A Multi-Objective Decision Making Model for Remanufacture-To-Order System

Surendra M. Gupta
(with contributions from Aditi Joshi and Ammar Alqahtani)
Laboratory for Responsible Manufacturing (LRM)
Department of Mechanical and Industrial Engineering
Northeastern University
Boston, MA 02115, U.S.A.

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Background

- Rapid advancement in product technology has led to shorter product life cycles and premature disposal of products.
- This has resulted in the dramatic decrease of natural resources and an alarming decrease in the number of landfill sites.
- As a remedy for these problems, local governments are imposing stricter environmental regulations.
- In order to comply with these regulations, firms invest in environmentally conscious manufacturing in all phases in a product's life cycle (i.e., from conceptual design to end of life processing).
- They also set up specific facilities for product recovery.

Product Recovery

- Product Recovery aims to minimize the amount of waste sent to landfills by recovering materials and parts from old or outdated products by means of recycling and remanufacturing (including reuse of parts and products)

Reasons Companies get involved in Product Recovery

- Legislation
- Profitability
- Environmental concerns and sustainability

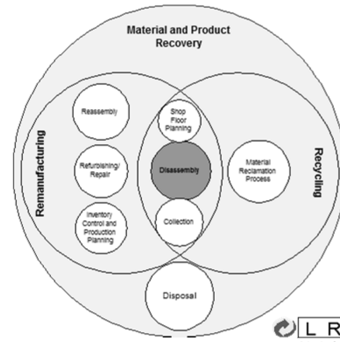
Choices in Product Recovery

- Recycling
  - Definition: Recycling is the process of recovering the material content of end-of-life (EOL) products by performing the necessary disassembly, sorting and chemical operations
  - Identities of parts of EOL products are lost
- Remanufacturing
  - Definition: Remanufacturing is the process of performing the required disassembly, sorting, refurbishing and assembly operations in order to bring parts of an EOL product (or the entire product) to a desired level of quality
  - Identities of parts of EOL products are not lost

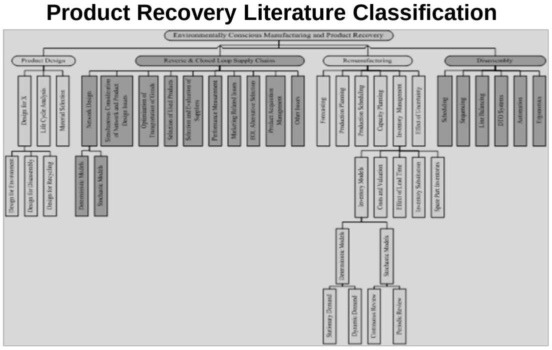
Disassembly

- Definition: Disassembly is a systematic method for separating a product into its constituent parts, components, subassemblies, or other groupings.
- It may be partial, i.e., product is not fully disassembled; or
- It may be complete, i.e., product is fully disassembled.
- It may be done destructively using operations such as cutting, and crushing etc.; or
- It may be carried-out non-destructively using operations such as un-screwing, and un-snapping etc.

Components of Product Recovery



Environmentally Conscious Manufacturing and Product Recovery Literature Classification



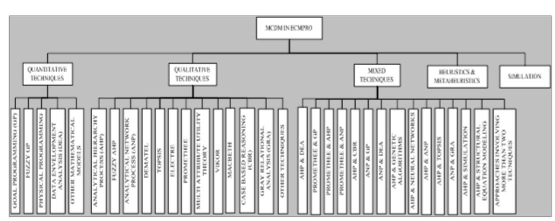
Multi Criteria Decision Making Techniques

- In order to solve the problems associated with environment conscious manufacturing and product recovery (ECMPRO), researchers have developed various algorithms, models, heuristics, and software.
- Among them, multi criteria decision making techniques have played an important part since those techniques can simultaneously consider more than one objective.
- Moreover, they are very good at modeling conflicting objectives, a common characteristic of ECMPRO issues (e.g., maximization of revenue from product recovery operations vs. minimization of environmental consequences of those operations).

