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Surendra M. Gupta
Northeastern University

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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 address***

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

Multi-Criteria Decision Making For Disassembly-To-Order System Under Stochastic Yields

Prasit Imtanavanich and Surendra M. Gupta*
Laboratory for Responsible Manufacturing
334 SN, Department of MIE
Northeastern University
360 Huntington Avenue
Boston, MA 02115, USA

ABSTRACT

In this paper, we consider the problem of determining the optimal number of returned products to disassemble to fulfill the demand for a specified number of parts. This is known as the disassembly-to-order (DTO) problem. The deterministic yield version of this problem has been addressed in the literature. Recently, the stochastic yield version of this problem with a single objective has also been reported in the literature. In this paper, we extend the methodology to include multiple objectives. To this end, we model the DTO problem using integer goal programming. The stochastic problem is solved by transforming it into its deterministic equivalent problem. This conversion is accomplished by considering the specific structures of the products with one core and one part ("one-to-one structure") and apply it to handle the products with one core and multiple parts ("one-to-many structure"). For these special cases it is possible to solve the stochastic problem analytically so that valuable insights can be gained by comparing the stochastic and deterministic solutions. This will help us to determine effective deterministic yield equivalents. We present a case example to illustrate the methodology.

Keywords: Disassembly; goal programming; stochastic; yields; reuse; recycling.

1. INTRODUCTION

In recent years, high demand for electronic products has stimulated the development of new technologies in electronics manufacturing. With new technologies, more and more new products are frequently introduced into the market. Together with desires of customers to acquire products with newest technologies, old products with older technologies are neglected. As a result, the life spans of the old products that still have some useful life left in them is shortened and they became obsolete prematurely.

Obsolete products are sometimes called end-of-life (EOL) products. There are many ways to manage these products. For example, they could be recycled, reused or disposed of. Disposal adds to reduction in the number of landfills and is harmful to the environment if improperly done. Governments, along with manufacturers and consumers, are aware of these problems. This awareness has resulted in the establishment of several environmental regulations. Since many of these EOL products are in a good working condition, it is preferable to recycle or reuse them. This also helps save part acquisition and product disposal costs.

Disassembly is the first process to retrieve components and materials from EOL products for reuse and recycling. Since take-back products are received in a variety of conditions, it is difficult to know beforehand exactly how many products would be needed for disassembly to fulfill the demand for parts and materials. This uncertainty complicates the disassembly process. One way to manage such a problem is to use heuristic procedure to convert the stochastic model into a deterministic model and then solve the deterministic problem. Thus, the main objective here is to optimize the

*Correspondence: e-mail: gupta@neu.edu; URL: http://www.coe.neu.edu/~smgupta/
Phone: (617)-373-4846; Fax: (617)-373-2921

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number of take-back products to be disassembled in order to maximize the profit of selling components and materials, while maintaining environmental care.

In this paper, we present a multi-criteria 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 disassemble them to satisfy each goal and meet demands for components and materials under different constraints and stochastic elements. A numerical example is considered to illustrate the methodology.

2. LITERATURE REVIEW

Disassembly has been studied by many researches in recent years. Some of them have focused on profit maximization while others have studied the disassembly process itself. We briefly review some of the relevant literature of these areas.

Veerakamolmal and Gupta[3] presented a method to determine the minimum makespan of a disassembly process. Stuart and Qin[9] proposed models to maximize the net revenue with processing and inventory capacity constraints. Sodhi and Reimer[13] introduced two mathematical programming models, one to minimize the cost of recycling and the other to maximize the recycling profit. Boon, Isaacs and Gupta[15] provided a net profit function for recyclers to investigate and report the factors that most influence the profit, and to assess the effect of changes in different variables on recycler's profits. Kongar and Gupta[14] proposed a multi-criteria decision making approach for disassembly-to-order system to determine the number of end of life products to be taken back and disassemble to satisfy the demand of each item. Inderfurth and Langella[19] introduced an approach for solving the disassembly-to-order problems under stochastic yields.

In the area other than maximizing profit or minimizing cost, Veerakamolmal and Gupta[4] introduced the model using DFDI (Design for Disassembly Index) to compare the merits and drawbacks of different product designs. Zhou, Caudill and Sebastian[5] proposed a multi-lifecycle product recovery model to consider full potential of recovering and reengineering materials from one product to create others many times over. Stuart and Qin[10] introduced a mixed-integer programming model to consider whether or not to process continuously at a particular station. Lambert and Gupta[16] presented the tree network model, which combines the advantages of the disassembly graph approach, and the component disassembly optimization model. Rose, Stevels and Ishll[18] provides a web based tool called ELDA (End-Of-Life Design Advisor) to present a statistical analysis of the case studies, and they also introduced the preliminary work of End-Of-Life Strategy Environmental Impact Model (ELSEIM) to predict end of life strategies for products, and to present an alternative method that uses the environmental impact scores from an in-depth life cycle analysis.

Moyer and Gupta[2] presented a survey of works related to environmentally conscious manufacturing, recycling and complexity of disassembly in the electronics industry. Kasteren, Van Schijndel and De Ron[12] described the heavy metal issues in consumer electronics recycling and a new way of solving these problems. A summary of the literature discussed above as well as some other relevant literature is summarized in Table 1.

