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Issues in environmentally conscious manufacturing and product recovery: a survey

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Abstract

Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) has become an obligation to the environment and to the society itself, enforced primarily by governmental regulations and customer perspective on environmental issues. This is mainly driven by the escalating deterioration of the environment, e.g. diminishing raw material resources, overflowing waste sites and increasing levels of pollution. ECMPRO involves integrating environmental thinking into new product development including design, material selection, manufacturing processes and delivery of the product to the consumers, plus the end-of-life management of the product after its useful life. ECMPRO related issues have found a large following in industry and academia who aim to find solutions to the problems that arise in this newly emerged research area. Problems are widespread including the ones related to life cycle of products, disassembly, material recovery, remanufacturing and pollution prevention. In this paper, we present the development of research in ECMPRO and provide a state-of-the-art survey of published work. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Disassembly; Environmentally conscious manufacturing; Product recovery; Recycling; Remanufacturing; Reuse; Survey

1. Introduction

During the industrial revolution, environmental issues were not addressed when designing

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and manufacturing products. However, in the last decade or so, Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) has become an obligation to the environment and to the society itself, enforced primarily by governmental regulations and customer perspective on environmental issues. Environmentally conscious manufacturing (ECM) is concerned with developing methods for manufacturing new products from conceptual design to final delivery and ultimately to the end-of-life (EOL) disposal such that the environmental standards and requirements are satisfied. Product recovery, on the other hand, aims to minimize the amount of waste sent to landfills by recovering materials and parts from old or outdated products by means of recycling and remanufacturing (including reuse of parts and products). Fig. 1 depicts the interactions among the activities that take place in a product life cycle.

ECMPRO is mainly driven by the escalating deterioration of the environment. Today's high-tech society requires thousands of different products which ultimately result in billions of tons of materials discarded, most of which end up in landfills. According to the US Environmental Protection Agency (EPA), in 1990 the amount of waste generated in the USA reached a whopping 196 million ton up from 88 million ton in the 1960s [212].

As a consequence of both fast depletion of the raw materials and an increasing amount of different forms of waste (solid waste, air and water pollution etc.), two commonly accepted primary objectives have been gaining momentum: (1) create environmentally friendly products, (i.e. green products); and (2) develop techniques for product recovery and waste management.

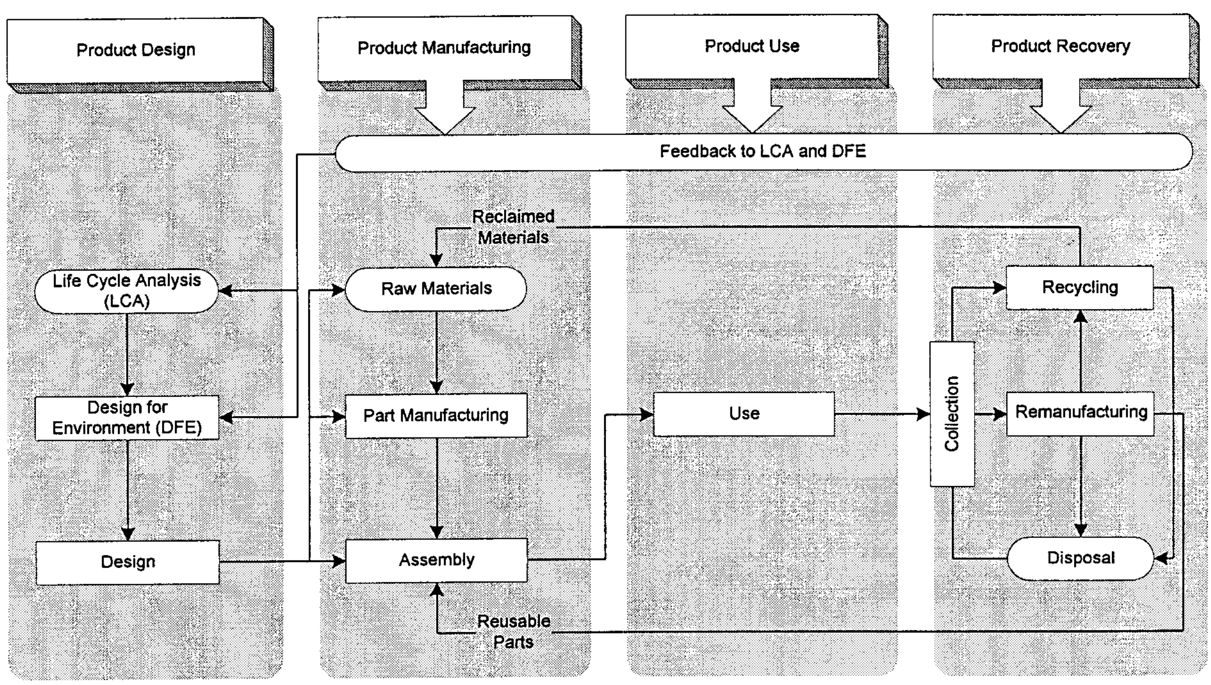

Fig. 1. Interactions among the activities in a product life cycle (the activities within the boxes with rounded edges represent the supporting activities in the associated life stage).

In order to design a product which is environmentally benign, the life cycle of the product should be well understood [275]. Life cycle analysis (LCA) spans over the development, manufacturing, use and disposal stages of the product (Fig. 1). At each of these stages, environmentally friendly decisions need to be made [199–201]. These have prompted campaigns such as design for recycling (DFR), design for environment (DFE) and design for disassembly (DFD).

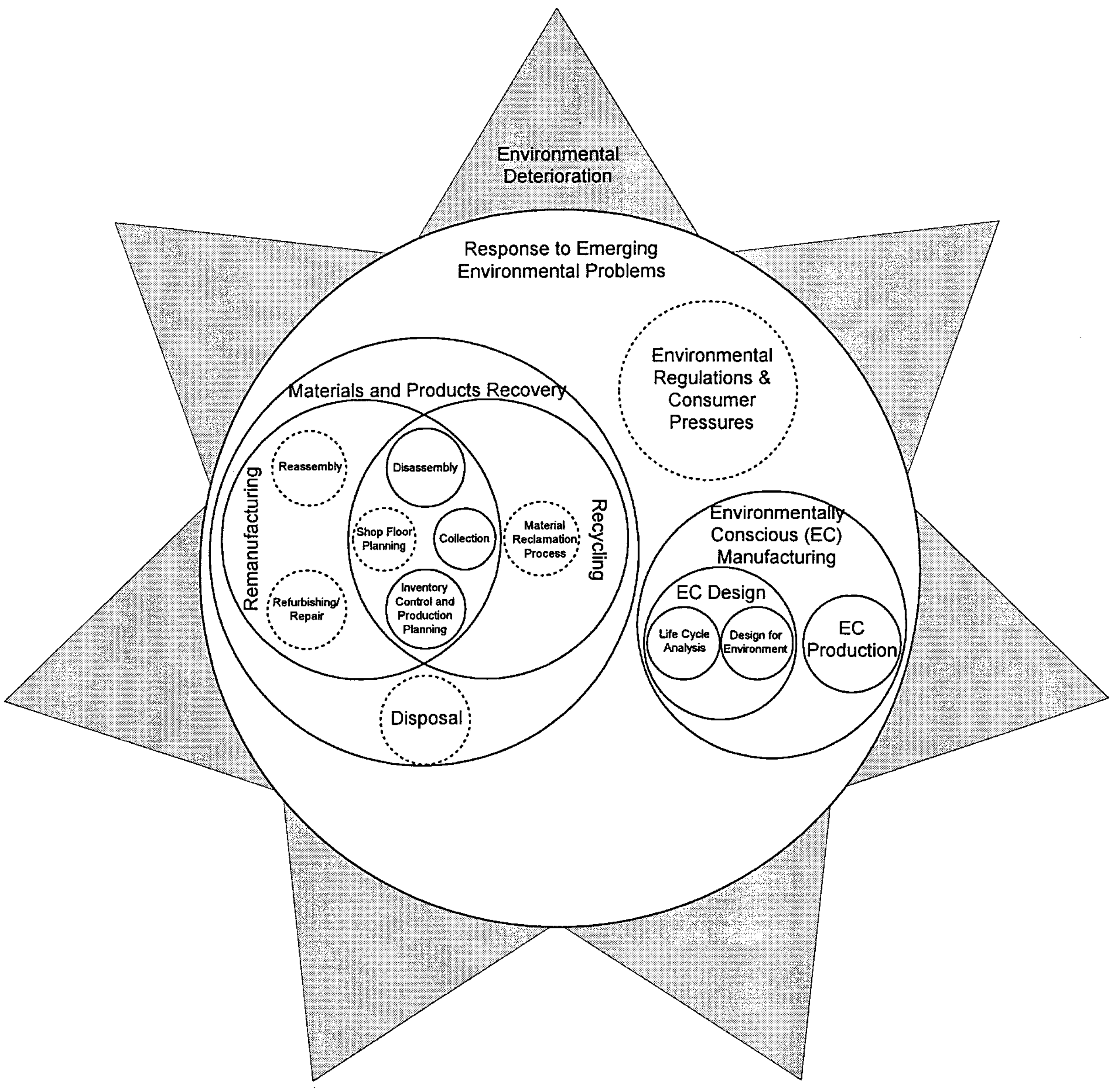

Fig. 2. Interactions among the topics covered in this paper (the topics within the dotted circles, although covered in the paper, do not appear under separate headings).

