Use of MCDM techniques in environmentally conscious manufacturing and product recovery: State of the art

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A B S T R A C T

Increasing environmental awareness of customers and stricter environmental regulations by local governments force manufacturers to invest in environmentally conscious manufacturing which involves the application of green principles to all phases of a product's life cycle from conceptual design to final delivery to consumers, and ultimately to the end of life (EOL) disposal. They also setup facilities for product recovery which is the recovery of materials and components from returned or EOL products via disassembly, recycling and remanufacturing. To address these new issues efficiently, multi criteria decision making (MCDM) techniques are used in order to evaluate the economic and environmental indicators. This paper presents over 190 MCDM studies in environmentally conscious manufacturing and product recovery (ECMPRO) by classifying them into three major categories. Insights from the review and future research directions conclude the paper.

Keywords:
Environmentally conscious manufacturing
Product recovery
Multi criteria decision making
Review

1. Introduction

Substantial improvements in the efficiency of the resource use in manufacturing and reduction of the wastes and emissions generated are required in order to not compromise the health and life standards of future generations. As a response to this societal challenge, stricter environmental regulations and new customer requirements oblige firms to invest in environmentally conscious manufacturing which involves the evaluation of environmental performances of all phases in a product's life cycle (i.e., from material selection to end of life processing option). Due to its social, environmental and economic benefits, product recovery through reverse supply chains is also gaining more and more industrial interest [1,2]. Product recovery preserves resources by reducing the consumption of verging raw materials, water and energy. In addition, this process plays a key role in minimizing the amount of waste sent to landfills and diminishing air and water pollution [3,4]. Through recycling, remanufacturing and reuse, product recovery aims to retrieve valuable parts and materials from discarded or end of life (EOL) products.

It had come naturally to firms to evaluate the economic and environmental benefits of such initiatives. Since different kinds of indicators have to be compared in this case, the multi criteria decision making (MCDM) techniques appeared to be the appropriate tools to use. This review presents an analysis of the application of different MCDM techniques in order to help the decision makers implement environmentally conscious manufacturing principles or to engage them in product recovery activities. Over 190 scientific articles published between 1996 and 2014 are concerned by this study.

Fig. 1 presents a global view of a closed-loop supply chain (CLSC). The analysis of the academic literature showed that the topics most addressed with MCDM are green supplier selection and evaluation, disassembly planning, reverse logistics and CLSC design, etc. This is highlighted in Fig. 1 and detailed in Fig. 2 and Table 1.

It was shown in several studies that disassembly is a critical operation in product recovery process since all product disposal options (e.g., recycling, remanufacturing) require the disassembly of EOL products at some level [198–200]. Significant improvements can be achieved in the profitability of product recovery options by effectively planning disassembly process. One of the important disassembly planning problems is the disassembly to order problem which involves the determination of the number of EOL products to process to fulfill a certain demand for products, parts and/or materials under a variety of objectives and constraints.

The MCDM techniques are used both for evaluation and design problems, the major distinction between them is based on whether

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http://dx.doi.org/10.1016/j.jmsy.2015.04.010

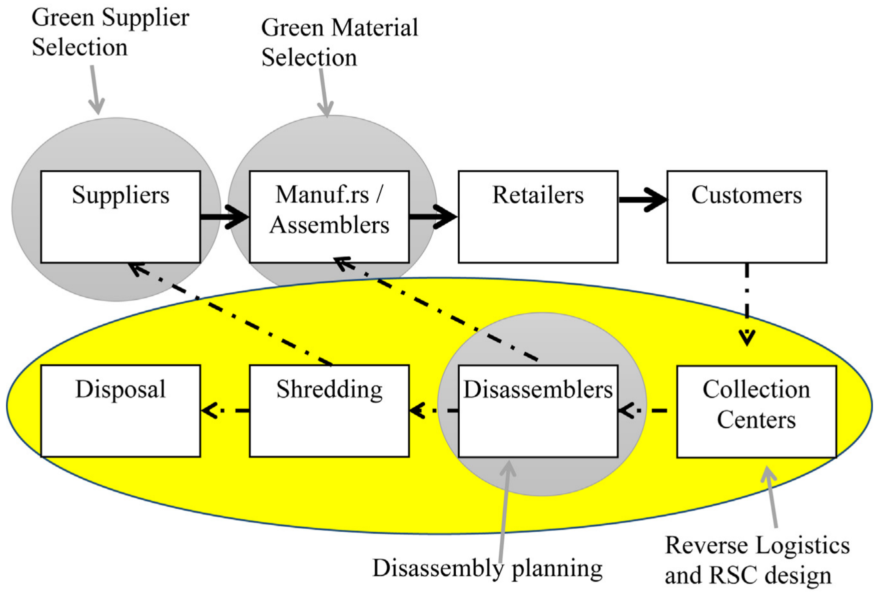

Fig. 1. Closed-loop supply chain.

the solutions/alternatives are explicitly (evaluation problems) or implicitly (design problems) defined. Another criterion of the classification of MCDM techniques is the intervention of the decision maker which can be required a priori (given goals, weights for the objectives), interactive or a posteriori (sorting of given solutions). Based on these observations, the rest of the article is organized in the following way. First, the techniques that are used for searching for new solutions under consideration of multiple optimization objectives are presented in Section 2. This category includes such well known techniques as goal programming and physical programming but also the heuristics and metaheuristics. Section 3 overviews the techniques used for the classification of feasible solutions and Pareto-based ranking. Section 4 overviews the studies implementing both optimization and classification techniques. Finally, concluding remarks are given in Section 5.

2. Multi-objective optimization techniques

These techniques aim at achieving the optimal or aspired goals by considering the various interactions within the given constraints [201].