Table 1. Relevant literature sorted by year

Year	Article	Author(s)	Model	Objective/Main Point
1997	Environmental Concerns and Recycling/Disassembly Efforts in the Electronics Industry	Leanne K. Moyer and Surendra M. Gupta		Survey of previous works related to environmentally conscious manufacturing, recycling and complexity of disassembly in the electronics industry
1998	High-Mix/Low-Volume Batch of Electronic Equipment Disassembly	Pitipong Veerakamolmal and Surendra M. Gupta	The procedure to minimize the process makespan	To calculate to minimized process makespan
1999	Analysis of Design Efficiency for the Disassembly of Modular Electronic Products	Pitipong Veerakamolmal and Surendra M. Gupta	Model using Design for Disassembly Index (DfDI)	To compare the merits and drawbacks of different product designs
	Multi-Lifecycle Product Recovery for Electronic Products	Mungchu Zhou, Reggie Caudill and Donald Sebastian	Multi-lifecycle product recovery model, Optimal retirement planning and design selection methods	To consider the potential of recovering and reengineering materials and components from one product to create others many times over
	Electronic Products at their end-of –life: Options and Obstacles	Jonathan Linton		To explain the options for both the collecting and processing of electronics products at their end-of-life and state the technical and social factors that inhibit environmentally conscious
	Computer Take-Back and Recycling : An Economic Analysis for Used Consumer Equipment	Leah B. Jung and Thomas J. Bartel		To present economic data from the San Jose Consumer Computer Collection and Recycling Pilot and to compare the data to economics from alternate electronic equipment management scenarios
2000	Environmental Issues in Electronics Manufacturing: A Review	Brian Ellis		A review paper, covering the various concerns about electronics manufacturing industry
	A Model for Discrete Processing Decisions for Bulk Recycling of Electronics Equipment	Julie Ann Stuart and Qin Lin	Discrete Processing and Reprocessing Materials Recovery Models	To maximize net revenue subject to the constraints of processing capacity and inventory capacity of in-process products
	A Refine-or-Sell Decision Model for a Station with Continuous Reprocessing Options in an Electronics Recycling Center	Julie Ann Stuart and Qin Lin	Mixed-Integer Programming Model	To consider the continuous reprocessing option, accumulation of output for shipment, and the number of shipments per period, then determine whether or not to reprocess continuously at a particular station
	An Assessment of DFE Practices in Leading US Electronics Firms	Michael Lenox, Andrew King and John Ehrenfeld		To provide the information of the implementation of the Design For Environment (DFE), mainly in AT&T, Digital, IBM and Xerox
	Heavy Metals in Consumer Electronics Recycling : A Multidisciplinary Approach	J.M.N Van Kasteren, PPAJ. Van Schijndel and A.J. De Ron		To describe the heavy metal issues in consumer electronics recycling and a new way of solving these problems

Year	Article	Author(s)	Model	Objective/Main Point
2001	Models for Recycling Electronics End-Of-Life Products	Manbir S. Sodhi and Brian Reimer	Mathematical Programming Model (Source Models) Mathematical Programming Model (Recycler Models)	To minimize the cost of the recycling or, if possible, maximize the profit from the recycling To maximize the recyclers profit after subtracting the cost of acquiring, transporting the items
	A Multi-Criteria Decision Making Approach For Disassembly-To-Order Systems	Elif Kongar and Surendra M. Gupta	Goal Programming Model	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
2002	Strategies and Economics in the Disassembly of Personal Computers : A Case Study	Sanchoy Das, Vishakar Mani and Reggie Caudill		To report the use of WebVDM tool to analyze a personal computer from a disassembly perspective
	Economic Sensitivity for End Of Life Planning and Processing of Personal Computers	Jane E. Boon, Jacqueline A. Isaacs and Surendra M. Gupta	The net profit function of the recyclers	-To investigate and report the factor that most influence the profitability of end of life processing of personal computers -To assess the effect of changes in different variables on recycler profits
	Demand-Driven Disassembly Optimization for Electronic Products	A.J.D. Lambert and Surendra M. Gupta	The Tree Network Model	To combine the advantages of both approaches (the disassembly graph approach and the component-disassembly optimization model) without the disadvantages (redundancy and non linearity)
	Method for Formulating Product End Of Life Strategies for Electronics Industry	Catherine M. Rose, AB Stevels and Kosuke Ishll	A web based tool called The End-Of-Life Design Advisor (ELDA) The preliminary work of End-Of-Life Strategy Environmental Impact Model (ELSEIM)	To present a statistical analysis of the case studies, their product characteristics and end of life strategies -To predict end of life strategies for product based on their product characteristics - To present an alternative method that uses the environmental impact scores from an in-depth life cycle analysis
2003	An Approach for Solving Disassemble-To-Order Problems Under Stochastic Yields	Karl Inderfurth and Ian M. Langella	Mixed Integer Linear Programming Model Using Stochastic Equivalent Yields	-To minimize the total cost -To compare the performance between the using of mean yield values, one-to-one heuristic and one-to-many heuristic

3. PROBLEM STATEMENT

3.1 Nomenclature

The nomenclature used in this paper is given below:

η_k	Negative deviation from the kth goal
ρ_k	Positive deviation from the kth goal
ASC_j	Available storage space for component type j (unit)
BRC_j	Number of bad-to-reuse components type j in the reuse process (unit)
c^s_{ij}	Split core cost for each component j of each product i ($)
cdc_j	Unit disposing cost for component type j ($/unit)
cdd_j	Unit destructive disassembly cost for component j ($/unit)
cdm_j	Unit disposing cost for material type j ($/unit)
cdp_j	Unit disposing cost for product i ($/unit)
cir_j	Unit in-plant recycling cost for material j ($/unit)
cnd_j	Unit non-destructive disassembly cost for component j ($/unit)
cor_j	Unit out-plant recycling cost for material type j ($/unit)
cpc_j	Unit procurement cost for component type j ($/unit)

