# A FUZZY GOAL PROGRAMMING APPROACH TO DISASSEMBLY PLANNING

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## ABSTRACT

*Today, the amount of waste created by the disposal of end-of-life products has reached epidemic proportions. A major contributing factor of this phenomenon is the shortened life times of products. The most effective way to address this problem is to optimize the end-of-life (EOL) processing activities of products. There are many alternatives for the EOL processing of products, e.g., reuse, recycle, storage and proper disposal. All of these activities require a certain level of disassembly. Since disassembly tends to be a very expensive operation, special attention should be given to it for it to be efficient. For this reason, disassembly process planning, which provides a feasible sequence of disassembly, has been the focus of several recent studies. We present a disassembly-to-order system where the products are taken back from the last user and/or collectors, disassembled for the retrieval of reusable components and resold in order to meet a certain level of demand. We model it as a multi-criteria decision making problem under uncertainty using the fuzzy goal programming technique. A case example is provided to illustrate the methodology.*

**Keywords:** *Fuzzy Goal Programming, Multi-Criteria Decision Making, End-of-Life Processing, Disassembly-to-Order System.*

## الملخص

في الوقت الراهن وصلت كميات النفايات والمخلفات في نهاية عمر المنتجات إلى كم هائل لم يسبق له مثيل. ويرجع السبب الرئيسي في ذلك إلى قصر عمر منتجات. وحتى يمكن معالجة هذه المشكلة أو تخفيفها الاستفادة القصوى من تلك المخلفات. هناك الكثير من البدائل يمكن بها الاستفادة من كل أو بعض أجزاء المنتج مثل إعادة الاستخدام، والتدوير، والحفظ أو التخلص الملائم. كل هذه الأنشطة تتطلب مراحل إعادة تفكيك ملائمة. عملية إعادة التفكيك للمنتجات تعتبر عملية مكلفة ينبغي إعطائها الفهم الكامل حتى تكون ممكنة. لهذا السبب يلزم التخطيط لعمليات التفكيك التي تقدم مراحل تفكيك واقعية كانت محط تركيز الدراسات الحديثة. نحن نقدم نظام التفكيك بناءً على الطلب حيث المنتجات تؤخذ من المستخدم الأخير أو من يقوم بتجميعها ليتم تفكيكها وإعادة استخدامها وبالتالي بيعها لمقابلة حد معين من الطلب عليها. النموذج المقترح يتناول اتخاذ قرار في عدد من المعايير الغير ثابتة باستخدام برمجة الهدف الغائم. ولهذا الغرض سوف نقدم دراسة حالة لتوضيح هذا المنهج.

## 1. INTRODUCTION

Today, the amount of waste created by the disposal of end-of-life products has reached epidemic proportions. A major contributing factor of this phenomenon is the shortened life times of products. This is due to the rapid technological development of new products and an increasing demand for the latest technology by the consumers. The consumers routinely discard enormous number of still functioning products. This leads to an increasing amount of virgin material usage and rapid disappearance of landfills. The most effective way to address this problem is to optimize the end-of-life (EOL) processing activities of products.

As part of the need for EOL processing of products, many governments have instituted the concept of extended product responsibility and have encouraged the industries to embrace it. Today, in many countries, the manufacturers are not only responsible to design and produce energy efficient products in an environmentally benign manner, they are also responsible for the EOL processing of the products. Many governments have promulgated this law under the title of “take-back policies”.

There are many alternatives for the EOL processing of products, e.g., reuse, recycle, storage and proper disposal. Reuse activities include the repair, refurbish and cleaning processes with or without adding additional value to the product, while recycling is performed in order to regain the material value of the EOL product. Storing the EOL product under the premise that there may be a future demand, is another way of avoiding unnecessary disposal. Of course, the least desirable option is land filling. However, if it must be done, care must be exercised to dispose of products that have the least hazardous contents.

All of the above activities require a certain level of disassembly. EOL products may be disassembled wholly or partially in order to perform environmentally benign operations. Since disassembly tends to be a very expensive operation, special attention should be given to it for it to be efficient. For this reason, disassembly process planning, which provides a feasible sequence of disassembly, has been the focus of several recent studies.

In this paper, disassembly process planning is performed in a multi-period environment. We present a disassembly-to-order system where the products are taken back from the last user and/or collectors, disassembled for the retrieval of reusable components and resold in order to meet a certain level of demand. The surplus components are recycled or stored for usage in subsequent periods or properly disposed of.

We model the above as a multi-criteria decision making problem under uncertainty. Since the decision maker has to address various goals, it is highly unlikely that the aspiration levels of the decision maker will be strictly determined (or crisp). In this case, the aspiration levels (such as related cost and profit values, and/or the quantitative measures) are more likely to be

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in the “approximately less (more) than” and/or “more (less) is better” form. Hence, we use fuzzy goal programming technique for this disassembly-to-order system. A case example is provided to illustrate the methodology.

