Management of End of Life Products with Design Alternatives

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Abstract : This paper considers a product recovery facility which receives sensors and Radio Frequency Identification (RFID) tags embedded End-Of-Life (EOL) products. Sensors and RFID tags acquire components' dynamic and static life cycle data during their economic lives. The captured life cycle data provides information about products' contents and conditions. The information also helps to determine the remaining lives of products and components which are then translated into quality levels. The example considered here presents an advanced-repair-to-order-disassembly-to-order system. It disassembles the components to meet the components' demands, repairs the products to meet the products' demands and recycles the materials to meet the materials' demands. The received EOL products may have different design alternatives. The EOL product of any design can be utilized to fulfill the components', products', and materials' demands. The objective of the proposed goal programming model is to determine how to process the EOL products in order to meet the components products' and materials' demands.

Key Words : Reverse supply chain, Sensor embedded products, Design alternatives, Goal programming

1. Introduction

Original Equipment Manufacturers (OEMs) are encouraging the implementation of product recovery techniques due to the strict environmental regulations and public awareness. OEMs are often required by law to take responsibility of their products when they reach their End-Of-Lives (EOLs), which has fueled the importance of Reverse Supply Chains (RSCs). RSC involves collection, transportation and management of EOL products. Appropriate management of EOL products leads to reduction in the use of virgin resources, decrease in the use of landfills and cost savings from the reuse of EOL products, disassembled components and recycled materials.

The management of EOL products may involve choosing between direct reuse, repair, remanufacturing, recycling, or disposal. Direct reuse involves the reuse of the whole product as is for its original task. In repair option, damaged parts are changed in order to have a fully functional product. Remanufacturing consists of refurbishment of used products up to a quality level similar to a new product. The aim of recycling is to recover materials from the returned products. Disposal involves the landfill or incineration of the used products. Out of these, disposal is the least desirable option.

All these options may require some disassembly. Disassembly comprises the separation of the desired components, subassemblies, and materials from EOL products.

Disassembly is also useful in collecting information about the quality and quantity of EOL products so that appropriate decisions could be taken.

Most of the real world decision making problems are inherently multi-objective with conflicting criteria. There are various tools for solving Multi-Criteria Decision Making (MCDM) problems e.g. Goal Programming (GP), Linear Physical Programming (LPP), Analytic Hierarchy Process (AHP) etc. GP is one of the most commonly used multi-criteria decision making technique. This paper uses GP for determining the best strategy for management of EOL products with different design alternatives. Manufacturers produce products using various design alternatives. The number and types of components, materials used, their assembly and size can differ among these design alternatives. A company will select only those EOL products for which certain criteria are met including criteria related to costs, quality and amount of disposal.

The EOL products referred to in this paper have sensors and Radio Frequency Identification (RFID) tags embedded in them. A sensor is a device that detects the value or change in values of measurements such as temperature, pressure etc. which can be converted into some useful and meaningful life cycle related data. A Sensor Embedded Product (SEP) contains such sensors which monitor the product's use cycle and record its life cycle data. The sensors record dynamic data while the product is in use and provide information about patterns of usage, number of use cycles, run time in each use cycle, environmental conditions, service history about inspections and replaced and repaired parts. RFID tag is a product identification and tracking device. An RFID system is composed of mainly two parts, readers and tags. The tags are attached to the products, and the readers generate signals to provide

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power for a tag and to create an interrogation signal. The tag contains static information about the product such as name, manufacturer, stock keeping unit number, cost, sale date, make and model, disassembly sequence, and bill of materials. This information can be updated after every maintenance upgrade and repair. RFID tags and sensors are used together to retrieve static as well as dynamic data. Products embedded with these tags are called Combined Intelligent Products (CIPs). The product life cycle data obtained from sensors and RFID tags is used to estimate the remaining life times of components and products which enable decision makers to optimally determine what to do with each EOL component or product so that the desired demands are satisfied.