cse_i	Unit separation cost for product *i* ($/unit)
ctb_i	Unit take-back cost for product *i* ($/unit)
cuh_j	Unit holding cost for component type *j* ($/unit)
CDD	Cost of destructive disassembly ($)
CDI	Cost of disposal ($)
*CDI**	Aspiration level for *CDI* ($)
CM_{ij}	Multiplicity of component type *j* in product type *i* (unit)
CND	Cost of non-destructive disassembly ($)
CPR	Cost of procuring component for reusing ($)
*CPR**	Aspiration level for *CPR* ($)
CRE	Cost of recycling ($)
CST	Cost of storage ($)
CTB	Cost of take-back EOL products ($)
*CTB**	Aspiration level for *CTB* ($)
DRC_j	Demand for reuse component type *j* (unit)
$DREM_j$	Demand for recycle material type *j* (unit)
GRC_j	Number of good-to-reuse components type *j* in the reuse process (unit)
i	Index for EOL product type
IPC_j	In-plant capacity of component type *j* (unit)
j	Index for component type
pc_j	Resale value for component type *j* ($/unit)
pm_j	Resale value for material type *j* ($/lb)
OPC_j	Procured component type *j* from outside supplier (unit)
RCS	Component sale revenue ($)
RMS	Materials sale revenue ($)
sev_j	Unit equivalent value for component type j ($/unit)
SDY_j	Stochastic non-destructive disassembly yield (%)
SDY_j^+	Upperbound of SDY_i value
SDY_j^-	Lowerbound of SDY_i value
SGP_i	Stochastic good condition percentage for product type *i* (%)
SRC_j	Stochastic reusable percentage for component type *j* (%)
SRE_j	Stochastic recyclable percentage for component type *j* (%)
SVL	Stored component value ($)
TDC_j	Total number of disassembly components and materials type *j* (unit)
$TDDM_j$	Total amount of destructive disassembly materials type *j* (unit)
$TDIC_j$	Total number of disposing component type *j* (unit)
$TDIM_j$	Total number of disposing material type *j* (unit)
$TDIP_i$	Total number of disposing product type *i* (unit)
TDP_i	Total number of product type *i* to be disassembled (unit)
TIR_j	Total amount of material type *j* to be recycled in-plant (unit)
TOR_j	Total amount of material type *j* to be recycled out-plant (unit)
$TNDC_j$	Total number of non-destructive disassembly components type *j* (unit)
TPR	Total profit value ($)
*TPR**	Aspiration level for *TPR* ($)
TRC_j	Total number of component type *j* sent to reuse process (unit)
$TREM_j$	Total amount of material type *j* to be recycled (unit)
$TWRM_j$	Total weight of recycled material type *j* (lb)
TSC_j	Total number of stored components type j (unit)
TTBi	Total EOL products type *i* ordered (unit)
WM_j	Weight of material type *j* (lb)

3.2 Disassembly-to-order system

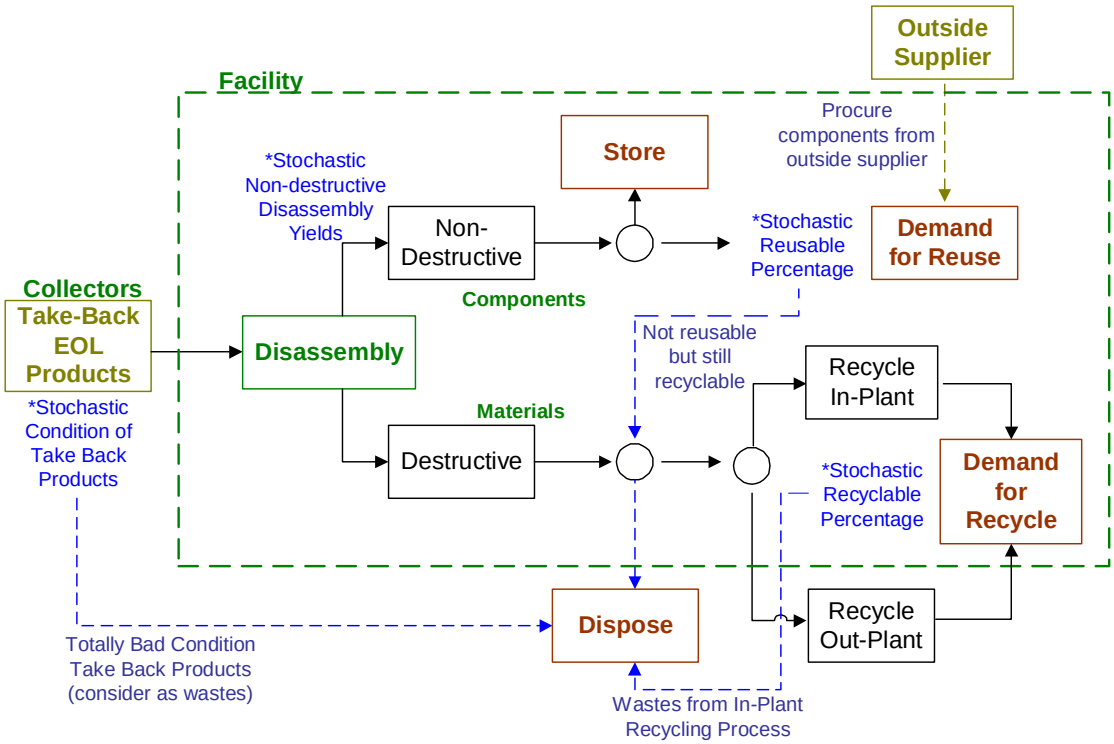

Figure 1. Disassembly-to-order system

Disassembly is the process of systematic removal of the desired components or materials from the original assembly so that the components or materials are obtained in the desired form (Kongar and Gupta[14], 2001). Disassembly-to-order (DTO) is a system where varieties of EOL products are taken back from the last users to the disassembly facility and are disassembled to satisfy the demands for components and materials. Disassembly can be selective (only selected items are disassemble), complete (all items are disassembled), destructive (items are allowed to be damaged), non-destructive (no item is allowed to be damaged), etc. In this paper, we focus on destructive and non-destructive disassembly.

The DTO process starts with the retrieval of take-back EOL products from collectors (Figure 1). The bad-conditioned products are sent to disposal. The good-conditioned products are disassembled, either by destructive or non-destructive disassembly. The yield from non-destructive disassembly is stochastic. The components obtained from non-destructive disassembly will either be reused or stored. In sorting for the reuse process, the components are divided into two groups, good for reusing and bad for reusing. Good components are used to satisfy the demand for reused components. Additional components may be supplemented from outside supplier to satisfy the demand. Bad components, together with materials from destructive disassembly, are sent to the recycling process, either in-plant or out of plant, to satisfy the demand for recycled materials. In-plant recycling is limited to the available in-plant capacity. Since it is difficult to recover all the materials from all the components recycled, the yield is stochastic. Components that exceed the demand for reuse, recycle and storage are sent to disposal along with the waste materials from the recycling process.

In this paper, goal programming is used to determine the number of each product type to be taken back and disassembled to satisfy the demand of components and materials under a variety of physical, financial, environmental constraints and stochastic elements, while maximizing total profit and minimizing the costs of take-back EOL products, disposal and procuring the components. There are four stochastic elements; stochastic condition of take-back products, stochastic reusable percentage, stochastic recyclable percentage and stochastic non-destructive disassembly yields. We use uniform distribution to represent the first three of the stochastic elements, and a heuristic procedure to represent the last stochastic element.

