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PRODUCT RECOVERY SYSTEMS: A REVIEW OF THE CURRENT LITERATURE AND RESEARCH OPPORTUNITIES

ÜRÜN GERI KAZANIM SISTEMLERI: MEVCUT LITERATÜRÜN VE ARAŞTIRMA İMKANLARININ İNCELENMESI

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Abstract

In the last few decades, due to serious waste material accumulation and rapid depletion of scarce resources, interest in sustainable production practices has increased. As a consequence regaining and re-integrating end-of-lifecycle products to the industry into the different stages of the production process have become more important. By virtue of these developments, product recovery systems emerged as a new field of research in addition to the traditional manufacturing systems. This study aims to review this new research field, classify the studies in the current literature and present the possible research questions for future studies.

Key Words: product recovery systems, reverse logistics, literature review, sustainable production practices.

Özet

Son yıllarda ciddi boyutlardaki atık madde birikimi ve kıt kaynakların hızla tükenmesi nedeniyle sürdürülebilir üretim sistemlerine olan ilgi artmış ve kullanım ömrü sonundaki ürünlerin yeniden endüstriye kazandırılması daha önemli hale gelmiştir. Bu gelişmelerin bir sonucu olarak, geleneksel üretim sistemlerine ek olarak ürün geri kazanım sistemleri yeni bir araştırma alanı olarak ortaya çıkmıştır. Bu çalışma, bu yeni araştırma alanını incelemeyi, mevcut yazındaki makaleleri

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konularına göre sınıflandırmayı ve gelecekteki çalışmalar için olası araştırma sorularını ortaya koymayı amaçlamaktadır.

Anahtar Kelimeler: ürün geri kazanım sistemleri, tersine lojistik, yazın taraması, sürdürülebilir üretim sistemleri

Introduction

Over the last few decades, ever worsening environmental problems (e.g. rapid depletion of scarce resources and landfills, alarmingly increasing waste material accumulation and consequential environmental pollution) and their serious consequences for the future of humankind have increased the environmental consciousness of all social segments. Consumers' preference for environmentally friendly products and brands has increased; governments' enforcements for proper waste management and recovery of the utmost value from end-of-life products toughened and NGOs' emphasis on environmental friendly technologies and practices have accelerated. In the industry, this growing concern on the environment materialized in the increasing emphasis put on sustainable manufacturing practices. In this sense, regaining and re-integrating end-of-lifecycle products to the industry into different stages of the production process have become more important in the recent years. As De Brito and Dekker (2004: 3) indicate while only the flow of products from raw material to end consumer was important twenty years ago, today firms, especially the manufacturing industry, are also really concerned with the flow of products from end customer back to producers or strictly speaking recovery centers. As a consequence of all these developments, product recovery systems emerged as a new field of research in addition to the traditional manufacturing systems. This study aims to provide an overview of the field, outline the current literature and discuss the research opportunities. The organization of the paper is as follows: First we define what a product recovery system is and examine the processes included. Then we discuss various motivators of product recovery activities and present an outline of the current literature on the topic of product recovery. We conclude our paper with a discussion of the gaps in the current literature and possible research opportunities.

What is a Product Recovery System?

In the last few years, manufacturing firms, especially the Original Equipment Manufacturers (OEMs), have begun to pay close attention to the production and distribution systems that will enable them to collect and recover used products besides manufacturing new ones. The primary drivers of this increasing emphasis on recovery systems can be sought both in the recent regulations of governments about the disposal of waste materials/used products and the increasing importance of establishing a green image in the eyes of customers as well as the possible economic gains that can be obtained from such systems. In fact, recovery systems can be considered in relation to the broad area of sustainable development. Brundtland (1998:1) defined the sustainable development in an EU report as *"…to meet the needs of the present without compromising the ability of future generations to meet their own needs."*

De Brito and Dekker (2004: 4) argue that recovery systems can be regarded as the implementation of sustainable development at the firm level since it prescribes retaining the utmost value embedded in products. According to Gungor and Gupta (1999: 812) product recovery is the act of minimizing "*the amount of waste sent to landfills by recovering materials and parts from old or outdated products by means of recycling and remanufacturing (including reuse of parts and products)."* Jayaraman (1999:497) defines a product recovery system, as a recoverable product environment, including strategies to increase product life through repair, remanufacturing, and recycling of products.

