Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art

Mehmet Ali Ilgin \textsuperscript{a,1}, Surendra M. Gupta \textsuperscript{b,*}

\textsuperscript{a} Department of Industrial Engineering, Dokuz Eylul University, Buca 35160, Izmir, Turkey
\textsuperscript{b} Laboratory of Responsible Manufacturing, 334 SN Department of MIE, Northeastern University, Boston, MA 02115, USA

\textbf{Abstract}

Gungor and Gupta [1999, Issues in environmentally conscious manufacturing and product recovery: a survey. Computers and Industrial Engineering, 36(4), 811–853] presented an important review of the development of research in Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) and provided a state of the art survey of published work. However, that survey covered most papers published through 1998. Since then, a lot of activity has taken place in EMCPRO and several areas have become richer. Many new areas also have emerged. In this paper we primarily discuss the evolution of ECMPRO that has taken place in the last decade and discuss the new areas that have come into focus during this time. After presenting some background information, the paper systematically investigates the literature by classifying over 540 published references into four major categories, viz., environmentally conscious product design, reverse and closed-loop supply chains, remanufacturing, and disassembly. Finally, we conclude by summarizing the evolution of ECMPRO over the past decade together with the avenues for future research.

\textsuperscript{*}Corresponding author. Tel.: +1 617 3734846.
E-mail addresses: mehmetal.ilgin@deu.edu.tr (M.A. Ilgin), gupta@neu.edu (S.M. Gupta).
\textsuperscript{1} Tel.: +90 232 4127601.

1. Introduction

Gungor and Gupta (1999) presented a review addressing the issues in Environmentally Conscious Manufacturing and Product Recovery (ECMPRO). Since then, the area of ECMPRO has witnessed a surge in research activity due to growing awareness in protecting the environment (Gupta and Lambert, 2008). Although several reviews have appeared since the publication of Gungor and Gupta’s (1999) review, none of them considers all aspects of ECMPRO. This paper presents a comprehensive summary of the ECMPRO literature that has been added since the publication of Gungor and Gupta’s review.

Environmentally Conscious Manufacturing (ECM) deals with green principles that are concerned with developing methods for manufacturing products from conceptual design to final delivery to consumers, and ultimately to the End of Life (EOL) disposal, that satisfy environmental standards and requirements.

Recent discussions about global warming in various media outlets have started to send warning signals to the masses about its seriousness. The former U.S. Vice President Al Gore has been on a crusade to make the general public aware of the importance of protecting the environment. Because of this, the Norwegian Nobel Committee recognized him with the 2007 Nobel Peace Prize for his efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change.

Environmental awareness and recycling regulations have been putting pressure on many manufacturers and consumers, forcing them to produce and dispose of products in an environmentally responsible manner. These have created a need to develop algorithms, models, heuristics, and software for addressing designing, recycling, and other issues (such as the economic viability, logistics, disassembly, recycling, and remanufacturing) for an ever-increasing number of products produced and discarded.

The purpose of this paper is to give an overview of the recent literature on ECMPRO. As can be seen in Table 1, the scope of every previous review is limited to a specific area in ECMPRO. In this paper, we present a holistic view of ECMPRO by covering a wide range of published work. The literature is organized into four main areas, namely, product design, reverse and closed-loop supply chains, remanufacturing and disassembly (see Fig. 1). In each main area, papers are classified into appropriate subcategories. In Section 2, environmental practices and tools employed in product design
are discussed. The issues related to the design and management of reverse and closed-loop supply chains are presented in Section 3. Section 4 analyzes the operations management issues peculiar to reverse logistics.

### Table 1

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| Veerakamolmal and Gupta (2000) and Kuo et al. (2001) and Kuo et al. (2001) give good overviews of the concepts, applications, and perspectives of various DFX methods. For detailed information on DFX, we refer the reader to the book by Huang (1996). Since this review’s emphasis is on the environmental issues, we only consider the ECM and product recovery related DFX tools, namely, Design for Environment, Design for Disassembly and Design for Recycling.  

#### 2.1. Design for environment

Design for environment (DFE) is the design of products in a way that the potential environmental impact throughout the life cycle is minimized (Fiksel, 1996; Billatos and Basaly, 1997; Giudice et al., 2006; Bevilacqua et al., 2007). Some researchers develop Quality Function Deployment (QFD)-based DFE methodologies for the simultaneous consideration of environmental criteria and customer requirements. Cristofari et al. (1996) introduce a methodology called green QFD which considers quality requirements, environmental impact, and production costs at the design phase. Zhang et al. (1999) improve the green QFD by developing a new methodology called green QFD II which combines Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) into QFD matrices and provides a mechanism to deploy customer, environmental and costing requirements throughout the entire product development process. Green QFD III proposed by Mehta and Wang (2001) simplifies the detailed LCA and complex product comparison algorithm of Green QFD II. Santos-Reyes and Lawlor-Wright (2001) develop a four-phase methodology. In phase 1 and phase 2, eco profile strategies are defined and prioritized using Analytic Hierarchical Process (AHP). In phase 3 and phase 4, eco-performance strategies are identified and associated with eco profile strategies using QFD. Madu et al. (2002) present a step by step approach for environmentally conscious design. First, AHP is used to prioritize customer requirements. Then, QFD is used to match design requirements to customer requirements. A cost-effective design plan is finally developed by applying Taguchi experimental design and Taguchi loss function. Kuo and Wu (2003) first apply QFD to translate customer needs into the six categories of environmentally technical measures. Then Grey Relational Analysis (GRA) is employed in this QFD matrix to determine the best design alternative based on the product’s life cycle, i.e. raw material, manufacturing, assembly, disassembly, transportation, customer usage, and disposal. Bovea and Wang (2003) introduce an approach for identifying environmental improvement options by taking customer preferences into account. The LCA methodology is applied to evaluate the environmental profile of a product while a fuzzy approach based on the House of Quality in the QFD methodology provides a more quantitative method for evaluating the imprecision of the customer preferences. Masui et al. (2003) develop a QFD-based four-phase methodology for DFE in the early stage of product development process. The most important components in product design are identified in phase 1 and phase 2. Phase 3 and phase 4 involve the determination of the most suitable design changes among various candidates with respect to environmental improvement. Sakao (2007) extends the Masui et al. (2003) by integrating LCA and TRIZ (Theory of Inventive Problem Solving) into QFD. Bovea and Wang (2007) propose a DFE methodology which integrates QFD, LCA, LCC and contingent valuation techniques for the evaluation of the customer, environmental, cost criteria and customer willingness-to-pay, respectively. The most commonly used technique in DFE methodologies is the environmental impact is Life Cycle Analysis (LCA) (Veerakamolmal and Gupta, 2000). Grote et al. (2007) integrate TRIZ, DFX tools and LCA to develop a DFE methodology. Bevilacqua et al. (2007) present a product design methodology by integrating DFE and LCA. LCA is also an integral part of various QFD-based DFE

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#### 2. Environmentally conscious product design

Traditional product development aims at achieving improvements in design with respect to cost, functionality and manufacturability. However, increasing importance of the environmental issues forces product designers to consider certain environmental criteria in the design process. In order to help product designers make environmentally friendly design choices, a number of methodologies have been developed. This section presents an overview of these methodologies by organizing them into three categories, viz., Design for X, life cycle analysis and material selection.

##### 2.1. Design for X

Design for X (DFX) involves different design specialties such as design for manufacture, design for quality etc. Meerkamm (1994),
methodologies (Zhang et al., 1999; Mehta and Wang, 2001; Sakao, 2007; Bovea and Wang, 2003, 2007).

There are also studies in literature that use fuzzy logic (FL) to handle imprecise and vague information in the early design stage. Kuo et al. (2006) use AHP to construct the hierarchical structure of the environmentally conscious design indices. Then, fuzzy multi-attribute decision-making model is used to select the best design alternative. Li et al. (2008b) employ a fuzzy connected graph to represent the product structure while AHP is used to convert life cycle environmental objectives along with other functional and production concerns into fuzzy relationship values. Using the fuzzy graph a graph-based clustering algorithm recommends a modular design based on minimization of the difficulty involved in disassembly and recycling of the EOL products. Qian and Zhang (2009) develop a methodology for environmentally conscious modularity assessment of electromechanical products by using fuzzy AHP.

A number of tools were developed for the evaluation of product designs with respect to environmental criteria. Green Design Advisor (GDA) proposed by Feldmann et al. (1999) considers metrics related to product information (e.g. number of materials), materials used in the product (e.g., toxicity), disassembly and recyclability of the product (e.g., time for disassembly). Then, an overall score for environmental impact is obtained by combining all metrics using multi-attribute value theory. Lye et al. (2002) develop a computer-based design evaluation tool, called ECoDE, to assess the environmental impact of components in a product. ECoDE employs AHP for the comparison and ranking of each criterion. The scores against each of the criteria are calculated by using a multi criteria rating technique for both components and the overall product. A product or component with a large score has a less severe impact on the environment. Knight and Curtis (2002) describe a software tool which quantifies the economic and environmental effects of the disassembly by simulating the disassembly process. Hopkinson et al. (2006) present the application of a DFE software in a rapid manufacturing environment. Mathieux et al. (2008) develop a recovery-conscious design method for the multi criteria and quantitative analysis of the recoverability of complex products. For an overview of DFE tools and strategies we refer the reader to Kalisvaart and van der Horst (1995) and Bhamra (2004). Park and Tahara (2008) simultaneously consider the quality, environmental and customer satisfaction related aspects of products by using Producer-Based Eco Efficiency (PBEE) and Consumer-Based Eco Efficiency (CBEE). PBEE is used to identify the key issues of a product as related to product quality and environmental impact whereas consumer satisfaction and environmental impact related product characteristics are identified by using the CBEE. Data Envelopment Analysis (DEA) is used to quantify product values to the producers and consumers into one single value and the LCA was used to quantify the environmental impact of a product. Mascle and Zhao (2008) use FL and feature modeling to evaluate parts together with the disassembly efficiency and liability. Platcheck et al. (2008) define a new product development methodology comprising of four phases: briefing phase, development phase, projectation phase and communication phase. They insert environmental criteria into the different phases of the methodology.

Boks and Stevels (2007) emphasize the fact that dissemination of DFE information requires the consideration of the intended audience and relevant contexts. Johansson et al. (2007) investigate the different mechanisms for their potential to support integration between product designers and environmental specialists.