Even though LCA may seem to be the most important solution to environmental problems, its immediate effect is in the early stages of new product development. However, the biggest damage to the environment occurs when the product completes its useful life. Thus, understanding and developing techniques for end-of-life management of the products by means of product/material recovery [286] are extremely crucial considering the millions of products that have already been developed without incorporating their undesired effects on the environment. Recovery of products are usually performed in two ways: recycling and remanufacturing. Recycling aims to recover the material content of retired products by performing the necessary disassembly, sorting and chemical operations. On the other hand, remanufacturing preserves the product's (or the part's) identity and performs the required disassembly, sorting, refurbishing and assembly operations in order to bring the product to a desired level of quality. Disassembly has proven its role in material and product recovery by allowing selective separation of desired parts and materials. Besides being able to recover valuable precious materials by material recovery, good component removal via disassembly could provide parts for discontinued products and reduce the lead times in the assembly of new products [32,209].

The above raised issues have captured the attention of industries, governments and academia. In this paper, our objective is to offer an overview of the up-to-date literature in the field of ECMPRO. We cover a wide range of published work, organize their discussion into appropriate categories and provide some concluding remarks. The paper is intended to be as thorough as possible by covering most of the subject matter relevant to ECMPRO. Fig. 2 depicts the interactions among the topics covered in this paper. The topics placed in the same circle interact with each other. We envision the environment as a flower. The flower is being threatened for extinction. The topics in ECMPRO (represented by circles in Fig. 2) are the stamens of the flower. The survival of the flower depends on the survival of the stamens. If the stamens of the flower die or are not spread, the flower (environment) will become extinct. Thus, it is imperative that we preserve the stamens (i.e. follow good ECMPRO practices) in order to leave healthy flowers (environment) for our next generation. In Section 2, we give a background on the environmental degradation and the development of environmentally friendly practices. Section 3 looks into the environmentally conscious manufacturing of new products including environmentally conscious design and production. In Section 4, we detail the issues related to materials and product recovery. Section 5 presents other related issues such as pollution prevention and waste management. Lastly, in Section 6, we present our conclusions.

2. Background

Our environment has limited resources, i.e. the materials we convert into products, energy, water and air supply and the places where we dispose of old products, are limited. Our society uses these resources to improve the living standard. However, we also need to provide for a sustainable environment for the next generation. To this end, we need to identify the extent of the problem and take corrective action. Many researchers have been doing just that. In this section we present the problems identified in the literature and discuss the response by researchers.

2.1. Decreasing earth's resources and increasing environmental problems

Ever since the industrial revolution, the number of manufactured products has increased dramatically. The current state of manufacturing processes require the use of trillions of tons of different forms of natural resources (raw materials, energy, water, etc.). The per capita consumption is especially acute in the developed nations [87,165,219,276,299]. Wann [307] reports that an average American consumes 20 tons of materials every year. Energy consumption is also at dramatic levels: every day the average American uses the equivalent of twenty-seven years of stored solar energy in the form of fossil fuels [307]. The products originating from renewable and non-renewable natural resources evolve into waste after their useful lives. Waste can be defined as redundant goods, by-products or residues that have no value and must be disposed of at a cost [132]. Different forms of waste (hazardous and non-hazardous) have been generated by both manufacturers and consumers for decades [233]. Bylinsky [35] reports that according to the National Academy of Sciences, 94% of the substance that is pulled out of the earth, enters the waste stream within months. According to the Environmental Protection Agency (EPA), about 12 billion ton of industrial waste is generated annually in the United States and the scary part is, over a third of this amount is hazardous waste [76]. Another estimated figure shows that by the year 2005, every family in the USA will own a computer [35]. That suggests that used computers will enter the waste stream as fast as we produce them. Europe is facing similar problems. According to Hentschel [132], in Germany, the amount of electronic waste had reached a volume of more than 800,000 ton annually in the early 90s.

The number of landfill sites where we can bury the non-hazardous solid waste is going down with the increasing amount of waste. Pohlen and Farris II [230] reported that in the U.S., landfill sites had gone down from 18,000 in 1985 to 9000 in 1989 and the fall is expected to continue at an even faster rate than before. Since old recycling methods, such as dumping, burying and burning in the open field, are no longer desirable due to tough new environmental laws and increasing consumer concerns [17,174,222,224], new methods have to be explored [53,253,315]. For example, the importance of removing hazardous materials from refrigerators, such as freon (which is a type of gas that has been proven to be destroying the ozone layer of the atmosphere), ABS (Acrylonitrile-Butadiene-Styrene), PVC (Polyvinyl Chloride), BS (Bile Salts) and PUR (Polyurethane) foam, cannot be ignored [222,224]. Similarly, making responsible end-of-life choices for conventional military munitions is very crucial [54].

Every day we face more and more environmental problems such as the depletion of the ozone layer as a result of extensive use of chlorofluorocarbons (CFCs) [224] and global warming. Worsening of these problems must stop if our planet must continue to be a livable place.

2.2. Response to negative environmental developments

The good thing about us as a society is that we learn from our mistakes and experiences.

Wann [307] perfectly emphasizes the interactions between the environmental problems and the future of the society. The society as a whole has developed a heightened environmental awareness in response to numerous environment related problems that have recently surfaced [9,84,86,157,158,226]. However, it is crucial to minimize the response time for corrective action to environmental problems as long delays could lead to irreversible damage.

The governments, the industries [256,265] and the public have been very receptive and responsive to the environmental problems. The common goal is to integrate environmentally friendly thinking into daily practices. Fig. 3 depicts the interactions among the responsible parties on environmental issues.

One of the reasons for rapid developments in the material recovery and the ECM practices is the changing consumer perspective [10,296,297,312]. Recently, consumers have become aware of their environment and the potential problems that can be created by neglecting it. Therefore, they have started to show more interest in buying products that are environmentally friendly and which will be taken back by their manufacturers at the end of their useful lives for recycling etc. This has become an incentive for the manufacturers to design and market environmentally friendly products (or 'green products') to gain advantage in the marketing platform against their competitors. Therefore, companies have started to analyze the product life cycle in order to insert the environmental component into the product design to produce a product that has a low production cost and is environmentally friendly [232,252,275].

The manufacturers and consumers are also forced by many environmental laws and legislation to pay more attention to the environmental issues. In many countries, the environmental protection laws, regulations and tax implications are already in place or in the works [52]. Frosch [85] describes the development of environmental regulations in the USA which has been applied in three stages since Earth Day 1970. The first stage is the 'end-of-pipe regulation' which defines restrictions on the types of materials that can be discarded, as well as where and how can they be discarded. Some of the well-known laws under this stage are the

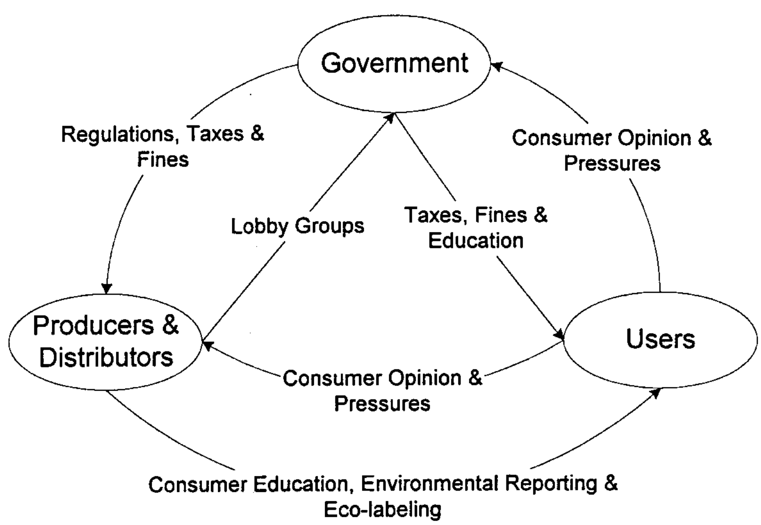

Fig. 3. Interactions between government, users, producers and distributors [320].

Clean Air Act, the Clean Water Act and the Resource Conservation Act. The second stage started with the Pollution Prevention Act of 1990, which focused on reducing pollution within the industrial processes. Finally, in the third stage, the aim is to encourage 'clean production' with the coordination of industry and the Environmental Protection Agency (EPA). The European Community has passed laws prohibiting the disposal of more than 15% of an automotive product by the year 2002 and this percentage drops to 5% in the year 2015 [212]. In Europe, government initiatives to make both manufacturer and user responsible for disposing of the wastes associated with a product are commonly being practiced. A German legislation mandated that as of 1 January 1994, manufacturers and retailers must take back and salvage products at the end of their lives and must design new ones with recycling in mind [219]. Material recycling goals proposed in the law stated that by 1995, steel, non-ferrous metals, tires, glass and plastics must be recycled to the level of 100, 85, 40, 30 and 20%, respectively [219]. Other European countries have similar measures on their agenda [134,225]. In addition to making laws that enforce ECMPRO practices, taxation has been used as another weapon in fighting pollution problems. Several European countries, including Denmark, Norway and the Netherlands, have introduced wide-ranging pollution taxes and established government commissions to investigate whether further measures should be introduced [6]. Crognale [52] sees the environmental regulations and laws as the basis for environmental management.

Besides the legislation and laws that enforce clean production, the material/product recovery techniques to reduce the amount of the raw material used and the amount of waste to be landfilled are also very crucial [83,159,261,286].

2.3. Summary

In this section, we highlighted various environmental problems, viz., the ever increasing consumption of limited natural resources, the amount of waste generated, the decreasing number of landfill sites and the increasing level of pollution. We then discussed the response to the negative environmental problems by the researchers, the governments, the manufacturers and the public. From the discussion, it became clear that there is a sense of urgency emerging to respond to the environmental problems throughout the society.

3. Environmentally conscious manufacturing (ECM)

ECM involves producing products such that their overall negative environmental effects are minimized [251,308,311,312]. ECM consists of the following two key issues:

1. understanding the life cycle of the product and its impact on the environment at each of its life stages and
2. making better decisions during product design and manufacturing so that the environmental attributes of the product and manufacturing process are kept at a desired level.