2.1. Multi-objective linear and non-linear programming

Wang et al. [64] develop a multi-objective mixed-integer programming formulation for a green supply chain network design problem by considering the trade-off between the total cost and the environment influence. They apply the normalized normal constraint method to solve the multi-objective model. Pishvaee and Razmi [70] design an environmental supply chain under uncertainty using multi-objective fuzzy mathematical programming. There are two objectives (viz., minimizing the total cost and minimizing the total environmental impact) and the multi-objective programming model is solved by using ε-constraint method. Ramezani et al. [72] present a stochastic multiobjective model for the design of a forward/reverse supply chain network with the goals of maximization of profit, maximization of responsiveness and minimization of defective parts from suppliers. ε-Constraint method is used to determine a set of Pareto-optimal supply chain configuration. Özkır and Başlıgil [73] propose a fuzzy multi-objective optimization model for the design of a closed-loop supply chain network by considering three objectives: maximizing satisfaction level of trade, maximizing satisfaction degrees of

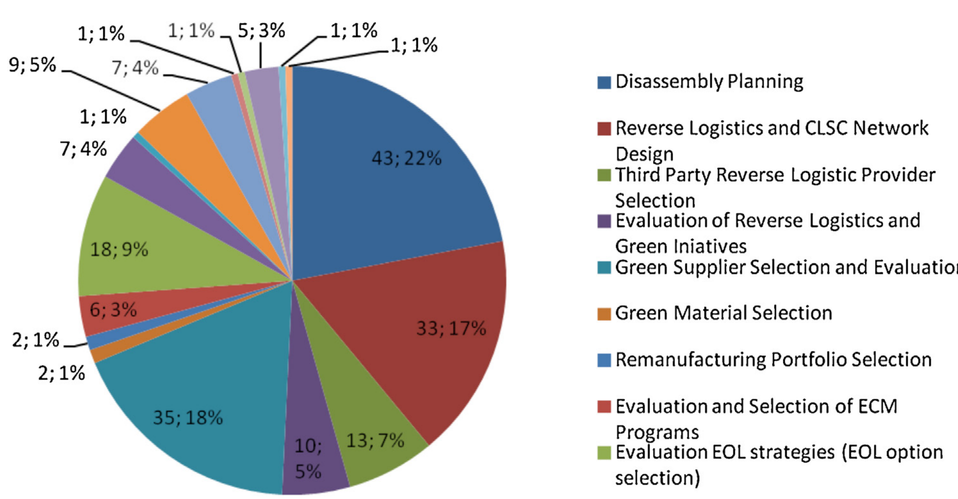

Fig. 2. Main decision and optimization problems addressed in ECMPRO.

Table 1
Classification of references based on ECMPRO issues.

Issue	References
Disassembly planning	Gupta and Taleb [5]; Taleb and Gupta [6]; Zeid et al. [7]; Kongar and Gupta [8]; Gupta and Veerakamolmal [9]; Veerakamolmal and Gupta [10]; Kongar et al. [11]; Lambert and Gupta [12]; Imtanavanich and Gupta [13–17]; McGovern and Gupta [18]; Langella [19]; McGovern and Gupta [20]; Agrawal and Tiwari [21]; McGovern and Gupta [22]; Lu et al. [23]; Kongar and Gupta [24]; Xanthopoulos and Iakovou [25]; Ding et al. [26,27]; Massoud and Gupta [28,29]; Kongar and Gupta [30]; Ondemir and Gupta [31]; Guo et al. [32]; Wang et al. [33]; Avikal et al. [34,35]; Rickli and Camelio [36]; Aydemir-Karadag and Turkbey [37]; Avikal et al. [38]; Ghazilla et al. [39]; Kalayci and Gupta [40–45]; Ondemir and Gupta [46,47].
Reverse logistics and CLSC network design	Pochampally et al. [48]; Pochampally and Gupta [49]; Gupta and Nukala [50]; Nukala and Gupta [51,52]; Pochampally and Gupta [53]; Pochampally et al. [54]; Tuzkaya and Gulsun [55]; Dehghanian and Mansour [56]; Pochampally et al. [57,58]; Barker and Zabinsky [59]; Buyukozkan and Berkol [60]; Harraz and Galal [61]; Chaabane et al. [62]; Sasikumar and Haq [63]; Wang et al. [64]; Paksoy et al. [65]; Jamshidi et al. [66]; Ilgin and Gupta [67]; Pochampally and Gupta [68]; Mehrbod et al. [69]; Pishvaee and Razmi [70]; Samanlioglu [71]; Ramezani et al. [72]; Özkır and Başlıgil [73]; Ozceylan and Paksoy [74,75]; Shokohyar and Mansour [76]; Ghorbani et al. [77]; Mirakhorli [78]; Nurjanni et al. [79]; Wang et al. [80].
Third party reverse logistic provider selection	Meade and Sarkis [81]; Efendigil et al. [82]; Kannan et al. [83]; Saen [84]; Cheng and Lee [85]; Saen [86,87]; Azadi and Saen [88]; Zhou et al. [89]; Ravi [90]; Govindan et al. [91]; Zareinejad and Javanmard [92]; Senthil et al. [93].
Evaluation of reverse logistics and green initiatives	Ravi et al. [94]; Chiou et al. [95]; Sarmiento and Thomas [96]; Büyüközkan and Çiftçi [97]; Chiou et al. [98]; Senthil et al. [99]; Shaverdi et al. [100]; Lin [101]; Wang and Chan [102]; Mangla et al. [103].
Green supplier selection and evaluation	Noci [104]; Handfield et al. [105]; Humphreys et al. [106]; Zhang et al. [107]; Humphreys et al. [108]; Nukala and Gupta [109]; Hsu and Hu [110]; Lu et al. [111]; Yang and Wu [112]; Yu-zhong and Li-yun [113]; Ge [114]; Hsu and Hu [115]; Lee et al. [116]; Li and Zhao [117]; Tuzkaya et al. [118]; Chen et al. [119]; Awasthi et al. [120]; Grisi et al. [121]; Kumar and Jain [122]; Feyzioglu and Büyüközkan [123]; Thongchattu and Siripokapirom [124]; Wen and Chi [125]; Büyüközkan and Çiftçi [126]; Ciftci and Buyukozkan [127]; Shaik and Abdul-Kader [128]; Datta et al. [129]; Dai and Blackhurst [130]; Amin and Zhang [131]; Lee et al. [132]; Govindan et al. [91]; Kuo and Lin [133]; Punniyamoorty et al. [134]; Hsu et al. [135]; Kannan et al. [136]; Shen et al. [137].
Green material selection	Kim et al. [138]; Sakundarini et al. [139].
Remanufacturing portfolio selection	Jiang et al. [140]; Subramoniam et al. [141]
Evaluation and selection of ECM programs	Sarkis [142,143]; Rao [144]; Vinodh et al. [145]; Diabat et al. [146]; Ziout et al. [147].
Evaluation of EOL strategies (EOL option selection)	Lee et al. [148]; Kongar et al. [11]; Hula et al. [149]; Bufardi et al. [150]; Ravi et al. [151]; Kongar and Gupta [152]; Jun et al. [153]; Chan [154]; Chen et al. [155]; Wadhwa et al. [156]; Iakovou et al. [157]; Rao and Padmanabhan [158]; Ghazalli and Murata [159]; Chen et al. [160]; Remery et al. [161]; Mahapatara et al. [162]; Samantra et al. [163]; Dhouib [164].
Evaluation of recycling alternatives and programs	Gupta and Isaacs [165]; Isaacs and Gupta [166]; Boon et al. [167]; Yu et al. [168]; Boon et al. [169]; Gupta and Pochampally [170]; Yeh and Xu [171].
Operational issues in CLSC	Gupta and Evans [172].
Green design	Azzone and Noci [173]; Gungor [174]; Kuo et al. [175]; Choi et al. [176]; Li et al. [177]; Gao et al. [178]; Kuo [179]; Wang et al. [180]; Vinodh et al. [181].
Performance measurement of GSCs	Erol et al. [182]; Hsu et al. [183]; De Felice and Petrillo [184]; Shaik and Abdul-Kader [185]; Bhattacharya et al. [186]; Sangwan [187]; Mirhedayatian et al. [188].
Inventory problems	Bouchery et al. [189].
Evaluation of waste treatment strategies	Bereketli et al. [190].
Other	Walther et al. [191]; Vadde et al. [192]; Wittstruck and Teuteberg [193]; Chern et al. [194]; Liu and Huang [195].
Green supplier development	Dou et al. [196].
Partner selection	Yeh and Chuang [197].