2.1.2. Design for disassembly

Design for disassembly (DFD) can be defined as the consideration of the ease of disassembly in design process (Veerakamolmal and Gupta, 2000). Kroll and Hanft (1998) present a method for the evaluation of the ease of disassembly by using a spreadsheet-like chart and a catalog of task difficulty scores. The scores are determined based on the work-measurement analyses of standard disassembly tasks. Veerakamolmal and Gupta (1999) introduce Design for Disassembly Index (DFDI) to measure the design
efficiency. DFDI is calculated by using a disassembly tree which allows the identification of precedence relationships that define the structural constraints in terms of the order in which components can be retrieved. Kroll and Carver (1999) try to develop time-based DFD metrics to be used for comparing alternative designs of the same product. Das et al. (2000) estimate disassembly cost and effort by calculating a disassembly effort index comprising of seven factors: time, tools, fixture, access, instruct, hazard, and force requirements. Chen (2001) uses axiomatic design to develop integrated design guidelines and an evaluation score for the ease of disassembly and recycling called Integrated Disassembly and Recycling Score (IDRS). Ferrer (2001) proposes a framework for the determination of the disassembly and recovery process of a product by developing economic measures of recyclability, disassemblability and reusability. Desai and Mital (2003a) and Mital and Desai (2007) develop a methodology to enhance the disassemblability of products. They define disassemblability in terms of several factors such as exertion of manual force for disassembly, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, use of hand tools, etc. Time-based numeric indices are assigned to each design factor. A higher score indicates anomalies in product design from the disassembly perspective. Desai and Mital (2005) propose a quantitative DFD methodology by considering numerous ergonomic and conventional design attributes. Villalba et al. (2004) use a recyclability index of materials to determine if it is economically feasible to disassemble a product. Banda and Zeid (2006) present a computational methodology that enables designers to perform disassembly cost analysis in the design phase of a product. Gungor (2006) uses Analytic Network Process (ANP) to evaluate alternative connection types from a DFD perspective. Giudice and Kassem (2009) propose a DFD methodology for characterizing the disassembly depths of product components with respect to their need for removal and recovery at EOL.

As an alternative to the index-based approaches to DFD, Viswanathan and Allada (2001) emphasize the importance of product configuration in DFD. They propose a formal model, called the Configuration-Value (CV) model, to evaluate and analyze the effect of configuration on disassembly. In a follow-up paper, Viswanathan and Allada (2006) develop a model for the combinatorial configuration design optimization problem. Design solutions proposed by the model are tested by using a hierarchical evolutionary programming-based algorithm. Kwak et al. (2009) develop a novel concept, called “eco-architecture analysis” in which a product is represented as an assembly of EOL modules. Optimal EOL strategy is developed by determining the most desirable eco-architecture.

Chu et al. (2009) propose a CAD-based approach that can automatically generate a variant of 3D product structure by modifying the combination of parts, assembly method and assembly sequence. A Genetic Algorithm (GA)-based computing scheme is employed to determine an optimal product structure from the design alternatives generated by the approach.

2.1.3. Design for recycling

Design for recycling (DFR) focuses on the design attributes which support the cost-effective recycle and disaggregation of the materials embodied in the product (Masanet and Horvath, 2007). Coulter et al. (1998) present a simple metric in order to determine the appropriate separation process in the early design phase. Knight and Sodhi (2000) develop mathematical models which allow the evaluation of products for bulk recycling by determining the cumulative net profit/cost as materials separation proceeds. Liu et al. (2002) integrate AHP and Neural Network (NN) to develop a procedure for recyclability assessment. Boon et al. (2002) explore the electronic goods recycling infrastructure to identify the conditions required for profitable recycling of PCs. Ardente et al. (2003) present a computer-based tool called ENDLESS to calculate a “Global Recycling Index” based on energy, environmental, technical and economic indicators. Wright et al. (2005) try to improve the recyclability of a fiber optic cable design using a methodology called CHAMP (Chain Management of Materials and Products). CHAMP involves the evaluation of a design for both economic and environmental impacts on a life cycle basis. Pento (1999) shows that improved recyclability of paper reduces the amount of waste generated. The DFR methodology proposed by Ferrao and Amaral (2006) allows for the identification of economically optimum recycling strategies while satisfying given recycling and reuse rates. Masanet and Horvath (2007) develop an analytical framework to quantify the economic and environmental benefits of DFR practices for plastic computer enclosures during the design process. Houe and Grabot (2007) develop a prototype system for the conversion of the recyclability norms in textual form into constraints which can be propagated through the product structure in order to identify the inconsistencies between the present design and a given norm.

2.2. Life cycle analysis

Life cycle analysis (LCA) is a method used to evaluate the environmental impact of a product through its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal. Majority of the researchers use LCA within a DFE methodology as a tool to measure the environmental impact of a product’s design (Zhang et al., 1999; Mehta and Wang, 2001; Bovea and Wang, 2003, 2007; Bevilacqua et al., 2007; Roks and Stevels, 2007; Sakao, 2007; Grote et al., 2007).


Another LCA-assisted methodology is Life Cycle Engineering (LCE) which can be defined as the design of product life cycle by making choices on product concept, structure, materials and processes. The environmental and resource consequences of these choices are evaluated using LCA (Giudice et al., 2006). For more information on LCE, we refer the reader to the books by Hundal (2001) and Giudice et al. (2006).

2.3. Material selection

Selection of materials for a particular application is affected mainly by mechanical factors including weight, processability. Cost is also an important criterion. However, in recent years, environmental factors have also been considered in material selection at an increasing rate. In order to deal with the environmental criteria in design process, a number of tools and methodologies were presented by researchers. Holloway (1998) extends a conventional material selection technique, material selection charts, by integrating environmental concerns into it. Giudice et al. (2005) develop a systematic method which minimizes the environmental impact of the selected materials while satisfying the functional and performance requirements. Tseng et al. (2008) carry out a green material cost analysis to recommend materials that cause less
In general, network design models can be classified into two categories: deterministic and stochastic. While deterministic models ignore uncertainty associated with RL and closed-loop networks in model building, stochastic models integrate the uncertain characteristics of RL and closed-loop networks into modeling process.

### 3.1. Network design

In general, network design models can be classified into two categories: deterministic and stochastic. While deterministic models ignore uncertainty associated with RL and closed-loop networks in model building, stochastic models integrate the uncertain characteristics of RL and closed-loop networks into modeling process.

### 3.1.1. Deterministic models

Most of the deterministic models consider only reverse flows. Mixed Integer Linear Programming (MILP) is the most commonly used modeling technique. Barros et al. (1998) propose a two-level location model for recycling sand from construction waste. A heuristic procedure based on a linear relaxation strengthened by valid inequalities to generate a lower bound is proposed. Louwers et al. (1999) use a non-linear programming model and a linear approximation solution procedure to determine the location and size of regional recycling centers for a carpet waste management network. Realf et al. (1999, 2000a) propose MILP models for the RL network design for the carpet recycling. Krikke et al. (1999b) develop an MILP model for the design of a RL network for a copier manufacturer. Jayaraman et al. (1999) propose a binary mixed integer programming model to determine the location of remanufacturing/distribution facilities and to find the optimum quantities of transshipment, production and stocking for cores and remanufactured products. Fleischmann et al. (2000) investigate the general characteristics of product recovery network design problem based on the case studies from different industries. Shih (2001) develops a mixed integer programming (MIP) model to design a RL system for recycling computers and home appliances. Xu et al. (2002) develop a discrete-time linear analytical model for a multi-time-step, multi-type hazardous-waste RL system based on the minimization of total RL operating costs. Schultmann et al. (2003) combine facility location planning and flow-sheeting-based process simulation for the design of a spent-battery RL network. Jayaraman et al. (2003) propose models and solution procedures to develop an efficient strategy for a RL network designed for hazardous products. The aim of the study is to determine the number and location of the collection centers and refurbishing sites and the corresponding flow of hazardous products. The proposed heuristic concentration procedures combined with heuristic expansion components have the ability of solving relatively large problems with up to 40 collection sites and 30 refurbishment sites. However, their model and solution procedures ignore the multiple period problems, freight rate discounts and inventory cost savings resulting from consolidation of returned products. Wang and Yang (2007) try to develop better heuristics for solving the location-allocation problem of recycling e-waste by comparing their heuristics with the heuristics proposed by Jayaraman et al. (2003). Their MIP model is based on the model proposed by Shih (2001). They also exploit the real – world parameters of Taiwan e-waste recycling industry used by Shih (2001). Amini et al. (2005) use binary integer programming to design the RL network for the repair operations of a major international medical diagnostics manufacturer. Du and Evans (2008) setup an MILP optimization model for the design of the RL network for a third party logistics company providing logistics service for the post sale service operations of a manufacturing company. A solution approach is proposed by combining three search algorithms: scatter search, the dual simplex method and the constraint method. Pati et al. (2008) formulate a mixed integer GP model to determine the facility location, route and flow of different varieties of recyclable waste-paper in the multi-item, multi echelon and multi-facility decision-making framework. Srivastava (2008a,b) present a multi period two-level hierarchical optimization model for RL network design problem. The first MILP optimization model determines the opening decision for collection centers based on the minimization of investment (fixed and running costs of facilities and transportation costs). Disposition decisions, location and capacity addition decisions for rework sites at different time periods together with the flows to them from collection centers are determined by the second MILP optimization model based on maximization of profit. Min and Ko (2008) develop an MIP model together with a GA.
in order to solve the location-allocation problem related to the repair facilities of a third party logistics service provider. Lee et al. (2009) develop a novel GA to solve the mathematical model associated with a RL network. Dehghani and Mansour (2009) propose a multi objective GA to design a product recovery network. Pishvaee et al. (in press) use Simulated Annealing (SA) to solve the MILP model associated with a RL network design problem.

In recent years, simultaneous consideration of reverse and forward flows has become a popular approach to the deterministic network design problem. Fleischmann et al. (2001) propose an MILP-based generic Recovery Network Model (RNM) to compare the traditional logistic design with the simultaneous design of forward and reverse network. After applying their model to two case studies from the literature, they state that for many cases product recovery can be integrated with existing logistic structure in an efficient way while other cases require the integrated design of reverse and forward logistic networks. Salema et al. (2007) point out that Fleischmann et al. (2001) do not take into consideration some important problems of real RL networks such as capacity limits on production/storage, multi product production, and uncertainty in demand/return flows. In order to deal with these shortcomings, they extend the RNM and develop an MILP formulation for a capacitated multi product RL model by considering forward flows. In another paper, Salema et al. (2005) present a two-level approach for the same problem. Beamon and Fernandes (2004) propose a multi period MILP model for a closed-loop supply chain to determine the location and sorting capabilities of warehouses together with the amount of material to be transported between each pair of sites. Sim et al. (2004) use a Linear Programming (LP)-based GA for the design of a closed-loop supply chain. Sheu et al. (2005) propose a linear optimization model that considers forward and reverse logistics flows. Zhou et al. (2005) integrate a Mixed Integer Non-Linear Programming (MINLP) model and GA in order to solve a distribution problem with forward and reverse flows. Lu and Bostel (2007) use a lagrangian heuristic approach to solve a location problem of a remanufacturing RL network considering forward flows. Ko and Evans (2007) construct an MINLP model and propose a GA-based heuristic procedure for the forward/reverse network design problem of a third party logistics provider. Uster et al. (2007) use Benders decomposition with alternative multiple cuts to propose an exact solution for the large scale MILP model associated with a closed-loop supply chain network. Wang et al. (2007) present a bi-level programming model for a supply chain in order to jointly determine location and inventory policies by considering product returns. Lee et al. (2007a) propose a closed-loop supply chain network design model for a Third Party Logistics Provider (3PL) by considering two objectives: maximization of the returned products shipped from customers back to the collection facilities and minimization of the total costs associated with the forward and reverse logistics operations. After developing a compromise solution using fuzzy GP, a GA is employed to solve the problem. Lee et al. (2007b) develop a GA to solve the MILP model associated with the closed-loop supply chain design of a 3PL. Lee and Dong (2008) integrate Tabu Search (TS) and network simplex algorithm to solve the location-allocation problem of an end-of-lease computer recovery network. Demirel and Gökşen (2008) develop an MILP model to determine the optimal manufacturing, remanufacturing, and transportation quantities together with the optimal locations of disassembly, collection and distribution facilities. Mutha and Pokharel (2009) propose a mathematical model for the design of a multi echelon closed-loop supply chain involving five retailers, four warehouses, three reprocessing centers, five spare part markets, three factories, one recycling center, one disposal site, six new module suppliers and six distribution centers. Kannan et al. (2009a) use GA and particle swarm optimization in order to design a multi echelon closed-loop supply chain in a build to order environment. Wang and Hsu (2010) employ a spanning-tree-based GA to solve an IP model associated with the design of a closed-loop supply chain. Salema et al. (in press) use a graph approach based on the conventional concepts of nodes and arcs to develop a generic model for the simultaneous design and planning of supply chains with reverse flows. Kannan et al. (in press) propose an MILP model for a closed-loop supply chain network design problem and then develop a GA-based heuristic as a solution methodology. Yang et al. (2009) use theory of variational inequalities to formulate and optimize the equilibrium state of a closed-loop supply chain network.