## 2. LITERATURE REVIEW

Several studies have recently emerged that address various aspects of disassembly. The following is a brief review of the most relevant literature in disassembly.

### 2.1. Disassembly Planning

Gupta and Taleb [1994] proposed an algorithm for scheduling the disassembly of a discrete, well-defined product structure. The algorithm got its inspiration from Material Requirements Planning (MRP) and determines the disassembly schedule for the components such that the demands for those components are satisfied. In their subsequent papers, [Taleb *et al*, 1997] and [Taleb and Gupta, 1997] improved the methodology to include components/materials commonality as well as the disassembly of multiple product structures. Recently, [Veerakamolmal and Gupta, 1998] proposed methods that provide solutions for component recovery planning. The authors determined the number and type of products to disassemble in order to satisfy the demand for a set of components while minimizing the disassembly and disposal costs. [Veerakamolmal and Gupta, 1999] extended their product recovery concept to analyzing the design efficiency of electronic products for studying the effect of EOL disassembly and disposal on the environment. [Erdos *et al*., 2001] concentrated on the modeling and evaluating EOL options using liaison graphs. The authors developed three algorithms for maximizing the revenue while determining the optimum disassembly plan. Lambert and Gupta [2002] addressed the problem of demand driven disassembly using tree network model.

Veerakamolmal *et al*. [1997] applied planning and sequencing techniques to create an efficient disassembly plan by taking advantage of the product modularity, which minimizes the total processing time and thus the cost of disassembly. [Zussman, 1995] suggested a two-level disassembly planning approach by considering both the recycling network and the disassembly process. [Zussman and Zhou, 2000] discussed the design and implementation of a process planner for disassembly processes. [Gungor and Gupta, 1997, 1998] addressed the problems of disassembly processes and disassembly sequence planning. [Meacham *et al.*, 1999] analyzed optimal disassembly configurations for single and multiple products. [Huang *et al*., 2000] applied neural network approach to disassembly processing problem. Recently, [Moore *et al*., 2001] used Petri Nets for modeling products with complex AND/OR precedence relationships for disassembly process planning. [Neuendorf *et al*., 2001] also used Petri Nets approach to model products with parts commonality for disassembly scheduling. [Kuo, 2000] used a recursive search algorithm to define the subassemblies in the product structure to find the optimum way to disassemble. [Ong and Wong, 1999] proposed an

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approach to determine the subassemblies automatically. The authors used interference graphs to determine the appropriate subassemblies.

Several authors have applied mathematical programming in the area of disassembly and recycling. [Isaacs and Gupta, 1997] and [Boon *et al.*, 2000] investigated the impact of automobile design on disposal strategies by using goal programming to solve the problem. [Hoshino *et al.*, 1995] used a goal programming model to analyze the profitability and recycling rates for manufacturing systems. [Lambert, 1999] used linear programming to facilitate disassembly sequence generation. [Kang *et al.*, 2001] used an integer-programming model to address the parallel disassembly sequencing problem. [Shih, 2001] proposed an algorithm to minimize the overall EOL activity costs using mixed integer programming.

For more information on disassembly and product recovery see [Gupta and McLean, 1996], [Moyer and Gupta, 1997], [Gungor and Gupta, 1999], [Tang *et al.*, 2000] and [Lee *et al.*, 2001].

### 2.2. Fuzzy Set Theory and Applications

Fuzzy set theory has been the subject of many studies in the literature [Zimmerman, 1996]. The theory has found its way in a wide variety of applications including multiple decision-making problems. Fuzzy set theory allows vagueness in defining goals and aspiration levels. Often, the decision maker is ambiguous about the priorities of goals and their possible outcomes. Fuzzy goal programming (FGP) allows the use of vague aspiration levels for decision-making purposes [Ramik, 2000].

Many authors have considered applications of fuzzy set theory since the early 1930s [Zimmerman, 1996]. [Tiwari et al., 1986] introduced priority structure in Fuzzy Goal Programming (FGP). The authors' approach aimed to utilize the lexicographic order of Goal Programming (GP) providing ease in calculations. In their subsequent work, [Tiwari et al., 1987] introduced a simple weighted additive model to solve FGP. Other authors also considered a FGP approach for preemptive priority models.

Today, fuzzy set theory and its applications are still the focus of much research. This is because FGP reduces the combinatorial complexity of problems. [Chen and Tzeng, 2001] considered fuzzy multi-objective modeling to solve supply chain problems. The supply chain in their study consisted of purchasing/production and transportation phases. [Ramik, 2000] investigated GP problems with alternatives and goals being fuzzy sets. The author proposed a unifying approach covering various approaches from the literature.