customers and maximizing total closed-loop supply chain profit. The mixed integer programming model proposed by Ozceylan and Paksoy [75] determines the optimum transportation amounts together with the location of plants and retailers by considering multiple periods and multiple parts. The proposed model is based on the minimization of transportation, purchasing, refurbishing and fixed costs and scenario analysis is used to investigate the effect of various parameters (demand, capacity etc.). Ozceylan and Paksoy [74] develop a fuzzy multi-objective linear programming model for the design of a closed-loop supply chain by considering the uncertainty associated with capacity, demand and reverse rates. There are two objectives of the model: minimization of total manufacturing and distribution costs and minimization of total fixed costs of plants and retailers. Mirakhorli [78] proposes an interactive fuzzy multi-objective linear programming model to solve a fuzzy bi-objective (viz., minimization of total cost and minimization of total delivery time) reverse logistics network design problem. Pareto optimal solutions are obtained using weighted sum approach. Nurjanni et al. [79] integrate three scalarization approaches, namely weighted sum method, weighted Tchebycheff and augmented weighted Tchebycheff to solve the mathematical model associated with a closed-loop supply chain network. The model minimizes overall costs and carbon dioxide emissions. Samanlioglu [71] proposes a multi-objective mixed integer model for the location-routing decisions of industrial hazardous material management. Minimization of the total cost, minimization of the total transportation risk and minimization of the total risk for the population around treatment and disposal centers are the objectives of the model and the multi-objective programming model is solved by using lexicographic weighted Tchebycheff method.

Bouchery et al. [189] reformulate the classical economic order quantity model as a multiobjective problem and call it as sustainable order quantity model. They also considered a multi-echelon extension of this model. The set of efficient solutions (Pareto optimal solutions) is analytically characterized for both models. In addition, an interactive procedure helping decision makers in the quick identification of the best option among these solutions is proposed.

2.2. Crisp and fuzzy goal programming

Goal programming is an extension of linear programming due to its ability of handling multiple and often conflicting objectives

[202]. Two variants of goal programming are prevalent in the literature. The first one is known as lexicographic or preemptive goal programming while the second one is termed weighted or non-preemptive goal programming. Preemptive goal programming assumes that all goals can be clearly prioritized and that satisfying a higher priority goal should carry more importance than a lower priority goal. Non-preemptive goal programming assumes that all goals should be pursued. However, in this case, all deviations from the goals are multiplied by some weights (based on their relative importance) and summed up to form a single utility function that is optimized.

Kongar and Gupta [8] present a preemptive integer goal programming model for the disassembly-to-order process so as to satisfy various economical, physical and environmental goals simultaneously. Imtanavanich and Gupta [14] use preemptive goal programming for solving the multi-criteria disassembly-to-order problem under stochastic yields. Massoud and Gupta [29] extend Imtanavanich and Gupta [14] by using preemptive goal programming to solve a similar problem under stochastic yields, limited supply, and quantity discount.

McGovern and Gupta [22] use lexicographic goal programming to solve disassembly line balancing problem which involves the determination of a sequence of parts for removal from an end of life product that minimizes the resources for disassembly and maximizes the automation of the process and the quality of the parts or materials recovered. In Xanthopoulos and Iakovou [25], lexicographic goal programming is employed to determine the most desirable components of an EOL product to be non-destructively disassembled. Ondemir and Gupta [47] develop a lexicographic mixed-integer goal programming model for an advanced remanufacturing-to-order and disassembly-to-order system utilizing the life-cycle data collected, stored and delivered by the Internet of Things.

Goal programming is employed in Gupta and Isaacs [165] to investigate the effect of lightweighting on the dismantler and shredder profitabilities associated with EOL vehicle recycling industry of USA. Isaacs and Gupta [166] propose a goal programming based methodology to explore changes to the current U.S. vehicle recycling infrastructure considering their effects on dismantler and shredder profitabilities. Boon et al. [167] and Boon et al. [169] use goal programming to evaluate the materials streams and process profitabilities for several different aluminum-intensive vehicle (AIV) processing scenarios

Gupta and Evans [172] develop a non-preemptive goal programming model for operational planning of closed-loop supply chains considering multiple products and operations associated with the product, subassembly, part and material levels.

Kongar and Gupta [30] develop a goal programming model of a disassembly-to-order system to determine the best combination of the number of each product type to be taken back at the end-of-life and disassembled to meet the demand for items and materials retrieved from them under a variety of physical, financial and environmental constrains so as to achieve the preemptive goals of maximum total profit, maximum sales from materials, minimum number of disposed items, minimum number of stored items, minimum cost of disposal and minimum cost of preparation, in that order.