Some researchers focus only on the collection of used products from the consumers. Bautista and Pereira (2006) formulate the collection point location problem as a set covering and MAX-SAT problem. They develop GA and GRASP (Greedy Randomized Adaptive Search Procedure) methodologies to solve the set covering and MAX-SAT formulation, respectively. Min et al. (2006a) present a non-linear integer program for solving the multi echelon RL problem involving product returns without considering temporal consolidation issues in a multiple planning horizon. Min et al. (2006b) present a mixed integer non-linear model to determine the number and location of initial collection points and centralizedized return centers. The model involves the determination of the exact length of holding time for consolidation at the initial collection points and total RL costs associated with product returns in a multiple planning horizon. A solution procedure based on GA is proposed to solve the model. Wojanowski et al. (2007) develop an analytical model for the collection facility network design and pricing policy by considering the impact of the deposit refund on the sales rate and return rate. Aras and Aksen (2008) propose an MINLP model for collection center location problem with distance and incentive-dependent returns under a drop-off policy. Aras et al. (2008) extend Aras and Aksen’s (2008) model by considering a pickup policy with capacitated vehicles. Cruz-Rivera and Ertel (2009) construct an uncapacitated facility location model in order to design a collection network for EOL vehicles in Mexico. de Figueiredo and Mayerle (2008) develop an analytical model with the associated algorithmic solution procedure to design minimum-cost recycling collection networks with required throughput.

Instead of determining the location of collection centers in an optimal way, Tuzkaya and Gulsin (2008) propose an integrated ANP-fuzzy technique for the evaluation of potential collection center locations. Bian and Yu (2006) use AHP in order to evaluate the alternative RL operation locations for an international electrical manufacturer. Pochampally and Gupta (2008) integrate AHP and fuzzy set theory to determine potential facilities from a set of candidate recovery facilities. Kannan et al. (2008) investigate the use of AHP and fuzzy AHP for selecting the collection center location in a RL network. Pochampally and Gupta (2009) employ a four-phase approach to evaluate the efficiencies of collection and recovery facilities, viz. (1) identification of criteria for evaluation of the facilities of interest, (2) use of fuzzy ratings of existing facilities to construct a neural network that gives the importance value for each criterion, (3) employment of a fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) approach to obtain the overall ratings of the facilities of interest, and (4) employment of Borda’s choice rule to calculate the maximized consensus ratings of the facilities of interest.

Determination of the appropriate reverse channel structure for the collection of used products from customers is an important issue in RL network design. Savaskan et al. (2004) investigate the reverse channel structure selection problem for a single manufacturer single retailer case. Savaskan and Van Wassenhove (2006) extend Savaskan et al. (2004) by considering two retailers in
a competitive retailing environment. Bhattacharya et al. (2006) analyze the impact of centralized and decentralized channel structures in the optimal order quantity of a retailer from a manufacturer which makes new products and orders remanufactured products from a remanufacturer. Karakayali et al. (2007) analyze centralized as well as remanufacturer- and collector-driven decentralized channels. Walther et al. (2008) develop a negotiation-based coordination mechanism which allows for the decentralized assignment of recycling tasks to the companies of a recycling network. Hong et al. (2008) compare centralized and decentralized decision making in a RL system. In centralized model, a decision maker gives decisions for the entire system while the decentralized model involves several independent entities individually operated by self-interested parties.

### 3.1.2. Stochastic models

Design of reverse and closed-loop supply chain networks involves a high degree of uncertainty associated with quality and quantity of returns. In order to deal with this uncertainty, researchers developed various stochastic models. Robust optimization is a commonly used technique to deal with the uncertainty in RL network design. Realff et al. (2000b, 2004) propose a robust MILP model to support decision-making for RL network design. The model can search for solutions close to the mathematically optimal solutions for a set of alternative scenarios identified by a decision maker. Hong et al. (2006) also develop a robust MILP model based on the maximization of the system net profit for specified deterministic parameter values in each scenario. A min–max robust optimization methodology is employed to find a robust solution for all of the scenarios.

Stochastic programming is a popular alternative to robust optimization. Lister and Dekker (2005) propose a stochastic programming-based approach for the sand recycling case study given in Barros et al. (1998). A generic stochastic model is developed by Lister (2007) for closed-loop supply chains. Lee et al. (2007c) develop a stochastic programming-based approach for a product recovery network design problem. Chouinard et al. (2008) consider the randomness related with recovery, processing and demand volumes in a closed-loop supply chain design problem by developing a stochastic programming model. They use a sample average approximation-based heuristic to solve the problem. Lee and Dong (2009) propose a stochastic programming model to deal with the location and allocation decisions of a RL network under uncertainty. They integrate sample average approximation and SA in order to solve this model.

Lieckens and Vandaele (2007) propose an MINLP model by integrating a conventional RL MILP model with a queuing model to deal with the dynamic and stochastic aspects of RL networks. A GA-based technique, Differential Evolution, is used to solve the MINLP model.

Qin and Ji (in press) use fuzzy programming to deal with the uncertainty associated with the design of RL networks. They integrate fuzzy simulation and GA for the design of a RL network.

### 3.2. Simultaneous consideration of network and product design issues

Some researchers develop reverse or closed-loop supply chain network design models by explicitly considering the issues related with product design. Krikke et al. (2003) develop an MILP model to support decisions on both design structure of a product, i.e. modularity, reparability and recyclability, and the design structure of the logistic network. Fernandez and Kekale (2005) investigate the impact of the product modularity on closed-loop supply chain design is studied by Krikke et al. (2004).

### 3.3. Optimization of transportation goods

Efficient and effective planning of transportation activities is a crucial factor in the cost-effective management of RL networks. A majority of the studies in literature try to determine the vehicle routes in RL networks using different versions of well-known Vehicle Routing Problem (VRP). Some researchers consider only return flows. Mourao and Almeida (2000) and Mourao and Amado (2005) provide heuristic methods in order to solve the mixed capacitated arc routing problem of a refuse collection network. Blanc et al. (2004) use a VRP to obtain reliable estimates of transportation costs in a recycling network redesign problem. Blanc et al. (2006) propose a multi–depot pickup and delivery model with capacitated vehicles and alternative delivery locations for the collection of containers from EOL vehicle dismantlers in the Netherlands. They solve the model using a heuristic developed by integrating route generation and set partitioning. Schultzmann et al. (2006) develop a symmetric capacitated VRP to generate a tour schedule with minimal cost for EOL auto RL network. TS is used to find the optimum schedule. Krikke et al. (2008) combine route generation and set partitioning to solve the VRP associated with the low-frequency collection of materials disassembled from EOL vehicles. Kim et al. (2009a) construct a VRP for an RL network in South Korea and then propose a TS algorithm to solve the problem.

Route planning with integrated return and delivery flows was also investigated by the researchers. Dethloff (2001) considers a RL system in which customers have both pickup and delivery demands. He models this system as a Vehicle Routing Problem with Simultaneous Delivery and Pickup (VRPSDP). Then a heuristic construction procedure is developed to solve the problem. Dethloff (2002) uses the heuristic procedure proposed in Dethloff (2001) to solve the VRP with backhauls. Gribkovskai et al. (2007) model VRPSDP as an MILP model and develop general solutions using conventional construction and improvement heuristics and TS. Alshamran et al. (2007) examine the blood distribution network of the American Red Cross in which products are delivered from a central processing point to customers (stops) in one period are available for return to the central point in the following period. They develop a heuristic procedure to develop route design and pickup strategies simultaneously.

### 3.4. Selection of used products

Although OEMs in some countries are obligated to take products at the end of their useful life, many third party firms collect used products to make profit. These firms select used products by comparing the revenues from recycle or resale of products’ components and collection and reprocessing costs of the used products (Pochampally et al., 2009c). The most commonly used technique in selection of used product for reprocessing is construction of a cost benefit function. Veerakomolmal and Gupta (1999) propose a cost benefit function to select the best product for reprocessing from a set of candidate used products. The value of cost benefit function is calculated by subtracting sum of revenue terms from the sum of cost terms. Pochampally and Gupta (2005) and Pochampally et al. (2009b) modify this cost benefit function by considering the probability of breakage and the probability of missing components in the used product of interest. Then an integer linear programming model is formulated based on the maximization of the modified cost benefit function. Pochampally and Gupta (2008) propose a fuzzy benefit function by considering the uncertainty associated with revenues and costs. Cost benefit
function technique is preferred when the evaluation criteria could be presented in terms of classical numerical constraints. For the case of presentation of evaluation criteria in terms of range of different degrees of desirability, Pochampally et al. (2009c) present a Linear Physical Programming (LPP) formulation.

3.5. Selection and evaluation of suppliers

Due to the differences between the reverse and forward flows in terms of the cost and complexity of transportation, storage and/or handling operations, many firms outsource their RL operations to Third Party Logistics Providers (3PLs) (Meade and Sarkis, 2002; Efendigil et al., 2008). In order to support decision makers in selection of the 3PLs, researchers developed multiple criteria decision-making methodologies. Meade and Sarkis (2002) use ANP to develop a conceptual model for selecting and evaluating 3PLs. Presley et al. (2007) integrate Activity Based Costing (ABC), balanced scorecard, AHP and QFD to select between two competing 3PLs. Efendigil et al. (2008) present a holistic approach based on the NN and FL for selecting a 3PL in the presence of vagueness. Tsai and Hung (2009) employ preemptive GP with environmental goals, ABC goals, and supply chain goals to solve treatment supplier selection problem of an electronic equipment manufacturer. Performance weights of suppliers are calculated using AHP. Pochampally et al. (2009b) propose a TOPSIS-based methodology to rate candidate companies that collect and sell used products. The methodology considers the concerns of three different categories of people: consumers, local government officials and manufacturers. Kannan et al. (2009b) use fuzzy TOPSIS and interpretive structural modeling for the problem of selection of best 3PL. In order to solve the same problem, Kannan (2009) employs AHP and fuzzy AHP while Saen (in press) develops a DEA-based methodology.

Consideration of environmental factors in forward logistic supplier selection problem was also studied by some researchers. Lu et al. (2007) employ an AHP-based decision-making methodology for the performance measurement and evaluation of the suppliers based on the environmental criteria. A FL process is also integrated with the AHP to reduce subjective bias in designing a weighting system.