The first issue is necessary for drawing lines to determine how the product will evolve from the drawing board and how it will affect the environment throughout its life stages. If we fully understand the life cycle of the product, we can then transfer this information onto the actual development of the product (which addresses the second issue of ECM) (Fig. 4). In addition, understanding the end-of-life stage of the product is critical since one of the largest impact on the environment occurs at that stage.

During the design stage of the product, there are different objectives that the designers may focus on. Depending on the end-of-life strategy of the product, the design of the product can be realized to increase recyclability, manufacturability, disassemblability and to minimize the effect on the environment. When designing a product with environmental features, material selection should also be considered as a key element.

Once the design decisions of a product are complete and the materials for its production are identified, the product's environmental attributes are pretty much set. However, in addition to design and materials decisions, issues involving selection of energy source, cooling systems and handling of hazardous byproducts etc. must be controlled during the manufacturing process to achieve a complete ECM concept.

3.1. Environmentally conscious design (ECD)

ECD aims to design products with certain environmental considerations. In the literature, both the life cycle analysis (LCA) of the product and the design for environment (DFE) are emphasized.

3.1.1. Life Cycle Analysis or Assessment (LCA)

LCA is a process for assessing and evaluating the environmental, occupational health and resource consequences of a product through all phases of its life, i.e. extracting and processing raw materials, production, transportation and distribution, use, remanufacturing, recycling and final disposal [2,3]. LCA examines and quantifies the energy and materials used and wasted and assesses the impact of the product on the environment. LCA usually facilitates the systematic collection, analysis and presentation of environmentally related data.

The steps involved in LCA, which are commonly repeated in the literature, are as follows [165,203]:

- identification of the goals and boundaries of LCA,
- analysis of inventory to achieve a balance between material and energy in the system,

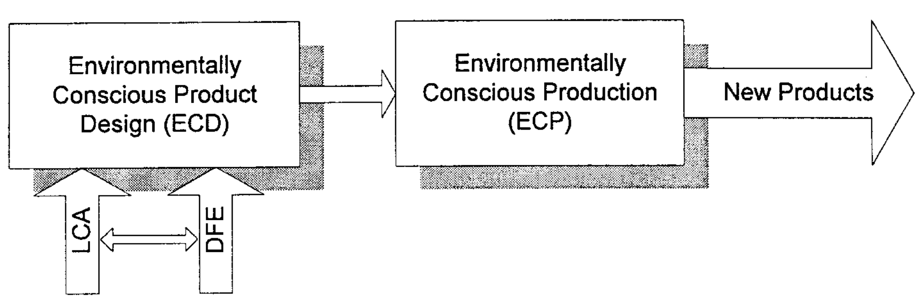

Fig. 4. Environmentally conscious manufacturing.

- evaluation of the system's impact on the environment,
- assessment of the most promising system improvements to reduce the negative environmental impact.

LCA has applications in many areas. The results of an LCA may provide the basis for the development of environmental laws, taxes and regulations. Industries may use LCA to support product development so that the overall environmental impact of the product is minimized. Qualitative and quantitative characteristics of the product life cycle are taken into account by means of LCA during the conceptual design of each new product. This enables designers to estimate the costs and benefits associated with the design attributes of the product, energy consumption, materials requirement and after-life choices of the product. Many companies make use of LCA to support their public claim of environmental responsibility.

The scope of LCA involves tracking all the materials and energy flows of a product from the retrieval of its raw materials out of the environment to the disposal of the product back into the environment [203]. The complexity of the LCA problem grows when the product structure is large and complex and the number of factors to be considered increases. Utilizing the power of computers for collection, organization and analysis of necessary data can help shorten the time it takes to conclude the LCA related decision process. In practice, however, such a process could be extremely involved if the limits of the system are not clearly defined. Therefore, prior to the execution of LCA, the associated goals and boundaries of the Life Cycle must be defined. Although the goals of LCA are system dependent, the economic issues are valid for all systems and have been commonly studied in the literature [13,128,129,162,187,263]. Based on the observations made by Keoleian and Menerey [165], LCA can be treated as an optimization problem by maximizing the added value and minimizing the resource consumption and waste dispersion activities. Bras and Emblemsvåg [29] and Emblemsvåg and Bras [70] develop activity-based cost functions by considering various uncertainty factors which are likely to occur in LCA.

Ishii et al. [155] and Ishii [152] developed a software called LINKER (which has been developed using ToolBook under Microsoft Windows) by concentrating on advanced planning for product retirement and addressing the level to which a product should be disassembled. LINKER allows the user to evaluate a design at various stages of the life cycle. After entering the required data into the software's input stream, LINKER displays the disassembly times for components and fasteners, the compatibility index and the retirement cost breakdown for each clump, including the reprocessing and disassembly cost. These results are used to create better designs to satisfy the measures of the designer. A couple of improvements to this technique were made (including a better cost function) by Di Marco et al. [61].

Other computer supported LCA tools have also been developed. For example, Rosen et al. [242] present a CAD tool for life cycle design whereas Hooks et al. [140] describe a simulation-based tool. Some researchers concentrate on the development of a knowledge-base that can provide understanding of the connections among various elements of life cycle design [23,126,167,309]. Sweatman and Simon [281] summarize a variety of computer-based LCA tools and classify them into groups with an aim to develop a toolkit which can be used throughout the design process. Similarly, Steinhilper [275] highlights computer aided tools used in a pilot computer application for the disposal stage of the product's life.

Researchers have also focused on other issues in LCA. Some investigated the entire life cycle of the product [127,218], while others have dealt with the effects of LCA on specific design issues (also referred as life-cycle engineering design) [100,152–156,202,217,313,331]. Some other researchers have analyzed the life cycle of a product so as to minimize the hazardous byproducts and pollution during the product's life [77,78,138,147,287]. Kriwet et al. [176] study the trade-off between the LCA decisions and the marketability of the product. Researchers have also evaluated the effects of material selection on the environment [39,321]. Other studies have concentrated on the recycling stage of the product to create new product designs with increased recyclability [34,180] while some simply focused on how to extend the useful life of a product [97]. One of the possible LCA improvements is the development of successful decision techniques which would lead to better designs of products and services [203].

The variety of LCA-related studies indicate that LCA requires contributions from all members of the society, e.g. public pressure groups, educational institutions, industries and governmental agencies [127,236,310]. Even though the preliminary studies of LCA go back to the late 1960s, the research effort is still increasing in the field of Life Cycle Assessment.

3.1.2. Design for environment (DFE)

Knowledge gained during LCA needs to be transferred into the initial design of a new product (Fig. 1). It is actually possible to focus on a specific stage of the product's life such that the environmental impact is minimized in that stage as well as emphasizing the entire life of the product. Researchers have analyzed different stages of a product's life and developed techniques and logistics to improve the design of the product from an environmental perspective. These techniques, all together, are referred as the *design for environment* (*DFE*) [12,22,28,49,50,76,93,95,98,99,126,186,192,205,245,269]. Fiksel [76] presents an excellent overview of DFE concepts and practices. Fiksel defines DFE as: "... a systematic consideration of design performance with respect to environmental, health and safety objectives over the full product and process life cycle." According to the author, DFE can be broken down into many stages, including, manufacturing, consumer use and the end-of-life of the product. Throughout these stages, different forms of design strategies can be envisioned as the pieces of DFE. For example, in order to minimize the effect of the product on the environment at the manufacturing stage, design objectives may include design for energy conservation to reduce the energy use in production and to be able to use renewable forms of energy and design for minimizing the discharge of hazardous byproduct during production. Similar concerns are also valid during the distribution of the product. Finally, during the end-of-life stage of the product, there are design objectives to increase the output of the product recovery. These include design for material and product recovery [181,262], design for disassembly [27,45,65–67,185,193,255,260], design for waste minimization, design under legislation and regulations, etc.

Design for recycling (DFR) [131,241] suggests making better choices for material selection [51,259] such that the processes of material separation and material recovery become more efficient. Some general characteristics of DFR are as follows:

- long product life with the minimized use of raw materials (source reduction),
- easy separation of different materials,

- fewer number of different materials in a single product while maintaining compatibility with the existing manufacturing infrastructure,
- fewer components within a given material in an engineered system,
- increased awareness of life cycle balances and reprocessing expenses,
- increased number of parts or subsystems that are easily disassembled and reused without refurbishing,
- more adaptable materials for multiple product applications and
- fewer 'secondary operations' reducing the amount of scrap and simplifying the recovery process.

On the other hand, design for remanufacturing (or part recovery) [156,161] suggests the use of reusable parts and packaging.

Disassembly is used both in recycling and remanufacturing to increase the recovery rate by allowing selective separation of parts and materials. Thus, designing for disassembly (DFD) is important and therefore it has been given special attention. DFD initiatives lead to the correct identification of design specifications to minimize the complexity of the structure of the product by minimizing the number of parts, increasing the use of common materials and choosing the fastener and joint types which are easily removable. DFD is often carried out using software due to the complexity of the problem. Hesselbach and Kühn [136] present a computer-based method that supports the design of a product in terms of disassemblability. In order to identify the disassemblability of the product, the authors propose an assessment method. Kroll et al. [177] propose a rating scheme that allows the designers to translate properties of a design into quantitative scores and thus provide a means of identifying weaknesses in the design and comparing alternatives. Hrinyak et al. [145] present a benchmark of the software available for DFD.