4. HEURISTIC PROCEDURE

Since the EOL products brought back to the facility are received in a variety of conditions, it is impossible to know the exact yield of components. However, we can estimate the probability of the yield. This way, the satisfaction of the demand depends on how accurately we can predict the yield value. If the actual yield is lower than the prediction, we may have to supplement the components by buying them from outside supplier to satisfy the demand. If the actual yield is higher than the prediction, we may incur a disposal cost due to excess components. Therefore, predicting accurate yield value is very important in the disassembly process. The following equations are used to identify the number of procured components (OPC_j) and the number of disposed components ($TDIC_j$).

$$OPC_j = \max[DRC_j - \sum_i (TTB_i \cdot CM_{ij} \cdot SDY_j);0] \tag{1}$$

$$TDIC_j = \max[\sum_i (TTB_i \cdot CM_{ij} \cdot SDY_j) - DRC_j;0] \tag{2}$$

Next, we consider the basic deterministic model, the objective of which is to minimize the total cost function, which is comprised of total take-back cost, total procurement cost and total disposal cost.

$$\min \qquad TC_D = \sum_i (TTB_i \cdot ctb_i) + \sum_j (cpc_j \cdot OPC_j) + \sum_j (cdc_j \cdot TDIC_j) \tag{3}$$

$$s.t. \qquad \sum_i (TTB_i \cdot CM_{ij} \cdot SDY_j) + OPC_j - TDIC_j = DRC_j \tag{4}$$

$$TTB_j,\ OPC_j,\ TDIC_j \geq 0, \text{ and are integer}$$

After applying stochastic OPC_j and $TDIC_j$ from equation (1) and (2) into the deterministic problem described in (3) and (4), assuming that in the stochastic case the target of the firm is to minimize the expected cost, the optimization for the stochastic problem is formulated as follows:

$$TC_S = \underset{SDY_{ij}}{E} \{\sum_i (TTB_i \cdot ctb_i) + \sum_j (cpc_j \cdot \max[DRC_j - \sum_i (SDY_j \cdot TTB_i \cdot CM_{ij});0]) +$$

$$\sum_j (cdc_j \cdot \max[\sum_i (SDY_j \cdot TTB_i \cdot CM_{ij}) - DRC_j;0])\} \tag{5}$$

$$s.t. \qquad TTB_i \geq 0 \text{ and integer } \forall i.$$

There are many complexities of solving the stochastic problems for the general case of multiple products and components. In this paper, we solve it heuristically by replacing the stochastic yields by deterministic equivalents and solving the remaining deterministic problem (Inderfurth and Langella[19], 2003). The question is how to find these deterministic equivalents. In this paper, we use one-to-one heuristic approach, which helps us to calculate the deterministic equivalents.

4.1 One-to-one heuristic

For this approach, we consider a product with a single core and a single component. Which means if we have a product with multiple components, we have to split the product into one-to-one relationship (see figure 2.). In order to do this, we have to split the core cost, take-back cost plus the separation cost, attributed to each component. One reasonable rule of splitting up the cost is to do it proportionally to the respective procurement costs of the components. For example, in the Figure 2, if the core cost is \$9 and procurement costs of components A, B and C are \$2, \$3 and \$4 respectively, the split core costs of component A, B and C will be \$2, \$3 and \$4 respectively.

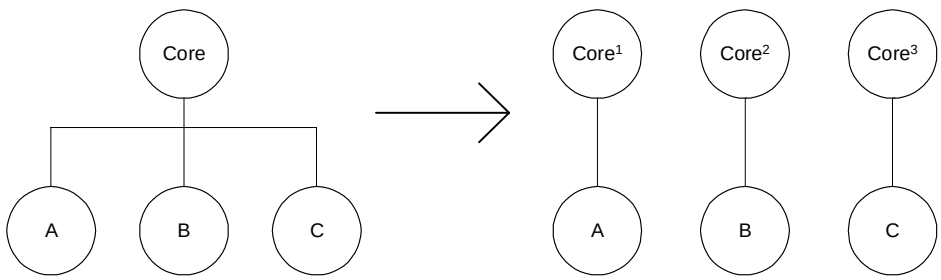

Figure2. Product split into one-to-one relation.

Split core cost for each component of each product (c^s_{ij}) can be calculated by

$$c^s{}_{ij} = (ctb_i + cse_i) * (pc_j / \sum_j pc_j) \tag{6}$$

In order to keep the analysis simple, we assume that each stochastic yield rate SDY_{ij} has a continuous density function $g_{ik}(SDY_{ij})$. Therefore, each yield realization is bounded from below and above, for example $SDY_j^- \geq SDY_j \geq SDY_j^+$. Since this heuristic approach is based on a system with only a single core and a single component, we can neglect the indices of core and component, and the multiplicity of each component in model equation (5). Hence we have the stochastic objective function TC_S for one-to-one heuristic as:

$$TC_S = TTB \cdot CM \cdot SDY + cpc \cdot \int_{SDY^-}^{DRC/TTB} (DRC - TTB \cdot SDY) \cdot g(SDY) \cdot d(SDY) +$$

$$cdc \cdot \int_{DRC/TTB}^{SDY^+} (TTB \cdot SDY - DRC) \cdot g(SDY) \cdot d(SDY) \tag{7}$$

It is well known that the cost function TC_S is convex in TTB. Therefore simple differential calculus will give us the optimal number of take-back products TTB to be processed by disassembly and it turns out to be a multiple of demand, with multiplier $1/\gamma$ (see Yano and Lee[1] (1995)).

$$TTB = DRC / \gamma \tag{8}$$

with γ from

$$\int_{\gamma}^{SDY^+} SDY \cdot g(SDY) \cdot d(SDY) = \frac{cpc \cdot \overline{SDY} + ctb}{cpb + cdc} \tag{9}$$

where $\overline{SDY}$ equals the expected yield rate.