3.6. Performance measurement

Simulation is the most commonly used technique to study the effect of different factors on the performance of a reverse or closed-loop chain. Georgiadis and Vlachos (2004) present a System Dynamics Simulation (SDS) model to analyze the long term behavior of a closed-loop supply chain with respect to alternative environmental protection policies concerning take-back obligation, proper collection campaigns, and green image effect. Biehl et al. (2007) develop a Discrete Event Simulation (DES) model for a carpet RL supply chain and carry out an experimental design study to analyze the impact of the system design factors together with the environmental factors on the operational performance of the RL system. Kara et al. (2007) model RL network of EOL white goods in Sydney Metropolitan Area using DES. They carry out some what-if analysis using the DES model to determine the most important factors in the performance of the RL system. Georgiadis and Besiou (2008) use a SDS model to examine the impact of legislation, green image factor and DFE on the long term behavior of a closed-loop supply chain with recycling activities.

Pochampally et al. (2009a) define metrics for the performance evaluation of a reverse/closed-loop supply chain. They also propose a QFD and LPP-based mathematical model to measure the performance of a reverse/closed-loop supply chain.

In some studies, the effect of green practices such as ISO 14000, LCA on the performance of a supply chain is investigated. Sarkis and Cordeiro (2001) use DEA to present the performance differences between pollution prevention and end of pipe environmental management policies. Sarkis and Talluri (2004) investigate the use of DEA as an environmental performance measurement tool by presenting an illustrative example. Wagner et al. (2001) give a good overview of empirical studies investigating the relationship between the environmental and economic performance. Hervani et al. (2005) present an integrated framework for study, design and evaluation of green supply chain management performance tools based on the experiences, case studies and other literature related to performance measurement in green supply chains. Kainuma and Tawara (2006) propose a multiple attribute utility theory approach integrating supply chain return on asset, customer satisfaction, and LCA.

Country or region-based studies were also presented by the researchers. Zhu and Sarkis (2004), Zhu et al. (2005, 2007) try to analyze the relationship between the green supply chain management practices and performance in China. Rao and Holt (2005) study the effects of green supply chain practices on the performance and competitiveness of a sample of organizations in South East Asia.

3.7. Marketing-related issues

The most commonly studied marketing-related issues include the pricing of manufactured and remanufactured products, competition in remanufacturing and selection of an optimal return policy. Guide et al. (2003) consider a remanufacturing system in which the used phones with different quality levels are remanufactured to a single quality level and are sold at a certain price. The selling price of remanufactured products could be completely determined by the acquisition prices of returns since they assume that demand and return flows perfectly matched. Demand is assumed to be the function of the price. They develop a heuristic to determine the optimal acquisition price of the used phones and selling price of the remanufactured phones with the aim of maximizing the profit which is given as the difference between the total revenue and acquisition and remanufacturing costs. Mitra (2007) extends Guide et al. (2003) in four ways. First, he does not consider acquisition prices by focusing on a manufacturer which is responsible to recover the returns. Second, more than one quality level is considered for remanufactured products. Third, he considers a probabilistic situation where not all items may be sold, and the unsold items may have to be disposed of. Finally, demand is modeled as a function of price and availability or supply of recovered goods. Vadde et al. (2007) investigate the pricing policies of reusable and recyclable components for third party firms involved...
in discarded product processing under strict environmental regulations. Qiao et al. (2008) develop game theory-based models to jointly determine the collecting, wholesale and retail prices in a closed-loop supply chain. Qu and Williams (2008) compare two hulk pricing strategies for an automotive shredder under constant, increasing and decreasing trends for ferrous metal and hulk prices. Liang et al. (2009) try to determine the acquisition price of the cores in an open market based on the options framework and the geometric Brownian motion followed by the sales price of the cores. Karakayali et al. (2007) develop models to determine the optimal acquisition price of EOL products and the selling price of remanufactured parts by considering centralized as well as remanufacturer- and collector-driven decentralized channels. Mukhopadhyay and Setoputra (2004) propose a model to obtain optimal policies for price and the return policy in terms of certain market reaction parameters for e-business based on maximization of profit. Debo et al. (2005) investigate the joint pricing and production technology selection problem faced by an Original Equipment Manufacturer (OEM) operating in a market where customers differentiate between the new and the remanufactured products. Voralayan and Ryan (2006) model the sale, return, refurbishment, and resale processes as an open queueing network to find the optimal price and proportion of refurbished products. Some researchers study the competition between OEM and an independent operator who may intercept product cores produced by OEM to sell the remanufactured products in future periods. Majumder and Groenevelt (2001) consider a two-period model in which OEM may or may not remanufacture in the second period. Ferrer and Swaminathan (2006) extend Majumder and Groenevelt’s (2001) study to a multi period setting where the independent operator competes with the OEM in the second and subsequent periods. They also find closed form solutions for prices and quantities and characterize an optimum solution region which was numerically explored by Majumder and Groenevelt (2001). Ferguson and Toktay (2006) try to determine the new product pricing decisions and recovery strategy of an OEM in a two-period model by assuming that OEM has an easier access to the used product and average variable cost of remanufacturing increases with the quantity remanufactured. Ferrer and Swaminathan (in press) extend Majumder and Groenevelt (2001) and Ferguson and Toktay (2006) studies by considering more than two periods with differentiated remanufactured products. Webster and Mitra (2007) and Mitra and Webster (2008) develop two-period models to analyze the effect of take-back laws and government subsidies on competitive remanufacturing strategy, respectively. Heese et al. (2005) analyze a three-stage game involving sequential decisions of two OEMs whether to takeback used products during the first two stages. In the third stage, both firms simultaneously determine the price for their new products together with the discount offered for returned products.

An effective return policy can be used as a marketing tool to increase sales. There are studies in the literature analyzing return policies within the RL context. Mukhopadhyay and Setoputra (2005) develop a profit maximization model to determine the optimal return policy for build to order products. Yao et al. (2005) investigate the role of return policy in the coordination of supply chain by using a game theory-based methodology. Yalabik et al. (2005) develop an integrated product returns model with logistics and marketing coordination for a retailer servicing two distinct market segments. Mukhopadhyay and Setoputra (2006) investigate the role of a Fourth Party Logistics (4PL) as a return service provider, and propose optimal decision policies for both the seller and the 4PL. Robotis et al. (2005) investigate the use of remanufacturing as a tool to satisfy the demand arising from secondary markets. They point out that use of remanufacturing to satisfy the demand form secondary markets reduces the number of units procured from the advanced market for the reseller.

3.8. EOL alternative selection

Determination of the best option for EOL products is an important problem faced by OEMs. There are five commonly used options for a product at its end of life: direct reuse, repair, remanufacturing, recycling, and disposal. Direct reuse involves the reuse of the whole product as is for its original task. In repair option, damaged parts are changed in order to have a fully-functional product. Remanufacturing consists of refurbishment of used products up to a quality level similar to a new product. The aim of recycling is to recover materials from the returned products. Disposal involves the landfill or incineration of the used products. Development of a decision model to select between these options requires the consideration of various qualitative and quantitative factors such as environmental impact, quality, legislative factors, cost, etc. Mathematical programming models were extensively used by researchers to develop EOL option selection methodologies. Krikke et al. (1998) use stochastic Dynamic Programming (DP) to determine a product recovery and disposal strategy for one product type based on the maximization of net profit considering relevant technical, ecological and commercial feasibility criteria at the product level. In follow-up papers, Krikke et al. (1999a,b) apply the methodology proposed in Krikke et al. (1998) to real life cases on the recycling of copiers and monitors, respectively. Teunter (2006) extends Krikke et al. (1998) by considering multiple disassembly processes and partial disassembly. Lee et al. (2001b) determine the EOL option of each part by defining the objective function as the weighted sum of economic value and environmental impact. Das and Vedlarajah (2002) propose a mixed integer program to determine the optimal part disposal strategy based on the maximization of the net profit. Jorjani et al. (2004) develop a piecewise linear concave program to determine the optimal allocation of disassembled parts to five disposal options (refurbish, resell, reuse, recycle, landfill) based on the maximization of the overall return.

Ritchey et al. (2005) develop a mathematical model to evaluate the economic viability of remanufacturing option under a government mandated take-back program. Willems et al. (2006) use LP to investigate the effect of reductions in the expected disassembly time and cost on the optimal EOL strategy. Tan and Kumar (2008) use an LP model to evaluate three EOL options for each part, namely, repair, repackage or scrap.

In some studies, Multi Criteria Decision Making (MCDM) methodologies are presented. Hula et al. (2003) present a multi objective GA to consider the trade-offs between environmental and economic variables in the selection of EOL alternatives. Bufardi et al. (2004) obtain a partial ranking of EOL options using the ELECTRE III MCDM methodology. Chan (2008) extends Bufardi et al. (2004) by developing a GRA-based MCDM methodology which considers complete ranking of EOL options under uncertainty environment. Jun et al. (2007) develop a multi objective evolutionary algorithm to select the best EOL options of parts for maximizing the recovery value of an EOL product including recovery cost and quality. Fernandez et al. (2008) develop a fuzzy approach to evaluate five recovery options and one disposal option by considering four criteria: product value, recovery value, useful life and level of sophistication. Wadhwa et al. (2009) propose a FL-based MCDM methodology to consider the knowledge of experts (evaluators or sortation specialists) in the selection of most appropriate alternative(s) for product reprocessing with respect to existing criteria. Iakovou et al. (2009) develop an MCDM methodology, called “Multicriteria Matrix”, which considers the residual value, environmental burden, weight, quantity and ease of
disassembly of each component in the evaluation of EOL alternatives for a product. Xanthopoulos and Iakovou (2009) use GP to determine the most attractive subassemblies and components to be disassembled for recovery from a set of different types of EOL products.

Gonzalez and Adenso-Diaz (2005) propose a bill of material-based method for the joint determination of depth of disassembly and EOL option for the disassembled parts based on the maximization of the profit. Kleiber (2006) tries to develop dynamic policies for three different new product development projects (design for single use, design for reuse, and design for reuse with stockkeeping) which differ with respect to EOL recovery strategy. Shih et al. (2006) develop a Case Based Reasoning (CBR)-based methodology to determine the product EOL strategy. Staikos and Rahimifard (2007a,b) integrate AHP, LCA and cost benefit analysis to determine the most appropriate reuse, recovery and recycling option for postconsumer shoes. Rahimifard et al. (2004) and Bakar and Rahimifard (2007) develop computer-aided decision support systems to support the EOL option selection process.


3.9. Product acquisition management

Highly uncertain nature of quantity, quality and timing of returns requires effective policies for the acquisition of used products. Uncontrolled acquisition of used products results in excessive inventory levels or low customer satisfaction (i.e. stockouts due to insufficient used products). According to Guide and Jayaraman (2000), product acquisition management acts as an interface between RL activities and production planning and control activities for firms. There are two most commonly used product acquisition systems: waste stream system and market-driven system (Guide and Pentico, 2003; Guide and Van Wassenhove, 2001). In waste stream, the firms encouraged by the legislation passively accept all product returns from the waste stream. On the other hand, market-driven system employs financial incentives to encourage users to return their products to the firm.