DFD is just one of the aspects of DFE. However, DFE comes with more than one task. Glantschnig [94] identifies three components of DFE, viz., the challenges faced by product designers and environment specialists, the green design challenges from a company's point of view and the external factors and forces that affect the design decisions. The ultimate goal of green design is to reduce the overall environmental damage when producing goods and providing services [64]. To achieve this goal, in addition to this cooperative work, availability of guidelines, checklists and software-based DFE tools also play a key role. Azzone and Noci [11] introduce an integrated measuring method for the greenness of new products. In this integrated method, at every stage of the product development, required decision making initiatives are identified. The authors utilize a modified version of the AHP (Analytic Hierarchy Process) model to compare alternative decisions by evaluating the change in the environmental features and the economical performance of the design. According to the authors, the AHP model is the most effective model — among multicriteria decision making approaches — for comparing different 'green' product development alternatives. The authors note that "...such a model (1) integrates all the criteria into a single overall score for ranking decision options and (2) particularly appeals to decision makers involved in the evaluation of very complex programs." A technique similar to AHP, ANP (Analytical network process) was used by Sarkis [249]. Other metrics for DFE were developed by Veroutis and Fava [305]. A paper by Bras and Hammond [30] describes a set of metrics for assessing the remanufacturability of a product design by examining the performance of the product. Hesselbach and Kühn [135] introduce an assessment software tool to evaluate disassembly features of alternative product designs. Srinivasan et al. [272,273] propose a virtual environment tool for DFD. Ridder and Scheidt [240] study the disassembly system of Sony Corporation to develop a real life-based assessment tool to improve the disassembly qualities of Sony's products.

Some additional DFE efforts in the industry have been reported in the literature [139,171,191,248]. A survey of DFE tools currently available is presented by Mizuki et al. [205].

Besides DFE approaches, the environmental effect of a product can also be reduced by designing the product for a longer life. The following design considerations may take place in the manufacturing and recovery stage: design for repair, design for assembly, design for minimum tool requirement for disassembly and so on. Some researchers refer to product design improvement efforts as design for 'X' (DFX) where X stands for a design under consideration such as Manufacturability, Testability, Installability, Compliance, Reliability, Disassembly etc. [59,88,258,327]. DFX is an integrated approach to designing products and processes for cost-effective, high quality downstream operations from manufacture through service and maintenance. DFX aims to reduce time to market, lower cost and increase quality of the product.

3.2. Environmentally conscious production (ECP)

In addition to environmentally friendly product designs resulting from DFE initiatives, issues involving production must also be addressed to have a complete concept of environmentally conscious manufacturing [76,250,320]. These issues include selecting energy sources necessary for production, designing cooling systems and handling hazardous byproducts. Currently, numerous production techniques, material handling systems and energy sources are available. Utilizing some sort of an assessment tool to select among them may be valuable financially as well as improve the environmental features of the production system. Bock [26] develops a tool to come up with a good material and process combination. Similar models have been developed to analyze how the selection of different manufacturing processes effect the environment [274,314].

Many companies monitor their waste generation as a result of their manufacturing processes. Several techniques have been proposed for such a monitoring process. For example, weighting methods were proposed to measure the chemical and toxic discharges of different manufacturing methods used [142,143,278,279]. Rupp and Graham [244] evaluate a printed circuit board (PCB) production plant from an environmentally consciousness point of view. Pellerin [221] examines the effect of automation on environmental indicators of a production system.

3.3. Industry examples

The automotive industry leads in research and development activities in response to the negative environmental developments. For example, Chrysler, Ford and GM researchers are trying to improve disassemblability features of their automobiles to take 'ease of destruction' together with 'ease of construction' into consideration. The new European Ford model, Mondeo, is claimed to be 85% recyclable [147]. Another example is the efforts of Mercedes-Benz to implement a total vehicle recycling program with two main elements: vehicle design and vehicle recycling. Billatos and Nevrekar [22] highlight the Benz design efforts which include choosing environmentally compatible and recyclable materials for components, reducing the volume and variety of plastics used, making plastics parts with logos and avoiding composite materials as much as possible. Mercedes Benz started taking scrap cars back in 1991 and has been performing the material recovery process as part of their environmentally friendly production program. The information gathered from the recycling process is transferred as DFE and DFR initiatives to the new product design stage. Mercedes and Swatch have jointly designed a prototype car entirely realized in vegetable fibers (at the expense of metals) and valuable special materials [11]. Another German car company, BMW, recently announced a pilot program in North America to test the feasibility of recycling BMW automobiles; because of the strict German laws the company already recycles cars in Europe [31]. Targeting three US cities, BMW will give owners a $500 credit towards the purchase of a new or used BMW for turning in a car to a dismantling center. BMW has been using color coding for differing plastic materials for the past 15 yr. The color coding scheme allows development of efficient dismantling and disassembly techniques. BMW transfers the knowledge gained from dismantling and disassembly processes into new product development [4]. Using DFD principles and more recyclable components in the original design, BMW hopes to increase the percentage of recycled car weight from the present 75 to 90% in the future [22]. BMW targets to produce a car out of 100% recycled parts by the year 2000 [147].

Similar efforts are being made by the German manufacturing arm of General Motors (GM), Adam Opel AG [22], Volkswagen [48], Nissan Motor Company [219] and Volvo Car Corporation [17]. Volvo has been trying to increase the efficiency of its recycling methods by giving grants to universities and research institutions. The grants have been awarded to projects on life-cycle analysis, dismantling methods, materials recycling, energy recovery, disposal of environmentally hazardous materials and transportation of materials to/from recycling centers.

Consumer electronics and computer industries are also involved in the environmental movement. There are a lot of small and big companies investing into these causes. Digital, Proctor & Gamble and Canon are working to improve the recycleability of their products [5]. Digital uses the 6*R* approach on their used products (6*R* means *Recycle, Reclaim, Refurbish, Remanufacture, Resell* and *Reuse*) [63].

Xerox Corporation strongly believes that environmentally conscious practices will become a customer requirement in the near future and is taking appropriate actions to prepare by applying life cycle design and DFE on its products. The company's goal is to achieve 0% end-of-pipe parts headed for landfills [4]. AT&T Bell Laboratories considers 'environment' as a component of their well understood DFX program [88,94].

Watson [310] reports that Intel Corporation estimates that by the year 2000, between 50 and 100 million transistors will be on a single chip in configurations that perform a variety of functions. The number of transistors in a Pentium chip is 3.1 million. Increasing the number of transistors in a single chip will result in fewer chips to build and fewer chips to dispose, lowering the resource consumption as well as lowering the generation of waste. Intel has also developed a chip level technology to put PCs in a 'sleep' mode in which the power consumption is reduced 6–10 fold. One of the world's biggest computer market share holders, IBM, has had a pollution prevention program since 1971. The goal is to achieve continuous improvement in the reduction of hazardous waste generated from IBM's manufacturing processes and its used products. IBM also develops design specifications for its new products to improve product's end-of-life material recovery [90].

Household goods manufacturers are also encouraged by the current environmentally-driven green manufacturing efforts [22,165].

Another important area related to green production is packaging, since better packaging methods can significantly decrease the use of materials. For example, Colgate [35] has created a very smart design for the packaging of toothpaste. The toothpaste comes in a plastic tube which can stand on its own top. Thus, it does not require a carton box unlike other similar products.

3.4. Summary

In this section, we detailed the concept of environmentally conscious manufacturing (ECM) which aims to minimize the impact of the product on the environment by incorporating the environmental thinking into both design and production processes. In order to assess the impact of the product on the environment, all of its life phases must be examined. Knowledge gathered from life cycle assessment (LCA) sets the stage for the design for environment (DFE) initiative of the product. In addition to the product design consideration, the production system must also be designed and operated with minimum impact on the environment. The current literature on LCA and DFE tends to be qualitative rather than quantitative. Development of analytical techniques may provide a basis to combine LCA, DFE and production issues and analyze the trade-off among them. For further understanding of ECM, we recommend the papers by Darnall et al. [56], Browne et al. [33], Gupta [118], Moyer and Gupta [209] and Zhang et al. [325].

4. Recovery of materials and products

Johnson and Wang [159] define the recovery process as a combination of remanufacture, reuse and recycle whereas Thierry et al. [286] divide recovery into repair, refurbish, remanufacture, cannibalize and recycle. A recent paper by Fleischmann et al. [83] categorizes recovery simply into material recovery and added value recovery. We also categorize the recovery process into material recovery [231] (recycling) and product recovery (remanufacturing) [289]. Material and product recovery are carried out mainly due to three reasons: (1) hidden economic value of solid waste, (2) market requirements and (3) governmental regulations. Material recovery mostly includes disassembly for separation and processing of materials (e.g. carrying out necessary chemical operations) of used products. The main purpose is to minimize the amount of disposal and maximize the amount of the materials returned back into the production cycle. Product recovery includes disassembly, cleaning, sorting, replacing or repairing bad components, reconditioning, testing, reassembling and inspecting. The recovered parts/products are used in repair, remanufacturing of other products and components and for sale to an outsider.

Various forms of the material/product recovery have been around for a long time. Automobile (metal scrap brokers), electronic and paper recycling are the most common examples [1,14,21,83,101,149–151,173,209,213,219,276,298,299]. Among these, the automobile recycling is most advanced. In the USA, while just 20% of glass, 30% of paper products and 61% of aluminum cans are recycled, 95% of the 10 million cars and trucks that are retired each year go to the recycler and for each of those cars, 75% by weight is recovered for reuse [21]. In Europe, according to the 1994 figures, the recovery rate (in percentage of total consumption) of paper products is relatively higher, about 43% [83]. The recovery rate of electronic consumer products (mostly computer products) is also fast developing [20].

In order to perform product recovery profitably and according to applicable laws and regulations, collection of retired products must be planned. Collection decisions involve location selection of collection centers (where retired products are collected and stored prior to distribution to recycling or remanufacturing facilities); layout design of collection centers (including material handling and storage); and transportation (designing the transportation networks to bring used products from many origins to a single collection center). The biggest challenge in collection related problems is the level of uncertainty involved in the quality and quantity of products collected.