For the uniformly distributed yield a closed-form formulation for γ is given by (see Inderfurth and Langella[19], 2003)

$$\gamma = \sqrt{\frac{pc \cdot (SDY^-)^2 + cdc \cdot (SDY^+)^2 + 2 \cdot c^s \cdot (SDY^+ - SDY^-)}{pc + cdc}} \tag{10}$$

In the correspondent deterministic problem from equation (3) and (4) for system with a single core and a single component, the optimal number of take-back products would be

$$TTB = DRC / SDY \tag{11}$$

Comparing between equations (8) and (11), we can use γ value as a deterministic equivalent for using in a deterministic model. Therefore solving the deterministic problem will generate the equivalent optimal result for a stochastic problem.

$$\hat{SDY} = \gamma \tag{12}$$

We used equation (6), (10) and (12) to calculate the deterministic yield equivalent factor for each component of each product in the model.

5. MATHEMATICAL MODEL FOR THE DTO SYSTEM

Since the problems in the real life situations are always varied and complicated, only one objective may not be sufficient for implementing. Therefore, goal programming model has been introduced in this paper. The basic purpose of goal programming is to satisfy several goals, which are relevant to the decision-making situation while restricting resources by constraints. For each goal, we can set the aspiration level, which is the minimum requirement level, or a limitation level as a constraint in the model.

5.1 The goals

The first goal is to obtain the total profit of the disassembly-to-order system of at least its aspiration level (*TPR**) and exceed it as much as possible. Mathematically, this can be achieved by minimizing the negative deviation (η_1) from the aspiration level (*TPR**), to maintain a value equal to zero. There is no restriction on positive deviation (ρ_1) to guarantee the best profit level. This goal can be formulated as follows:

$$\min \quad \eta_1 \tag{13}$$

$$s.t. \quad TPR + \eta_1 - \rho_1 = TPR^*$$

The second goal is to limit procurement cost to have a value no more than its limitation level (*CPR**). Thus the positive deviation (ρ_2) is minimized. This goal can be formulated as follows:

$$\min \quad \rho_2 \tag{14}$$

$$s.t. \quad CPR + \eta_2 - \rho_2 = CPR^*$$

The third goal is to minimize the cost of take-back products and limit to its limitation level (*CTB*). The better combination of take-back products can reduce the total cost, while satisfying the demands for components and materials still remains. Hence, the positive deviation (ρ_3) from the take-back cost is minimized. This goal can be formulated as follows:

$$\min \quad \rho_3 \tag{15}$$

$$s.t. \quad CTB + \eta_3 - \rho_3 = CTB^*$$

The forth goal is related to the environmentally conscious. Our desire is to minimize the number of disposed products, components and materials by minimizing the disposal cost and limit it to a limitation level (*CDI**). Therefore the positive deviation (ρ_4) from the disposal cost is minimized. This goal can be formulated as follows:

$$\min \quad \rho_4 \tag{16}$$

$$s.t. \quad CDI + \eta_4 - \rho_4 = CDI^*$$

These goals are ordered by priority. Hence, there are no weights assigned to any of the goals. The first priority goal would be to obtain the *TPR* value of at least its aspiration level (TPR^*), While the last priority goal would be to obtain the *CDI* value with no more than its limitation level (CDI^*).

5.2 Total profit value and related terms

The total profit value can be calculated by

$$TPR = RCS + RMS + SVL - CPR - CTB - CDI - CDD - CND - CST - CRE \tag{17}$$

Each term of the TPR function are described below

RCS is calculated as a function of the total number of reused component type *j* (TRC_j) and the unit resale value for component type *j* (pc_j). Therefore,

$$RCS = \sum_j (TRC_j \cdot pc_j) \tag{18}$$

RMS is calculated as a function of the total weight of recycled material type *j* ($TWRM_j$) and the price of material type *j* (pm_j). Therefore,

$$RMS = \sum_j (TWRM_j \cdot pm_j) \tag{19}$$

SVL is calculated as a function of the total number of stored components type j (TSC_j) and the unit equivalent value for component type j (sev_j). Therefore,

$$SVL = \sum_j (TSC_j \cdot sev_j) \tag{20}$$

CPR is a function of the number of procurement component type *j* (OPC_j) and procurement cost of component type *j* (cpc_j). Therefore,

$$CPR = \sum_j (OPC_j \cdot cpc_j) \tag{21}$$

CTB is calculated as a function of the total number of EOL products type *i* ordered (TTB_i) and the take-back cost for each product *i* (ctb_i). Therefore,

$$CTB = \sum_i (TTB_i \cdot ctb_i) \tag{22}$$

CDI is a function of the total number of disposing product type *i* ($TDIP_i$), disposing component type *j* ($TDIC_j$) and disposing material type *j* ($TDIM_j$) , and their corresponding disposing cost for product type *i* (cdp_i), component type j (cdc_j) and material type j (cdm_j). Therefore,

$$CDI = \sum_i (TDIP_i \cdot cdp_i) + \sum_j \{(TDIC_j \cdot cdc_j) + (TDIM_j \cdot cdm_j)\} \tag{23}$$

CDD is a function of the total amount of destructive disassembly materials type *j* ($TDDM_j$) and the destructive disassembly cost for material type *j* (cdd_j). Therefore,

$$CDD = \sum_j (TDDM_j \cdot cdd_j) \tag{24}$$

CND is a function of the total number of non-destructive disassembly components type *j* ($TNDC_j$) and the non-destructive disassembly cost for component *j* (cnd_j). Therefore,

$$CND = \sum_j (TNDC_j \cdot cnd_j) \tag{25}$$

CST is a function of the total number of stored components type *j* (TSC_j) and the corresponding unit holding cost (cuh_j). Therefore,

$$CST = \sum_j (TSC_j \cdot cuh_j) \tag{26}$$

CRE is a function of the total amount of materials recycled in plant (TIR_j), out plant (TOR_j), and the corresponding unit recycling cost in-plant (cir_j) and out-plant (cor_j). Therefore,

$$CRE = \sum_j \{(TIR_j \cdot cir_j) + (TOR_j \cdot cor_j)\} \tag{27}$$

5.3 Constraints

5.3.1 Disassembly Process:

The total number of products type i to be disassembled (TDP_i) has to be equal to total number of EOL product type i (TTB_i) ordered multiply by stochastic good condition percentage of product type i (SGP_i). Therefore,

$$TDP_i = TTB_i \cdot SGP_i \tag{28}$$

The total number of disassembly components and materials type j (TDC_j) has to be equal to the sum of the total number of EOL product type i (TTB_i) multiply by the multiplicity of component type j in product type i (CM_{ij}). Therefore,