Recently, [Chen et al., 2001] presented a method for automatically generating a multi-variable fuzzy inference system with nonlinear functions. [El-Wahed and Abo-Sinna, 2001] proposed a solution using fuzzy set theory and GP for multiple objective decision making (MODM)

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problems. The authors called their solution method as hybrid fuzzy goal programming (HFGP). HFGP algorithm converts a MCDM problem into its equivalent GP problem by fixing proper priorities and aspiration levels. The algorithm then determines the weight for the objective functions. The authors conclude that the solutions obtained by their algorithm were always optimal and coding for the methodology could be done effectively. Finally, [Gonzáles et al., 2001] studied the life cycle assessment of products using a fuzzy programming approach.

Motivated with the success of fuzzy goal programming, in this paper we consider a disassembly-to-order system where products are taken back from the last user and/or collectors, disassembled for the retrieval of reusable components and resold in order to meet a certain level of demand. However, before we formally formulate the problem, an introduction to fuzzy goal programming is provided in the next section.

## 3. FUZZY GOAL PROGRAMMING

Many mathematical programming frameworks require precise (quantitative) statements of the objective and constraints at the problem formulation stage. However, in real life situations, the decision maker often finds it difficult to express his/her wishes in strict expressions. Thus the decision maker would benefit immensely from a general framework for decision-making that possesses two key features. First, the framework must allow the problem formulation to *retain its multi-objective character* and second, the problem statement should allow for the possibility of *deliberate vagueness*.

Fuzzy programming introduces this vagueness and provides relatively easy-to-understand results by allowing the formulation of indefinite constraint sets. In fuzzy modeling the constraints are in the form of “essentially smaller than or equal to” ($\simeq$) (or, “essentially smaller than or equal to” ($\lesssim$), or essentially greater than or equal to” ($\gtrsim$)) rather than “smaller than or equal to” (or “greater than or equal to”) which implies certainty. Hence, the fuzzy goal $G(x)_\tau \simeq g_\tau$ implies that $G(x)_\tau$ can take a value both less than $g_\tau$ and greater than $g_\tau$ up to certain possible negative and positive limits respectively. For more information, see Tiwari et al. [1986, 1987].

## 4. PROBLEM FORMULATION

This paper presents a disassembly-to-order (DTO) system where the EOL products are taken back from the last users and/or collectors and brought into the facility, where the products are sorted, cleaned, refurbished and are prepared for further processing. Depending on the type of demand, the products are disassembled for their materials or components. If the component is disassembled for reuse or storage, non-destructive disassembly is carried out, otherwise destructive disassembly is performed for recycling or proper disposal.

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### 4.1. Nomenclature

The nomenclature used in this paper is provided as follows.

| | |
|---|---|
| $\alpha_j$ | Functionally defective rate for item *j* (percentage) |
| $\beta_j$ | Rate at which item *j* gets damaged during disassembly (percentage) |
| $\gamma_j$ | Rate at which customers replace item *j* (percentage) |
| $\mu q$ | Achievement level of the goals at the priority level q |
| $\tau$ | Index for the variables related to $G\tau(x) \gtrsim g\tau$ constraints |
| $\upsilon_j$ | Volume item *j* of product *i* (cubic inch) |
| $\omega$ | Index for the variables related to $G\omega(x) \lesssim g\omega$ constraints |
| $ARC$ | Total amount of recycled material (lb) |
| $AX \leq b$ | System constraints in vector notation |
| $AS$ | Available storage space (cubic inch) |
| $CAC$ | Cost of preparation of EOL products ($) |
| $CAC^*$ | Aspiration level for *CAC* ($) |
| $Cd$ | Destructive disassembly cost per hour ($/hour) |
| $CDD$ | Cost of destructive disassembly ($) |
| $CDI$ | Cost of Disposal ($) |
| $CDI^*$ | Aspiration level for *CDI* ($) |
| $CND$ | Cost of non-destructive disassembly ($) |
| $Cnd$ | Non-destructive disassembly cost per hour ($/hour) |
| $CRE$ | Cost of Recycling ($) |
| $CST$ | Cost of Storage ($) |
| $CTRCF$ | Transportation cost from collectors to facility ($) |
| $CTRFD$ | Transportation cost from facility to disposal ($) |
| $CTRFR$ | Transportation cost from facility to inside recycling ($) |
| $CTRFS$ | Transportation cost from facility to storage ($) |
| $ddt_j$ | Time required for disassembling item *j* (destructive) (hr) |
| $D_j$ | Resale demand for item *j* (unit) |
| $DR_k$ | Recycling demand for material *k* (lb) |
| $dt_j$ | Time required for disassembling item *j* (non-destructive) (hr) |
| $f(\mu)$ | Fuzzy achievement function |