4.1. Material recovery or recycling

Recycling is performed to retrieve the material content of the used and non-functioning products. As previously mentioned it is mainly driven by economic and regulatory factors. The economic value of used products is the reason for several recovery infrastructures. One of the best examples is the US automobile recycling infrastructure [130,264]. In the USA, for more than half a century, some very well developed automobile recycling centers provided hundreds of jobs and brought millions of tons of materials back into the production cycle. The effect of using nontraditional materials in automobiles on this infrastructure is analyzed by Isaacs et al. [151] and Isaacs and Gupta [149,150]. According to Isaacs and Gupta [149,150], recycling of automobiles essentially consists of two stages, viz., dismantling and shredding. Automobiles arrive at the dismantling facility directly from the end-user or from the auto dealers. The dismantler removes reusable components and particularly valuable materials fractions (e.g. large castings, batteries, etc.). Tires and fluids are also removed to allow the remaining hulk (which is the remaining body and the chassis) to be accepted by the shredding processor downstream. The hulk is flattened for ease of transport to the hulk shredder who buys the hulk from the dismantler. The shredder reduces the hulk into small pieces. Separation into ferrous, nonferrous and non-metallic automobile shredder residue fractions is achieved by the magnetic and density separation techniques. Then the materials are sorted to be sent to the demand points. As a result of this infrastructure, metal recyclers (or scrap ‘processors’) supply nearly half the USA’s iron, steel and copper, 55% of the lead, a third of the aluminum, plus assorted titanium, zinc, molybdenum from over 60 million tons of scrap gathered from an intricate web of suppliers [173]. Encouraged by the success of the automobile and electronic goods recycling in the USA, European companies are also developing ways to increase profitability in their recycling programs [36].

Economically-driven recovery process finds its application in the consumer electronics industry as well [57,72,254]. A typical computer contains gold, silver, palladium and platinum. The amount of precious materials is much higher in earlier manufactured electronics products. Recovery of precious materials from consumer electronic products requires proper equipment and is generally completed in mass [190]. Moyer and Gupta [209] report that a company in Canada with a specialized copper smelter, processed more than 100,000 ton of recyclable materials (one quarter of which consisted of electronics products) in 1993. From this material, the company recovered 34 ton of copper, 123 ton of silver, 7 ton of gold and 5 ton of platinum and palladium. A company in Irvine, California, reached $79 million in revenues in 1993 by mostly computer recycling [1].

Besides the recovery of highly valuable materials, other materials such as plastics [43] are being recovered due to environmental concerns. Regulatory electronics recycling is also practiced [62,228].

In order to find a balance between the resources invested in a recycling process (i.e. time and money) and value gained from the recovered materials, economic analysis of recycling process is sometimes carried out [40,159,214–216]. The objective, of course, is to continue the recovery process as long as the profitability is maintained.

Johnson and Wang [159] discuss a methodology for carrying out material recovery in an efficient way. The methodology incorporates an initial study to determine the percentage of product which is recoverable, the initial cost/benefit estimates of recovery and the initial goals of material recovery options, identifying the disassembly level which generates a preferred sequence of disassembly which will maximize the value gained from recovery and the implementation stage of strategies developed in the previous levels. Krikke et al. [175] propose a model to evaluate recovery strategies for the product including disassembly, recycling, reuse and disposal without violating the physical and economical feasibility constraints.

Hentschel et al. [133] present an approach to recycling system planning for used products at their end-of-life phase. The authors consider design and process attributes as well as the uncertainties that are likely to arise in a recycling system. In order to incorporate these attributes into the proposed approach, the authors utilize fuzzy-set theory and group technology.

4.2. Product recovery or remanufacturing

Lund [195–197] describes remanufacturing as "...an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Usable parts are cleaned, refurbished and put into inventory. Then the product is reassembled from old parts (and where necessary new parts) to produce a unit fully equivalent or sometimes superior in performance and expected lifetime to the original new product." Reyes et al. [235] present an assessment tool to find the reliability of recovered parts.

Fleischmann et al. [83] define remanufacturing as a process of bringing the used products back to 'as new' condition by performing the necessary operations such as disassembly, overhaul and replacement. Remanufacturing is also referred as recycling-integrated manufacturing [144]. Industries that apply remanufacturing typically include automobile industry, electronics industry and tire manufacturers [73–75,125,141]. A typical unit flow in remanufacturing [107] is shown in Fig. 5. Similar to the conventional production systems, in remanufacturing systems, there are operational, manufacturing, inventory, distribution and marketing related decisions to be made [170,277]. In general, the existing methods for conventional production systems cannot be used for the remanufacturing systems. Remanufacturing environments are characterized by their highly flexible structures. Flexibility is required in order to handle the uncertainties which are likely to arise.

4.3. Common issues in recycling and remanufacturing

4.3.1. Collection issues

In a product recovery environment, one of the major issues is the collection of the reused items and/or their packages [194,234]. In a conventional manufacturing environment, newly manufactured products from a single source are delivered to multiple destinations, thus having a diverging effect. This is referred to as *forward distribution*. On the other hand, used products originate from multiple sources and are brought to a single product recovery facility, resulting in a converging process. Flow of used products back into the production environment is known as *reverse distribution* [168]. Reverse distribution issues date back as early as 1975 [114].

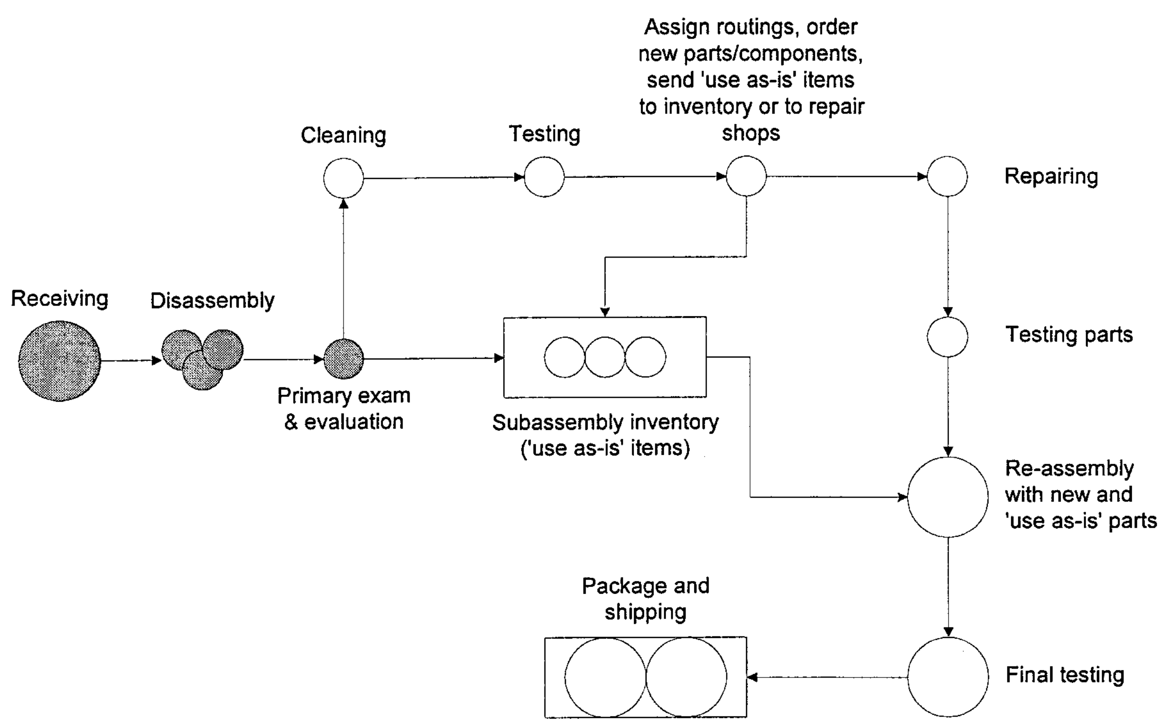

Fig. 5. A typical unit (a product or a part) flow in remanufacturing (modified from [107]).

Often, the collection of used products is carried out by the same parties which are involved in the process of forward distribution, e.g. suppliers, manufacturers, distributors, consumers and recyclers. Designing reverse distribution networks capable of capturing the relationships among the various parties is highly complex. It is especially difficult for companies with both forward and backward distribution requirements (i.e. for companies with remanufacturing integrated manufacturing systems). Complexity of the reverse distribution problems stems from the high degree of uncertainty inherent in the collection activities. The uncertainty occurs in terms of quantity and quality of the products.

One approach that is commonly taken in the literature is to model reverse distribution independent of forward distribution [92]. However, it is obviously more desirable to develop an integrated model to incorporate both forward and reverse flows of new and used products.

Distribution items (DIs) such as load carriers, containers and packaging materials, play an important role in reverse distribution. Flapper [79,82] and Lambert and Splinter [184] discuss the environmental, financial and operational effects of DIs, by analyzing their life cycles. Del Castillo and Cochan [60] develop an optimization model involving reusable containers which are returned back to manufacturers after the completion of forward dictribution. Other researchers also consider returnable distribution items in their studies [96,163,164,178].

4.3.2. Disassembly

Disassembly has recently gained a lot of attention in the literature due to its role in product recovery [160]. Disassembly activities take place in various recovery operations including remanufacturing, recycling and disposal. *Disassembly* may be defined as a systematic method for separating a product into its constituent parts, components, subassemblies, or other groupings [121]. Disassembly may be partial (product is not fully disassembled) or complete (product is fully disassembled). Even though approaching disassembly as the reverse of assembly may sound reasonable, for complex products, the operational characteristics of disassembly and assembly are quite different.