2. Literature Review

This section briefly reviews the literature related to the topic areas covered in this paper. There are two important review papers that are available in the literature and are directly related to the subject area of this paper. The first one is the state of the art survey paper by Gungor and Gupta (1999) covering papers in Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) published through 1998. The second one is also the state of the art survey paper in the same area covering papers published between 1998 and 2010 by Ilgin and Gupta (2010b). Together, they classified more than 870 papers (330 and 540 respectively) under four main categories, viz. environmentally conscious product design, reverse and closed-loop supply chains, remanufacturing and disassembly.

2.1 Disassembly

The main problem scholars face during disassembly is 'how much and in what order to disassemble' in order to fulfill components demands. To favor the ease of disassembly at the product's EOL, it is crucial to consider disassembly during the design phase of the product. Germani et al. (2014) proposed an approach to analytically calculate the disassembly time and cost of components and sub-assemblies. The authors also presented a case study to demonstrate the usefulness of the proposed approach.

Veerakamolmal and Gupta (2000) defined Design for Disassembly (DfD) as the ease of disassembly in the design process. Kroll and Hanft (1998) presented a method for evaluating ease of disassembly. Veerakamolmal and Gupta (1999) introduced a Design for Disassembly Index (DfDI) to measure the disassembly efficiency of a design. A disassembly tree identifies precedence relationships which define the structural constraints of the order in which components can be retrieved. DfDI is calculated by using this disassembly tree.

2.2 Selection of components

Ilgin and Gupta (2012) in their book presented a chapter on selection of used products. They considered the used product selection issue and illustrated it using two models. The first model illustrated a scenario in which classical constraints are used to present the evaluation criteria while the second model illustrated a scenario where ranges of different degrees of desirability are employed.

2.3 Sensors and RFID tags embedded products

Ilgin and Gupta (2011a) investigated the performance improvement potential of SEP in environmental supply chains. A discrete event simulation analysis was conducted on sensor embedded and non-sensor embedded products. Using paired-t-test on various performance measures, it was shown that sensor embedded products are better off in terms of costs and revenues. Ilgin and Gupta (2011b, 2011c) investigated sensor embedded air conditioner and washing machine disassembly lines with disassembly precedence relationships of components. Ilgin et al. (2011) performed a rigorous design of experiments study in order to investigate how beneficial the sensors embedded products are in a remanufacturing environment under uncertainty. Yang et al. (2009) demonstrated that sensor embedded products can enable suitable product related services including EOL recovery. Ngai and Riggins (2008) presented an academic literature review on RFID research activities by reviewing and classifying 85 papers published between 1995 and 2005. Kulkarni et al. (2005) examined the benefits of information provided by RFID tagged systems in decision making during product recovery stages.

Ondemir and Gupta (2008) developed a mathematical model that utilizes product life cycle data and remaining life estimates to fulfill the components demands that have a certain remaining life. Ondemir et al. (2012) extended the study to manage products demands as well. Ondemir and Gupta (2009) presented economic justification of establishing advanced disassembly-to-order systems in which sensor embedded EOL products are disassembled to fulfill demands for components and materials.

2.4 Multi-criteria decision making and goal programming

Ilgin et al. (2015) presented a state of the art review paper on the use of MCDM techniques in the field of environmentally conscious manufacturing and product recovery. The authors classified over 190 MCDM studies in environmentally conscious manufacturing and product recovery into three categories: multi-objective optimization, multi-criteria analysis and integration between them.

GP was first introduced by Charnes and Cooper (1961), although its first application was presented by Charnes et al. (1955). Schniederjans (1995) and Jones and Tamiz (2002) presented extensive literature reviews of GP. The book by Jones and Tamiz (2010) on GP can be referred for more detailed information about GP.

Kongar and Gupta (2002) presented a single period integer GP model for electronic products to determine the best possible combinations of multiple products to meet the items and materials demands while achieving the goals of maximum total profit, maximum material sales, minimum number of disposed items, minimum number of stored items, minimum cost of disposal and minimum cost of preparation. Kongar and Gupta (2006) extended Kongar and Gupta's (2002) method by using fuzzy GP to model the fuzzy aspirations of numerous goals. Imtavanich and Gupta (2006) used the heuristics developed by Inderfurth and Langella (2006) to handle the stochastic elements of disassembly to order system. They also proposed a GP

model to determine the number of returned products that satisfy the goals.