In the broadest sense, a product recovery system is composed of collection of used products from the end-consumers, inspection/sorting/selection of them, implementation of the most appropriate recovery strategy (e.g. repair, refurbish, remanufacturing, and recycling), disposal of non-recoverable waste materials/parts and redistribution of the remanufactured products to the appropriate markets. After the inspection/sorting/selection stage in which the collected cores are checked for their conditions and classified according to the applicable recovery alternatives, the used products that can be reused or resold with small changes are sent to a *repair* process, and either through fixing or replacement of old/end-of-life components, returned to working condition. On the other hand, those which are not good enough to be reintroduced to the market with such small modifications, go through the refurbishing process. *Refurbishing* is one level higher than repair in terms of the degree of reprocessing undertaken and it involves disassembly of a core into modules and inspection of all of its modules and reassembly of the accepted ones into refurbished products (Thierry et al., 1995:119-120). Technological upgrading of the outdated modules is also common in the refurbishing process. After refurbishing, comes remanufacturing at the third place in recovery hierarchy. Remanufacturing entails complete disassembly of used products into its parts and components, selection of the reusable ones, vigorous inspection/testing and if necessary reconditioning of them, and ultimately using them in the production of new products. Fleischmann et al. (1997:3) defines remanufacturing as a process of bringing used products back to an as new condition by performing the necessary operations such as disassembly, overhaul and replacement. Most of the time, remanufactured products are regarded in as-good-as new quality and introduced to the same markets with the virgin products. Seitz and Wells (2006:824) state that from a sustainability perspective, remanufacturing not only retains materials but also leads to considerable energy and economic value savings added to the products/parts in the production phase. Finally, as the last recovery option, *recycling* aims to recover only the raw materials from used products. In contrast to the other recovery options which try to retain a large proportion of the product's value-added by maintaining the identity and functionality of used products to a great extent; the primary purpose of recycling is to conserve the raw material value. To sum up according to the level of disassembly and processing these four recovery options can be ordered as repair, refurbishing, remanufacturing and recycling in which dismantling occurs at product, module, part and material level, respectively.

Among these recovery options, recycling, which is in fact the oldest one, has been the most prevalent strategy for waste management in many sectors of most industrial countries for years (Güngör and Gupta, 1999: 825). Nevertheless, despite being a rather new recovery type, remanufacturing seems to replace recycling and become the recovery strategy of the future since it offers not only higher economic opportunities for the manufacturers but also important contributions to the better maintenance of scarce world resources.

Factors Motivating Firms for Product Recovery

There exist several factors leading OEMs or independent recovery firms to collect and recover end-of-life products, which were once considered costly and economically infeasible. We can list the primary reasons for the increasing interest towards product recovery systems in the last few decades as follows;

1) Increasing environmental consciousness of society and pressures of stakeholders (NGOs, consumers, business partners and suppliers) on producers: Today, partly because of the worsening environmental problems like pollution, rapid depletion of natural resources, consumers begin to pay more attention to firms' consideration of environmental protection. Behaving in an environmentally responsible manner improves the *green image* of firms. Even in some cases environmentally responsible attitude can increase the demand for firms' products. For instance, Toffel (2004: 122) states that increasing the amount of recyclable contents in products and adopting sustainable practices such product recovery were found to have the greatest positive impact on consumer's willingness to use a firm's products and services in a survey.

Perhaps the most effective factor impelling producers to more sustainable production practices is the increasing pressure of non-governmental organizations (NGOs). Today many NGOs closely follow the practices of companies in end-of-life product collection and treatment, and prepare rankings on the basis of their environmental performance. Their primary aim is to mold a public opinion and as a result to influence the preferences of consumers. For instance, Greenpeace prepares and publicly announces environmental rankings for leading electronics manufacturers on the basis of several environmental performance criteria including amount recycled, voluntary take-back programs and the responsibility undertaken for used products. Similarly, Newsweek publishes an environmental performance ranking (Green Rankings) for the first 500 largest U.S. companies.

The partners in the supply chain and the competitors may also force a company towards product recovery and sustainable production practices. For instance, Walmart sets targets for its suppliers' greenhouse gas reduction and refuses to purchase from those suppliers who cannot meet these targets (Financial Times, 25 Feb 2010). The retailer also aims to create a single index on the environmental impact of products which could eventually be used in product labeling.

To sum up, it is an undeniable fact that growing public awareness and stress on environmentally friendly and sustainable industrial practices have substantial influence on the adoption of product recovery by the manufacturers.

2) Increasing number of environmental regulations and legislation: In the last few decades, especially with the deteriorating land filling and waste disposal problems, governments' concern for proper management of end-of-life products returning from end-consumers has increased. Especially in the European countries, 'extended producer responsibility' and 'polluter pays' principles have been widely acknowledged. As a result, a number of laws and regulations enforcing firms to undertake the responsibility for the whole life-cycle of their products have been enacted in countries such as the EU member states, Japan, and 23 states of the US. These legislation bases on the principle that the responsibility of manufacturers for their products does not end with sale, but extends beyond the consumer use till the end of product lifetime after which products should be either recovered or properly disposed under the OEMs' control. In this respect, some of the widely known regulations are European Commission (EC) Directive on Waste Electronic and Electrical Equipment (WEEE), EC Directives on End-of-Life Vehicles (ELV) and on Reusing, Recycling and Recovering of Motor Vehicles, EC Directive on Packaging and Packaging Waste, and Home Appliance Recycling Law (HARL) in Japan.