Table 1
Comparison of assembly and disassembly systems [32]

System characteristics	Assembly	Disassembly
Demand	dependent	dependent
Demand sources	single	multiple
Forecasting requirements	single end item	multi-item
Planning horizon	product life-cycle	indefinite
Design orientation	design for assembly	design for disassembly
Facilities and capacity planning	straightforward	intricate
Manufacturing system	dynamic and constrained	dynamic and constrained
Operations complexity	moderate	high
Flow process	convergent	divergent
Direction of material flow	forward	reverse
Inventory by-products	none	potentially numerous
Availability of scheduling tools	numerous	none

Tani and Güner [285] compare assembly and disassembly and describe the identifiers of the disassembly process. According to their observations, disassembly of a product can be performed by finding natural and easier ways whereas in assembly, the process needs to be highly optimized and sequences of parts to form a product must be clearly defined. Although the actual mechanism of disassembly is simpler than that of assembly, the operational scope of disassembly is much more complex than assembly. The general operational characteristics of disassembly and assembly systems are highlighted by Brennan et al. [32] and given in Table 1.

Both operational and physical differences between assembly and disassembly imply that the assembly planning knowledge may not be used 'as is' for the disassembly planning issues. Thus, there is a need to develop new techniques and methodologies to specifically address disassembly planning. The research in the disassembly field can be grouped in two major areas: (1) research related to identifying the extent to which disassembly of a product should be performed (disassembly leveling); and (2) research focusing on disassembly process planning.

4.3.2.1. Disassembly Leveling (i.e. how far to disassemble?). The disassembly leveling problem can be defined as achieving a disassembly level to which the product of interest is disassembled to keep profitability and environmental features of the process at a desired level. Even though complete disassembly may seem to provide the best way of minimizing the damage to the environment, some studies conclude that with the current recycling technology and market prices, complete disassembly is not profitable since the cost of disassembly is more than the market and environmental benefits. Thus, it is important to find a balance between the resources invested in the disassembly process and the return realized from it [19]. In the literature, finding the optimum balance between the resource requirement and the benefit of the disassembly process is studied, usually, using cost analysis. For example, de Ron and Penev [58] and Penev and de Ron [223] discuss the determination of disassembly level and sequences for products, which provide conditions for the generation of profit while considering the environmental problems. For this purpose, the authors utilize graph theory to represent the possible stages of the disassembly process and alternative disassembly strategies for every sub-assembly. In order to identify the best sequence and strategy of disassembly, besides the graph representation, cost analysis is carried out for every alternative considered.

Zussman and his colleagues exploit the disassembly leveling problem for improving the design of products. Zussman et al. [329] and Zussman [328] introduce a quantitative assessment tool which aids designers in choosing product designs that are more suitable for recycling. Cost analysis of disassembly, dumping, recycling and total recovery is performed by taking the uncertainty conditions of recycling into account. The authors also analyze the end-of-life options of products in order to minimize waste and maximize the benefit gained from recycling. These options are attached to a disassembly graph which is called a 'Recovery Graph'. In a recent paper, Pnueli and Zussman [229] propose an improved methodology that includes identifying the recovery options of all parts of the product, finding the weaknesses of the product and suggesting product redesigns such that the weak points are omitted. Geiger and Zussman [89] study the effect of uncertainty on the quality of the parts. Lambert [182,183] proposes a methodology to identify the disassembly level. The methodology is very similar to the one presented by Zussman et al. [329] and Zussman [328].

Navin-Chandra [215,216] approaches the disassembly leveling problem as a variation of the prize-collecting Traveling Salesman Problem (TSP) which is defined as follows: A traveling salesperson who gets a prize in every city visited and travels between cities with an associated cost, wants to maximize the profit which is the difference between the total prizes collected and the total travel cost. In disassembly applications, the cities are the parts to disassemble, the prize is the gain from disassembled components and the travel distance is the cost of disassembly. The salesperson need not go to all cities because the cost of travel to the remaining cities is more than the expected returns and has to find a directed path from starting city to any city at which the total profit is maximized. There is no need to return to the starting city. In order to create the disassembly table, the author presents a two-step algorithm as follows: (1) if any part is not obstructed by other parts in any disassembly direction, then it can be removed in that direction; (2) if any part is held only by a joint in some direction, then it can be removed by undoing that joint. Similar cost benefit analysis of material recovery process is carried out by Chen et al. [40]. The authors utilize their method by applying it to a real life example of a car dashboard.

Zhang et al. [326] develop a cost based systematic approach to PC recycling using a disassembly tree, which represents the assembly relationship between components of EOL products.

4.3.2.2. Disassembly process planning. Another important aspect of disassembly is to find efficient disassembly process plans [267,301,319]. A disassembly process plan (DPP) is a sequence of disassembly tasks which begins with a product to be disassembled and terminates in a state where all of the parts of interest are disconnected (thus it could be either partial or complete disassembly). The objective of disassembly process planning is to find optimal or near-optimal DPPs, which minimize the cost of disassembly (assuming that a certain level of disassembly is required) or obtain the best cost/benefit ratio for disassembly. The number of alternative DPPs grows exponentially as the number of the components increase in a product. Identifying the 'best' disassembly sequence requires a systematic approach operating under a given set of objectives and constraints. This problem is one of the most challenging problems in the field of disassembly.

One of the first papers in this field is by Subramani and Dewhurst [280] which utilizes a 'branch and bound' based algorithm to find a disassembly sequence that minimizes the total disassembly cost. The methodology involves the identification of local constraints for the removal of a part with respect to its disassembly direction and contacts with other parts. Beasley and Martin [16] emphasize the importance of identifying the geometric relationships among the parts in the process of DPP generation. Researchers in this field have considered various ways to represent the geometric relationships among parts, the most common being graphs and trees. For example, Lambert [182,183] develops a quantitative method for the disassembly of complex products by creating a graph showing all possible disassembly strategies and associated cost and revenue values. The problem is then converted into a shortest path problem, the solution techniques of which are readily available. Yan and Gu [318] introduce another graph-based heuristic for creating assembly sequences of products. Using the CAD structure of the product, a planner creates two types of graphs: a liaison graph and a contact relations graph. Using the liaison graph, the product is broken down into its sub-assemblies by using theory of graph splitting. Then, for every sub-assembly, a disassembly sequence is generated based on the contact relations graph. By merging the disassembly sequences of all sub-assemblies, a complete disassembly sequence is created for the product. Finally, an assembly sequence is developed by reversing the disassembly sequence, which is a shortcoming of this paper since reversing order between assembly and disassembly plans does not always hold. Veerakamolmal et al. [304] and Veerakamolmal and Gupta [301] introduce a graphical approach to achieve an efficient disassembly process plan. In their approach, a module-based disassembly subtree is generated and a minimum makespan algorithm is applied to each subtree to generate the best disassembly plan for the subtree. The algorithm is applied to the remaining subtrees to determine a near-optimal plan. The algorithm is used as part of a heuristic which minimizes the makespan of the disassembly processes in a component recovery system [302]. The model is applied to printed circuit boards with mounted computer chips for the purpose of disassembling boards and recovering and reusing useful materials [300]. Veerakamolmal and Gupta [303] and Gupta and Veerakamolmal [123] present a goal programming integrated heuristic to determine the number and type of products to disassemble, to fulfill the demand of various components in order to minimize the disassembly and disposal costs. Another graph based disassembly approach is proposed by Zhang and Kuo [324].

Chen et al. [41] present an algorithm for parallel disassembly by using a tree representation based on the removability of parts. In order to reduce the time complexity of finding a disassembly sequence, the authors introduce a simplified mating graph and develop a data structure to facilitate an efficient parallel disassembly algorithm. In the algorithm, the directionality of parts movement are also considered. Arai et al. [8] present a method to verify the assemblability of a product by considering motions of the disassembly process. The possible motions are generated to identify the next part and the motion to perform in the sequence of disassembly. The authors use a tree structure whose nodes and arcs denote configurations and possible motions of a disassemblable part. Dutta and Woo [69] propose a tree-based algorithm to create efficient sequences for disassembling components for repair and maintenance. The objective of the algorithm is to minimize the number of nondefective components to be removed for the removal of multiple defective components from an assembly. Lee and Kumara [189] consider partial (a part or a group of parts) as well as complete disassembly. The approach presented by the authors utilizes freedom and interference spaces in a product structure as the basis for feasibility of DPPs. In a recent paper, Srinivasan and Gadh [271] present a geometric algorithm to solve the selective disassembly problem. The goal is to find the optimum sequence to retrieve the desired part. The proposed algorithm uses 'wave propagation' approach that analyzes the product from the selected part outward and sequences the parts for selective disassembly. Lee and Gadh [188] present a geometry-based disassembly sequence generation approach for destructive disassembly.

Other methods have also been used in the field of disassembly process planning. For example, Arai and Iwata [7] present a simulation-based method for assembly/disassembly planning of a product by utilizing a CAD system. The method creates all possible movements for the disassembly of every subassembly in the product. This is identified from the solid CAD structural design of the product. During the identification of the movements, the effect of the gravity is also taken into account. Finally, the authors present an approach to find the best sequence of disassembly among all possible disassembly sequences. They develop their method with the assumption that the assembly sequence is the reverse of the disassembly sequence. However, this assumption is not universally valid. As previously discussed, reverse of assembly plans cannot always be used as disassembly plans due the physical and characteristics differences between assembly and disassembly. A paper by Vujosevic et al. [306] presents an approach for the simulation, animation and analysis of design for disassembly and maintainability. All geometrically feasible disassembly sequences are generated in order to identify the disassembly sequence that minimizes the disassembly time and cost. The authors also look into human factor problems arising during disassembly.