$$TDC_j = \sum_i (TTB_i \cdot CM_{ij}) \tag{29}$$

The total number of non-destructive disassembly components has to be no more than the sum of the multiplication of the total number of EOL product type i (TTB_i), the multiplicity of component type j in product type i (CM_{ij}) and non-destructive disassembly yields of component type j (SDY_j) calculated from eq.10. Therefore,

$$TNDC_j \le \sum_i (TTB_i \cdot CM_{ij} \cdot SDY_j) \tag{30}$$

The total amount of destructive disassembly materials type j ($TDDM_j$) has to be equal to the subtraction of the total number of disassembly components type j (TDC_j) by non-destructive disassembly components type j ($TNDC_j$). Therefore,

$$TDDM_j = TDC_j - TNDC_j \tag{31}$$

5.3.2 Reuse Process:

The number of components type j sent to reuse process (RPC_j) has to be less than or equal to the number of non-destructive disassembly of components type j ($TNDC_j$). Therefore,

$$RPC_j \le TNDC_j \tag{32}$$

The demand of reuse component type j (DRC_j) has to be equal to the sum of good-to-reuse component type j (GRC_j) and component type j procured from outside supplier (OPC_j). Therefore,

$$DRC_j = GRC_j + OPC_j \tag{33}$$

The number of good-to-reuse components type j (GRC_j) has to be equal to the multiplication of the number of components type j sent to reuse process (RPC_j) and their stochastic reusable percentage (SRC_j). Therefore,

$$GRC_j = RPC_j \cdot SRC_j \tag{34}$$

The number of bad-to-reuse components type j in the reuse process (BRC_j) has to be equal to the number of components type j sent to reuse process (RPC_j) subtract by the number of good-to-reuse component type j (GRC_j). Therefore,

$$BRC_j = RPC_j - GRC_j \tag{35}$$

The number of components type j procured from outside (OPC_j) has to be equal to the maximum between zero and the subtraction of the demand of reuse component type j (DRC_j) by the number of reusable component type j (GRC_j). Therefore,

$$OPC_j = Max\{0, (DRC_j - GRC_j)\} \tag{36}$$

5.3.3 Recycle Process:

The amount of materials type j to be recycled ($TREM_j$) has to be equal to the demand of recycle materials type j ($DREM_j$). Therefore,

$$TREM_j = DREM_j \tag{37}$$

The amount of materials type *j* to be recycled ($TREM_j$) has to be no more than the sum of the number of bad-to-reuse components type *j* (BRC_j) and the total number of destructive disassembly materials type *j* ($TDDM_j$). Therefore,

$$TREM_j \le BRC_j + TDDM_j \tag{38}$$

The amount of material type *j* to be recycled ($TREM_j$) has to be equal to the sum of the total amount of materials type *j* recycled in plant (TIR_j) and out plant (TOR_j). Therefore,

$$TREM_j = TIR_j + TOR_j \tag{39}$$

The amount of materials type *j* to be recycled in plant (TIR_j) has to be no more than in-plant capacity of material type *j* (IPC_j). Therefore,

$$TIR_j \le IPC_j \tag{40}$$

The total weight of the recycling material type *j* (TRM_j) is equal to the multiplication of the number of material type *j* to be recycled ($TREM_j$), weight of material type *j* (WM_j) and its stochastic recyclable percentage (SRE_j). Therefore,

$$TWRM_j = TREM_j \cdot WM_j \cdot SRE_j \tag{41}$$

5.3.4 Store Process:

The total number of stored component type *j* (TSC_j) is equal to the subtraction of the number of non-destructive disassembly component type *j* (NDC_j) by the number of components type *j* sent to reuse process (RPC_j). Therefore,

$$TSC_j = NDC_j - RPC_j \tag{42}$$

The total number of stored component type *j* (TSC_j) has to be no more than available storage capacity for component type *j* (ASC_j). Therefore,

$$TSC_j \le ASC_j \tag{43}$$

5.3.5 Disposing Process:

The total number of disposing product type *i* (TDP_i) is equal to the subtraction of the total number of EOL product type *i* ordered (TTB_i) by the number of product type *i* to be disassembled (TDP_i). Therefore,

$$TDP_i = TTB_i - TDP_i \tag{44}$$

The total number of disposing component type *j* (TDC_j) is equal to the sum of the number of bad-to-reuse components type *j* in the reuse process (BRC_j) and the total amount of destructive disassembly materials type *j* ($TDDM_j$), then subtract by the demand for recycle materials type *j* ($DREM_j$). Therefore,

$$TDC_j = BRC_j + TDDM_j - DREM_j \tag{45}$$

The total number of disposing material type *j* (TDM_j) is equal to the multiplication of the total amount of material type *j* recycled in-plant (TIR_j), weight of material type *j* (WM_j) and non-recyclable percentage ($1\text{-}SRE_j$)). Therefore,

$$TDM_j = TIR_j \cdot WM_j \cdot (1 - SRE_j) \tag{46}$$

*TTB_i, TDP_i, $TNDC_j$, RPC_j and GRC_j must be integer and all the variables must be non-negative. (47)

5.4 The GP model

The GP model can now be written as follows:

Find (TTB_j, $TNDC_j$, $TDDM_j$, TRC_j, $TREM_j$, TSC_j and $TDIC_j$) so as to:

Lexicographically minimize $u = \{(\eta_1),(\rho_2),(\rho_3),(\rho_4)\}$ (48)

Where $\{\eta_k, \rho_k\}$ are defined in Eq. (13) through Eq. (16) (the terms of which are explained in Eq. (17) through Eq. (27)),

Subject to:

Constraints defined in Eq. (28) through Eq. (47) and $\{\eta_k, \rho_k\} \geq 0$, $k = 1,..,4$.

5.5 Procedure to solve the GP model

The procedure to solve the GP model is as a diagram in the figure below.