3. ARTODTO System

An Advanced-Repair-To-Order-Disassembly-To-Order (ARTODTO) system receives sensors and RFID tags embedded EOL products. Sensors embedded in the products and RFID tags attached to the products capture the dynamic and static life cycle data respectively. Once the EOL product is received, all the captured data is stored in a database. The critical information about remaining lives of components is determined by means of this life cycle data and data retrieval mechanisms. Based on the remaining lives of components, they are divided into different life bins. For example, life bin 1 may contain components of remaining lives between one and three years, life bin 2 may contain components of remaining lives between three and five years and life bin 3 may contain components of remaining lives of at least five years. Figure 1 illustrates the flowchart of an ARTODTO system. Once the EOL products are received, some products are repaired to meet the products demands. Some products are disassembled and the conditions of the components are determined. The disassembled components can be operable or non-operable. The operable components are used to meet the components demands while the non-operable components are either recycled to meet the materials demands or are disposed of.

4. Nomenclature

Variable	Definition
DW	Disposal weight;
MV	Material value;
Q	Quality level;
TC	Total cost;
TDC	Total disassembly cost;
$TDIC$	Total disposal cost;
THC	Total holding cost;
$TOPC$	Total outside procurement cost;
TRC	Total recycling cost;
$TRPC$	Total repair cost;
$cdis_{jb}$	Parameter taking the value 1 if component j in remaining life bin b is disposed of;
dt^-	Negative deviation from the t^{th} goal, $t=1,2,3,4$;
dt^+	Positive deviation from the t^{th} goal, $t=1,2,3,4$;
def_{ijb}	1 if component j in EOL product i is disassembled because of remaining life deficiency and placed in remaining-life-bin b during repair, zero otherwise;
fd_j	Number of nonfunctional components js that are disposed of;
fr_j	Number of nonfunctional components js that are recycled;
l_{jb}	Number of components js purchased for remaining-life-bin;
r_{jb}	Number of components js in remaining-life-bin b that are recycled;
rep_{imjb}	1 if a component j from life-bin b needs to be used to repair EOL product i in order to make a product for life-bin m , zero otherwise;

Variable	Definition
rp_{ij}	1 if component j in EOL product i is disassembled during repair, zero otherwise;
s_i	1 if EOL product i is stored, zero otherwise;
sc_{jb}	Number of components js in remaining-life-bin b that are stored;
sm_k	Amount of material k stored;
w_i	1 if EOL product i is recycled, zero otherwise;
x_i	1 if EOL product i is disassembled for components, zero otherwise;
x_{ijb}	1 if component j in EOL product i is disassembled and placed in remaining-life-bin b , zero otherwise;
y_i	1 if EOL product i is repaired, zero otherwise;
y_{im}	1 if EOL product i repaired to make a product for remaining-life-bin m , zero otherwise;
z_i	1 if EOL product i is disposed of, zero otherwise;

Parameter	Definition
I	Set of EOL products on hand;
B	Set of remaining-life-bins (for components);
J	Set of components dealt with;
M	Alias for B (for products);
K	Set of materials dealt with;
b,i,j,k,m	Running numbers;
a_{ij}	1 if component j of EOL product i is functional, zero otherwise;
β_{ij}	Highest life bin a component can be placed in;
ca_{jb}	Outside procurement cost of a component j for life-bin b ;
ca_j	Assembly cost of a component j ;
cd_j	Disassembly cost of a component j ;
cds_j	Disposal cost of a component j ;
ch_j	Holding cost of a component j ;
crc_j	Recycling cost of a component j ;
dc_{jb}	Demand for component j in remaining-life-bin b ;
dp_m	Demand for product in remaining-life-bin m ;
dm_k	Demand for material k ;
fi_j	1 if component j of EOL product i is non-functional, zero otherwise;
h	Unit EOL product holding cost;
mh_k	Unit holding cost for material k ;
mis_{ij}	Binary parameter taking 1 if component j is missing in EOL product i , zero otherwise;
prc_k	Unit sales price of material k ;
ω_j	Weight of a component j ;