Use of Neural Networks (NN) for generation of DPPs is examined by Huang and Wang [146]. They develop an NN-based approach to identify the optimum disassembly sequence when maximizing the profit from the materials recovered. The authors utilize the Hopfield network which is widely used for optimization problems. In the words of authors: "the model is open to improvements."

Minami et al. [204] present an algorithm to generate feasible disassembly sequences for a product using *cellular automata* which are used to represent physical objects and their interactions. Cells assume a vector value, made up of a material/void indicator, a set of cell boundary edge states and an indicator of the allowable motion direction of the cell. Sets of rules that recognize parts and deduce allowable motions are described.

Gupta and his research group have done extensive work in the area of disassembly scheduling and process planning [32,115–117,119–123,166,206–209,282–284,300–304,322,323]. Brennan et al. [32], Gupta and McLean [119] and Gupta and Veerakamolmal [122] provide detailed information on disassembly planning issues and their driving forces. Zeid et al. [322,323] focus on planning for disassembly (PFD) problem. The authors propose the use of a case based reasoning (CBR) approach to assist planners in solving PFD problems. CBR is based on the sensible notion that problem solving can be assisted by the reuse of solutions to similar problems encountered in the past.

Gungor and Gupta [117] present a methodology to evaluate different disassembly strategies so that the best one could be chosen. The proposed methodology tries to minimize the direction of movement changes and the tool changes during disassembly. Gungor and Gupta [115] improve the methodology by introducing an algorithm to find the geometrically based feasibility constraints. Once the feasibility constraints are found, an optimal or near-optimal DPP is sought so as to minimize the direction of movement and tool changes during disassembly. By introducing a larger penalty for keeping valuable and hazardous parts longer in the base assembly during disassembly, the chosen DPP tends to minimize losses due to breakage of valuable parts and prolonged exposure of hazardous parts. The authors also introduce a method to handle uncertainty arising in disassembly due to defective parts and breakage during the disassembly process [116].

Xirouchakis and Kiritsis [316] propose a Petri net based methodology for disassembly planning considering the precedence relationships between the assemblies. Moore et al. [206–208] also present a Petri net-based approach to automatically generate disassembly process plans for product recycling and remanufacturing. First, the authors use an algorithm introduced by Gungor and Gupta [115] to generate a geometrically-based disassembly precedence matrix (DPM) from the CAD drawing of the product. They then introduce an algorithm to automatically generate a disassembly Petri net (DPN) from the DPM [208]. The resulting DPN is analyzed using the reachability tree method to generate feasible disassembly process plans (DPPs). Cost functions are used to determine the optimal DPP [207]. Since the reachability tree generation is *NP*-complete, they develop a heuristic to dynamically explore the v likeliest lowest cost branches of the tree, to identify optimal or near-optimal DPPs. The cost functions incorporate tool changes, changes in direction of movement during disassembly and individual part characteristics (such as hazardous parts) [115,117]. An example is used to illustrate the procedure. This approach can be used for products containing AND, OR and complex AND/OR disassembly precedence relationships. Moore et al. [206] extend the methodology allowing the use of XOR precedence relationships. Zussman et al. [330] propose another disassembly Petri net (DPN) for modeling and adaptive planning of disassembly processes. The objective of the study is to derive the optimal disassembly process plan whose terminal goal is not fixed and the objective function is maximized. This objective function is defined by the end-of-life (EOL) values (e.g. cost or benefit of reusing, refurbishing, material-recycling and damping) of the parts of the product.

In addition to generating good DPPs, there is a need to make the disassembly systems more efficient. Current disassembly systems are generally manual and labor intensive. Therefore, automation of disassembly systems appears to be worth investigating. In the disassembly literature, we have started to see some initial efforts made in that direction. For example, Tani and Güner [285] suggest the use of behavior-based robotics in disassembly systems in order to automate them. They emphasize the importance of an accurate vision system for successful implementation of robotics in the disassembly systems. Umeda and Arai [288] develop a vision system to automate the disassembly process. Kopacek and Kronreif [169] also suggest automation for disassembly operations of personal computers in order to minimize the total disassembly time.

4.3.3. Inventory control and production planning

Inventory control and production planning is well understood for conventional manufacturing systems. However, available techniques for conventional manufacturing environment are not always transferable to recycling and remanufacturing environments. Applicability of available techniques may vary from one system to another. For example, Guide and Srivasatava [110] list the following factors which induce complexity in a remanufacturing system:

- probabilistic recovery rates of parts from the inducted cores which implies a high degree of uncertainty in material planning,
- unknown conditions of the recovered parts until inspected, thus leading to stochastic routings and lead times,
- the part matching problem (units are often composed of serial number specific parts and components, along with common ones),
- the added complexity of a remanufacturing shop structure,
- the problem of imperfect correlation between supply of cores and demand for remanufactured units and
- uncertainties in the quantity and timing of returned products.

4.3.3.1. Inventory control. Inventory control models in recycling and remanufacturing have to keep track of such things as returned products, partially disassembled products, disassembled parts as well as new parts. These models are further complicated due to a high degree of uncertainty in the quantity and quality of retired products, arrival times of these products and demand occurrences for the recovered parts and products.

Deterministic models in which the return and demand rates are known in advance, are sometimes developed for benchmarking purposes [198,237–239,257]. However, stochastic models, in which the return and demand rates are probabilistic, provide better understanding of the inventory system. Inventory models in the area of repair and maintenance systems, where failed items and machines are instantaneously replaced with new ones, have some similarity to the remanufacturing models and are very well developed [18,42,44,211,227].

Both periodic and continuous review models for product recovery systems considering independent stochastic return and demand occurrences have been developed. Examples of periodic review models include: model in which returned products can be reused directly [47], model with a setup cost [164], model with separate inventories for serviceable and recoverable parts [268] and model considering effects of non-zero leadtimes for orders and recovery [148].

Several examples of continuous review models also exist in the literature. Heyman [137] finds an optimal balance between inventory holding cost and production cost. Muckstadt and Isaac [210] develop a model for a remanufacturing system with non-zero leadtimes and a control policy with the traditional (s, Q) rule. They present an approximation method to determine the optimal values of s and Q. Van der Laan et al. present a different approximation method [292,295]. Salomon et al. [246], van der Laan and Salomon [293] and van der Laan et al. [291,294] develop PUSH and PULL strategies for joint production and inventory for a system using both new and recovered parts. Korugan and Gupta [172] consider a system with recoverable and serviceable inventories. The system is modeled as an open queueing network with finite buffers and analyzed using the expansion methodology.

4.3.3.2. Production planning and scheduling. Applicability of traditional production planning and scheduling methods to product recovery systems is very limited due to the previously highlighted differences. Thus, either new methodologies have to be developed or the necessary modifications have to be made to the traditional methods to handle the complications due to the recovery systems [290].

Some researchers have analyzed the recovery options of the product by carrying out the part level cost and benefit analysis considering the cost of activities required during the recovery process and the physical properties of the product [59,159,175,223,286]. Others have studied scheduling activities in a product recovery system. Some techniques utilize Material Requirements Planning (MRP) using reverse bill of materials (BOM) [80,81,179,220]. Gupta and his colleagues look at the scheduling problem by incorporating disassembly activities. Gupta and Taleb [121] and Taleb and Gupta [282] present an algorithm that can be applied to a product structure where there is a certain demand for components and a need to know the number of root items to disassemble in order to fulfill the demand for those components. The algorithm is designed for a single product case by using the modified reverse MRP algorithm. According to the authors, in conventional MRP, demand occurs at the end item level, whereas in the disassembly case, the demand is motivated by the component level of the product structure. Even though the objective of MRP in both conventional and disassembly cases are the same, the algorithm in the disassembly case is much more complex. Taleb et al. [284] improve the algorithm to incorporate complex products with parts and materials commonality. Gupta and Taleb [120] and Taleb and Gupta [283] further extend the algorithm to address the case of multiple complex products with parts commonality.

A mathematical model formulation for a recycle-oriented manufacturing system is presented by Hoshino et al. [144]. The authors analyze the recycle-oriented manufacturing system using an optimization model. The model is designed for a system which produces a single product with m parts. Each part has three attributes associated with it: (1) re-usable part, (2) not re-usable but re-producible part and (3) not re-producible/re-usable part. The model is formulated as a goal programming problem with two objectives: maximization of the total profit and maximization of the recycling rate. Another example of mathematical formulation is a deterministic linear programming model developed by Clegg et al. [46].

In remanufacturing, due to the high degree of uncertainty, it is important to control the flow of parts at the shop floor level. Guide and Srivastava [107] and Guide et al. [104] evaluate various part order-release strategies in a remanufacturing environment using a simulation model of a Naval aviation depot's aircraft engine components workshop. The paper discusses the use of four types of order release strategies: a level strategy, a batch strategy, a local order release strategy and a global order release strategy. The authors evaluate these alternatives using a simulation model which was written in SLAM II with FORTRAN coded interfaces. Guide [102] proposes scheduling using the drum-buffer-rope concept as an alternative method to MRP.

Guide et al. [113] and Guide and Spencer [105] develop a simulation based capacity planing approach for remanufacturing systems. The authors use Rough Cut Capacity Planning (RCCP) —the process of converting the production plan and/or the master production schedule into capacity needs for key resources: work resource, machinery, warehouse space, suppliers capabilities and money. An evaluation of capacity planning techniques has been presented by Guide et al. [113]. Guide and his colleagues have studied different control scenarios in the remanufacturing environment [103,106,108,109,111,112].

Kizilkaya and Gupta [166] propose a flexible kanban system for a disassembly cell in a disassembly integrated manufacturing system in which new parts and used parts, retrieved via disassembly, are used for a new product assembly. Rosen et al. [243] and Siddique and Rosen [266] present a virtual planning tool for analyzing the disassembly and remanufacturing systems.

Fleischmann et al. [83] present an excellent review of the industrial reuse of products and materials from an OR perspective.