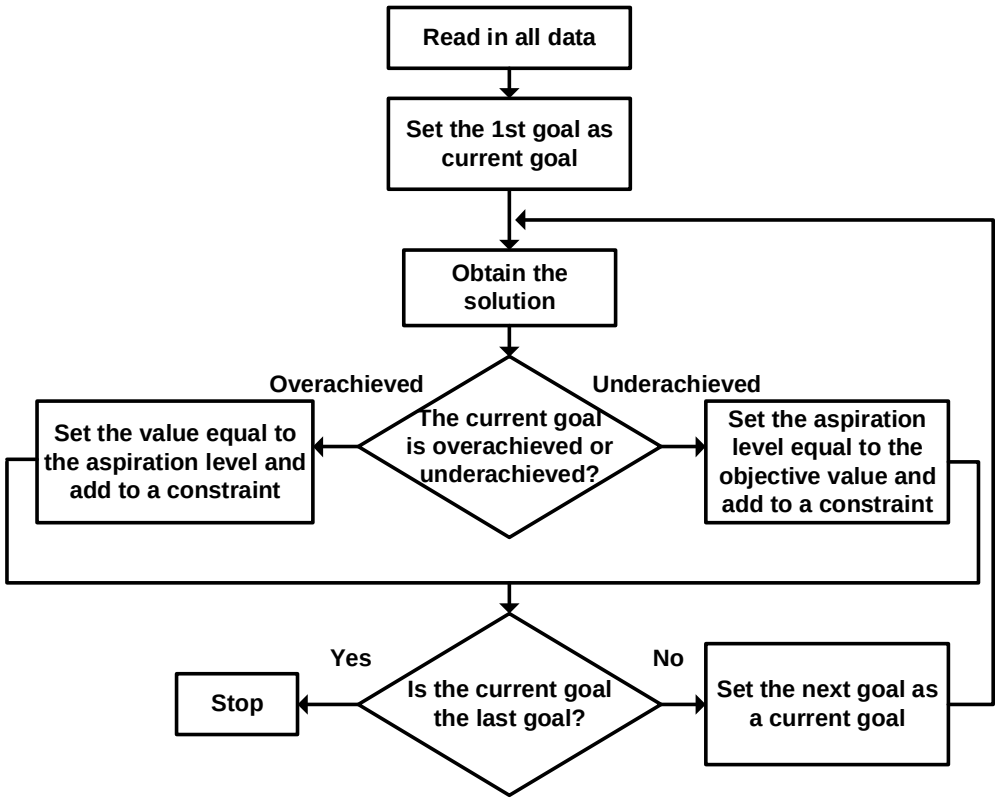

Figure 3. Procedure to solve GP model

6. CASE EXAMPLE

We consider a case example to demonstrate the application of the disassembly-to-order model. The objective of the model is to determine the best combination of the EOL products to be taken back to the facility and disassemble to satisfy the demand of each component and material, while achieving the aspiration level of each goal.

In this example, we have 4 products as each of them has 8 components. The structures of products are shown in figure 4. Also, the component multiplications for each product are shown in the figure. The input data are given in table 2.