MCDM Techniques used in ECMPRO

- Quantitative Techniques
  - Goal Programming and Fuzzy Goal Programming
  - Physical Programming
  - Data Envelopment Analysis
- Qualitative Techniques
  - AHP, Fuzzy AHP, ANP
  - TOPSIS, ELECTRE, PROMETHEE, VIKOR, MACBETH, DEMATEL, Case Based Reasoning, Gray Relational Analysis
- Mixed Techniques
  - Integration of Two or More MCDM Techniques
- Heuristic and Metaheuristic Techniques
- Simulation

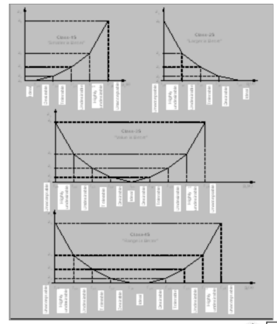
Classification of MCDM Techniques used to Solve ECMPRO Issues



Linear Physical Programming (LPP)

- LPP has the ability to avoid the weight assignment by providing a preference function.
- DM determines a suitable preference function and specifies ranges of different degrees of desirability (ideal, desirable, tolerable, undesirable, highly undesirable, and unacceptable) for each criterion. There are eight preference functions classified into 8 classes, 4 soft and 4 hard.

Linear Physical Programming



Remanufacturing-To-Order System

- RTO system disassembles, remanufactures and recycles EOL products to meet the products, components and materials demands.
- Outside procurement is considered to avoid back-orders.
- Disassembly can be destructive or non-destructive.
- All the data stored on EOL products is retrieved using sensor readers when they arrive at the product recovery facility.

LPP Model

- The objectives of the proposed RTO system are: minimizing the total cost, minimizing the disposal weight, maximizing the quality level and maximizing the material sales revenue. The system is formulated using LPP as follows:
- Objective Function
- The LP objective function is written as:
- minϕ = $\sum_{u \in U} \sum_{s \in \{2,3,4,5\}} (\omega_{us}^{+} d_{us}^{+} + \omega_{us}^{-} d_{us}^{-})$

LPP Model (cont.)

- Smaller-is-better (Class 1-S):
- Total Cost (TC)(g1): Total cost is written as the sum of total disassembly cost (TDC), total remanufacturing cost (TRMC), total recycling cost (TRC), and total outside procurement cost (TOPC).

$$g_1 = TC = TDC + TRMC + TRC + TOPC$$

Where,

$$TDC = \sum_{i \in I} [x_i \sum_{j \in J} ((1 - el_{ij}) * a_{ij} cd_j + f_{ij} cb) + xd_i cb \sum_{j \in J} (a_{ij} + el_{ij})]$$

$$TRMC = \sum_{i,j \in J} [y_i cb(f_{ij} + el_{ij}) + cd_j \sum_{b \in B} rm_{ijb} + ca_j \sum_{t \in T, m \in M} y_{itm} (def_{itmj} + mis_{itj})]$$

LPP Model (cont.)

$$TRC = cr_j \sum_{j \in J} (rb_j + \sum_{b \in B} r_{jb})$$

$$TOPC = \sum_{j \in J, b \in B} c_{jb} l_{jb}$$

- Disposal Weight (DW) (g2): the disposal weight is given as:

$$g_2 = DW = \sum f_{ij} * (1 - PRC_j) * w_j$$

LPP Model (cont.)

- **Class2-S: Larger-is-better**

- **Quality level (Q) (g3): The quality level is given as:**

$$g_3 = Q = \sum_{i \in I, j \in J, b \in B} a_{ij}(\beta - b)$$

- **Material sales revenue (*MSR*) (g_4): The material sales revenue is given as:**

$$g_4 = MSR = \sum_{k \in K} prc_k (dm_k + sm_k)$$

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LPP Model (cont.)

- **System Constraints:**

- **All constraints of the system belong to hard classes.**

$$\overline{x_i} + xd_i + \overline{y}_i \le 1 \qquad \forall i$$

$$\sum_{b \in B} x_{ijb} = (1 - el_{ij}) a_{ij} \overline{x_i} \qquad \forall i, j$$

$$\sum_{\{b \in B | cin_{ijb} = 0\}} x_{ijb} = 0 \qquad \forall i, j, b$$

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LPP Model (cont.)

$$\sum_{t \in T, m \in M} y_{itm} = \overline{y_i} \qquad \forall i$$

$$\sum_{i \in I} y_{itm} = dp_{tm} \qquad \forall t, m$$

$$\sum_{i \in I} [a_{ij} x_{ijb} + rm_{ijb} - \sum_{t \in T, m \in M} rep_{itmjb}] + l_{jb} - r_{jb} \qquad \forall j, b$$

