, pp.35-47

RevLog, 1998, The European Working Group on Reverse Logistics, http://www.fbk.eur.nl/OZ/REVLOG/, last visited on 15th of June, 2008

Rogers, D. S., Tibben-Lembke, R., 1998, “Going Backwards: Reverse Logistics Trends and Practices”, Reverse Logistics Executive Council, University of Nevada, Reno, NV, pp.14.

Rogers, D. S., Banasiak K., Brokmann, K., Johnson, T., Tibben-Lembke, R.S., 2001, “Reverse Logistics Challenges”, Council of Logistics Management Annual Conference Proceedings, Oak Brook, IL.

Silver, E. A., Kelle, P., 1989, “Forecasting the Returns of Reusable Containers”, Journal of Operations Management, Vol. 8, No.1 pp.17-35.

Stock, J., Speh, T. and Shear, H., 2002, “Many happy (product) returns”, Harvard Business Review, July, pp.16-17.

Stock, J., Reverse Logistics, Council of logistics management, Oak Brook, Illinois, 1992

Souza, G.C., Guide, V.D.R., Van Wassenhove L., and Blackburn, J.D., 2005, "Time Value of Commercial Product Returns", Management Science, 52, 8, 1200-1214.

Thierry M., Salomon, M., Van Nunen, J. and Van Wassenhove, L., 1995, “Strategic issues in product recovery management”, California Management, 37 (2):114-135.

Trebilcock B., 2002, “The seven deadly sins of reverse logistics”, Logistics Management, J–4

Turkish Environmental Act, 1983, Legislation number 2872, Official Journal 18132.

UK Environment Protection Act (c.43), 1990, http://www.opsi.gov.uk/acts/acts1990/Ukpga_19900043_en_1.htm, last visited on 21st of October 2008

WEEE Directive 2002/96/EC of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE), 2003, Joint declaration of the European Parliament, the Council and the Commission relating to Article 9, Official Journal L 037, 13/02/2003, pp. 24 – 39. http://eur-lex.europa.eu/LexUriServ/ LexUriServ.do?uri=CELEX:32002L0096:EN:HTML, last visited on 21st of October 2008

Wilding, R. and Delgado, T., 2004, "Rfid – Applications within the supply chain", Supply Chain Practice Volume 6, No.2, pp. 36-49

Williams, E. D., Sasaki, Y, 2003, "Energy Analysis of End-of-life Options for Personal Computers: Resell, Upgrade, Recycle", International Symposium on Electronics and the Environment, pp. 187- 192

Willems, B., Dewulf, W., Duflou, J., 2004, "End-of-life strategy selection: a linear programming approach to manage innovations in product design", International Journal of Production Engineering and Computers, Vol. 6 (7), 45-53

Zikopoulos C., Tagaras G., 2006, "Impact of uncertainty in the quality of returns on the profitability of a single-period refurbishing operation", European Journal of Operational Research 182 (2007) 205–225

Zikopoulos, C., Tagaras, G., 2008, "On the attractiveness of sorting before disassembly in remanufacturing", IIE Transactions, 40:3, 313 - 323

APPENDIX A

DATA SHEET FOR REVERSE LOGISTICS RESEARCH TRENDS

Table A.1 Cumulative Numbers of Papers Published In Various Areas of Interest by Years

Years	Reverse Logistics	Closed-Loop Supply Chains	WEEE	Product Recovery
1989	0	300	10	300
1990	100	200	40	300
1991	400	200	20	430
1992	0	300	50	370
1993	200	200	40	360
1994	200	300	30	400
1995	0	400	50	450
1996	0	400	50	400
1997	100	400	80	460
1998	100	550	60	480
1999	300	570	110	540
2000	300	670	140	610
2001	700	870	250	660
2002	1.700	890	260	600
2003	2.700	1.100	370	680
2004	3.100	1.140	590	820
2005	3.150	1.130	770	810
2006	3.580	1.200	1.100	950
2007	3.840	1.423	977	980

Source: Google Scholar academic document search engine

APPENDIX B

CLASSIFICATION OF SELECTED LITERATURE

Table B.1 Selected Literature on Reverse Supply Chains Grouped According to Characteristics of Decision Problems