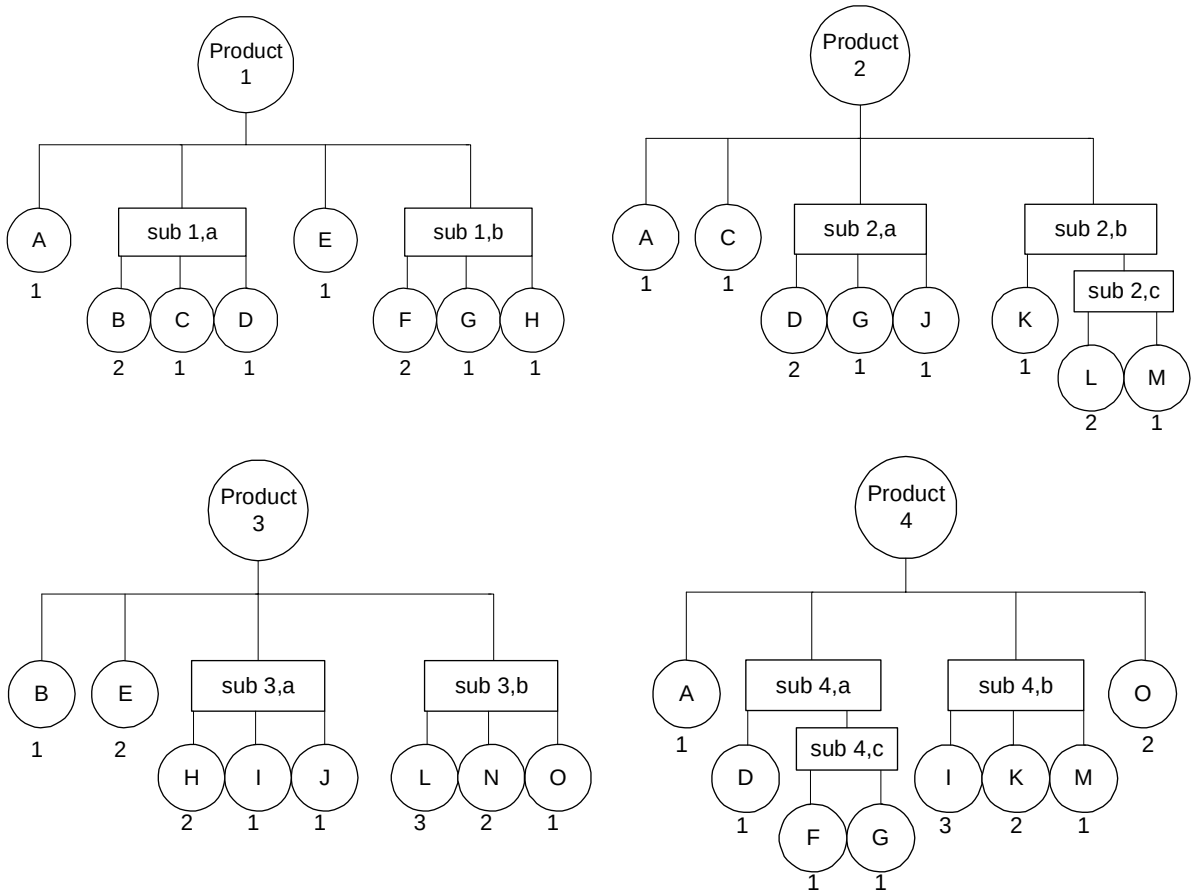

Figure 4. Product structures for case example

Table 2. Input data for the case example

Component j	pc_j	pm_j	DRC_j	$DREM_j$	cuh_j	SVL_j	cdd_j	cnd_j	cdc_j	cdm_j	OPC_j	SRC_j	SRE_j	WC_j
A	12	7	400	250	0.45	10	0.35	0.55	0.6	0.4	12	0.8	0.8	1.2
B	11	5	400	250	0.35	10	0.35	0.55	0.4	0.2	11	0.85	0.9	1.6
C	10	7	350	200	0.5	9	0.25	0.5	0.7	0.5	10	0.85	0.7	1.4
D	9	8	450	250	0.45	8	0.3	0.6	0.7	0.5	9	0.75	0.85	1.2
E	12	8	350	220	0.55	11	0.35	0.55	0.8	0.6	12	0.8	0.9	1.3
F	10	6	300	250	0.65	9	0.3	0.4	0.4	0.2	10	0.8	0.7	0.8
G	11	6	450	220	0.55	9	0.25	0.6	0.9	0.7	11	0.9	0.65	1.1
H	10	4	400	220	0.55	9	0.4	0.5	0.7	0.5	10	0.95	0.85	1.5
I	13	6	450	280	0.4	12	0.3	0.55	0.6	0.4	13	0.8	0.8	1.2
J	10	6	300	200	0.4	9	0.45	0.5	0.8	0.6	10	0.85	0.75	0.8
K	11	7	350	220	0.35	10	0.25	0.4	0.9	0.7	11	0.9	0.7	1.6
L	11	8	400	250	0.5	10	0.4	0.55	0.5	0.7	11	0.95	0.85	0.9
M	12	8	400	200	0.5	10	0.3	0.45	0.8	0.6	12	0.75	0.85	0.9
N	11	6	300	220	0.45	10	0.3	0.4	0.8	0.6	11	0.8	0.9	0.9
O	12	7	350	250	0.5	11	0.35	0.5	0.9	0.7	12	0.7	0.75	1.1

*Note. We use *U(0.9,1)* for SGP_i value, *U(0.7,0.9)* for SRC_j value and *U(0.65,0.9)* for SRE_j value.

Additional data needed for the case example are $SDY^- = 0$, $SDY^+ = 1$, $ctb_j = \{35, 32, 35, 34\}$, $cdp_j = \{4, 4, 4, 4\}$, $SGP_j = \{.91, .95, .92, .96\}$ for $i = 1, 2, 3$ and 4. $cir_j = 1$ and $cor_j = 1.8$, $IPC_j = 120$ and $ASC_j = 20$ for all j value. Aspiration level are $TPR^* = 24000$, $CPR^* = 10000$, $CTB^* = 38000$, $CDI^* = 2500$.

From the equation (6), (10) and (12), we can calculate the stochastic non-destructive disassembly yield value of each component of each product as shown in the table below.

Table 3. Disassembly yield factor for one-to-one heuristic

Product1		Product2		Product3		Product4	
Component	SDY_j	Component	SDY_j	Component	SDY_j	Component	SDY_j
A	0.52	A	0.5	B	0.56	A	0.5
B	0.55	C	0.5	E	0.52	D	0.53
C	0.52	D	0.53	H	0.56	F	0.53
D	0.55	G	0.5	I	0.52	G	0.5
E	0.52	J	0.53	J	0.56	I	0.5
F	0.55	K	0.5	L	0.56	K	0.5
G	0.52	L	0.53	N	0.56	M	0.5
H	0.55	M	0.5	O	0.52	O	0.5

We used Lingo 7 to solve the goal programming problem. The results are shown in the tables below.

Table 4. Values of various variables at different steps of the procedure to solve the GP model

Goals	**Aspiration level**	**1st Run**	**Goal 1**	**Goal 2**	**Goal 3**	**Goal 4**
Total profit variable (TPR)	**≥ 24000**	25471.55	**24000**	**24000**	**24000**	**24000**
Procurement cost (CPR)	**≤ 10000**	15645	8603	**9997**	**9994**	**9994**
Take-back EOL products cost (CTB)	**≤ 38000**	33210	39460	37950	**37990**	**37990**
Disposing cost (CDI)	**≤ 2500**	2081.2	2917.49	2656.23	2488.6	**2488.6**
Other important variables						
Components sale revenue (RCS)		62300	62300	62300	62300	62300
Materials sale revenue (RMS)		21181.6	21181.6	21181.6	21181.6	21181.6
Stored component value (SVL)		2152	1470	996	1203	1203
Storage Cost (CST)		104.95	70.25	45.7	59.25	59.25
Destructive disassembly Cost (CDD)		1586.45	1938.65	1863.4	1808.55	1808.55
Non-destructive disassembly cost (CND)		2710.4	3098.85	2988.65	3006	3006
Recycling cost (CRE)		4824	4863.3	4976.6	5338.1	5338.1

Table 5. Detailed numbers of take-back EOL products

Take-Back Product 1 = 340
Take-Back Product 2 = 180
Take-Back Product 3 = 270
Take-Back Product 4 = 320

Table 6. Detailed numbers of components for each process

Component	$TNDC_j$	$TDDM_j$	TRC_j	GRC_j	OPC_j	$TREM_j$	TSC_j	$TDIC_j$
A	396	385	395	316	84	250	1	214
B	472	383	460	391	9	250	12	202
C	244	233	240	204	146	200	4	69
D	510	442	508	381	69	250	2	319
E	411	381	410	328	22	220	1	243
F	395	521	375	300	0	250	20	346
G	395	386	390	351	99	220	5	205
H	439	353	420	399	1	220	19	154
I	580	575	560	448	2	280	20	407
J	226	188	220	187	113	200	6	21
K	389	390	380	342	8	220	9	208
L	440	460	420	399	1	250	20	231
M	237	238	236	177	223	20	1	97
N	272	214	270	216	84	220	2	48
O	430	421	430	301	49	250	0	300

7. CONCLUSIONS

Applying stochastic elements to a multi-criteria decision-making approach makes the model more realistic. Since in the real situation, these stochastic elements do not have a constant value. One-to-one heuristic and a uniform distribution are reasonable approach to provide stochastic equivalent yield value for implementing in a deterministic model. The model in this paper was implemented to achieve an aspiration level of all goals while satisfying all constraints under four stochastic elements.

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