4.4. Summary

In this section, we reviewed the materials and products recovery issues. We divided the recovery process into two categories: (1) Recycling which aims to reclaim the material content of retired (or used) products; (2) Remanufacturing which targets to bring the parts of a product or the product as a whole to a desired level of quality to reuse, resell or reassemble.

We also discussed collection, disassembly, inventory control and production planning issues of used products, all of which are important in recycling and remanufacturing.

The collection issues present a great deal of difficulty because retired products originate from multiple origins and head to a single destination. The high level of difficulty is due to the uncertainty involved in the process ranging from the quantity of products to their delivery logistics to the placement of collection centers. Based on the current literature, we conclude that the collection process is yet to be fully understood.

Lately, disassembly is one of the most actively researched areas in the context of material and product recovery. Various practical and theoretical techniques are being developed for manual and automatic disassembly processes.

Many papers in the area of inventory control, production planning and scheduling issues in recycling and remanufacturing utilize the well known Operations Research (OR) techniques to solve these emerging problems. For several applications of OR techniques in the environmental management area, see the papers by Bloemhof-Ruwaard et al. [25] and Daniel et al. [55].

5. Other related research

In addition to ECM and materials and product recovery issues, problems related to waste management and pollution prevention have also been addressed in the literature. In this section we highlight some research related to these issues.

The major objectives of waste management are: (1) reducing the waste at the source of generation by using appropriate materials, equipment and techniques; (2) reusing and recycling the waste; and (3) finding better ways for waste treatment, by keeping the disposal as the least desired option [247,315].

In addition to the waste reduction issues, problems involving collection of the solid waste has been of interest to researchers. Caruso et al. [37] model a solid waste management system (including collection, transportation, incineration, composting, recycling and disposal) using a multi-objective location-allocation model which is supported by planning heuristics.

Haastrup et al. [124] present a decision support system, for urban waste management in a regional area, for evaluating general policies for collection and for identifying areas suitable for locating waste treatment and disposal plants. The paper describes the identification and collection of relevant information, the structuring of a database, the design of combinatorial optimization algorithms for solving the core location problem, the study of models for evaluating the different alternatives and their framing in a complete multicriteria decision model.

Bloemhof-Ruwaard et al. [24] study the problem of the simultaneous design of a distribution network with plants and waste disposal units and the coordination of product flows and waste flows within this network. The objective is to minimize the sum of fixed costs for opening plants and disposal units and variable costs related to product and waste flows. The problem is NP-hard and is formulated by using a mixed integer linear program.

Giannikos [91] presents a multiobjective model for locating disposal or treatment facilities and transporting hazardous waste along the links of a transportation network. Some of the nodes of this network may be population centers generating hazardous waste which must be

Table 2
Categories of the references

Category[a]				References[b]
GD				[6,9,17,35,52–54,63,76,84–87,132,134,157,158,165,174,199–201,212,219,222, 224–226,230,233,253,256,261,265,276,296,297,299,307,312,315,322]
ECM	ECMGEN			[10,11,17,25,31,33,48,55,56,63,118,199–201,219,232,249–252,256,265,297,308, 310–312,320,325]
	ECD	LCA		[2–4,13,23,29,34,39,61,70,77,78,97,100,126–129,138,140,147,152–156,162,165,167,176,180, 187,202,203,217,218,236,242,263,275,281,287,309,310,313,321,331]
		DFE		[5,11,12,22,27,28,30,35,45,49–51,59,64–67,76,88,93–95,98,99,126,131, 135,136,139,145,156,161,171,177,181,185,186,191–193,205,240,241,245,248,249, 255,258–260,262,269,272,273,305,327]
	ECP			[22,26,76,142,143,147,221,232,244,250,274,278,279,288,314,320]
M&PR	M&PRGEN			[1,14,20,21,45,73–75,83,90,118,149,151,159,173,195–197,209,213,219,231, 261,276,286,298,299]
	REC			[1,36,40,43,57,62,101,130,133,149–151,159,173,175,190,209,214–216,228,254,264]
	REM			[18,25,30,42,44,46,73–75,79,83,118,125,141,144,148,161,170,195–197,213,220,227,235, 277,289,290,293,295]
	REC&REMCOM	COL		[60,79,82,83,92,96,114,125,141,163,164,168,178,184,194,234]
		DIS	DISLEV	[19,32,40,57,58,72,89,160,182,183,215,216,223,229,326,328,329]
			DPP	[7,8,16,41,69,115–117,119,122,123,146,160,169,182,183,188,189,204,206–208,266,267,271,280, 285,288,300–304,306,316–319,322–324,330]
		IC&PPS	IC	[18,42,44,47,83,137,148,164,170,172,198,210,211,227,237,238,246,257,268,277,291–295]
			PPS	[32,46,59,80,81,83,102–113,120,121,125,141,144,159,166,170, 175,179,195,220,223,235,243,266,277,282–284,286,290]
Other	WM&PPV			[15,24,37,38,68,71,91,124,233,238,239,247,270,315]

[a] See Table 3 for the meaning of the abbreviations.
[b] Some references belong to more than one category.

Table 3
Abbreviations used in Table 2

Abbreviation	Abbreviation of	Meaning
COL	collection	papers covering collection issues in materials and products recovery
DFE	design for environment	research on DFE
DIS	disassembly	papers on disassembly (includes DISLEV and DPP)
DISLEV	disassembly leveling	research concentrating on "how far to disassemble?"
DPP	disassembly process planning	research focusing on disassembly process planning
ECD	environmentally conscious design	papers on ECD (includes LCA and DFE)
ECM	environmentally conscious manufacturing	papers on ECM (includes ECMGEN, ECD and ECP)
ECMGEN	environmentally conscious manufacturing general discussion	research aiming to discuss the ECM in general without focusing on a specific subject
ECP	environmentally conscious production	papers on ECP
GD	general discussion	research discussing environment related issues from a macro point of view (much like editorial letters)
IC	inventory control	papers on IC
IC&PPS	inventory control & production planning and scheduling	papers on IC&PPS (includes IC and PPS)
LCA	life cycle analysis	papers on LCA
M&PR	materials & products recovery	papers of M&PR (includes M&PRGEN, REC, REM and DIS)
M&PRGEN	materials & products recovery general discussion	research discussing the M&PR in general without focusing on a specific subject
PPS	production planning and scheduling	papers on PPS
REC	recycling	research specializing on recycling
REC&REMCOM	recycling and remanufacturing common	papers on common issues in recycling and remanufacturing
REM	remanufacturing	research specializing on remanufacturing
WM&PPV	waste management & pollution prevention	research on waste management and pollution prevention issues

transported to the treatment facilities. A goal programming model to solve the problem is developed and a small hypothetical example is presented.

Everett and Applegate [71] present an analysis of a solid waste transfer system and describe the implementation of an actual waste transfer system in Kansas. The model considers several parts of a waste transfer system such as transfer mode, sizing of tipping floors and vehicle traffic flow. The waste system with its associated capabilities and limitations is clearly defined. The following are also considered: the average peak day and peak hour solid waste transfer, quantities in the year under consideration, the mode of transfer, waste storage area requirements, number of scales, number of tipping stalls and the required queue length for the number of trucks that can wait between the scale-house and the tipping area. The authors assume that the truck arrivals are exponentially distributed.

A network analysis model is developed for hazardous waste transfer systems by Batta and Chiu [15]. Spengler et al. [270] develop a mixed-integer linear programming model for recycling of industrial byproducts and dismantling and recycling of products at the end of their lives. Other mathematical modeling techniques have also been used for waste management [38,238,239].

Dunn and El-Halwagi [68] develop a systematic and generally applicable methodology for the optimal design of recycle/reuse process networks to minimize emission of hydrogen sulfide from pulp and paper plants.

6. Conclusions

In this paper, we presented a review of the state-of-the-art literature on environmentally conscious manufacturing and product recovery (ECMPRO). The reviewed work, grouped into various categories, is presented in Table 2 (Table 3 for abbreviations used). Some references belong to more than one category. Some general conclusions from our literature review are as follows:

- Environmental issues are gaining justifiable popularity among society, governments and industry due to negative environmental developments.
- Research shows that the manufacturing of environmentally friendly products is crucial in order to minimize the use of virgin resources. This can be achieved by studying the life cycle of the product from its design stage to its retirement stage and incorporating this information into engineering design and production.
- Reclamation of materials and parts from outdated products is equally crucial in fighting against the environmental degradation. The recovery process reverses the one-way production and helps us move closer to a sustainable system.
- Disassembly is an important component of remanufacturing which is currently labor intensive and expensive. Thus, it is very important to develop automated disassembly systems which may eliminate the drawbacks of manual disassembly, i.e. lengthy disassembly completion time, human exposure to possible hazardous materials and byproducts, expensive labor use, etc.
- For successful implementation of ECM and recovery processes, it is necessary to develop qualitative and quantitative decision tools. The applicability of traditional tools is limited because the objectives, constraints and other characteristics of the traditional systems are different from those for the ECMPRO systems.
- Effort must be made for ECMPRO systems to be profitable so that the incentive for development and planning of these systems continues.
- National environmental laws and regulations must be globalized because our environment is a global issue rather than an individual nation's problem.
- Although the current development in ECMPRO research is encouraging, it is being conducted in clusters. It is, therefore, necessary that interactions between these research

efforts be studied in order to develop interrelationships and determine the global effect of this field.
- The ECMPRO research should take advantage of the powerful tools available in Industrial Engineering and Operations Research.

Although ECMPRO research is still in its infancy, it is gaining the attention of people in industry, government and academia. The research effort is growing fast. However, from our review of the current state of the research on ECMPRO, we conclude that there is a lack of sufficient analytical research and a lot of work still remains.

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