Several different forms of financial incentives are used by firms in market-driven system including deposit systems, cash paid for a specified level of quality, credit toward a new unit (Guide and Van Wassenhove, 2001). The implementation of different forms of financial incentives and their impact on the performance of the RL activities are the main research issues in product acquisition management literature. Klauser and Hendrickson (2000) present an implementation of buy-back programs in power-tools industry. Guide and Van Wassenhove (2001) present a real-life case study to illustrate the implementation of a quality-dependent incentive policy in which pre-determined prices are offered for products with a specific nominal quality level. Guide et al. (2003), Aras and Aksen (2008) and Aras et al. (2008) determine optimal incentive values under a quality-dependent incentive policy. Aksen et al. (2008) extend Aras et al. (2008) by considering a government subsidized collection system. Wojanowski et al. (2007) investigate the use of a deposit refund system which requires payment of a certain deposit at the time of purchase, which is refunded upon the return of the used product. Kaya (2010) determines the optimal incentive value in case of stochastic demand and partial substitution between original and remanufactured products.

Ostlin et al. (2008) investigate seven different types of closedloop relationships for the acquisition of used products. The relationships identified are ownership-based, service contract, direct-order, deposit-based, credit-based, buy-back and voluntary-based relationships.

3.10. Other issues

In addition to the issues covered in this section, some other issues including the feasibility of outsourcing, the importance of information technology, equipment leasing, cash flows and barriers in RL were also studied by the researchers.

Serrato et al. (2007) develop a Markov decision model to test the hypothesis that outsourcing in RL is more suitable in case of highly variable returns. They report that there are sufficient conditions on the cost parameters and the return fraction that guarantee the existence of an optimal threshold policy for outsourcing. Chan (2007) reports the results of a case study on the collaborative use of returnable packaging materials between a manufacturer and an OEM supplier. Krumwiede and Sheu (2002) develop a RL decision-making model which supports PLs in their assessment of the feasibility of RL activities.

Dhanda and Hill (2005) investigate the role of information technology in RL through a case study. Daughters et al. (2005) point out the importance of resource commitment to information technology in RL by analyzing a survey of businesses in the automobile aftermarket industry.

Horvath et al. (2005) propose a Markov chain-based methodology to investigate the expectations, risks, and potential shocks associated with cash flows arising from RL activities. They also provide managerial guidelines for avoiding liquidity problems associated with RL activities.

Sharma et al. (2007) develop an MILP model for the simultaneous consideration of RL decisions with equipment leasing ones. After validating the model, they present potential applications of the model for alternative scenarios.

Ravi and Shankar (2005) use Interpretive Structural Modeling (ISM) methodology to analyze the interaction among the major barriers, which hinder or prevent the application of RL in automobile industries. Based on the results of a case study, they point out that strategic management issues like lack of awareness of RL and lack of commitment by top management have higher driving power.

4. Remanufacturing

Remanufacturing is an industrial process involving the conversion of worn-out products into like-new conditions (Aksoy and Gupta, 2005; Kim et al., 2006d). In remanufacturing, the products are completely disassembled and some parts are machined to like-new condition, which sometimes includes cosmetic operations. Remanufactured products usually have shorter lead times. However, the high variability of remanufacturing operations makes the use of traditional operations management techniques difficult. That is why, researchers developed new methodologies to deal with various operations management issues in remanufacturing including forecasting, production planning and scheduling, capacity planning, inventory management and effect of uncertainty.
4.1. Forecasting

Accurate estimation of product returns is an important input for the analysis of remanufacturing systems. However, the uncertainty in the timing and quantity of returns make the use of traditional forecasting methods impossible (Marx-Gomez et al., 2002). That is why the researchers develop their own forecasting approaches to predict the product returns. Kelle and Silver (1989) develop four forecasting methods with different information requirements to predict the container returns throughout the lead time. Toktay et al. (2000) employ the methods developed by Kelle and Silver (1989) to estimate the total number of circuit boards for the Kodak’s single-use camera return network. de Brito and van der Laan (2009) and Toktay et al. (2004) investigate the performance of the forecasting methods proposed in Kelle and Silver (1989) by considering the impact of imperfect information on inventory related costs.

Linton and Yeomans (2003), Linton et al. (2002, 2005) try to estimate the waste stream resulting from disposal of the CRTs in USA for the period between the years 2000 and 2050. First they develop a waste disposal model which captures the uncertainty related with the television lifecycle, the CRT weight in the televisions, the time between television failure and actual enterance time to the waste stream, the proportion of televisions that are reclaimed. Then, future television sales are estimated by considering three technological change scenarios: no technological change, moderate change, aggressive change. These scenarios are investigated using Monte Carlo simulation.

Marx-Gomez et al. (2002) propose a FL-based forecasting method to provide estimates for the return values of scrapped products. First, they develop a simulation model to generate data on return amounts, sales and failures. Then a fuzzy inference system is designed to estimate the return amounts for a specific planning period. Finally, a neuro-fuzzy system is employed for the multi period forecasting of the return values.

4.2. Production planning

A production planning system for remanufacturing assists managers in planning how much and when to disassemble, how much and when to remanufacture, how much to produce and/or order for new materials, and coordinates disassembly and reassembly (Guide et al., 1999a). Ferrer and Whybark (2001) develop a Material Requirements Planning (MRP)-based methodology to determine how many and which cores to buy, what mix of cores to disassemble, and which components should be assembled to meet demand. Souza and Ketzenberg (2002) and Souza et al. (2002) consider a firm that meets demand for an order with remanufactured products, new products or a mix of both. There is a capacity limitation on production and a service-level constraint measured in terms of the average order lead time. They use a two-stage GI/G/1 queuing network model to find the optimal, long-run production mix that maximizes profit subject to the service-level constraint. In order to test the robustness of the model, a DES model is also developed by considering some real life issues such as stochastic product returns and stochastic production yield. Gupta and Veerakamolmal (2001) use an integer programming (IP)-based algorithm for the determination of the number of products to disassemble in order to fulfill the demand for various components for remanufacturing in different time periods. Jayaraman (2006) proposes a mathematical programming model to determine the number of units of core type with a nominal quality level that is disassembled, disposed, remanufactured and acquired in a given time period. Inventory of modules and cores that remain at the end of a given time period can also be determined by the model. Kim et al. (2006d) develop an MIP model in order to determine the quantity of products/parts processed in the remanufacturing facilities/subcontractors and the amount of parts purchased from the external suppliers based on the maximization of the total remanufacturing cost saving. Lu et al. (2006) develop a short-term bulk recycling planning model to determine what products to accept, process, and reprocess. DePuy et al. (2007) present a production planning method which estimates the expected number of remanufactured units to be completed in each future period together with the number of components needed to be purchased to avoid any projected shortages. Li et al. (2009) integrate a hybrid cell evaluated GA with a DES model to optimize the production planning and control policies for dedicated remanufacturing. Xanthopoulos and Iakovou (2009) propose an MILP-based aggregate production planning model which can determine how many EOL products and components should be collected, non-destructively or destructively disassembled, recycled, remanufactured, stored, backordered and disposed in each period.

4.3. Production scheduling

Due to greater degree of uncertainty and complexity of remanufacturing systems, researchers have developed several remanufacturing-oriented scheduling methodologies. The most commonly used technique to test the performance of these methods is DES. Guide (1996) uses DES modeling to compare an MRP-based current production planning and control system with a Drum-Buffer-Rope (DBR)-based proposed system for a real life remanufacturing facility. He questions the use of MRP in remanufacturing systems by stating that highly variable remanufacturing environment lacks the stability which is one of the fundamental requirements for a successful MRP system. Guide (1997) extends Guide (1996) by testing the performance of priority dispatching rules in DBR environment using the DES analysis. Guide et al. (1997b) report that consideration of product structure in the selection of specific priority dispatching rules provides faster flow times and a better delivery performance. Guide and Srivastava (1997a) develop a DES model for the evaluation of order release strategies in a remanufacturing environment. Guide et al. (1997a) investigate the disassembly release mechanisms and priority dispatching rules via a DES model. Guide et al. (1998) analyze the effect of proactive expediting policies on mean flow time, mean lateness, mean root mean square lateness and mean percentage late criteria by using a DES model. Guide et al. (1999b) develop a DES model to investigate the effect of lead time variation on the performance of the disassembly release mechanisms. Guide et al. (2000) carry out a DES analysis to examine the performance of several priority dispatching rules for a repair shop. Guide et al. (2005b) analyze the performance of static priority rules for a remanufacturing system with shared facilities.

4.4. Capacity planning

Various researchers have developed capacity planning and Rough Cut Capacity Planning (RCCP) techniques considering the characteristics of remanufacturing environments. Guide and Spencer (1997) develop an RCCP method for remanufacturing firms by considering probabilistic material replacement and probabilistic routing files. Guide et al. (1997c) compare the modified RCCP techniques with traditional RCCP techniques. Based on the results, they state that traditional techniques tend to perform poorly in a recoverable environment. LP and simulation were used to develop capacity plans for remanufacturing facilities. Kim et al. (2005) develop a mathematical model to determine the capacity of remanufacturing facilities based on the maximization of the saving from the investment on
remanufacturing facilities. Georgiadis et al. (2006) and Vlachos et al. (2007) develop SDS models for the remanufacturing capacity planning in closed-loop supply chains. Georgiadis and Athanasiou (in press) extend the Georgiadis et al.'s (2006) SDS model by considering two sequential product lifecycles of two product types, under two scenarios about the market with regard to customer preferences over the product types. Franke et al. (2006) integrate LP and DES to generate capacity plans for a cell phone remanufacturing facility.

4.5. Inventory management

Consideration of the product returns and remanufacturing options causes two additional complexities in traditional inventory management approaches. First, an uncertain element is added due to uncertain product returns. Second, there is a need for coordination between the remanufacturing and regular mode of procurement (Inderfurth and van der Laan, 2001). Researchers have developed various inventory models to deal with these complexities. In this section, we review these models by considering the different modeling approaches for demand and returns. The other inventory management issues including costs and valuation, effect of lead times and spare part inventories are also covered in this section.

4.5.1. Inventory models

In this study, we mainly consider two types of inventory models: deterministic and stochastic. In deterministic models the stationary and dynamic demands are considered while the stochastic models are organized into two categories: periodic review and continuous review.

4.5.1.1. Deterministic models. These models are based on the assumption that demand and return quantities are known for entire planning horizon. They try to find an optimal balance between fixed setup costs and variable inventory holding costs.

4.5.1.1.1. Stationary demand. In case of stationary demand, deterministic models exploit the logic of Economic Order Quantity (EOQ) to find an optimal trade-off between fixed setup costs and variable inventory holding costs (Fleischmann et al., 1997). Assuming infinite production rates for manufacturing and remanufacturing, the first EOQ model with item returns was developed by Schrady (1967). Nahmias and Rivera (1979) extend Schrady's model by considering two sequential product lifecycles of two product types, under two scenarios about the market with regard to customer preferences over the product types. Franke et al. (2006) integrate LP and DES to generate capacity plans for a cell phone remanufacturing facility.

4.5.1.1.2. Dynamic demand. Modifications of classical Wagner-Whitin algorithms were used to deal with the dynamic demand in the earlier studies. More recent studies develop DP-based algorithms to find the optimal parameter values. Richter and Sombrutzki (2000) extend the Wagner/Whitin algorithm for a deterministic recovery system by assuming a linear cost model thermodynamics to reduce system entropy by considering the EQ repair and waste disposal model of Richter (1996a,b), Jaber and El Saadany (2009) incorporated the possibility of lost sales into the inventory models presented in Richter (1996a,b), El Saadany and Jaber (in press) extend Dobos and Richter (2003, 2004) by considering a price and quality dependant return rate. Jaber and El Saadany (in press) incorporate the learning effects in production and remanufacturing (repair) into the model of Dobos and Richter (2003, 2004).