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|---|---|
| $gc$ | Aspiration levels of goals in subset q |
| $Gu$ | Goal function for goal u |
| $h_j$ | Holding cost for item $j$ (\$/unit) |
| $i$ | Index for EOL product |
| $j$ | Index for item |
| $L_{ij}$ | Number of items $j$ of product $i$ to be disposed (unit) |
| $Lu$ | Lower tolerance limit for the fuzzy goals |
| $NDIS$ | Number of disposed items (unit) |
| $NDIS^*$ | Aspiration level for $NDIS$ (unit) |
| $NRC$ | Total number of recycled items (unit) |
| $NRU$ | Total number of reused items (unit) |
| $NSTR$ | Number of stored items (unit) |
| $NSTR^*$ | Aspiration level for $NSTR$ (unit) |
| $PRC_j$ | Recyclable percentage of item $j$ (percentage/unit) |
| $PRM_j$ | Resale value for reused item $j$ (\$/unit) |
| $Q_{ij}$ | Component multiplicity factor for item $j$ of product $i$ (unit) |
| $R_{ij}$ | Number of items $j$ of product $i$ to be recycled (unit) |
| $RMS$ | Materials sale revenue (\$) |
| $RMS^*$ | Aspiration level for $RMS$ (\$) |
| $RMV[k]$ | Market value of material $k$ (\$/lb) |
| $RPS$ | Product sale revenue (\$) |
| $RQ_j$ | Amount obtained from recycling item $j$ (lb) |
| $RQ_j[k]$ | Amount of material $k$ obtained from recycling item $j$ (lb) |
| $TB$ | Take back cost (\$) |
| $TPR$ | Total profit value (\$) |
| $TPR^*$ | Aspiration level for $TPR$ (\$) |
| $TS$ | Total space occupied by the stored items (inch cube) |
| $Uv$ | Upper tolerance limit for the fuzzy goals |
| $UCAC_i$ | Unit cost of preparation for product $i$ (\$/unit) |
| $UCDI_j$ | Unit cost for disposing item $j$ (\$/unit) |
| $UCRE_k$ | Unit cost for recycling material $k$ (\$/unit) |
| $UCTRCF_i$ | Unit transportation cost from collectors to facility (\$/unit) |

| | |
|---|---|
| $UCTRFD_j$ | Unit transportation cost from facility to disposal ($/unit) |
| $UCTRFM_k$ | Unit transportation cost from recycling to material retailer ($/unit) |
| $UCTRFR_j$ | Unit transportation cost from facility to inside recycling ($/unit) |
| $UCTRFS_j$ | Unit transportation cost from facility to storage ($/unit) |
| $UTB_i$ | Unit take-back cost for product *i* ($/unit) |
| $V_{ij}$ | Number of stored item *j* of product *i* (unit) |
| $W_{ij}$ | Weight of item *j* in product *i* (lb) |
| $X_{ij}$ | Number of reused item *j* of product *i* (unit) |
| $Y_i$ | Number of EOL product *i* ordered (unit) |

## 4.2 Functions and Constraints

### *4.2.1. Revenue Functions*

There are two sources of revenues in the DTO system, viz., the revenue from the sales of demanded materials (*RMS*) and the revenue from the sales of demanded components (*RPS*). The revenue functions can be written as follows:

*RMS* is a function of the amount of materials sold $\left(\sum_j\left(RQ_j[k]\right)\right)$ and the market value of material obtained (*RMV*[*k*]) from each material type *k*. The amount of materials sold is a function of the number of component *j* recycled ($\sum_i R_{ij}$), the weight of component *j* ($\sum_i W_{ij}$) and the percentage of marketable material obtained from component *j* ($PRC_j$). Therefore, by summing the revenue over all components, *RMS* can be obtained as follows:

$$RMS = \sum_k\left(\sum_j\left(RQ_j[k]\right).RMV[k]\right) \tag{2}$$

where, regardless of the material type (*k*), the obtained amount ($RQ_j$) can be calculated as:

$$RQ_j = \left(\sum_i R_{ij}\right).\left(\sum_i W_{ij}\right).PRC_j \tag{3}$$

*RPS* is a function of the demand for component type *j* ($D_j$) and the unit sale price for component type *j* ($PRM_j$). Therefore, *RPS* can be mathematically expressed as follows:

$$RPS = \sum_j (D_j)\ .PRM_j \tag{4}$$

### *4.2.2. Cost Functions*

The various costs considered in the model include: the take back cost (*TB*), transportation cost from collectors to the facility (*CTRCF*), transportation cost from facility to outside recycling plant (*CTRFR*), transportation cost from facility to disposal site (*CTRFD*), transportation cost

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from facility to storage location (*CTRFS*), the cost of preparation of EOL products (*CAC*), the cost of destructive disassembly (*CDD),* the cost of nondestructive disassembly (*CND*), recycling cost (*CRE*), storage cost (*CST*) and disposal cost (*CDI*).