5. Problem Formulation

The ARTODTO system receives EOL products with multiple design alternatives. The system is evaluated based on four criteria. This multi-criteria decision making problem is formulated using GP. The four criteria considered here are referred to as goals and are listed below in the order of priorities:

Goals:

1. Total cost
2. Quality level
3. Material value (value of the amount of material sold and amount of material sent to storage)
4. Disposal weight

1. The first goal to minimize the total cost (TC) is formulated as follows:

Goal: minimize d_1^+

$$\text{Subject to: } TC + d_1^- - d_1^+ = TC^* \quad (1)$$

Fig. 1 ARTODTO system

2. The second goal to maximize the quality level (Q) is formulated as follows:

Goal: minimize d_2^-

$$\text{Subject to: } Q + d_2^- - d_2^+ = Q^* \quad (2)$$

3. The third goal to maximize the material value (MV) is formulated as follows:

Goal: minimize d_3^-

$$\text{Subject to: } MV + d_3^- - d_3^+ = MV^* \quad (3)$$

4. The fourth goal to minimize the total disposal weight (DW) is formulated as follows:

Goal: minimize d_4^+

$$\text{Subject to: } DW + d_4^- - d_4^+ = DW^* \quad (4)$$

where,

1. Total Cost: The total cost (TC) is the sum of total disassembly cost (TDC), total repair cost (TRPC), total recycling cost (TRC), total outside procurement cost (TOPC), total disposal cost (TDIC), and total holding cost (THC). Therefore the total cost can be written as:

$$TC = TDC + TRPC + TRC + TOPC + TDIC + THC \quad (5)$$

i. Total disassembly cost (TDC): An EOL product may contain operable and non-operable components (broken or zero remaining life). A complete disassembly of EOL products is assumed here. Therefore the total disassembly cost is formulated as follows:

$$TDC = \sum_{i \in I, j \in J} x_i(a_{ij}cd_j + f_{ij}cd_j) + (z_i + w_i)cd_j \quad (6)$$

- ii. Total repair cost (TRPC): It consists of disassembly of broken, extra and remaining-life-time deficit components, and assembly of required ones. Therefore total repair cost is formulated as follows:

$$TRPC = \sum_{i \in I, j \in J} [rp_{ij}(cd_j + ca_j) + mis_{ij}ca_j] \quad (7)$$

- iii. Total recycling cost (TRC): Broken components are recycled to meet the material demands. If broken components are not sufficient then recovered operable components are recycled to fulfill the demand.

$$TRC = \sum_{j \in J} crc_j(\sum_{b \in B} r_{jb} + \sum_{i \in I} w_i + fr_j) \quad (8)$$

- iv. Total outside procurement cost (TOPC): It is a product of unit purchase cost and total number of procured components.

$$TOPC = \sum_{j \in J, b \in B} c_{jb}l_{jb} \quad (9)$$

- v. Total disposal cost (TDIC): It is defined as the cost of product disposal, component disposal and material disposal.

$$TDIC = \sum_{j \in J} cds_j * (\sum_{b \in B} cdis_{jb} + \sum_{i \in I} z_i + fd_j) \quad (10)$$

- vi. Total holding cost (THC): It is a function of stored EOL products, components, and materials.

$$THC = h \sum_{i \in I} s_i + \sum_{j \in J} ch_j \sum_{b \in B} sc_{jb} + \sum_{k \in K} mh_k sm_k \quad (11)$$

2. Quality level: Total quality level is the difference between the highest life bin the component could be placed in and the life bins they are actually used in.

$$Q = \sum_{b \in B} rep_{imjb}(b - m) + ((a_{ij} * y_{im} - \sum_{b \in B} rep_{imjb})(\beta_{ij} - m)) \quad (12)$$