Turkey has also adopted several EU Directives on waste management mainly due to the integration process to the Union. However, still Turkish regulations on EOL treatment are quite recent and product recovery is new for the Turkish industry. Especially the regulations on high technology products such as automobiles or electronics are either still in draft form or enacted in the last couple of years. Some important regulations currently in force in Turkey are: *regulation on the control of waste oils (30/07/2008), regulation on the control of end-of-life vehicles (30/12/2009), regulation on the spent batteries and accumulators (31/08/2004) and regulation on the control of packaging waste (24/06/2007).*

3) Rapidly depleting landfills and the consequent problem of environmental pollution: As discussed in previous sections, one of the most important goals of product recovery systems is minimizing the amount of waste sent to landfills or disposal. In EU-27 countries each individual generated 496 kg of municipal waste on average in 1998 and 285 kg of this amount was land filled. The waste amount increased by 28 kg in 2008, but the amount land filled was decreased to 207 kg (Europe in figures, 2010). Pollution arising from land filling has always been so serious for the EU that the European Commission enacted a separate directive (Council Directive 1999/31/EC of 26 April 1999) including strict requirements on the characteristics of waste that can be land filled and how the procedure should be managed to reduce environmental impact. For the US, Ferguson and Toktay (2006: 351) report that in 1999, fourteen states had no landfill capacity left already.

In Turkey in 1998 per capita municipal waste was 510 kg and the land filled amount was 371 kg which were both higher than the EU averages. Although in 2008 these amounts decreased to 428 and 356, respectively, still they are quite high, and serious measures should be taken to prevent waste accumulation. Hence, adoption and dissemination of proper waste management and product recovery activities carry great importance for our country as well.

4) Possible economic gains in collecting reusing or recovering used products and materials: Expected economic gains and other benefits are the main factors that lead to voluntary and proactive involvement of manufacturers in product recovery. In contrast to what was believed in the past, today it is widely accepted that product recovery systems can contribute to firm performance a great deal in economic terms. Some of these contributions can be listed as follows;

Raw materials, components or parts retained from EOL products can be used as inputs in new production and as spare parts in after sales and repair services. These can also provide a valuable base for the parts and components supply of no longer produced models.

- Energy consumption, waste disposal costs and landfill needs can considerably be reduced.
- Capabilities gained through product recovery can be utilized in new product development/design.

Mabee et al. (1999: 358) express that cost reductions by remanufacturing have been estimated as 30-60% of new production. Ayres et al. (1997: 557-558) coin the word ‘double dividends’ in order to attract attention to both increased profits and cost reductions for the firm, and the environmental improvement for the society. The authors argue that the purchased parts and materials and the waste disposal constitute a large proportion of a manufacturer’s cost and these cost items can simultaneously be avoided through strategic recovery and remanufacturing systems. Xerox Corporation, Kodak, FujiFilm, Electrolux, HP, IBM, Ford Motor Company, and Mercedes-Benz are just some of the examples which successfully carry out recovery operations and obtain economic gains from this business.

Another significant contribution of recovery activities is the improved product development and design capabilities that may be attained with the help of the experience gained in recovery operations. Knowledge about and familiarity with the most frequent part/product failures may provide manufacturers with insights and new ideas about future product designs and product characteristics besides decreasing the repair and after-sale service costs.

5) Corporations' own social responsibility principles and targets: Today, manufacturing firms' concerns are no longer limited with producing in the most efficient way and selling their goods with the highest possible profit. Partly because of the increasing consciousness and sensitivity of consumers for the global environmental problems (e.g. pollution, depletion of natural resources, climatic changes) and partly because of the crucial effect of brand image on market demand, firms have begun to set social responsibility targets for themselves and prepare reports presenting their activities in these respects. For instance, Global Reporting Initiative (GRI) which is a network-based organization has pioneered a common and world-wide sustainability reporting framework for companies from various sectors. In the initiative, companies register to the system voluntarily and prepare their sustainability reports according to the principles and the framework set by GRI which are then publicly announced on the web site of the initiative.

Since product recovery is one of the most effective ways of working for the social well-being and contributing to environmental protection, commitment to self set social responsibility principles is another driving factor for the adoption of product recovery systems as is the case in IBM Europe, Xerox, and HP (Toffel, 2004: 122).

Outline of the Research Topics on Product Recovery Systems

Under the broad area of recovery systems, one can list several problems that should be investigated. In fact, all the relevant problems and issues that have been examined for the forward manufacturing systems for years can be reconsidered for recovery systems. Hence, since its emergence, several researchers have attempted to determine and outline specific aspects and important problems of product recovery systems. For instance, the overview by Fleischmann et al. (1997: 3-17) as being one of the earliest reviews in the field, subdivides the field into 3 main areas, namely distribution planning, inventory control, and production planning and classify the situations in which reuse occurs according to reuse motivation (being economical and ecological), type of recovered items (spare parts, packages and consumer goods), form of reuse (reused directly, repair, recycling, and remanufacturing) and involved actors (members of the forward channel or specialized parties).

On the other hand, Thierry et al. (1995: 114-135) widen the scope of the field and including the waste management make a classification according to the recovery options as direct reuse, product recovery management (repair, refurbishing, remanufacturing, cannibalization and recycling) and waste management (incineration and land filling).