Harraz and Galal [61] propose a goal programming based methodology to solve a product recovery network design problem involving the determination of the locations for the different facilities and the amount to be allocated to the different end of life (EOL) options. Chaabane et al. [62] develop a goal programming based sustainable supply chain design methodology by considering carbon emissions, suppliers and sub-contractors selection, total logistics costs, technology acquisition and the choice of transportation modes.

Aspiration levels (goals) are considered concise and precise in goal programming. However, there are many occasions that a decision maker cannot specify the goal values precisely. Fuzzy goal programming takes this uncertainty into consideration by employing the concept of membership functions based on fuzzy set theory [203].

Kongar et al. [11] and Kongar and Gupta [152] use fuzzy goal programming to solve the disassembly-to-order problem defined in Section 1. Mehrbod et al. [69] first develop a multi-objective mixed-integer nonlinear programming formulation for a closed-loop supply chain. Then, this model is solved using interactive fuzzy goal programming (IFGP) which has the ability of addressing the imprecise nature of decision-makers' aspiration levels for goals. Ghorbani et al. [77] develop a fuzzy goal programming model for the design of a reverse logistics network. Imtanavanich and Gupta [13] employ weighted fuzzy goal programming to solve the multi-period DTO problem. Imtanavanich and Gupta [17] integrate genetic algorithms with weighted fuzzy goal programming to solve a similar DTO problem.

2.3. Physical programming

Physical programming uses a preference function to represent the decision maker's preference. In physical programming, DM determines a suitable preference function and specifies ranges of different degrees of desirability (desirable, tolerable, undesirable, etc.) for each criterion. There are eight preference functions classified into 8 classes, 4 soft and 4 hard [12,204].

The analysis of the literature showed that the physical programming approach has been mostly used for the network design of reverse and closed-loop supply chains and for planning problems in disassembly-to-order (DTO) systems.

In Pochampally et al. [48], linear physical programming (LPP) is employed to identify potential facilities from a set of candidate recovery facilities operating in a region by considering several criteria (viz., quality of products at recovery facility, ratio of throughput to supply of used products, multiplication of throughput by disassembly time, and customer service rating of the recovery facility). Pochampally and Gupta [49] develop an LPP-based reverse supply chain design methodology involving three phases. Economical products to be re-processes are selected from a set of candidate cores in phase I. Phase 2 involves the determination of potential recovery facilities using the criteria and classes defined in Pochampally et al. [48]. Phase 3 determines the right mix and quantities of products to be transported in the reverse supply chain. The strategic and tactical planning model developed by Nukala and Gupta [51] determines the following variables simultaneously: the most economical used-product to re-process, efficient production facilities and the right mix and quantity of goods to be transported across the supply chain. Similar models are presented in Pochampally et al. [54,84] and Ilgin and Gupta [67].

Quality function deployment (QFD) and LPP are integrated in Pochampally et al. [57] to measure the "satisfaction level" of a reverse/closed-loop supply chain with respect to various performance measures such as reputation and innovation. Pochampally et al. [58] present a similar model.

An LPP-based methodology for collection center selection problem is presented in Pochampally and Gupta [68] considering eight criteria (viz., sigma level (SL), per capital income of people in residential area (PR), utilization of incentives from local government (UG), distance from residential area (DR), distance from highways (DH), incentives from local government (IG), space cost (SC), labor cost (LC)).

An LPP model is developed in Kongar and Gupta [205] to solve a disassembly to order problem which involves the determination of the number of items to be disassembled for remanufacturing, recycling, storage and disposal. The criteria considered include average customer satisfaction, average quality achievement, resale revenue, recycling revenue, total profit, number of recycled items, average environmental damage, average environmental benefit and number of disposed items. Lambert and Gupta [12] present a similar model. A DTO problem is modeled by Kongar and Gupta [24] considering five goals (number of disposed items, total profit, number of recycled items, environmental damage and customer satisfaction). In Imtanavanich and Gupta [16], LPP is used to solve a multi-period DTO problem. Genetic algorithms and LPP are integrated in Imtanavanich and Gupta [15] to solve a DTO problem. The fitness value of GA is calculated using LPP. A multi-period DTO problem with four objectives (viz., maximization of profit, minimization of procurement cost, minimization of purchase cost and minimization of disposal cost) is solved in Massoud and Gupta [28] by developing an LPP-based solution approach. Optimum disassembly, refurbishment, disposal, recycling and storage plans are determined by the LPP model developed by Ondemir and Gupta [31] for a demand-driven environment utilizing the life-cycle data collected, stored and delivered by sensors and RFID tags. Ondemir and Gupta [46] develop an LPP model to optimize a multi-criteria advanced repair-to-order and disassembly-to-order system involving sensor embedded products.

2.4. Heuristics and metaheuristics

A heuristic can be defined as a technique which seeks or finds good solutions to a difficult model. A meta-heuristic extends the heuristic concept by exploiting ideas and concepts from another discipline to help solve the artificial system being modeled. Genetic algorithms, simulated annealing and tabu search are the most commonly used metaheuristics [206]. In this section, we provide an overview of multi objective heuristic and metaheuristic approaches developed to solve ECMPRO related problems.

Gupta and Taleb [5] and Taleb and Gupta [6] presented a heuristic methodology for disassembling multiple product structures with parts/materials commonality. There are two companion algorithms in this methodology: the “Core Algorithm” and the “Allocation Algorithm”. The total disassembly requirements of the root items over the planning horizon are determined by the “Core Algorithm” and the schedule for disassembling the roots and the subassemblies are provided by “Allocation Algorithm”. Langella [19] extends this methodology by considering holding costs and external procurement of items.