*TB* is a function of the number of EOL products ordered ($Y_i$) and the cost of each product ($UTB_i$). Therefore,

$$TB \ = \ \sum_i (Y_i . UTB_i) \tag{5}$$

*CTRCF* is a function of the number of EOL products ordered ($Y_i$) and the transportation cost per unit from collectors to the facility ($UCTRCF_i$). Therefore,

$$CTRCF = \ \sum_i (Y_i \, .UCTRCF_i) \tag{6}$$

*CTRFS* is a function of the number of components sent to storage (*NSTR*) and the transportation cost per unit from the facility to the storage location ($UCTRFS_j$). Therefore:

$$NSTR = \ \sum_j \sum_i V_{ij} \tag{7}$$

and

$$CTRFS = \sum_j \left( \sum_i V_{ij} \right) .UCTRFS_j \tag{8}$$

The demanded components and materials are sent to the distribution center. *CTRFR* is a function of the demand for each component, ($D_j$), and material ($DR_k$) and the transportation cost per unit from the facility to the distribution center ($UCTRFR_j$) and per pound of material ($UCTRFM_k$). Therefore,

$$CTRFR = \ \sum_j (D_j . UCTRFR_j) + \sum_k (DR_k . UCTRM_k) \tag{9}$$

*CTRFD* is a function of the number of components sent to disposal (*NDIS*) and the transportation costs per unit from facility to the disposal site ($UCTRFD_j$). The number of components sent to disposal include the non-demanded components ($L_{ij}$), functionally defective components ($\sum_i (X_{ij}) . \alpha_j$), where $\alpha_j$ is the functionally defective rate for component *j*, the components damaged during disassembly ($\sum_i (X_{ij}) . \beta_j$), where $\beta_j$ is the rate at which component *j* gets damaged during disassembly, and components replaced by the customer with other types that are neither demanded as parts nor contain the demanded type of materials recycled ($\sum_i (X_{ij} + R_{ij}) . \gamma_j$), where $\gamma_j$ is the rate at which customers replace component *j*. Therefore:

$$NDIS = \left( \sum_i \left( L_{ij} \right) + \sum_i \left( X_{ij} \right) . (\alpha_j + \beta_j) + \sum_i \left( X_{ij} + R_{ij} \right) . \gamma_j \right) \tag{10}$$

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and

$$CTRFD = \sum_j \left( \sum_i \left(L_{ij}\right) + \sum_i \left(X_{ij}\right).(\alpha_j + \beta_j) + \sum_i \left(X_{ij} + R_{ij}\right).\gamma_j \right).UCTRFD_j \tag{11}$$

*CAC* is a function of the number of EOL products ordered ($Y_i$) and the cost of preparing each product ($UCAC_i$ ). Therefore:

$$CAC = \sum_i Y_i.UCAC_i \tag{12}$$

*CDD* is the cost of destructive disassembly (considered for the components that are recycled for their material content or the components that are sent to landfills for proper disposal) and is a function of number of components to be recycled and disposed $\left(\sum_i \left(R_{ij} + L_{ij}\right)\right)$, the cost per hour (*cd*) and the time of disassembling each component ($ddt_j$). Therefore:

$$CDD = \sum_j \left( \sum_i \left(R_{ij} + L_{ij}\right)\right).\, cd.ddt_j \tag{13}$$

*CND* is the cost of non-destructive disassembly (considered for the components that are reused or the components that are sent to storage) and is a function of number of components to be reused and stored $\left(\sum_i \left(X_{ij} + V_{ij}\right)\right)$, the cost per hour (*cnd*) and the time of disassembling each component ($dt_j$). Therefore:

$$CND = \sum_j \left( \sum_i \left(X_{ij} + V_{ij}\right)\right).\, cnd.dt_j \tag{14}$$

*CRE* is a function of the amount of material recycled $\left(\sum_j \left(RQ_j[k]\right)\right)$ and the corresponding unit recycling cost ($UCRE_k$). Therefore:

$$CRE = \sum_k \left( \sum_j \left(RQ_j[k]\right).UCRE_k \right) \tag{15}$$

*CST* is a function of the number of stored components ($\sum_i V_{ij}$ ), the volume of each component ($\nu_j$) and the holding cost per unit volume (*h*). Therefore:

$$CST = \left( \sum_j \left( \sum_i V_{ij} \right).\nu_j \right).h \tag{16}$$

*CDI* is a function of the number of disposed components $\left(\sum_i L_{ij}\right)$, and the corresponding unit disposal cost ($UCDI_j$). Therefore:

$$CDI = \sum_j \left( \sum_i L_{ij} \right).\, UCDI_j \tag{17}$$

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### *4.2.3. Total Profit Function*

The total profit value (*TPR*) is the difference between all the revenues and all the costs considered in the model. Therefore, *TPR* can be written as follows:

$$\begin{aligned} TPR = {} & RMS + RPS - TB - CTRCF - CTRFR - CTRFD - CTRFS \\ & - CAC - CDD - CND - CRE - CST - CDI \end{aligned} \tag{18}$$