Teunter (2001) develops EOQ formulae by using different holding cost rates for manufactured and recovered items. Koh et al. (2002) develop a joint EOQ and EPQ model for a system in which the stationary demand can be satisfied with remanufacturing or procurement. They extend previous studies by considering a capacitated repair facility. As an extension to Koh et al. (2002), Wee et al. (2006) allow shortage backorders and develop a search procedure for the optimal ordering and recovery policy. Teunter (2004) develops simple expressions for the determination of optimal lot sizes for the production/procurement of new items and for the recovery of returned items. The expressions are more general than those in the literature in a sense that they are valid for finite and infinite production rates as well as finite and infinite recovery rates. Konstantaras and Papachristos (2006) extend the Dobos and Richter (2000) extension to Richter (1996a,b), Mabini et al. (1992) consider stockout service-level constraints and a multi-item system. Richter (1999a,b, 1997) present EOQ waste disposal and repair models with variable remanufacturing and return rates. They determine the optimal number of remanufacturing and production batches for the different values of the return rate. Richter and Dobos (1999) and Dobos and Richter (2000) develop integer non-linear models for the analysis of EQ repair and waste disposal problem with integer setup numbers. It is found that the pure strategy (total repair or total waste disposal) is optimal. Dobos and Richter (2003) investigate a production-recycling system by assuming that there is only one recycling lot and one production lot. Dobos and Richter (2004) generalize the results of Dobos and Richter (2003) by considering multiple production and recycling lots. Dobos and Richter (2006) extend the model of Dobos and Richter (2004) by relaxing the assumption of perfect quality of the returned items. El Saadany and Jaber (2008) extend Richter (1996a,b) by considering the costs associated with switching between production and recovery runs. They also point out that ignoring the first time interval causes an overestimation of holding costs due to an unnecessary residual inventory. Jaber and Rosen (2008) apply the first and second laws of
with no backordering and negligible lead times. Their model is applicable only for the case of large quantity of used products. In other words, they assume that the quantity of used products matches the demand of remanufactured goods. In a follow-up paper, Richter and Weber (2001) extend this model by considering variable manufacturing and remanufacturing costs. Richter and Gobsch (2003) apply the Richter and Sombrutzki’s (2000) model in a just in time framework. Minner and Kleber (2001) use control theory to find an optimal policy for a remanufacturing system with dynamic demand by considering no backorders and lead times. Kiesmüller (2003a) extends Minner and Kleber (2001) by finding an optimal policy for the case of positive and different lead times for production and remanufacturing. Golany et al. (2001) model the lot sizing problem with remanufacturing as a network flow problem. They present a polynomial time algorithm for the case of linear costs. In a follow-up paper, Yang et al. (2005) propose a polynomial time algorithm for the case of concave costs. Kleber et al. (2002) use Pontryagin’s Maximum Principle to determine the optimal policy by considering multiple remanufacturing options. However they assume that no backorders are allowed and lead times are zero. Beltran and Krass (2002) consider the dynamic lot sizing problem with directly saleable returns. In order to determine the manufacturing and disposal decisions, they develop a DP algorithm with \(O(N^3)\) complexity for the case of concave costs. Teunter et al. (2006) study the dynamic lot sizing problem with product returns and remanufacturing by considering two scenarios for setup costs: a joint setup cost for manufacturing and remanufacturing (single production line) or separate setup costs (dedicated production lines). By modeling both problems as MIP programs, the authors propose a DP algorithm for the joint setup cost case. They also provide the modified versions of Silver Meal (SM), Least Unit Cost (LUC), and Part Period Balancing (PPB) heuristics for both setup cost schemes. Konstantaras and Papachristos (2007) propose an optimal policy that specifies the period of switching from remanufacturing to manufacturing, the periods where remanufacturing and manufacturing activities take place and the corresponding lot sizes. Bera et al. (2008) investigate a production-remanufacturing control problem based on the assumptions of stochastic product defection and fuzzy upper bounds for production, remanufacturing and disposal.

4.5.1.2. Stochastic models. In stochastic models, stochastic processes are employed to model demand and returns. Continuous and periodic review policies are two common approaches used in stochastic models.

4.5.1.2.1. Continuous review models. These models use continuous time axis and try to determine the optimal static control policies based on minimization of the long-run average costs per unit of time (Fleischmann et al., 1997). Heyman (1977) presents the first study in this area by considering a continuous review strategy for a single item inventory system with remanufacturing and disposal. He derives an optimum disposal level by assuming no fixed ordering costs and instantaneous outside procurement. As an extension to Heyman (1977), Muckstadt and Isaac (1981) develop a model involving non-zero lead times for repair and procurement and non-zero fixed costs. However, their model does not include disposal of the products and an approximate numerical procedure is used to determine the optimal parameter values. van der Laan et al. (1996a,b) extend Muckstadt and Isaac (1981) by adding a disposal option. They compare a number of policies numerically for this model. van der Laan and Salomon (1997) and van der Laan et al. (1998b) present a detailed analysis of different policies to control serviceable and recoverable stock in the above setting by considering non-zero lead times for both sources. They mainly consider two policies: a push and a pull-driven recovery policy. van der Laan et al. (1999a) extend van der Laan et al. (1999b) by considering stochastic lead times for manufacturing and remanufacturing. Fleischmann et al. (2002) optimize the parameters of a \((s, Q)\) policy for a basic inventory model involving Poisson demand and returns. Fleischmann and Kuik (2003) use general results on Markov decision processes to develop an average cost optimal \((s, S)\) policy for an inventory system involving independent stochastic demand and item returns. van der Laan and Teunter (2006) use certain extensions of \((s, Q)\) policy and propose closed form expressions for each policy to calculate near optimal policy parameters by assuming the equality of manufacturing and remanufacturing lead times. Zanoni et al. (2006) consider some inventory control policies extended from the traditional inventory control models such as \((s, Q)\) and \((s, s)\) for a hybrid manufacturing/remanufacturing system where demand, return rate, and lead times are stochastic. They use DES to compare different inventory control policies based on the total cost. Heisig and Fleischmann (2001) address planning stability of production and remanufacturing setups in a product recovery system. In the above models, priority decision between manufacturing and remanufacturing is taken based on an average cost comparison. Aras et al. (2006) question the reliability of this technique and develop two alternative strategies that use either manufacturing or remanufacturing as the primary source to satisfy demand.

Korugan and Gupta (1998) develop a queueing network model to analyze the behavior of a multi echelon inventory system with returns. Toktay et al. (2000) develop a closed queueing network model to investigate the procurement of new components for recyclable products. Bayindir et al. (2003) present a queueing network model comprising of manufacturing/remanufacturing operations, supplier’s operations for the new parts and useful life time of the product. Using this model, they try to investigate the conditions on different system parameters (lifetime of the product, supplier lead time, lead time and value added of manufacturing and remanufacturing operations, capacity of the production facilities) that make remanufacturing alternative attractive considering the total cost. Ching et al. (2003) develop a closed form solution for the system steady-state probability distribution for an inventory model with returns and lateral transshipments between inventory systems. Nakashima et al. (2002, 2004) develop Markov chain models to analyze the behavior of stochastic remanufacturing systems. Takahashi et al. (2007) consider a decomposition process in which recovered products are decomposed into parts, materials and waste. The performance of the proposed policies is evaluated by using a Markov chain model of the system.
parameters of a stochastic remanufacturing system with multiple reuse options.


Newsboy problem can be considered as a special case of periodic review models with only one period (Dong et al., 2005). Vlachos and Dekker (2003) and Mostard and Teunter (2006) extend the classical newsboy problem to incorporate returns. Their main aim is to determine the initial order quantity. Vlachos and Dekker (2003) assume that a constant portion of the sold products is returned and products can be resold at most once. Mostard and Teunter (2006) extend Vlachos and Dekker (2003) by analyzing a newsboy problem in which sold products are returned with a certain probability and resold provided they are not damaged.

4.5.2. Costs and valuation

Valuation of the inventory and the determination of the holding cost rates are two important topics studied by researchers. There are a number of studies investigating the effect of different holding cost setting rules on the performance of a remanufacturing system. Teunter et al. (2000) carry out a simulation analysis to evaluate the performance of alternative rules to set the inventory holding cost rates for a continuous review model with stochastic demand and return of items, and fixed positive lead times for manufacturing and remanufacturing. Teunter and van der Laan (2002) show that the Average Cost (AC) approach may not always be appropriate for a deterministic RL inventory model with both remanufacturing and disposal of returned products. For the stochastic version of the same problem, van der Laan (2003) uses an exact procedure rather than simulation to compare Net Present Value (NPV) and AC rules. Corbacioglu and van der Laan (2007) show that the correct holding cost rates are different from traditional valuation methodology and demonstrate the impact of this finding on operational performance for a two product two source remanufacturing environment. Akcali and Bayindir (2008) investigate the effect of different inventory holding cost setting rules on the performance of a disassembly and recovery system. Tang et al. (2004) develop an MRP theory and decision analysis-based methodology to calculate the values of the return products. Then, these values are used to estimate the inventory holding costs.

4.5.3. Effect of lead time

Researchers developed models to investigate the effect of manufacturing, procurement and remanufacturing lead times on inventory control policies. Inderfurth (1997) uses DP to develop simple optimal replenishment and disposal policies for a stochastic product recovery system by considering lead times for procurement and remanufacturing. He states that optimal decision rules can be derived if the difference between lead times is at most one period. van der Laan et al. (1999a) provide a numerical analysis of the effects of lead time duration and lead time variability on total expected costs in production/inventory systems with remanufacturing. van der Laan et al. (1999b) analyze the effect of lead times by assuming a deterministic manufacturing lead time and a deterministic remanufacturing lead time, rather than a deterministic manufacturing lead time and stochastic remanufacturing lead time resulting from limited remanufacturing capacity. Inderfurth and van der Laan (2001) consider a remanufacturing system in which lead times for remanufacturing and regular procurement differ. For this system, they define lead time as a decision variable and develop a DP approach to investigate the effect of lead time. Ferrer (2003) and Ferrer and Ketzenberg (2004) analyze the impact of shorter supplier lead times on manufacturing costs. Mahadevan et al. (2003) investigate the effect of manufacturing and remanufacturing lead times on optimal parameter value and total cost. Teunter et al. (2004) propose strategies for hybrid manufacturing/remanufacturing systems with long manufacturing lead time and short remanufacturing lead time. Tang and Nain (2004), Zhou et al. (2006), and Zhou and Disney (2006) use control theory and simulation to investigate the effect of manufacturing/remanufacturing lead time on system performance. Tang et al. (2007) try to estimate the planned lead time in a manufacture-to-order remanufacturing environment by assuming a normally distributed lead times. In a follow-up paper, Bao et al. (2008) question this normality assumption and use the Minimum Relative Entropy (MRE) method to approximate the lead time distribution. They report that the MRE approach provides a better approximation than the normal approximation.