Genetic algorithms (GA) are numerical optimization algorithms inspired by both natural selection and natural genetics. They are generally used to search large, non-linear search spaces where expert knowledge is lacking or difficult to encode and where traditional optimization methods fall short [207]. GAs are by far the most frequently used metaheuristic to solve ECMPRO related problems. Jun et al. [153] develop a multi-objective evolutionary algorithm to determine the best EOL option. In Hula et al. [149], multi objective GA is used to determine the most appropriate EOL option. The green supply chain partner selection problem is solved in Yeh and Chuang [197] by developing two multi objective genetic algorithms. The multi-objective genetic algorithm developed by Sakundarini et al. [139] considers technical, economic and recyclability requirements for the selection of materials with high recyclability. Rickli and Camelio [36] develop a multi-objective genetic algorithm to optimize partial disassembly sequences based on disassembly operation costs, recovery reprocessing costs, revenues and environmental impacts. Chern et al. [194] develop a heuristic called genetic algorithms based master planning algorithm (GAMPA) which solves the master planning problem of a supply chain network involving multiple final products, substitutions, and a recycling process. Liu and Huang [195] use multi objective genetic algoritms to solve two scheduling problems involving economic and environment-related criteria. Wang et al. [80] present an application of multi-objective genetic algorithms in closed-loop supply chain network design.

Besides GAs, researchers have applied several other metaheuristics to ECMPRO related problems. Guo et al. [32] propose a multi-objective scatter search algorithm to solve the selective disassembly problem which involves the determination of optimal disassembly sequences for single or multiple target components. Jamshidi et al. [66] develop a mathematical model for the design of a supply chain by simultaneously considering cost and environmental effect. A memetic algorithm integrated with the Taguchi method is utilized to solve the model.

Disassembly Line Balancing Problem (DLBP) is an important and actively researched problem in ECMPRO (see McGovern and Gupta [208] for more information on DLBP). It is a multi-objective problem as described by Gungor and Gupta [209] and has been mathematically proven to be NP-complete by McGovern and Gupta [20] which makes the desire to achieve the best balance computationally expensive when considering large sized problems. Thus, the need to obtain near optimal solutions efficiently have led various authors to use a variety of heuristic and metaheuristic techniques such as

- genetic algorithms (GA) [20,37],
- ant colony optimization (ACO) [21,41],
- simulated annealing (SA) [43],
- tabu search (TS) [45],
- artificial bee colony (ABC) [42],
- particle swarm optimization (PSO) [40],
- river formation dynamics (RFD) [44].

Battaia and Dolgui [210] and Delorme et al. [211] present an overview of multi-objective approaches developed for the design of assembly and disassembly lines.

2.5. Integration of simulation and optimization techniques

Simulation is generally employed to analyze complex processes or systems. It involves the development and analysis of models that have the ability of imitating the behavior of the system being analyzed [212].

Shokohyar and Mansour [76] deal with the electronic waste management problem of Iran by developing a simulation-optimization model which determines the locations for collection centers and recycling plants. Fuzzy controlled agent based simulation framework proposed by Zhang et al. [107] evaluates the environmental performance of the suppliers.

3. Multi-criteria analysis techniques

While the multi-objective optimization techniques search for new solutions in solution space, multi-criteria analysis techniques consider limited number of predetermined alternatives and discrete preference ratings [201]. In this section, we present such techniques as analytical hierarchy process, fuzzy analytical hierarchy process, analytical network process, data envelopment analysis, DEMATEL, TOPSIS, ELECTRE, PROMETHEE, multi attribute utility theory, VIKOR, MACBETH, case based reasoning, gray relational analysis, and others.

3.1. Analytical hierarchy process

The analytical hierarchy process (AHP) is a multi-criteria decision making tool formalized by Saaty [213]. It uses simple mathematics to support decision makers in explicitly weighing tangible and intangible criteria against each other for the purpose of resolving conflict or setting priorities.

Azzone and Noci [173] use AHP to evaluate the environmental performance of alternative product designs. In Choi et al. [176], the relative importance of five design for environment strategies are compared using AHP. Wang et al. [180] develop an AHP-based green product design selection methodology which does not require the designers to conduct detailed analysis (e.g., life-cycle assessment) for every new product option. Kim et al. [138] employ AHP to evaluate the recycling potential of materials based on environmental and economic factors.

Noci [104] proposes a green vendor rating system using AHP. Handfield et al. [105] develop an AHP-based methodology to assess the relative performance of several suppliers considering environmental issues. Dai and Blackhurst [130] develop a four-phase methodology for sustainable supplier assessment by integrating quality function deployment (QFD) and AHP. First, customer requirements are linked with the company's sustainability strategy. Then the sustainable purchasing competitive priority is determined. Next, sustainable supplier assessment criteria are developed. Finally, AHP is employed to assess the suppliers. Shaik and Abdul-Kader [185] first develop a reverse logistics performance measurement system which is based on balanced score card and performance prism. Then, AHP is integrated with this system to calculate the overall comprehensive performance index (OCPI).

Barker and Zabinsky [59] use sensitivity analysis with AHP to provide insights into the preference ordering among eight alternative reverse logistics network configurations. In Jiang et al. [140], AHP is used for remanufacturing portfolio selection. Ziout et al. [147] develop an AHP-based methodology to evaluate the sustainability level of manufacturing systems. The AHP-based methodology proposed by Sarmiento and Thomas [96] identifies improvement areas in the implementation of green initiatives. Subramoniam et al. [141] use AHP to validate the Reman Decision-Making Framework (RDMF) developed in Subramoniam et al. [214].

3.2. Fuzzy analytical hierarchy process

There are two characteristics of AHP often criticized in the literature: use of unbalanced scale of judgments and its inability to adequately handle the inherent uncertainty and imprecision in the pair-wise comparison process [215]. Fuzzy analytical process which integrates AHP with the concepts of fuzzy set theory is often used by reserachers to overcome these limitations of AHP.

AHP and fuzzy multi attribute decison making are integrated in the environmentally conscious design methodology proposed by Kuo et al. [175]. Li et al. [177] integrate AHP and fuzzy logic to determine an optimal modular formulation in modular product design with environmental considerations.

Yu et al. [168] use fuzzy AHP to determine the most appropriate recycling option for EOL products considering three criteria: environmental impact, recycling associated cost and recoverable material content.

In Lu et al. [111], Lee et al. [116], Grisi et al. [121], Ciftci and Buyukozkan [127] and Amin and Zhang [131], fuzzy AHP is used to integrate environmental factors into supplier evaluation process. Lee et al. [132] propose a fuzzy AHP based approach to determine the most important criteria for green supplier selection in the Taiwanese hand tool industry. In Chiou et al. [95], fuzzy AHP is employed to compare the green supply chain management (GSCM) practices of American, Japanese and Taiwanese electronics manufacturers operating in China. Chiou et al. [98] employ fuzzy AHP to select the most important criteria in reverse logistics implementation. Efendigil et al. [82] present an approach integrating fuzzy AHP and artificial neural Networks for the third party reverse logistics provider selection problem.