### *4.2.4. Constraints*

In this paper we consider complete disassembly, implying that all the components in the product structure will be disassembled. Hence, the number of components retrieved from each EOL product ordered ($Y_i . Q_{ij}$) has to equal to the number of components that are reused ($X_{ij}$), recycled ($R_{ij}$), stored ($V_{ij}$) and disposed ($L_{ij}$). Therefore,

$$Y_i \,.\, Q_{ij} = (X_{ij} + R_{ij} + V_{ij} + L_{ij}),\ \forall\ i,j \tag{19}$$

Demand must be satisfied without allowing any backorders. Hence, the components disassembled for reuse must exceed the demand by the amount lost $(D_j .(\alpha_j + \beta_j + \gamma_j))$. Therefore, the demand constraints becomes:

$$D_j .(1 + \alpha_j + \beta_j + \gamma_j) \le \sum_i X_{ij}, \forall\ j \tag{20}$$

Same reasoning also holds for the demand of material. The amount disassembled for recycling must exceed the demand by the amount lost $(DR_k .(\gamma_j [k]))$.

$$DR_k .(1 + \gamma_j [k]) \le RQ_j [k], \forall\ j \tag{21}$$

The total number of components recycled (*NRC*) can be expressed as follows:

$$NRC = \sum_j DR_j \tag{22}$$

and the total amount of recycled material is:

$$ARC = \sum_k \left( \sum_j RQ_j [k] \right) \tag{23}$$

The total space (*TS*) occupied by the stored components have to be less than or equal to the total available space in storage (*AS*). *TS* is a function of the number of stored component *j* ($\sum_i V_{ij}$) and its corresponding volume ($v_j$). Therefore:

$$TS = \sum_j (v_j . \sum_i V_{ij}) \tag{24}$$

and

$$TS \le AS \tag{25}$$

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Note that the total number of reused components (*NRU*) is:

$$NRU = \sum_i \sum_j (X_{ij}) \tag{26}$$

All the variables must be non-negative integers. Thus,

$$\{Y_i\}, \{X_{ij}\}, \{R_{ij}\}, \{V_{ij}\}, \{L_{ij}\} \geq 0 \text{ and integer; for all } i \text{ and } j. \tag{27}$$

### 4.3. The Steps to Solve the FGP model of the DTO System

***Step 1.*** Determine the goals for the DTO system. Define the priority level of each goal. Construct the set(s) of goals.

***Step 2.*** Obtain Linear Programming (LP) solutions using various goal(s) as the objective functions.

***Step 3.*** Determine the achievement level of each goal and construct the FGP model.

***Step 4.*** Solve FGP model for the current goal set.

***Step 5.*** If the achievement levels are found to be satisfactory GO TO Step 6. Else, if at least one of the achievement levels is unsatisfactory or no feasible solution is found, GO TO Step 3.

***Step 6.*** If all the goal sets have been considered, STOP. Otherwise, set the next goal set of importance as the current goal set, fix the previous achievement levels as constraints. GO TO Step 4.

## 5. NUMERICAL EXAMPLE

We employ a numerical example to illustrate the application of the DTO model. Consider three different products (see Figure 1 for the product structures), which are subject to disassembly for their components and materials. The data used in the example is given in Table 1. Additional data for the example is as follows: Market value of material, $RMV[k] = \{23, 1, 12\}$¢/lb, $\forall\ k, k = 1,2,3$ (1 : aluminum, 2 : glass, 3 : plastic). Unit recycling cost, $UCRE_k = \{4, 0.2, 2.5\}$¢/lb $\forall\ k, k = 1,2,3$. Cost per hour for destructive disassembly, $cd$ = \$12.5/hr and non-destructive disassembly, $cnd$ = \$14.69/hr. Holding cost per unit volume, $h$ = 30¢/ cu in. Functionally defective rate in component $j$, $\alpha_j = 0.05$, $\forall\ j, j = 1, \ldots, 29$. The rate at which component $j$ gets damaged during disassembly, $\beta_j = 0.01$, $\forall\ j, j = 1, \ldots, 29$. The rate at which customers replace component $j$, $\gamma_j = 0.01$, $\forall\ j, j = 1, \ldots, 29$. Total available space in storage, $AS$ = 5,000,000 cu in. Demand for material, $DR[k] = \{500, 400, 500\}$¢/lb, $RMV[k] = \{23, 1, 12\}$¢/lb. Also, $g_1 = 550{,}000$ and $L_1 = 500{,}000$; $g_2 = 30{,}000$ and $L_2 = 4{,}447$; $g_3 = 9{,}200$ and $U_3 = 4{,}447$; $g_4 = 9{,}580$ and $U_4 = 700$.