4.5.4. Inventory substitution

Some remanufacturing inventory models include the possibility of substitution between manufactured and remanufactured products. Inderfurth (2004) and Bayindir et al. (2005) try to develop optimal policies for hybrid manufacturing/remanufacturing systems in which there is a significant difference between the remanufactured and new products and a new product can be offered as a substitute to the remanufactured product in case of a shortage of a remanufactured product. They consider continuous review (S–1, S) inventory control policy for both types of products. Bayindir et al. (2007) extend these two studies by considering a finite production capacity. Yongjian et al. (2006) consider the problem with multiple product types and multiple periods and develop a DP-based approximate solution procedure to obtain near optimal solutions. However, they assume that demand and return quantities in each period are deterministic and there is no capacity constraint on production.

4.5.5. Spare part inventories

The studies in this category try to develop spare parts inventory policies by considering the recovered parts from EOL products as a source of spare parts supply. Fleischmann et al. (2003) consider the use of disassembly as a source of spare parts in a case study conducted in IBM. They use a basic analytic inventory model and a simulation model to test alternative policies based on alternative channel designs and alternative coordination mechanisms. Spengler and Schroeter (2003) and Schröter and Spengler (2004) use SDS modeling to evaluate various spare part acquisition alternatives for electronic equipment in EOL phase. Inderfurth and Mukherjee (2008) develop an integrated approach by considering various spare part acquisition alternatives. First they use a decision tree for structuring the underlying decision problem and demonstrating the interdependencies of different alternatives to choose. Then stochastic DP is employed for developing simple decision rules and a heuristic solution procedure for determining the parameters of a simple order-up-to policy. Ilgin and Gupta (2008a) propose a GA-based simulation-optimization methodology to determine the optimal final order quantities for a number of spare parts considering only the parts recovered from discarded EOL products as a source of spare parts during post product life cycle. Ilgin and Gupta (2008b) present a simulation-optimization study to determine the optimum reorder and order quantity levels for the spare Printed Circuit Boards (PCBs) by simultaneously considering two spare parts acquisition alternatives: the recovered PCBs from EOL TVs and newly purchased PCBs.
4.6. Effect of uncertainty

One of the problems associated with remanufacturing is the high degree of variability in the operation processing times. The uncertainty in the quantity, quality and timing of returned products further complicates the analysis of remanufacturing systems. Some of the researchers develop decision-making models to investigate the impact of this high level of uncertainty on the behavior of remanufacturing systems. Ferrer (2003) and Ferrer and Ketzenberg (2004) develop decision models to analyze a remanufacturer’s trade-off between limited information about remanufacturing yields and potentially long supplier lead times. They state that identification of product yield early in the disassembly process is significantly more valuable than placing purchase orders with a short lead time. Ketzenberg et al. (2003) investigate the impact of having advanced remanufacturing yield information in long-run average flow time. As an extension to these three studies, Ketzenberg et al. (2006) carry out a study on the value of information in remanufacturing by simultaneously considering the uncertainties related with demand, return and yield. Ketzenberg (2009) extends Ketzenberg et al. (2006) by considering disposal of returned products and a capacitated product recovery system. Inderfurth (2005) uses numerical analysis to investigate the effect of uncertainties related with return, quality and demand on the recovery behavior.


As an alternative to the static modeling, dynamic control methods are used in some studies to analyze the effect of uncertainty. Tang and Naim (2004) carry out mathematical and simulation analyses to test the robustness of push type hybrid manufacturing–remanufacturing system to various uncertainties of the remanufacturing process. Zhou et al. (2006) carry out a similar analysis for a pull type system. In a follow-up paper, Zhou and Disney (2006) use control theory and simulation to investigate the impact of lead time and return rate on inventory variance and the bullwhip phenomenon. Huang et al. (2009b) develop dynamic closed-loop supply chain models by considering the uncertainty due to time-delay in remanufacturing and returns, system cost parameters and customer demand’s disturbances. Some studies investigate the use of inventory buffers to deal with material recovery uncertainty and probabilistic routings. Guide and Srivastava (1997b, 1998) develop DES models to investigate the use of inventory buffers in an MRP system. Minner (2001) studies the use of inventory buffers in a supply chain with internal and external product returns and reuse. Helber (1998) uses Markov process models to determine average buffer levels for assembly/disassembly networks with limited buffer capacity and random processing times. Aksoy and Gupta (2005) combine open queueing networks, decomposition principle and expansion methodology to determine a near optimal buffer allocation plan for a remanufacturing cell with finite buffers and unreliable servers.

The uncertainty in the timing of returns was investigated by some researchers. Atasu and Çetinkaya (2006) develop cost optimization models to investigate the impact of the timing of returns on the cost efficiency of a simple remanufacturing system. Guide et al. (2005a, 2006), Geyer et al. (2007) investigate the concept of “time value of returns” which involves the use of returns at the best possible time, i.e. whenever suitable market conditions for returns occur.

5. Disassembly

Disassembly can be defined as the systematic separation of an assembly into its components, subassemblies or other groupings (Moore et al., 2001; Pan and Zeid, 2001). Disassembly is an important process in material and product recovery since it allows for the selective separation of desired parts and materials. We refer the reader to a recent book by Lambert and Gupta (2005) for the detailed information on the general area of disassembly. This section starts with the investigation of the studies on the two important phases of disassembly process, scheduling and sequencing. Then a review of the studies on disassembly line balancing, disassembly to order systems, ergonomics and automation of disassembly systems is presented.

5.1. Scheduling

Disassembly scheduling is the scheduling of the ordering and disassembly of EOL products to fulfill the demand for the parts or components over a planning horizon (Veerakamolmal and Gupta, 1998; Lee and Xiouchakis, 2004). In general, disassembly scheduling problems can be categorized as capacitated and uncapacitated. For the uncapacitated case, Gupta and Taleb (1994) propose an MRP-like algorithm for disassembly scheduling of a discrete, well-defined product structure. The algorithm determines the quantity and timing of disassembly of a single product to fulfill the demand for its various parts. Taleb et al. (1997) and Taleb and Gupta (1997) extend the Gupta and Taleb (1994) by considering components/materials commonality and the disassembly of multiple product types. Lee and Xiouchakis (2004) suggest a two-phase heuristic algorithm for the objective of minimizing various costs related with the disassembly process. In the first phase, Gupta and Taleb’s (1994) algorithm is used to find an initial solution. The second phase improves this initial solution using backward move. Barba-Gutierrez et al. (2008) extend the reverse MRP algorithm of Gupta and Taleb (1994) by developing a methodology which allows lot sizing in reverse MRP. Kim et al. (2003) propose a heuristic algorithm based on the LP relaxation for the case of multiple product types with parts commonality with the aim of minimizing the sum of setup, disassembly operation and inventory holding costs. Kim et al. (2006b) develop a two-phase heuristic by extending the Kim et al.’s (2003) study. The first phase involves the construction of an initial solution using the LP relaxation heuristic suggested by Kim et al. (2003). The second phase improves the initial solution using DP. Lee et al. (2004) present three IP models for the three cases of the uncapacitated disassembly scheduling problem, i.e. a single product type without parts commonality and single and multiple product types with parts commonality. Kim et al. (2006d) propose a branch and bound algorithm for the case of single product type without parts commonality.

For the capacitated case, Mecham et al. (1999) present an optimization algorithm by considering common components among products, and limited inventory of products available for
disassembly. Lee et al. (2002) develop an IP model based on the minimization of sum of disassembly operation and inventory holding costs. However, the model requires excessive computation times to find optimal solutions for practical-sized problems. As an extension to Lee et al. (2002), Kim et al. (2006a) develop a Lagrangian heuristic algorithm to find an optimal solution for practical problems in a reasonable amount of time. In this study, disassembly setup costs were also included in objective function. Kim et al. (2006c) propose an optimal algorithm for the case of single product type without parts commonality based on the minimization of the number of disassembled products. According to this algorithm, first an initial solution is determined using the Gupta and Taleb’s (1994) algorithm. Then, the feasibility of this solution is checked. If the solution is not feasible, it is modified to satisfy the capacity constraints.


5.2. Sequencing

Disassembly sequencing deals with the problem of determining the best order of operations in the separation of a product into its constituent parts or other groupings (Dong and Arndt, 2003; Moore et al., 1998). Various graphical approaches were developed to solve the disassembly sequencing problem. Lambert (1997) presents an AND/OR graph-based graphical method for the generation of the optimum disassembly sequence. Kaebernick et al. (2000) use a cluster graph which is created by sorting the components of a product into different levels based on their accessibility for disassembly. Torres et al. (2003) develop an algorithm based on the product representation to establish a partial non-destructive disassembly sequence of a product. Li et al. (2006) present a Disassembly Constraint Graph (DCG) to generate possible disassembly sequences for maintenance. Dong et al. (2006) propose a method for the automatic generation of disassembly sequences from a hierarchical attributed liaison graph.


Due to combinatorial nature of the disassembly sequencing problem, there is an increasing trend in the use of metaheuristics. Seo et al. (2001) develop a GA-based heuristic algorithm to determine the optimal disassembly sequence considering both economic and environmental aspects. Li et al. (2005) integrate DCG and a GA to develop an object oriented intelligent disassembly sequence planner. Kongar and Gupta (2006b), Giudice and Fargione (2007), Dutta et al. (2008a) and Hui et al. (2008) present GA-based approaches for disassembly sequencing of EOL products. Gonzalez and Adenso-Diaz (2006) propose a scatter search-based methodology to deal with the optimum disassembly sequence problem for complex products with sequence-dependent disassembly costs by assuming that only one component can be released at each time. Chung and Peng (2006) develop a GA to generate a feasible selective disassembly plan considering batch disassembly and tool accessibility. Shimizu et al. (2007) apply genetic programming as a resolution method to derive an optimal disassembly sequence. Revelliots (2007) presents a reinforcement-learning-based approach to provide (near-) optimal disassembly sequences. Tripathi et al. (2009) present a fuzzy disassembly sequencing problem formulation by considering the uncertainty inherent in quality of the returned products. They develop an Ant Colony Optimization (ACO)-based metaheuristic to determine the optimal disassembly sequence as well as the optimal depth of disassembly. Kongar and Gupta (in press) employ a multi objective TS algorithm to generate near optimal/optimal disassembly sequences.

In some studies, heuristic procedures are developed. Gungor and Gupta (1998) develop a methodology to evaluate different disassembly strategies. They also propose a heuristic procedure to determine the near optimal disassembly sequences. Gungor and Gupta (1998) address the uncertainty related difficulties in disassembly sequence planning. They present a methodology for disassembly sequence planning for products with defective parts in product recovery. Kuo (2000) provides a disassembly sequence and cost analysis study for the electromechanical products during the design stage. He divides disassembly planning into four stages: geometric assembly representation, cut-vertex search analysis, disassembly precedence matrix analysis, and disassembly sequences and plan generation. The disassembly cost is categorized into three types: target disassembly, full disassembly, and optimal disassembly. Gungor and Gupta (2001b) use a branch and bound algorithm for disassembly sequence plan generation. In Erdos et al. (2001), a heuristic is used to decompose the problem by discovering the subassemblies within the product structure. Then,


5.3. Line balancing

Disassembly operations can be performed at a single workstation, in a disassembly cell or on a disassembly line. Although a single workstation and disassembly cell is more flexible, the highest productivity rate is provided by a disassembly line. Moreover, the disassembly line is more suitable for automated disassembly (Gungor and Gupta, 2001a).