Gupta and Nukala [50] use fuzzy AHP to identify potential facilities in a set of candidate recovery facilities operating in a region. Shaverdi et al. [100] employ fuzzy-AHP to determine the effective factors associated with the sustainable supply chain management in publishing industry.

De Felice and Petrillo [184] integrate AHP and simulation to simultaneously improve the performance of inventory management and reverse logistics management.

The approach proposed by Punniyamoorty et al. [134] combines AHP and structural equation modeling (SEM) for the selection of suppliers considering economic as well as environmental factors.

Thongchattu and Siripokapirom [124] model the green supplier selection problem using AHP. Neural Networks are used to determine criteria weights.

3.3. Analytical network process

Analytical network process (ANP) was developed by Saaty [216] as a generalization of AHP. It releases the restrictions of hierarchical AHP structure by modeling the decision problem as an influence network of clusters and nodes contained within the clusters.

ANP is used in Cheng and Lee [85] for investigating the relative importance of service requirements as well as selecting an appropriate third party reverse logistics provider. Meade and Sarkis [81] employ ANP for the evaluation and selection of third party reverse logistics providers. Hsu and Hu [110] and Hsu and Hu [115] integrate hazardous substance management to supplier selection using analytical network process (ANP). Büyüközkan and Çiftçi [97] use fuzzy ANP to evaluate green supply chain management practices of an automotive company. Büyüközkan and Çiftçi [126] propose a fuzzy ANP based methodology for sustainable supplier selection.

Ravi et al. [151] use ANP together with BSC to determine the most suitable EOL option for EOL computers. Chen et al. [160] solve green supply chain management strategy selection problem of a Taiwanese electronics company using ANP.

Sarkis [142] employs ANP to evaluate environmentally conscious business practices. In Vinodh et al. [145], environmentally conscious business practice model proposed by Sarkis [142] is adopted for the evaluation of sustainable business practicess in an Indian relays manufacturing organization. Chen et al. [155] use ANP to evaluate several green supply chain management strategies (viz., green design, green purchasing, green marketing, green manufacturing). Bhattacharya et al. [186] develop an intra-organizational collaborative decision-making (CDM) approach for performance measurement of a green supply chain (GSC) by integrating fuzzy ANP and balanced score card. Tuzkaya and Gulsun [55] integrate ANP with fuzzy TOPSIS to evaluate centralized return centers in a reverse logistics network.

Gungor [174] develops an ANP-based methodology to evaluate connection types in design for disassembly.

Govindan et al. [91] develop a two-phase model for the selection of third party reverse logistics providers. In this model, AHP is employed to identify the most prioritized factors while ANP is used to select the reverse logistic providers.

3.4. Data envelopment analysis

Data envelopment analysis (DEA) is used to evaluate the performance of a set of peer entities called Decision Making Units (DMUs) which convert multiple inputs into multiple outputs [217].

Kumar and Jain [122] develop a DEA model of green supplier selection by considering carbon footprints of suppliers as a necessary dual role factor. Mirhedayatian et al. [188] evaluate the performance of green supply chains by developing a network DEA model involving dual-role factors, undesirable outputs and fuzzy data.

The data envelopment analysis based methodology proposed by Saen [84] determines the most efficient third party reverse logistics (3PL) provider considering quantitative and qualitative data. Saen [86] proposes a DEA based third party reverse logistic provider selection methodology for the case of multiple dual factors while Saen [87] and Azadi and Saen [88] provide 3PL selection models involving both multiple dual factors and imprecise data. Zhou et al. [89] develop a fuzzy confidence DEA model to select third-party recyclers.

Wen and Chi [125] integrate AHP/ANP with DEA for developing a green supplier selection procedure. First, DEA distinguishes the efficient candidates of suppliers from the entire group. Then, AHP/ANP is used for further analysis without making efforts on unnecessary suppliers.

Sarkis [143] integrates ANP and data envelopment analysis (DEA) to evaluate environmentally conscious manufacturing programs. Kuo and Lin [133] develop a methodology by coupling ANP and DEA for green supplier selection.

3.5. DEMATEL

DEMATEL (Decision Making and Evaluation Laboratory) method is used to identify causal relationships among the elements of a system. The main output of this technique is a causal diagram which uses digraphs instead of directionless graphs to describe the contextual relationships and the strengths of influence among the elements [218].

Lin [101] uses fuzzy-DEMATEL to analyze the interrelationships among three issues (green supply chain management practices, organizational performance and external driving factors) associated with green supply chain management implementation.

3.6. TOPSIS

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) determines the best alternative based on the concept of compromise solution which has the shortest distance from the ideal solution and the greatest distance from the negative ideal solution in an Euclidean sense [201].

Gupta and Pochampally [170] propose a fuzzy-TOPSIS based approach for the evaluation of recycling programs with respect to drivers of public participation. Remery et al. [161] propose a TOPSIS-based end of life option selection methodology called ELSEM while Wadhwa et al. [156] use fuzzy TOPSIS for option selection problem in reverse logistics. Gao et al. [178] construct a fuzzy TOPSIS model to evaluate a set of feasible green design alternatives. A fuzzy TOPSIS approach is proposed in Yeh and Xu [171] for the evaluation of alternative recycling activities of a recycling company considering various sustainability criteria with environmental, economic, and social dimensions. Vinodh et al. [181] use fuzzy TOPSIS to determine the best sustainable concept among five sustainable concepts (viz., design for environment, life cycle assessments, environmental conscious quality function deployment, theory of inventive problem solving and life cycle impact assessment). Mahapatara et al. [162] develop a fuzzy TOPSIS methodology to evaluate different reverse manufacturing alternatives (remanufacturing, reselling, repairing, cannibalisation and Refurbishing). Diabat et al. [146] develop a fuzzy-TOPSIS-based methodology to assess the importance of GSCM practices and performances in an automotive company.

Kannan et al. [83] integrate interpretive structural modeling and fuzzy TOPSIS in order to select the best third party reverse logistics provider. Awasthi et al. [120], Govindan et al. [219] and Shen et al. [137] use fuzzy TOPSIS to generate an overall performance score for measuring the environmental performance of suppliers.