3. Material value: Material value is the sum of material demand and the amount of stored materials multiplied by the unit material sales price factor, and summing over all material types

$$MV = \sum_{k \in K} prc_k(dm_k + sm_k) \quad (13)$$

4. Disposal weight: Disposal weight is calculated by multiplying all the components to be disposed of with their corresponding weights

$$DW = \sum_{j \in J} (\sum_{b \in B} cdis_{jb} + \sum_{i \in I} z_i + fd_j)\omega_j \quad (14)$$

Constraints:

1. An EOL product is disassembled, repaired, disposed of, recycled or left untouched (stored). Therefore,

$$x_i + y_i + z_i + w_i + s_i = 1, \forall i \quad (15)$$

2. Complete disassembly implies that all the components of a product are disassembled if that product is to be disassembled and a component can be placed in only one bin after disassembly. Therefore,

$$\sum_{b \in B} x_{ijb} = x_i a_{ij}, \forall i, j \quad (16)$$

3. EOL product is repaired to produce only one product for only one life-bin. Therefore,

$$\sum_{m \in M} y_{im} = y_i, \forall i \quad (17)$$

4. Product demand is met by repaired EOL products. The number of products produced by repairing EOL products in product life-bin m should at least be equal to the product demand.

$$\sum_{i \in I} y_{im} = dp_m, \forall m \quad (18)$$

5. Component demand is satisfied by recovered and procured operable components. Recovered components are obtained from the disassembled and repaired EOL products. For each life bin b and component j, the number of recovered and procured components must be at least equal to the components demand after components used in repair, recycled, stored, and disposed of are taken out. Therefore,

$$\sum_{i \in I} (x_{ijb} + def_{ijb}) - \sum_{i \in I, m \in M} (rep_{imjb}) + l_{jb} - r_{jb} - sc_{jb} - cdis_{jb} = dc_{jb}, \forall b, j \quad (19)$$

6. Non-functional, missing and remaining-life-time deficient components must be replaced with components having remaining life time that is sufficient for producing a product for product-life-bin m. Therefore,

$$\sum_{\{b \in B, m \in M | b \geq m\}} rep_{imjb} = y_{im}(f_{ij} + mis_{ij} + dfc_{imj}), \forall i, j, m \quad (20)$$

Table 1 Received EOL refrigerator details

EOL Refrigerator	Remaining life of components (j) (years)				
	Cabinet(1)	Compressor (2)	Condenser (3)	Expansion Valve (4)	Evaporator (5)
1	3.56	5.28	*	2.43	1.68
2	*	3.42	0	3.49	2.57
3	1.45	0	5.46	5.5	3.7
4	1.68	3.4	1.68	2.96	5.12
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
195	2.65	4.29	*	1.96	0
196	0	5.68	3.49	3.12	7.08
197	*	1.43	0	2.57	4.58
198	5.78	2.61	4.16	3	3.8
199	6.56	5.87	2.96	2.6	*
200	2.87	0	1.08	3.24	4.65

‘*’ indicates missing components and ‘0.00’ indicates non-operable (broken components or components with remaining lives less than one year) components.

Table 2 Disassembly and assembly costs

Components (j)	Disassembly Costs (\$ /unit)		Assembly Costs (\$ /unit)	
	Design 1	Design 2	Design 1	Design 2
Cabinet (1)	0.00	0.00	0.00	0.00
Compressor (2)	1.80	1.50	1.80	1.50
Condenser (3)	0.90	1.00	0.90	1.00
Expansion valve (4)	0.50	0.60	0.50	0.60
Evaporator (5)	2.00	3.00	2.00	3.00

Table 3 Outside procurement and holding costs

Components (j)	Outside Procurement Costs (\$ /unit)			Holding Costs (\$ /unit)
	Bin 1	Bin 2	Bin 3	
Cabinet (1)	25	38.47	50	5
Compressor (2)	102.52	155.63	210.5	10.5
Condenser (3)	50	80.26	102.58	16
Expansion valve (4)	18.28	26.35	35	2.5
Evaporator (5)	94.23	141.48	186.56	10.5

6. Numerical Example

To illustrate the methodology, a device embedded (sensors and RFID tags) EOL refrigerator ARTODTO system is considered. The refrigerator has two design alternatives. All the received EOL refrigerators may not be in good condition. There may be some missing or broken components. All the use phase information is captured by the sensors embedded in the EOL refrigerators. The quality level of a component is defined by the remaining life of that component. Based on this remaining life, components are separated into three life-bins. The first life-bin holds components whose remaining lives are between one and two years. The second life-bin holds components whose remaining lives are between two and three years. The third life-bin holds components with remaining lives of three years or more.