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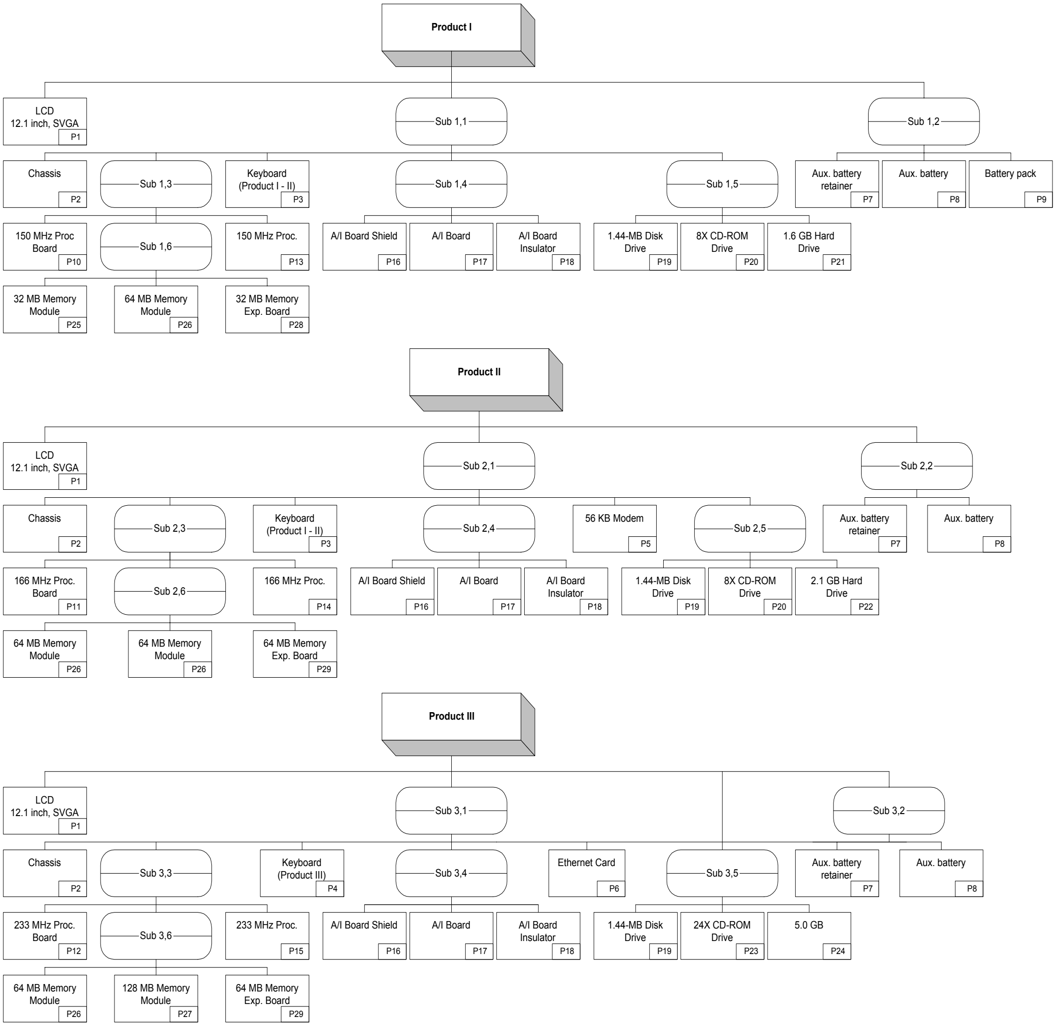

Figure 1. Structures of the End-of-Life Products

The goals for the DTO system are defined as follows:

1. Financial Goal: Total Profit Value (*TPR*) has to be essentially greater than a certain aspiration level ($TPR^*$). Thus:

   $G_1$: $TPR \gtrsim g_1$, where $g_1$ is the aspiration level for the first goal ($g_1$: $TPR^*$)

2. Recycling Goal: Number of recycled components has to be essentially greater than a certain aspiration level. Thus:

   $G_2$: $NRC \gtrsim g_2$, where $g_3$ is the aspiration level for the third goal ($g_2$: $NRC^*$)

3. Disposal Cost Goal: The cost of disposal has to be essentially less than a certain value. Thus:

   $G_3$: $(CRC \lesssim g_3$, where $g_3$ is the aspiration level for the third goal ($g_3$: $CDI^*$)

4. Disposal and inventory goal: The sum of the number of disposed and stored components should essentially be less than a certain aspiration level (this goal avoids the environmental burden of disposal as well as keeps the inventory level under control). Thus:

   $G_4$: $NDIS + NSTR \lesssim g_4$, where $g_4$ is the aspiration level for the fourth goal ($g_4$: $(NDIS + NSTR)^*$)

The goal sets for the DTO system are: Priority 1: $G_1$ and $G_2$; Priority 2: $G_3$; and Priority 3: $G_4$.

Initial LPs are solved and the results are shown in Table 2.