Wittstruck and Teuteberg [193] integrate fuzzy AHP and TOPSIS for recycling partner selection. Senthil et al. [99] determine the best reverse logistics operating channel by combining AHP and fuzzy TOPSIS. Wang and Chan [102] integrate fuzzy TOPSIS and AHP for the evaluation of new green initiatives. In Ravi [90] and Senthil et al. [93], AHP-TOPSIS integration is employed for the selection of third party reverse logistics providers.

3.7. ELECTRE

ELECTRE (ELimination Et Choix Traduisant la REalité (in French) which means, elimination and choice expressing reality) performs pair-wise comparisons among alternatives for each one of the attributes separately to establish outranking relationships between the alternatives [220]. These outranking relations are built in such a way that it is possible to compare alternatives. The information required by ELECTRE consists of information among the criteria and information within each criterion [221].

Bufardi et al. [150] employ ELECTRE III for the selection of the best EOL alternative.

3.8. PROMETHEE

PROMETHEE (preference ranking organization method for enrichment evaluation) is a prescriptive method that enables a decision maker to rank the alternatives according to the his/her preferences. It requires a preference function associated with each criterion as well as weights indicating their relative importance. While the PROMETHEE I gives partial ranking of alternatives PROMETHEE II gives a complete ranking [222,223].

Avikal et al. [35] develop a PROMETHEE based methodology for assigning the disassembly tasks to workstations of a disassembly line. Ghazilla et al. [39] use PROMETHEE to evaluate alternative fasteners in design for disassembly.

Avikal et al. [34] solve the disassembly line balancing problem by developing an AHP-TOPSIS based methodology. In the proposed heuristic, the important criteria, which play a significant role in the product disassembly process, are selected. Then AHP is applied to calculate the weight of each criterion. Finally, PROMETHEE uses these weights to determine the ranking of the tasks for the assignment to the disassembly stations. Avikal et al. [38] modify Avikal et al.'s methodology [34] by using fuzzy AHP instead of AHP.

Tuzkaya et al. [118] evaluate the environmental performance of suppliers by developing a methodology that integrates fuzzy ANP and Fuzzy PROMETHEE.

3.9. Multi attribute utility theory (MAUT)

In multi attribute utility theory, decision maker represents a complex problem as a simple hierarchy and subjectively evaluates a large number of quantitative and qualitative factors considering risk and uncertainty. It can be used in both deterministic and stochastic decision environments [224].

Erol et al. [182] integrate fuzzy entropy and fuzzy multi-attribute utility (FMAUT) to measure the sustainability performance of a supply chain. First, fuzzy entropy method is used to determine the importance levels for the indicators. Then, fuzzy MAUT is utilized to calculate the aggregated performance indices with respect to each aspect of sustainability. Shaik and Abdul-Kader [128] present use MAUT to develop an integrated and comprehensive framework for green supplier selection by considering traditional aspects as well as the environmental and the social factors.

3.10. VIKOR

VIKOR (VlseKriterijumskaOptimizacija I KompromisnoResenje (in Serbian), which means multi-criteria optimization and compromise solution) method determines the compromise ranking-list, the compromise solution, and the weight stability intervals for preference stability of the compromise solution obtained with the initial (given) weights. It is especially useful when there are conflicting criteria in the decision problem [225].

Rao [144] proposes a VIKOR-based methodology for the selection of environmentally conscious manufacturing programs.

The green supplier selection and evaluation methodology developed by Datta et al. [129] integrates VIKOR with an interval-valued fuzzy set. Samantra et al. [163] use the methodology proposed in Datta et al. [129] to determine the best product recovery option.

Sasikumar and Haq [63] propose a two-step methodology for the design of a closed-loop supply chain. First, VIKOR is used to select the best third-party reverse logistics provider (3PRLP). Then, a mixed integer linear programming model is developed to make decisions on raw material procurement, production and distribution.

3.11. MACBETH

MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) is a technique similar to AHP. The only difference is that MACBETH uses an interval scale while AHP adopts a ratio scale [226].

Dhouib [164] proposes a fuzzy MACBETH methodology to evaluate options in reverse logistics for waste automobiles tires.

3.12. Case based reasoning

Case based reasoning is based on a memory-centered cognitive model. In this method, a reasoner remembers a previous situation similar to the current one and uses that to solve the new problem [227,228].

Zeid et al. [7] present a CBR-based methodology to determine the disassembly plan of a single product. Extending Zeid et al. [7], Gupta and Veerakamolmal [9] and Veerakamolmal and Gupta [10] develop CBR approaches to automaticaly generate disassembly plans for multiple products.

Humphreys et al. [106] consider environmental factors in supplier selection process by developing a knowledge-based system (KBS) which integrates case-based reasoning (CBR) and decision support components.

Kuo [179] integrates AHP and CBR to simplify the calculation of recyclability index which is used to evaluate the recyclability of an EOL product. Ghazalli and Murata [159] integrate AHP and CBR to evaluate EOL options for parts and components.

3.13. Gray relational analysis

In gray relational analysis, simple mathematical relations are used to deal with uncertain, poor and incomplete information. It solves multi attribute decision making problems by combining the entire range of performance attribute values being considered for every alternative into one, single value [229].

Chan [154] employs gray relational analysis to rank the product EOL options under uncertainty with respect to several criteria at the material level. Li and Zhao [117] integrate threshold method and the gray correlation analysis for the selection of green suppliers. In Chen et al. [119], fuzzy logic and gray relational analysis are integrated to determine suitable suppliers by considering various environment-related criteria.

In Dou et al. [196], analytical network process and gray relational analysis are integrated to determine effective green supplier development programs.

3.14. Other techniques

Zareinejad and Javanmard [92] develop an integrated methodology for third-party reverse logistics provider selection. First, relationships among the attributes are analyzed using analytic network process (ANP). Then, intuitionistic fuzzy set (IFS) and gray relation analysis (GRA) are integrated in order to determine the most suitable third party reverse logistics provider under uncertain conditions.

Hsu et al. [183] develop a balanced score card to measure the sustainable performance in semiconductor industry. Fuzzy Delphi method and ANP are used to identify the related measures and perspectives of sustainable balanced score card activities.