Güngör and Gupta (1999: 811:853) simultaneously examine and relate Environmentally Conscious Manufacturing and Product Recovery (ECMPRO), as a result, they categorize recovery process into *material recovery* (*recycling*) and *product recovery* (*remanufacturing*).

A somewhat different and more recent classification scheme is put forth by Goggin and Browne (2000:185-188), who examine the resource recovery for end-of-life electrical and electronic products on the basis of *the organization behind the recovery system*, *the market segment it addresses* and *the size of the product*. The taxonomy is put forth as; 1) *public vs. private sector*, 2) *commercial vs. domestic market segments*, 3) *large vs. small products*.

Finally, de Brito and Dekker (2004: 9-21) come up with a rather comprehensive framework for analyzing the topic and suggest that '*why'*, '*how'*, '*what'* and '*who'* questions should be asked to investigate any recovery system. The authors ask 'why' question for both drivers of the receiver to collect and recover the used materials and reasons of the sender to return the used products. 'How' is asked to understand the processes carried out in recovery systems and to focus on recovery options while 'What' question is posed to describe product characteristics that are returned and favorable to recover. Lastly, 'who' is proposed to learn about the actors and their roles executing the system activities.

The previous sections have summarized the current perspectives on the general structure of a complete recovery system. Now, a framework can be put forth to systematically examine the existing quantitative models developed for problems arising in a product recovery environment. In this paper a functional classification of research topics on product recovery systems is presented. The first three subtopics of our classification are adopted from the framework of Dekker et al. (2004) and enhanced with recent studies. The classification and the subtopics under each area follow as;

1) *Distribution Management*

Network design issues, Return handling and warehousing, Collection and vehicle routing

2) *Production Planning and Inventory Control*

Valuation of recoverable inventories, Lot sizing in product recovery (PR) operations, Stochastic inventory control for PR, Dynamic control of PR operations, Production planning in PR

3) Supply Chain Perspective

Coordination in supply chain (SC), Long-term performance analysis of closed loop supply chains, Environmental performance, Value of information

4) Design for Recovery

Design for disassembly/recycling/remanufacturing, Impact of product design on recovery processes, Assessing the suitability of product structure/modularity for different types of recovery

5) Strategic Aspects of Recovery Systems

Product recovery strategies and practices in industry (through single or multi-firm case studies), Factors motivating manufacturers to adopt environmentally friendly practices, Effects of product recovery practices on firm performance

Besides being very comprehensive, one other benefit of the above classification is that it can also be used for the classification of traditional supply chain problems in the same way and enable comparison between traditional and reverse supply chains. Such kind of a comparison is helpful to see how the existing models pertaining to the problems of the traditional supply chains have been and can be extended or modified to handle recovery system problems and what difficulties and complexities can be encountered in this process.

The next sections will provide a review of the prominent studies under each of these five categories in order to present a complete state-of-art picture of the product recovery literature.

1) Distribution Management in Product Recovery Environments

Similar to forward production systems, issues related to collection and distribution management in a product recovery environment carry great importance for the success of both individual firms and the overall supply-chain. Three sets of problems taking place under this area are reverse logistics network design, vehicle routing and the internal handling of return products. Among these, reverse logistics network design is the most studied one probably because of the rising importance of network structure on the overall success of product recovery processes.

Network design problems, mainly consider infrastructure decisions like where to locate various facilities of a particular recovery system and how to link them in terms of transportation and storage (Fleischmann et al., 2003: 117-120). Some of the important decision tasks are the location and type of collection sites, location of inspection and reprocessing facilities for collected goods, and the distribution channels for the recovered products. Product recovery systems generally include both the reverse flow of used products and materials (cores) from the consumers to the remanufacturer and the forward flow of recovered products from the remanufacturer to the customers. Reverse logistics constitutes an important part of this network system and is defined 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 origin to the point of consumption for the purpose of conforming to customer requirements.."* (Rogers and Tibben-Lembke, 1998: 2).

From the current literature, it can be concluded that (1) closed-loop structure (Jayaraman et al., 1999: 497-499) and closely related possible interactions and resulting synergies between the collection and distribution channels, (2) existence of an intermediary stage which may consist of inspection, testing, or separation/sorting/categorization processes depending on the specific characteristics of the system (Fleischmann et al., 2000:659), (3) individualized returns with small quantities (Min et al., 2006: 56-69), and (4) supply-side uncertainty (on quantity, quality and timing) are the most prominent characteristics of reverse logistics networks which differentiate them from traditional logistics networks. To model reverse network design problems, facility location-allocation models based on mixed integer linear programming (MILP) generally with an objective of cost minimization are employed (Kroon and Vrijens, 1995: 64-65; Le Blanc et al., 2004: 294-295; Realff et al., 2004: 768-769; Krikke et al., 1999: 393-397). To account for uncertainty, current studies mostly employ scenario or parametric analysis (e.g. Kroon and Vrijens, 1995:66; Fleischmann et al., 2001: 166-169; Beamon and Fernandes, 2004: 275-278; Realff et al., 2004: 772-774). Still, though scarce there are also some other studies that employ different methods to deal with uncertainty; the first one is by Realff et al. (2004: 768-774) which incorporates uncertainty into the system through a robust-mixed-integer linear programming mode. Likewise more recently Hong et al. (2006:154-157) also employ an MILP model with a scenario-based min-max robust optimization methodology for the design of a large-scale system for the collection of used electronics in the state of Georgia. Another study directly incorporating uncertainty in the model is introduced by Listes and Dekker (2005: 273-277), which presents a stochastic programming based approach.