Where,

$$\sum_{\{b \in B | cin_{ijb} = 0\}} rm_{ijb} = (1 - el_{ij}) \sum_{t, m \in M} y_{itm} (def_{itmj} + ext_{itj}) \qquad \forall i, j$$

$$\sum_{\{b \in B | cin_{ijb} = 0\}} rm_{ijb} = 0 \qquad \forall j, b$$

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LPP Model (cont.)

$$\sum_{\{b \in B | b \ge m\}} rep_{itmjb} = y_{itm} (mis_{itj} + def_{itj}) \qquad \forall i, j, t, m$$

$$\sum_{\{b \in B | b < m\}} rep_{itmjb} = 0 \qquad \forall i, j, t, m$$

$$\sum_{j \in J} \gamma_{jk} (rb_j + \sum_{b \in B} r_{jb}) \ge dm_k \qquad \forall k$$

$$\alpha \sum_{i \in I} (f_{ij} + el_{ij})(\overline{x_i} + \overline{y_i}) \le rb_j \le \sum_{i \in I} (f_{ij} + el_{ij})(\overline{x_i} + \overline{y_i}) \qquad \forall j$$

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Numerical Example

- **10 different configurations of the products are available and each configuration deals with 6-10 components.**
- **The quality level of a component is defined by the remaining life of that component.**
- **Based on this remaining life, components are divided into three life-bins.**
- **The first life-bin holds components whose remaining life is at least one year. The second life-bin holds components whose remaining life is at least three years. The third life-bin holds components with remaining life of five years or more.**
- **The components with remaining life of less than one year are treated as nonfunctional.**

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Numerical Example (cont.)

Configurations of the Product types

Product types	Components									
	1	2	3	4	5	6	7	8	9	10
1	X	X	X	X	X	X	X	X		
2	X	X	X	X				X	X	X
3			X	X	X	X	X	X	X	X
4	X	X	X	X	X	X	X	X	X	X
5	X	X	X	X					X	X
6	X	X		X	X	X	X	X	X	X
7		X	X	X	X	X	X	X	X	X
8	X	X	X				X	X	X	X
9	X	X	X	X			X	X	X	X
10	X		X	X		X	X	X	X	X

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Numerical Example (cont.)

Remaining lives of components

EOL product	Components									
	1	2	3	4	5	6	7	8	9	10
1	4.35	NF	5.05	3.45	-	-	-	3.29	3.11	5.96
2	4.67	2.86	-	5.03	1.31	6.57	NF	3.38	NF	6.58
3	3.03	4.30	2.63	7.58	-	-	-	-	NF	NF
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
399	3.07	3.58	4.74	NF	-	-	4.88	4.07	1.75	4.62
400	3.15	3.99	6.01	2.43	-	-	3.64	5.27	NF	4.43

Numerical Example (cont.)

Components Demands

Component	Remaining Life Bins		
	Bin1	Bin2	Bin3
1	20	22	17
2	16	12	15
3	22	22	8
4	31	20	14
5	15	31	16
6	26	33	19
7	35	33	15
8	14	17	14
9	26	23	17
10	29	25	12

Numerical Example (cont.)

Products Demands

Product types	Remaining Life Bins		
	Bin1	Bin2	Bin3
1	6	4	8
2	6	4	10
3	12	10	8
4	12	2	8
5	10	0	6
6	2	6	8
7	10	8	10
8	6	10	12
9	6	6	8
10	4	10	8

Numerical Example (cont.)

Procurement, disassembly, assembly, recycling costs and material yields

Component	Procurement cost			Disassembly cost	Assembly cost	Recycling cost	Material A yield	Material B yield
	Bin1	Bin2	Bin3					
1	20	40	50	1.5	1.5	0.1	1	0
2	40	30	60	1.5	1.5	0.1	1	0
3	60	70	75	1.5	1.5	0.1	1	0
4	15	20	25	0.5	0.5	0.1	0	1.5
5	15	20	25	0.5	0.5	0.1	0	1.5
6	15	20	25	0.5	0.5	0.1	0	1.5
7	12	18	24	2	2	0.2	1.5	0
8	18	22	26	2	2	0.2	1.5	0
9	22	24	30	2	2	0.2	1.5	0
10	24	30	32	2	2	0.2	1.5	0

Numerical Example (cont.)