The model deals with 200 EOL refrigerators and 5 components. From each EOL refrigerator operable and non-operable components are identified and the remaining life associated with each operable component is determined. A

Table 4 Recycling and disposal costs

Components (j)	Recycling Costs (\$ /unit)	Disposal Costs (\$ /lb)
Cabinet (1)	10	0.23
Compressor (2)	10	0.23
Condenser(3)	16	0.23
Expansion valve (4)	4	0.23
Evaporator (5)	15	0.23

portion of the details of EOL refrigerators received is displayed in Table 1. Table 2, 3 and 4 display the disassembly and assembly costs, outside procurement and holding costs, and recycling and disposal costs respectively. The demands for components are shown in Table 5.

Product demands are assumed to be 10, 12, and 10 for the remaining life bins 1, 2, 3 respectively. Two types of materials are recovered through recycling, namely, plastic and steel. Component material yields, demands, holding costs and sale prices are given in Table 6.

The aspiration value for the total cost is \$1200; for quality level, it is 181; for material value it is \$500; and for

Table 5 Components demands

Components (<i>j</i>)	Remaining Life Bins		
	Bin1	Bin2	Bin3
Cabinet (1)	15	12	15
Compressor (2)	10	11	13
Condenser (3)	14	0	10
Expansion valve (4)	9	4	3
Evaporator (5)	13	15	7

Table 6 Material yields, demands, holding costs and sale prices

Components (<i>j</i>)		Plastic	Steel
Yield (lbs.)	Cabinet (1)	-	10.00
	Compressor (2)	5.00	-
	Condenser (3)	-	-
	Expansion valve (4)	-	-
	Evaporator (5)	12.00	-
Demand (lbs)		240.00	400.00
Holding cost(\$ /lb)		2.40	0.50
Sale price (\$ /lb)		12.00	2.50

Table 7 Variables

Goal	Aspiration level	Step1	Step2	Step3	Step4
Total Cost(\$)	1200	1389	1200	1200	1200
Quality Level	181	174	187	181	181
Material sales revenue(\$)	500	345.2	401.8	453.6	453.6
Disposal weight (lbs.)	0	32.2	24.3	15.5	7.9

disposal weight it is 0 lbs. due to the environmental regulations and responsibility.

7. Results

The multi-criteria decision making problem was formulated as a goal programming model and was solved using LINGO 13.0. Table 7 shows the aspiration levels in each step for each goal. It can be seen from the table that only the first and second goals of total cost and quality level respectively are achieved. The third and fourth goals of material sales revenue and disposal weight respectively are underachieved. 32 EOL refrigerators were repaired (25 of design 1, 7 of design 2), 160 were disassembled (105 of design 1, 55 of design 2), 5 were disposed of (5 of design 2) and 3 were stored (1 of design 1, 2 of design 2).

8. Conclusion

Original equipment manufacturers manage the End-Of-Life (EOL) products by implementing various EOL product recovery techniques such as reuse, recycling, remanufacturing and disassembly. EOL products may have multiple design alternatives and deciding which design alternative is to be used for fulfilling the demands can be an important decision. In this paper, a goal programming model was formulated to determine how to process the EOL products in order to meet the component', products' and materials' demands. Four goals considered were total cost, quality level, material sales revenue and disposal

weight. The first two goals of total cost and quality level are achieved while the third and fourth goals of material sales revenue and disposal weight were underachieved.

For future study, different multi criteria decision making techniques can be implemented to solve the problem stated in this paper. Also, this paper considered sensors and RFID tags embedded products which reduced the uncertainty about the quality and quantity of received EOL products. But not all products are embedded with sensors and RFID tags. Hence, for future study, products with no sensors or RFID tags embedded in them can also be considered.

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