Closely related with network design, another important topic under the area of distribution management is vehicle routing which examines the collection and transportation issues on a more micro level. Like network design problems, traditional MILP models along with continuous cost approximation methods are mostly employed to tackle the vehicle routing problems in a recovery environment (Dekker et al., 2004: 37). The critical question in this issue is the difference between the collection of cores and the distribution of virgin products. Beullens et al. (2004: 95-96) argue that two crucial differences are the low value of used products and the large degree of flexibility for deciding the timing and means of collection. These factors affect the possibility of various interactions between traditional distribution channels and the collection means for the used products.

The last issue under the distribution management area, return handling and warehousing which corresponds to internal logistics issues in traditional supply chains is one of least studied topics especially in a quantitative framework (de Brito and de Koster, 2004: 135). One exploratory study by De Koster et al. (2002: 407-421) provides important insights about retail operations of a large mail-order company in the presence of diverse return flows. Particularly the authors compare the handling of product and material returns of nine retailer warehouses and identify the problematic aspects of return handling in a real life setting.

2) Production Planning and Inventory Control

Inventory control and production planning is another main area investigated extensively in the context of product recovery management. This research stream deals with problems such as the discrepancy between supply and demand and the coordination of returns with other supply sources. Due to the substantial impact of product returns on inventory control issues, this topic has been one of the most popular research topics in this field. Lot sizing, safety stock and seasonal stock are some of the most prominent problems for which classical forward manufacturing models have been adapted to the product recovery context. Nevertheless, product recovery environments pose new complications to these classical inventory models. Two significant complications arising from return flows in lot sizing problems are (1) the emergence of an alternative supply mode (referring to inputs that may be obtained by remanufacturing process) and (2) the additional decision of whether to remanufacture or dispose a returned product (Dekker et al., 2004: 39). Hence, the traditional inventory models, where the only trade-off exists between set-up and inventory holding costs and manufacturers only need to make the strategic choice of batching or just-in-time approach, need to be extended with the consideration of two alternative supply modes for each of these strategies in the context of product recovery systems. Inclusion of return flows in the lot-sizing decisions is considered in several studies. For instance, Ashayeri et al. (1996: 74-96) discuss inventory control of service parts in a computer electronics company where both remanufacturing and virgin manufacturing are employed to replace defective parts, and lot sizing decisions are made for both procurement and remanufacturing processes. Similarly, Dobos and Richter (2004: 311-321) develop an EOQ model for a producer who faces stationary demand and has the options of production/procurement and recycling to satisfy the demand. The authors find that a pure strategy (either production or recycling) is always optimal to satisfy the market demand. In an extension of this study, Dobos and Richter (2006: 572-577) also take into account the quality of the returned products as a deterministic parameter and investigate the optimal buy-back and production strategies for the manufacturer. Some of the other studies that adapt traditional EOQ models into product recovery context are Richter (1996:313-324), Teunter (2001: 484-495) and Koh et al. (2002: 59-73). All of these models consider single product deterministic product recovery environments. They also apply the 'as-good-as new' principle, which is in fact a very common assumption in the other areas of product recovery research. Yet, in another study, Kleber et al. (2002: 122-139) relax some of these assumptions and examine a dynamic demands and returns environment where seasonal factors and different product qualities and markets are considered. In this setting, the authors propose a continuous inventory model to answer the questions of whether excess returns should be stored for future recovery or disposed of, and for which type of markets returned products should be used.

Taking into consideration the inherent uncertainty in the returned product flows, stochastic inventory control models are also proposed under the topic of inventory control. In this respect, Inderfurth (2005: 320-336) presents a multi period stochastic model to examine the impact of various uncertainties on the preference for product recovery and concludes that uncertainty in demand and returns can be a considerable obstacle to follow a recovery strategy. Likewise, in a broader scope study, Van der Laan et al. (2004: 203-216) provide an overview of stochastic inventory control models distinguishing between push and pull-driven recovery systems, and argue that lead time differences between alternative supply sources is an important complicating factor in this context.