Hsu et al. [135] combine DEMATEL, ANP and VIKOR to solve the recycled material vendor selection problem. First, DEMATEL and ANP are integrated to determine the degrees of influence among the criteria. Then, VIKOR is employed to rank the alternative vendors.

Yang and Wu [112] employ gray entropy method for green supplier selection problem while Yu-zhong and Li-yun [113] solve the same problem using extension method based on entropy weight. Humphreys et al. [108] use dynamic fuzzy membership functions to select green supplies. Feyzioglu and Büyüközkan [123] employ 2-additive Choquet integral to consider criteria dependencies in green supplier evaluation.

Rao and Padmanabhan [158] use digraph and matrix methods for the selection of best product end-of-life scenario. Bereketli et al. [190] evaluate alternative waste treatment strategies for electrical and electronic equipments using fuzzy LINMAP (linear programming technique for multidimensional analysis of preference). Iakovou et al. [157] develop a multi-criteria analysis technique called multi-criteria matrix to rank components according to their potential value at the end of their useful life. In Lee et al. [148], a multi objective methodology has been developed to determine an appropriate end-of-life option for a product based on the minimization of environmental impact and the costs associated with collection, recovery (e.g., remanufacturing, recycling) and disposal. Sangwan [187] develop a multi-criteria performance analysis tool to evaluate the performance of manufacturing systems based on environmental criteria. Mangla et al. [103] use interpretive structural modeling to analyze the interaction among the various green supply chain enablers/barriers (e.g., supplier commitment, cost, regulations).

4. Integration of multi-objective optimization techniques with multi-criteria analysis

This section presents an overview of the studies which integrate the multi-objective optimization techniques with multi-criteria analysis.

Walther et al. [191] present a two-step methodology for the evaluation of alternative scrap treatment systems. First, linear programming or weighted goal programming is used to determine short-term decisions. Then, the results obtained in the first step are used as a priori information for multi-criteria decision making tool, PROMETHEE at strategic level.

Nukala and Gupta [109] employ ANP-GP integration for the supplier selection problem of a closed-loop supply chain. First, the supply chain strategy is determined qualitatively by evaluating the suppliers with respect to several criteria. Then preemptive goal programming taking ANP ratings as input is used to determine the optimal quantities to be ordered from the suppliers.

In Ravi et al. [94], an integrated ANP-GP methodology is used to select reverse logistics projects. Following the determination of the level of interdependence among the criteria and candidate reverse logistics projects using ANP, zero-one goal programming determines the allocation of resources among reverse logistics projects by considering resource limitations and several other selection constraints.

Dehghanian and Mansour [56] integrate AHP and genetic algorithms for the recovery network design of scrap tires. In the proposed methodology, first, AHP is used to calculate social impacts. Then the Pareto-optimal solutions are determined by using a multi-objective genetic algorithm (MOGA).

Vadde et al. [192] analyze the pricing decisions of product recovery facilities by integrating multi-objective mathematical programming, genetic algorithms and AHP. The weights used in the objective function of the genetic algorithm designed to solve the multi-objective mathematical programming model are determined using AHP. Ge [114] integrates GA and AHP for the evaluation of green suppliers.

Pochampally and Gupta [53] develop a three-phase methodology for the effective design of a reverse supply chain network. The most economical product to reprocess from a set of different used products is selected in phase 1 using a fuzzy benefit function. AHP and fuzzy set theory are employed in phase 2 to identify potential facilities in a set of candidate recovery facilities. Phase III solves a single-period and single-product discrete location model to minimize overall cost across the reverse supply chain network.

Nukala and Gupta [52] integrate Taguchi loss functions, AHP and fuzzy programming to evaluate the suppliers and determine the order quantities in a closed-loop supply chain network. First, Taguchi loss functions quantify the suppliers attributes to quality loss. Then AHP is used to transform these quality losses into a variable that is used in the formulation of the fuzzy programming objective function. Finally, fuzzy programming determines the order quantities.

Buyukozkan and Berkol [60] integrate ANP, goal programming and quality function deployment to design a sustainable supply chain. ANP is employed to determine the importance levels in the house of qualiy by considering the interrelationships among the design requirements and customer requirements while zero-one goal programming is used to select the most suitable design requirements based on ANP results.

Paksoy et al. [65] first propose a fuzzy programming model with multiple objectives for the design of a closed-loop supply chain network. Then, various multi criteria techniques (viz., AHP, fuzzy AHP and fuzzy TOPSIS) are applied to weight the objectives and the corresponding results are discussed.

Kannan et al. [136] propose an integrated approach for supplier selection and order allocation in a green supply chain. First, the relative weights of supplier selection criteria are calculated using fuzzy AHP; then, fuzzy TOPSIS is employed to rank suppliers based on the selected criteria. Finally, MOLP model determines the optimal order quantity from each supplier using the weights of the criteria and ranks of suppliers.

5. Conclusions

In this paper, we presented a review of the state of the art literature on the use of multi-criteria decision making techniques in environmentally conscious manufacturing and product recovery (ECMPRO). The MCDM techniques were presented by category, i.e.; multi-objective optimization, multi-criteria analysis and the integration between them. The following general conclusions can be drawn from our literature review.

Since ECMPRO initiatives have economic and environmental consequences, majority of the studies simultaneously consider economic and environmental criteria. The most commonly used environmental criteria include green product design, reduction of material and energy use, use of environment friendly technology, pollution control, environmental management system, green purchasing, green packaging and hazardous substance management system.

There is a significant increase in the number of publications concerning the use of MCDM techniques for ECMPRO problems in recent years. This can be attributed to the increasing popularity of environmental issues among researchers.

Multi-criteria analysis is more popular than multi-objective optimization in ECMPRO. Among the most frequently used techniques, one can find AHP, ANP and TOPSIS. On the other hand, the use of other techniques as MACBETH, DEMATEL, ELECTRE, PROMETHEE is surprisingly rare.

Although simulation is very good at modeling complex systems, its integration with MCDM techniques for the solution of ECMPRO related problems is limited to a few studies. Hence, there are opportunities to develop multi objective solution methodologies integrating simulation with qualitative and/or quantitative MCDM techniques to solve complex ECMPRO issues such as disassembly planning, reverse logistics and CLSC design.

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