Disassembly Line Balancing Problem (DLBP) concerns with the assignment of disassembly tasks to a set of ordered disassembly stations while satisfying the disassembly precedence constraints and minimizing the number of stations needed and the variation in idle times between all stations (Altekin et al., 2008; McGovern and Gupta, 2007a). Gungor and Gupta (2001a) and Gungor and Gupta (2002) presented the first examples of disassembly line balancing algorithms. Gungor and Gupta (2001a) investigate the Disassembly Line Balancing Problem in the presence of task Failures (DLBP-F). A disassembly line balancing algorithm is presented to assign tasks to workstations such that the effect of the defective parts on the disassembly line is minimized. Gungor and Gupta (2002) discuss the disassembly line related complications and their effects. They also demonstrate the applicability of some important factors in disassembly to balance a paced disassembly line by modifying the existing concepts of assembly line balancing. Tang and Zhou (2006) develop a two-phase PNs and DES-based methodology to maximize system throughput and system revenue by dynamically configuring the disassembly system into many disassembly lines while considering line balance, different process flows, and meeting different order due dates.

Metaheuristics were also used to develop disassembly line balancing algorithms. McGovern and Gupta (2006) present an ACO algorithm to obtain optimal or near optimal solution. A collaborative ant colony algorithm was proposed by Agrawal and Tiwari (2006) for stochastic mixed-model U-shaped disassembly line balancing. In McGovern and Gupta (2007a), a number of combinatorial optimization techniques (exhaustive search, GA and ACO metaheuristics, a greedy algorithm, and greedy/hill-climbing and greedy/2-optimal hybrid heuristics) are applied to obtain near optimal solutions. They develop a known, optimal, varying size dataset to illustrate the implementation of the methodologies, measure performance and enable comparisons. McGovern and Gupta (2007b) develop a new formula for quantifying the level of balancing. They also present a first-ever set of a priori instances to be used in the evaluation of any disassembly line balancing solution technique. A GA is presented for obtaining optimal or near optimal solutions for DLBPs.

Some researchers use mathematical programming techniques to solve the DLBP. Altekin et al. (2008) provide an MIP formulation for profit maximization in partial DLBP. The proposed model simultaneously determines the parts and tasks, the number of stations and the cycle time. Dutta et al. (2008b) consider the problem of Disassembly Line Balancing in Real time (DLBP-R) and propose a mixed integer quadratic programming and branch and cut algorithm-based method. Koc et al. (2009) develop IP and DP formulations for DLBP by using an AND/OR graph to check the feasibility of the precedence relations among the tasks.

5.4. Disassembly to order systems

The objective of the Disassembly to Order Systems (DTOs) is the determination of the optimal lot sizes of EOL products to disassemble in order to satisfy the demand of various components from a mix of different product types that have a number of components and/or modules in common (Lambert and Gupta, 2002).

The first line of research involves the heuristics developed under the assumption of deterministic disassembly yield. Lambert and Gupta (2002) develop a method called tree network model by modifying the disassembly graph method for a multi product demand driven disassembly system with commonality and multiplicity. Kongar and Gupta (2002) propose a single period integer GP model for a DTO system to determine the best combination of multiple products to selectively disassemble to meet the demand for items and materials under a variety of physical, financial and environmental constraints and goals. Kongar and Gupta (2006a) extend Kongar and Gupta (2002) by using fuzzy GP to model the fuzzy aspiration levels of various goals. Langella (2007) develops a multi period heuristic considering holding costs and external procurement of items. Gupta et al. (in press) use NN to solve the DTO problem. Kongar and Gupta (2009) propose a LPP-based solution methodology which can satisfy tangible or intangible financial, environmental and performance related measures of DTO systems. Kongar and Gupta (in press) develop a multi objective TS algorithm by considering multiple objective functions, viz. maximizing the total profit, maximizing the resale/recycling percentage, and minimizing the disposal percentage.

The papers in the second line of research take into consideration the uncertainty related with disassembly yield. Inderfurth and Langella (2006) develop two heuristic procedures (i.e., one-to-one, one-to-many) to investigate the effect of stochastic yields on the DTO system. Intanavanich and Gupta (2006) use the heuristic procedures developed by Inderfurth and Langella (2006) to deal with the stochastic elements of the DTO system. Then, they use a GP procedure to determine the number of returned products that satisfy various goals.

5.5. Automation

The majority of the existing disassembly plants are based on the manual labor. However, increase in the amount of electronic scrap, the demand for higher productivity levels and increase in labor cost force firms to automate their disassembly processes (Santochi et al., 2002; Kopacek and Kopacek, 2006). That is why the researchers studied different aspects of disassembly automation in recent years. Seliger et al. (2002) develop modular disassembly processes and tools to be used in an integrated disassembly cell controlled by product accompanying information systems. Torres et al. (2004) present a semi-automated personal computer disassembly cell composed of several sub-systems. A computer vision subsystem is used for the recognition and localisation of the product and of each
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<td>EOSL</td>
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of its components. Disassembly sequence and planning of the disassembly movements are provided by a modeling subsystem. Weigl-Seitz et al. (2006) discuss the required equipment and suitable strategies for the automated disassembly by considering the disassembly of a video camera recorder and PC. They also propose a disassembly line layout with the suitable software structure. Robotized, semi-automated, flexible disassembly cells for minidisks, PCBs and mobile phones in industrial use are discussed by Kopacek and Kopacek (2006). A modular approach is also proposed for disassembly cells by integrating disassembly families, mobile robots and Multi Agent Systems (MAS). Kim et al. (2009b) investigate the advantages of emulation in control logic development and validation of new conceptual disassembly systems. Kim et al. (2007a) develop an adaptive and modular control system for the generation of automatic control sequences for a partly automated system by considering the availability of disassembly tools and the technological feasibility of disassembly and tools. Kim et al. (2009c) propose a dynamic process planning procedure which generates available alternatives by a database-supported procedure and selects the best suitable among them if a device or tool is not available. Software tools developed to optimize the disassembly process of discarded goods are discussed in Santochi et al. (2002), Wiendahl et al. (2001) present an overview of layouts and modules of automated disassembly systems developed at various companies and research institutes. Duta and Filip (2008) investigate several solutions for the design of robotic disassembly cells.

5.6. Ergonomics

The hands-on nature of disassembly tasks requires the consideration of ergonomic factors in the design of disassembly lines. However, the number of studies on the ergonomics of disassembly is very small. Kazmierczak et al. (2004) analyze the current situation and future perspectives for the ergonomics of car disassembly in Sweden using several explorative methods such as site visits, interviews. In a follow-up paper, Kazmierczak et al. (2005) analyze disassembly work in terms of time and physical work load requirements of constituent tasks. Kazmierczak et al. (2007) combine human and flow simulations to predict the performance of alternative system configurations in terms of productivity and ergonomics for a serial-flow car disassembly line. In order to address the uncertainty due to manual operations in disassembly, Tang et al. (2006) and Tang and Zhou (2008) define the effect of several human factors (e.g., disassembly time, quality of disassembled components, and labor cost) as membership functions in their fuzzy attributed PN models. Human involvement in disassembly was investigated by Bley et al. (2004) and Takata et al. (2001). Kazmierczak et al. (2004, 2005, 2007) and Tang et al. (2006) focus on the ergonomic aspects of disassembly.

6. Conclusions

This paper presented a review of the state of the art literature on Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) published since the 1999 review by Gungor and Gupta (1999). Table 2 shows the cited references organized into appropriate categories. The following general conclusions can be drawn from our literature review:

- Environmental issues have an increasing popularity among researchers. Hence, in recent years, there is a significant increase in the number of studies on ECMPRO.
- Product Design research mainly focuses on multi criteria techniques which allow for the simultaneous consideration of environmental, economic, consumer and material requirements. However, the environmental impact of production processes is ignored in most of these studies. Thus, there is a need for environmentally conscious product design methodologies that integrate design of products and processes.
- Reverse Logistics (RL) literature is dominated by the studies on location-allocation models. In order to develop a more integrated RL framework, more research is necessary on other issues such as marketing, competition, and technology.
- Remanufacturing systems are often analyzed by considering only one specific operations management issue (e.g., inventory management or production planning). In order to have a more realistic analysis of these systems, integrated methodologies should be developed.
### Table 3

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<td>ABC</td>
<td>Presley et al., 2007; Tsai and Hung, 2009</td>
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<td>ACO</td>
<td>Agrawal and Tiwari, 2006; McGovern and Gupta, 2006; Tripathi et al., 2009</td>
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**ABC**: activity based costing; **ACO**: ant colony optimization; **AHP**: analytic hierarchy process; **ANOVA**: analysis of variance; **AOP**: analytic network process; **B&B**: Branch & bound; **BDN**: Bayesian decision networks; **BSC**: balanced scorecard; **CBR**: case based reasoning; **DEA**: data envelopment analysis; **DES**: discrete event simulation; **DP**: dynamic programming; **EA**: evolutionary algorithms; **ELECTRE**: elimination and choice translating reality; **EP**: evolutionary programming; **ES**: expert systems; **FL**: fuzzy logic; **GP**: genetic programming; **GA**: genetic algorithms; **GRA**: grey relational analysis; **GT**: game theory; **IP**: integer programming; **LP**: linear programming; **LPP**: linear physical programming; **MC**: Markov chains; **MIP**: mixed integer programming; **NLP**: non-linear programming; **NN**: neural networks; **NS**: neighbourhood search; **PN**: petri nets; **PSO**: particle swarm optimization; **QFD**: quality function deployment; **QT**: queueing theory; **RA**: regression analysis; **RO**: robust optimization; **SA**: simulated annealing; **SDS**: system dynamics simulation; **SS**: stochastic programming; **ST**: tabu search; **TOPSIS**: technique for order preference by similarity to an ideal solution; **TS**: tabu search; **WP**: wave propagation.
• Disassembly sequencing and scheduling are widely studied areas by the researchers. Disassembly automation also received attention of researchers in recent years. Although a significant portion of the current disassembly systems is based on manual labor, the research on the ergonomics of disassembly is not well developed.

• A high degree of uncertainty exists in RL, remanufacturing and disassembly systems. The most popular approaches to deal with this uncertainty are simulation, stochastic programming, robust optimization, sensitivity and scenario analysis. More studies are needed to better control the effects of uncertainties.

• Majority of the studies use quantitative analysis. A broad spectrum of Industrial Engineering (IE) – Operations Research (OR) techniques were utilized in the studies. Table 3 gives a classification of reviewed papers based on the use of a specific IE or OR technique. There is an increasing trend in the use of artificial intelligence techniques including metaheuristics, fuzzy systems, and neural networks.

With stricter environmental regulations and increased environmental awareness in society, firms must educate their employees in environmental aspects of manufacturing to increase their competitive edge. Moreover, ECM principles should be incorporated into engineering curriculums at universities. We refer the reader to Borchers et al. (2006) and Kumar et al. (2005) for more information on the design of courses and programs with an ECM perspective.

While ECMPRO was in its infancy 10 years ago, today it is a well established and growing research area. The main reason for this rapid development is the increasing attention of governments, firms and academicians toward environmental issues such as decreasing natural resources and global warming. In this development period, research mainly focused on operational and tactical issues in order to satisfy the immediate needs of firms. There is a need to develop strategic models for the analysis of ECMPRO systems with respect to technological and organizational dynamics.

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