Finally, production planning issues are also examined in product recovery environments in a substantial number of quantitative models. However, Inderfurth et al. (2004: 249) argue that product recovery brings more complications to production planning and control than to the other functional areas. This arises partially from the specific operations of product recovery such as disassembling, reprocessing and inspection of returned products, and partially from the inherent uncertainty in return flows and outcome of the reprocessing operations. In this respect, Vlachos et al. (2006: 367-394) investigate capacity planning decisions in a remanufacturing environment and argue that these decisions are really complex for reverse supply chains due to the high variation in return flows. To cope with this additional complexity and evaluate the effectiveness of alternative long-term capacity planning policies for remanufacturing facilities, the study presents a simulation model based on system dynamics approach. In another study, Franke et al. (2006: 564-569) also make use of discrete event simulation to examine the periodic adaptation of an existing remanufacturing plan (obtained from a linear optimization model) in the cases of varying product, process and market constraints including the supply-side uncertainties (e.g. quality, quantity and processing time of returned products) into the analysis. In a very recent study, Denizel et al. (2010:394-404) use stochastic programming to examine multi period production planning of remanufactured products. They consider an environment where there are quality level differences among the product returns which serve as inputs to remanufacturing and determine the optimal amount to be graded, remanufactured and carried in inventory from each quality level of returned products. In addition to returns uncertainty, Shi et al. (2010:641-650) take into account the uncertainty in demand and in the acquisition price of returns as well, and consider a broader planning setting where there are multiple product types and the demands can be met by both remanufacturing and new production. In such a setting the authors seek to determine the optimal remanufacturing and new production quantity as well as the optimal acquisition price for returns through a nonlinear programming model.

To conclude, as presented in this section inventory control and production planning problems are widely investigated in the current literature. However, influences of product recovery on more strategic issues like the coordination of inventory and location decisions and the appropriate inventory cost metrics for returned products need to be further investigated.

3) Supply Chain Perspective

The third research stream of our classification scheme adopts a supply chain approach and aims to analyze the possible interactions between the different players in a recovery environment. This topic takes on a broader perspective and investigates those problems of a recovery system that cannot be restricted with a single operational area. The issues of coordination, analysis of the long-term behavior of close-loop supply chains, environmental impact of product recovery systems, simultaneous assessment of economic and environmental performance in close-loop supply chains, and effects of information technology to cope with inherent uncertainty in product recovery can all be classified under the supply-chain approach to product recovery systems.

Either closed-loop or open-loop in all supply chain systems, naturally, there exist multiple decision-makers, and the alignment of incentives among different decision makers carry important implications for the overall system performance. However, existing studies on product recovery systems mostly focus on problems with a single decision maker on a certain operational issue as illustrated in previous sections. They disregard the impact of possible interactions between different organizations in a product recovery environment. In this sense, Debo et al. (2004: 296) argue that as in traditional supply-chains, each decision maker will have an incentive to optimize her local objectives in a CLSC environment and it will not be possible to maximize the system performance by pursuing only the individual player's decisions in isolation. Still, through some mechanisms like *incentive alignment* (Pasternack, 1985: 169), *information sharing* and *functional integration* (Porteus and Whang, 1993: 1166-1181) that have become popular in traditional supply-chain research recently; obtaining some degree of coordination can be possible in a recovery system as well. Thus, papers adopting a supply chain approach to product recovery management generally use game-theoretic and micro-economic analysis tools and aim to investigate the implications of various interdependencies between different parties.

In this line, Savaşkan et al. (2004: 239-252) study the problem of selecting the most suitable reverse channel structure for the collection of used products from consumers via a Stackelberg model in which OEM acts as the leader in the decision making process. The authors consider three alternative decentralized channel structures namely; OEM undertakes the collection, OEM provides incentives and assigns collection to the retailer and OEM subcontracts the collection task to an independent third party and then, they compare these options in terms of the return rate, total supply chain profits, retail and wholesale prices. The findings of the study show that the party closer to the end-consumers, in this context the retailer, is the most effective undertaker of the collection task since she can effectively reflect the cost savings from the remanufacturing to the end-consumers. In an extension of this study, Savaskan and Van Wassenhove (2006: 1-14) consider a competitive retailing environment with two retailers. In this context, the authors argue that the retailers will prefer the direct collection structure (collection by the OEM), since in this case they can enjoy the vertical externality arising from the lower wholesale prices and can also avoid the investment costs needed to set up a collection system. In contrast, the manufacturer will vote for the indirect collection where the retailers carry out collection activities since she can benefit from both investment savings and increased sales arising from retailers' incentives to reduce prices in order to increase the return rate with the expectation of increased buy-back payments. The study concludes that the manufacturer will prefer retailer collection for product categories for which price competition is influential whereas she will favor manufacturer collection in product markets where retailers have less discretion on the prices.

Focusing on the important choice of product technology and market segmentation, another game theoretic model is put forth by Debo et al. (2005: 1193-1205) in the supply chain coordination context. The authors develop the model being inspired from the problems in the tire retreating industry and built on the observation that by investing in product technology the OEM can increase the amount of tires eligible for retreading and thus the supply of remanufactured products. The study mainly seeks to determine (1) the implications of the market characteristics on the optimal technology choice, (2) the effect of subsidies for remanufactured tires on the production decisions and (3) whether it is worth to produce a more expensive but remanufacturable product taking into account the fact that remanufactured products are valued less than the virgin ones in the market. A novel contribution of the study is the inclusion of remanufacturability level as a decision variable and a key determinant of the production cost.