	Strategic				*Tactical*				*Operational*					
Title/ Author	*Network design*	*Capacity Planning*	*Location*	*Coordination*	*Production planning*	*Distribution planning*	*Forecasting*	*MILP*	*Scheduling*	*Pricing*	*Inventory*	*Routing*	*Acquisition*	*Sorting*
Fleischmann, 2001	*x*		*x*											
Galbreth and Blackburn, 2006													*x*	*x*
Ferrer and Whybark, 2001, Inderfurth and Jensen, 1999					*x*									
Katzenberg, et al., 2003					*x*									
Souza et al. 2002					*x*									
Guide and Srivastava, 1998					*x*									
Guide, 2000								*x*						
Kroon and Vrijens., 2000				*x*		*x*								
Krikke et al., 2001	*x*							*x*						
Jayaraman, et al. 1999.			*x*							*x*	*x*			
Guide, 2000.					*X*									
Gupta, and Taleb, 1994.									*x*					
Penev, Ron, 1996.									*x*					
Lambert,1999.									*x*					
Guide, Spencer,1997					*x*									
Guide, Srivastava, Spencer, 1997		*x*												
Ray, Boyacı, Aras, 2003.										*x*				
Fleischmann, Beullens, Bloemhof-Ruwaard, Van Wassenhove, 2001.	*x*		*x*											
Dethlo, 2001.				*x*								*x*		
Kelle, Silver, 1989.							*x*							
van der Laan, Dekker, Van Wassenhove, , 1999.						*x*					*x*			
Toktay, Wein, and Zenios, 2000.						*x*					*x*			
Van der Laan, 1997.						*x*					*x*			
Guide, Srivastava, 1998.											*x*			

APPENDIX C

SPREADSHEET FOR BASE CASE

Table C.1 A Representative Layout of the Spreadsheet Model

Periods	1	8	COMMENTS	
Year	1	1	12%	Annual interest rate is assumed
Quarter	Q1	Q4	91	Days of period length assumed
Price Estimates				
pv Virgin Product Price	800	600	1,10	Factor for halving prices in 24 months
p1 Light Touched Product Price	640	480	20%	Discounted virgin price
p2 Refurbished Product Price	400	300	50%	Discounted virgin price
p3 Cannibailzed Price	120	120	120	Fixed
s Scrap Price	10	10	10	Fixed
Sales and Demand Forecasts				
dv Virgin Product Sales Forecast	200.000	200.000		Autonomous
d1 Maximum Light Touched Product Demand	8.000	8.000	4%	of period sales
d2 Maximum Refurbished Product Demand	8.000	8.000	4%	of period sales
Acquisition forecast				
A Agrregate forecast	20.000	20.000		
A1 Sales Returns Acquisition Forecast	6.000	6.000	3%	Period sales
A2 Warranty Returns Acquisition Forecast	8.000	8.000	4%	Period sales
A3 EoUReturns Acquisition Forecast	6.000	6.000	3%	Period sales
Pre-sorted Returned Products Quality Estimates by Options				
Sales Returns				
Light Touched	80%	80%	80%	
Refurbished	15%	15%	15%	
Cannibalized	3%	3%	3%	
Warranty Returns				
Light Touched	5%	5%	5%	
Refurbished	65%	65%	65%	
Cannibalized	15%	15%	15%	
EoU Returns				
Light Touched	0%	0%	0%	
Refurbished	10%	10%	10%	
Cannibalized	40%	40%	40%	
Aggregated Product Quality by Options				
Light Touched	5.200	5.200		
Refurbished	6.700	6.700		
Cannibalized	3.780	3.780		
Scrap	4.320	4.320		
Aggregateed Product Quality Distribution				
Light Touched	26%	26%		
Refurbished	34%	34%		
Cannibalized	19%	19%		
Scrap	22%	22%		
Acquisition and Transportation Costs				
ca1 Sales Returns Acquisition Cost	150	150	150	Valued by virgin product manufacturing cost
ca2 Warranty Returns Acquisition Cost	150	150	150	Valued by virgin product manufacturing cost
ca3 EoUReturns Acquisition Cost	30	30	30	Valued by rebate
cb Transportation Costs	2	2	2	Market price
Operation Costs				Corresponds to standard time in min/unit
cx1 Testing Work-center 1Operation Cost	2	2	2	25
cx2 Testing Work-center 2 Operation Cost	3	3	3	38
cx3 Testing Work-center 3 Operation Cost	2	2	2	25
cr1 Trimming Work-center Operation cost	3	3	3	38
cr2 Refurbishing Work-center Operation Cost	4	4	4	51
cr3 Cannibalizing Work-center Operation Cost	5	5	5	63
Replacement Costs by warehouses (For valuation and holding cost computation purposes only)				
chc Average Agregate Collection warehouse unit replac	114	114		
chc1 Sales Returns collection warehouse unit replacem	150	150		
chc2 Warranty Returns Collection warehouse unit repla	150	150		
chc3 EoP Returns Collection warehouse unit replaceme	30	30		
chr1 Raw Returns warehouse 1 unit replacement cost	116	116		
chr2 Raw Returns warehouse 2 unit replacement cost	118	118		
chr3 Raw Returns warehouse 3 unit replacement cost	121	121		
chw1 WIP Warehouse 1 unit replacement cost	118	118		
chw2 WIP Warehouse 2 unit replacement cost	121	121		
chw3 WIP Warehouse 3 unit replacement cost	123	123		
chp1 Recovered Products Warehouse 1 unit replaceme	121	121		
chp2 Recovered Products Warehouse 2 unit replaceme	125	125		
chp3 Recovered Products Warehouse 3 unit replaceme	128	128		