Desirable ranges for each criterion

	Total Cost	Disposal Weight	Quality Level	Material Sales Revenue
Ideal	≤5900	≤0	≥1990	≥6500
Desirable	(5900,6200]	(0,21]	[1850,1990)	[5400,6500)
Tolerable	(6200,7100]	(21,35]	[1200,1850)	[4200,5500)
Undesirable	(7100,8000]	(35,49]	[700,1200)	[2900,4200)
Highly Undesirable	(8000,9500]	(49,65]	[0,700)	[2300,2900)
Unacceptable	>9500	>65	<0	<2300

Results

- Linear physical programming weight (LPPW) algorithm was coded and run using MATLAB.
- Using the weights calculated, the mathematical model was constructed and solved using LINGO 13.0.
- 170 EOL products were disassembled to meet the components demands, 15 EOL products were disassembled destructively to obtain parts for recycling, 200 EOL products were remanufactured to meet the products demands and rest were left untouched.

Results (cont.)

Quality level bin in which disassembled components are placed

EOL product	Components									
	1	2	3	4	5	6	7	8	9	10
1	1	-	3	2	-	-	-	2	1	3
2	1	1	-	3	1	3	-	2	-	3
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
398	1	1	2	-	-	-	-	3	3	2
400	2	2	3	1	-	-	2	3	-	1

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Results (cont.)

Product types and quality levels of remanufactured EOL products

EOL product	Product type	Quality level
4	1	2
6	3	3
7	8	3
. . .	. . .	. . .
395	5	3
399	4	1

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Results (cont.)

Aspiration levels and values of criteria

Description	Aspiration levels	Value
Total Cost	Desirable	6050.13
Disposal Weight	Highly Undesirable	51.71
Quality Level	Undesirable	903
Material Sales Revenue	Tolerable	4623.89

The total cost fell under “Desirable” range, disposal weight under “Highly Undesirable” range, quality level under “Undesirable” range and material sales revenue under “Tolerable” range.

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Topical Areas of Some of Our Recent Work

- Design for Disassembly
- Disassembly Sequencing
- Disassembly-To-Order System
- Disassembly Line Balancing Problem
- Modified Kanban System for Disassembly
- Inventory Issues Stemming from Disassembly
- Optimal Buffer Allocation in Remanufacturing Systems
- Economic Analysis of US Automobile Recycling Infrastructure
- Strategic Planning Models for Reverse and Closed-Loop Supply Chains
- Sensors Embedded Products to Tackle Reverse Logistics Related Problems
- Solving Sequence-Dependent Disassembly Line Balancing Problem using Heuristics

Some of the Techniques Employed

Analytic Hierarchy Process
Analytic Network Process
Bayesian Updating
Borda's Choice Rule
Case-Based Reasoning
Cost-Benefit Function
Digital Simulation
Eigen Vector Method
Extent Analysis Method
Fuzzy Logic
Genetic Algorithm
Goal Programming
Graph Theory
Heuristics and Metaheuristics
JIT Philosophy
Linear Integer Programming
Linear Physical Programming
Mathematical Programming
Method of Total Preferences
MRP Techniques
Multi-Criteria Optimization
Neural Networks
Petri-Nets
Quality Function Deployment
Queueing Theory
Reliability Models
Sensitivity Analysis
Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
Theory of Constraints

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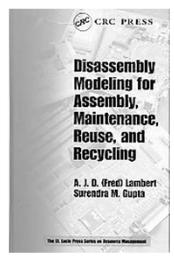

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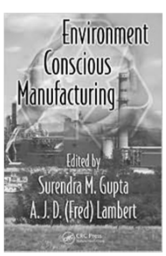

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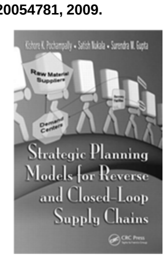

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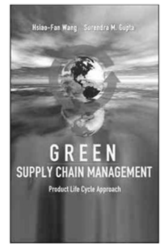

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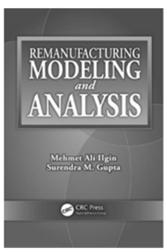

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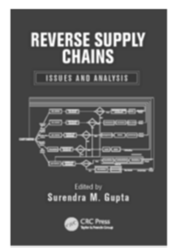

Additional Reading (forthcoming)

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Contact Information

Dr. Surendra M. Gupta, P.E.

Professor of Mechanical and Industrial Engineering and
Director of Laboratory for Responsible Manufacturing

334 SN, Department of MIE
Northeastern University
360 Huntington Avenue
Boston, MA 02115, U.S.A.

(617)-373-4846 Phone
(617)-373-2921 Fax
gupta@neu.edu E-mail.

http://www.coe.neu.edu/~smgupta/ Home Page

Thank you!