Another economic model to analyze the interplay between virgin and remanufactured products is developed by Ferrer and Swaminathan (2006: 15-26) under both two-period and multi-period scenarios. Similar to the other studies in this line, the study assumes that remanufacturing costs are smaller than those of new production. The authors seek to determine the optimal quantities and prices for each product type (remanufactured and newly produced) separately for the monopoly and duopoly cases. Under the duopoly case distinctively from the previous literature, the authors analyze a situation where the independent operator can recover the returned products and sell them in secondary markets with a price discount. One of the interesting conclusions of the study is that OEM will choose to increase the first period production (at the expense of reducing her total profits) to be able to increase the available core amount and fully benefit from remanufacturing savings in the second period. The authors argue that this strategy will become optimal if the remanufacturing savings is sufficiently large and conclude that OEM may even choose not to manufacture at all in the second period if a threshold value for remanufacturing savings is exceeded.

4) Design for Recovery

Design for recovery (disassembly/recycling/remanufacturing) can be examined under the broad concept of ‘design for environment (DFE)’ which has attracted considerable attention in the literature. Ferrer (2001: 16) argues that “*a product is designed for environment if all activities concerning its production process, usage, and disposal are environmentally friendly*”. Design for recovery can be considered as a general concept describing the appropriateness of the product design for the recovery operations and can be further categorized as design for disassembly (DFD), design for recycling (DFR) and design for remanufacturing (DFRm) which characterize design specifications for particular types of recovery operations. In this sense, design for disassembly deserves special attention since it has important implications on both remanufacturing and recycling activities. DFD applications seek to identify the most appropriate design specifications that will minimize the structural complexity of the product via minimizing the number of parts, increasing the amount of common materials and selecting easily removable fasteners and connectors (Güngör and Gupta, 1999:821-824). Similarly, design for remanufacturing advocates the use of reusable, durable and easily interchangeable components in products. Finally, design for recycling which is an older initiative, deals with material selection so that recovery of materials from the cores becomes easier and more efficient.

Although the importance and possible contributions of design processes to product recovery is widely acknowledged and expressed by several authors in the current literature, except a few studies, these concepts are not formally included into the quantitative models developed so far. In this sense, one interesting study is given by Ferrer (2001:15-26). He suggests that certain design characteristics like serviceability, infrequent design changes, and modularity (use of easily interchangeable and common components), which can be quantified by recovery cost, disassembly cost, and product value influence the remanufacturability of products to a great extent. The author comes up with the design measures of disassemblability, recyclability, and reusability and develops a heuristic to determine the recovery routine of a generic widget.

On the other hand, Mangun and Thurston (2002: 479-490) argue that reuse and remanufacturing of some components/parts may be more profitable than direct disposal; however a long range product planning should be undertaken to ease the comparison of these options and to assess their ultimate impacts on environment, cost, and reliability. The study provides a decision tool for manufacturers to assess whether a used product should be taken back and which parts of it should be reused, recycled or disposed under the scenarios of no market segmentation and market segmentation.

Finally, Mabee et al. (1999: 360-362) present design charts to find out the design attributes for each remanufacturing process (disassembly, sorting, and cleaning) by the help of cross-functional teams of engineers. The authors suggest that the design charts can be used as an assessment tool for the remanufacturing potential of a particular design and guide future design modifications.

5) Strategic Aspects of Recovery Systems

In addition to the previous streams which mostly focus on operational issues and use quantitative models for specific problems of product recovery systems, there exists another research stream which adopts a strategic perspective and aims to understand various problems of recovery systems from a holistic standpoint. This stream generally employs an empirical approach (mostly case method) and analyzes the strategic implications of product recovery in a qualitative manner.

To begin with, in a case study conducted within the engine manufacturing facilities of a major European car manufacturer, Seitz and Wells (2006: 824-836) provide in-depth insights into remanufacturing activities in automotive industry. In this empirical study; authors employ open-ended, non-directive interviews and process observation to reveal the main motivators leading automotive manufacturers to product recovery. The authors conclude that the main drivers for OEM to undertake remanufacturing operations are neither direct financial nor environmental reasons but simply the support intended for the brand values of ‘product longevity’, ‘quality’, and ‘prestige in marketplace’. Furthermore, the decision as to whether remanufacture a returned vehicle mainly depends on technical feasibility (e.g. achievability of as good as new standard) rather than economic or environmental factors.

Another study employing case method and investigating the effects of product modularity and CLSC designs on the success of product recovery systems is proposed by Krikke et al. (2004: 23-39). By means of three case studies conducted in different firms from different industries, the researchers conclude that three keys to optimal CLSC management are (1) matching the type of return needs with the appropriate CLSC, (2) ensuring modular reuse and, (3) obtaining reliable reuse information. The authors categorize the major determinants of success in product recovery business as (1) future supply chain developments (e.g. product modularity, postponement, mass customization) and (2) new technology (e.g. information technology, new separation techniques and life cycle design of products).