Table C.1 (Cont'd) A Representative Layout of the Spreadsheet Model

Decision Variables				
B Aggregate Quantity Transported to recovery facility	20.000	20.000		
S 1 Quantity sold as scrap from raw returnes warehous	0	0		
S 2 Quantity sold as scrap from raw returnes warehous	0	0		
S 3 Quantity sold as scrap from raw returnes warehous	0	0		
X 11 Quantity issued from raw returns warehouse 1 to t	20.000	9.231		
X 12 Quantity issued from raw returns warehouse 1 to t	0	0		
X 13 Quantity issued from raw returns warehouse 1 to t	0	10.769		
X 22 Quantity issued from raw returns warehouse 2 to t	0	0		
X 23 Quantity issued from raw returns warehouse 2 to t	14.800	6.831		
X 33 Quantity issued from raw returns warehouse 3 to t	0	9.672		
Sx3 Quantity Failed Test 3 and sold as scrap	4.320	9.478		
Y 11 Quantity issued from WIP 1 to Op 1	5.200	2.400		
Y 12 Quantity issued from WIP 1 to Op 2	0	0		
Y 13 Quantity issued from WIP 1 to Op 3	0	0		
Y 22 Quantity issued from WIP 2 to Op 2	0	0		
Y 23 Quantity issued from WIP 2 to Op 3	0	0		
Y 33 Quantity issued from WIP 3 to Op 3	0	17.793		
Q 1 Light Touched Product Sales Quantity	5.200	8.000		
Q 2 Refurbished Product Sales Quantity	0	8.000		
Q 3 Cannibalized Product Sales Quantity	0	36.720		
Operation Results				
Quantity Passed Test 1	5.200	2.400		
Quantity Passed Test 2	0	0		
Quantity Passed Test 3	10.480	17.793		
Quantity Failed Test 1	14.800	6.831		
Quantity Failed Test 2	0	0		
Quantity Failed Test 3	4.320	9.478		
Quantity Trimmed	5.200	2.400		
Quantity Refurbished	0	0		
Quantity Cannibalized	0	17.793		
Quantity Scrapped	4.320	9.478		
Labor Requiremente and Constraints (Man X Shift)				
Labor Use at Test 1	9	4	1500	Average cost per man per month assumed
Labor Use at Test 2	0	0		
Labor Use at Test 3	7	12		
Labor Use at Recovery Op 1	3	2		
Labor Use at Recovery Op 2	0	0		
Labor Use at Recovery Op 3	0	20		
Total Labor Use During Period	19	38		
Labor Availability by Period	300	300	300	Man Skilled labor availabile
End of Perid Inventories by Warehouses				
Ic Returns Collection warehouse aggregate eop invento	0,0	0,0		
Ir1 Raw Returns warehouse 1 eop inventory	0,0	0,0		
Ir2 Raw Returns warehouse 2 eop inventory	0,0	0,0		
Ir3 Raw Returns warehouse 3 eop inventory	0,0	0,0		
Iw1 WIP Warehouse 1 eop Inventory	0,0	0,0		
Iw2 WIP Warehouse 2 eop Inventory	0,0	0,0		
Iw3 WIP Warehouse 3 eop Inventory eop	10.480,0	0,0		
Ip1 Recovered Products Warehouse 1 eop Inventory	0,0	0,0		
Ip2 Recovered Products Warehouse 2 eop Inventory	0,0	0,0		
Ip3 Recovered Products Warehouse 3 eop Inventory	0,0	0,0		
Financial Results (X 1000)				
Net Sales	3.371	10.741		
Ligh Touched Product Sales Amount	3.328	3.840		
Refurbished Product Sales Amount	0	2.400		
Cannibalised Product Sales Amount	0	4.406		
Scrap Sales Amount	43	95		
Cost of Sales	2.407	2.489		
Acquisition Costs	2.280	2.280		
Transportation Costs	40	40		
Testing Costs	70	73		
Operation Costs	16	96		
Inventory Holding Costs	1,61	0,00	12	Shipments per period assumed
Gross Profit	964	8.252		
Net Present Value of Gross Profit		28.574.873		