Similarly, Thierry et al.'s (1995: 122-131) study also investigates the major strategic issues in product recovery management over three case studies (a copier manufacturer, BMW and IBM UK). The authors argue that an OEM should be able to acquire data on (1) the composition of products, (2) magnitude and uncertainty of return flows, and (3) markets for reprocessed products/components/materials to assess the costs and benefits of product recovery and make a decision accordingly. In this respect, the study examines the different types of product recovery operations in detail and investigates the strategic implications of each of these recovery phases. Similar to the previously discussed papers, Thierry et al. highlight the possible contributions of design for remanufacturing to the efficiency of product recovery systems.

The final group of empirical studies worth mentioning in this stream investigates the motivation of manufacturers to adopt environmentally friendly practices. In this respect, Handfield et al. (1997: 293-315) investigate the best practices in terms of environmental friendliness in the furniture industry. Carter and Ellram (1998: 86-98) develop a conceptual model of the different drivers of recovery activities (i.e. regulatory, supplier pressure, buyer pressures and competitive. Carter and Carter (1998: 660-680) focus on the determinants of environmental (green) purchasing and try to figure out the impact of different drivers through a survey among purchasing executives. Zhu and Sarkis (2004: 265-289) examine the impact of green supply chain management practices such as eco-design, cooperation with suppliers and customers and top management support on the environmental performance of the firms in China.

Important Conclusions about the Current Literature and Insights on Possible Future Research

Based on the literature review given in the previous sections, some important conclusions about the current state of product recovery research and some insights for future research can be summarized as follows;

- Despite the recent increase in the number of studies adopting supply chain perspective and providing a strategic and economic analysis of the product recovery decisions, there exist an obvious dominance of models focusing on operational problems like network design and inventory control. However, considering the novelty of product recovery business for majority of the manufacturers including the Turkish firms, studies which will address the decisions of whether to commence product recovery in the first place, and if commenced, how to conduct these generally costly operations will be very valuable in terms of both theoretical and practical perspectives.

- Studies focusing on more strategic decisions generally employ economic models borrowed from game theory and industrial economics literature. One common assumption of this kind of models is the ultimate profitability of remanufacturing compared to new production. In other words, they assume that a remanufactured product always costs less than a newly produced one (e.g. Ferrer and Swaminathan, 2006: 17; Savaskan and Van Wassenhove, 2006: 3; Savaşkan et al., 2004: 241). However, this assumption does not take into account the additional costs that may be incurred in the disassembly stage and may increase the overall cost of remanufacturing alternative over that of new production. Hence, inclusion of the disassembly cost as a separate parameter can contribute a lot to the viability of product recovery models. In that way, possible ways to decrease the cost of disassembly and, thus, the cost of remanufacturing (e.g. investment in modularity and product design) can also be explicitly considered in the relevant models.
- Another common implicit assumption of the existing models is the availability of all the necessary facilities or equipment for recovery operations. Most of the economic models analyzing the product recovery decisions on a strategic level do not take into account the necessary capacity investments which may create a trade-off and act as a deterrent factor for the adoption of product recovery alternative.
- D*esign for recovery* and *product modularity* are widely discussed and their benefits are qualitatively acknowledged in the context of product recovery research (Krikke et al., 2004: 381-409; Toffel, 2004: 120-140; Lebreton and Tuma, 2006: 639-652). However, only a few studies attempt to analyze the implications of these ideas on the success of recovery systems in a quantitative framework (Mangun and Thurston: 479-490, 2002; Ferrer, 2001: 373-393; Bras and Hammond, 1996: 5-22). Hence, models that will take into account the possible cost savings in recovery from product design improvements and examine the trade-off between the costs of technology investments needed for product redesign and the savings from improved design are still needed.
- Another important observation is the scarcity of empirical research. Although some studies include illustrative industry examples and focus on the case of one or a few companies, empirical research in a more comprehensive framework is not sufficient at best. Many aspects and features of product recovery systems show considerable variation from one setting to another. For instance, feasibility of different product recovery alternatives is not the same for all industries and product categories.

Product attributes (e.g. expected life-time, product design and structure, value of specific modules/components and relative life-span and durability of these components) and specific industry and market characteristics (e.g. the rate of technology and innovation, preference of the customers for recovered products) may considerably influence the appropriateness of different recovery options for different firms. Similarly, process technologies employed in forward production may also bear important implications for the achievability of different recovery options. Considering all these factors, a careful examination of current industrial practices can provide a useful tool and guide for the potential implementers of product recovery.

Conclusions

In this paper we examine product recovery systems and provide an overview of the current research in the field. We review the literature through a functional classification of the studies on product recovery and closed loop supply chains. Our review shows that especially in the last fifteen years there has been a great breakthrough in product recovery research. Problems that have been investigated in the context of traditional supply chains for years are adapted to closed loop supply chains and reexamined in this new setting. In these adaptations, it is observed that, due to the additional complexities in recovery systems (e.g. supply-side uncertainty) new approaches/methods are needed to tackle the problems in this new field. Furthermore, due to some special characteristics of recovery systems or closed loop structure new research questions come into the picture. Hence, as summarized in our paper there are still important topics that need further attention such as product redesign for recovery, impact of product design investments on recovery decisions and empirical investigation of actual industry practices in this research field.

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