Achievement level of each goal is chosen as, $\mu_1 = 1$, $\mu_2 = 1$, $\mu_3 = 1$, $\mu_4 = 1$. From eq. (1), the first subproblem related to the priority level –1 becomes:

$$\max f(\mu) = \sum_{q=1}^{2} (\mu_q) \text{ this is equivalent to, } \max (\mu_1 + \mu_2)$$

$$s.t. \qquad \mu_1 \leq \frac{(TPR - 500{,}000)}{50{,}000} \quad \text{and} \quad \mu_2 \leq \frac{(NRC - 25{,}523)}{4477}$$

$$\mu_1 \leq 1 \text{ and } \mu_2 \leq 1$$

$$\mu_1 \geq 0 \text{ and } \mu_2 \geq 0$$

and eq. (2-27)

The solution for the priority level –1 is found to be totally satisfied with achievement levels $\mu_1 = 1$ and $\mu_2 = 1$. The total profit, $TPR$ = \$ 550,000 and the number of recycled components, $NRC$ = 30,000 units. Since these results are satisfactory we define the new set of goals with the second priority level.

Table 1. Data Table for Numerical Example

| $j$ | **Description** | $UCDI_j$ **($)** | $dt_j$ **(s)** | $ddt_j$ **(s)** | $PRM_j$ **($)** | $v_j$ **(cu in)** | $D_j$ **(lb)** | $PRC_j$ **(%)** | $W_j$ **(lb)** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Display Assembly, 12.1-inch | 8 | .07 | .05 | 175 | 43.27 | - | 50 | 1.10 |
| 2 | Chassis | 9 | .08 | .06 | 0 | 15 | - | 100 | .50 |
| 3 | Keyboard – Pro I and II | 6 | .03 | .02 | 48 | 10 | - | 100 | .20 |
| 4 | Keyboard – Pro III | 6 | .03 | .02 | 48 | 10 | - | 100 | .20 |
| 5 | 56 KB Modem | 6 | .03 | .02 | 50 | 1.43 | 400 | - | .50 |
| 6 | Ethernet Card | 6 | .03 | .02 | 50 | 1.15 | 500 | - | .50 |
| 7 | Aux. Battery Retainer | 8 | .04 | .03 | 0 | 6.50 | - | - | .01 |
| 8 | Auxiliary Battery | 10 | .04 | .03 | 130 | 5.50 | - | - | .05 |
| 9 | Li-ion Battery Pack | 10 | .04 | .03 | 93 | 8.50 | - | - | .48 |
| 10 | 150 MHz – Proc. Board | 6 | .05 | .03 | 68 | 10 | - | 100 | .40 |
| 11 | 166 MHz – Proc. Board | 6 | .05 | .03 | 98 | 10 | - | 100 | .40 |
| 12 | 233 MHz – Proc. Board | 6 | .05 | .03 | 158 | 10 | - | 100 | .40 |
| 13 | 150 MHz Proc. w/ heats. | 6 | .05 | .03 | 125 | 25 | 500 | - | .60 |
| 14 | 166 MHz Proc. w/ heats. | 6 | .05 | .03 | 188 | 25 | 500 | - | .60 |
| 15 | 233 MHz Proc. w/ heats. | 6 | .05 | .03 | 225 | 25 | 550 | - | .60 |
| 16 | Audio/Inf. Board Shield | 7 | .04 | .02 | 10 | .18 | - | - | .01 |
| 17 | Audio/Inf. Board | 6 | .05 | .03 | 13 | .15 | - | - | .01 |
| 18 | Audio/Inf. Board Insulator | 6 | .05 | .03 | 10 | .18 | - | - | .01 |
| 19 | 1.44 MB Disk Drive | 7 | .06 | .04 | 13 | 7.2 | 550 | - | .68 |
| 20 | 8X CD-R Drive | 6 | .05 | .03 | 53 | 11 | 500 | - | .40 |
| 21 | 1.6 GB Hard Drive | 7 | .06 | .04 | 75 | 21.75 | 600 | - | .34 |
| 22 | 2.1 GB Hard Drive | 7 | .06 | .04 | 133 | 21.75 | 500 | - | .34 |
| 23 | 24X CD-RW Drive | 7 | .05 | .03 | 64 | 12.95 | 550 | - | .50 |
| 24 | 5.0 GB Hard Drive | 7 | .06 | .04 | 133 | 21.75 | 800 | - | .34 |
| 25 | 32 MB Mem. Module | 7 | .03 | .02 | 40 | .55 | 500 | - | .50 |
| 26 | 64 MB Mem. Module | 7 | .03 | .02 | 60 | .55 | 550 | - | .50 |
| 27 | 128 MB Mem. Module | 8 | .03 | .02 | 135 | .55 | 600 | - | .50 |
| 28 | 32 MB Mem. Exp. Board | 8 | .05 | .03 | 33 | .60 | 500 | 100 | .90 |
| 29 | 64 MB Mem. Exp. Board | 8 | .05 | .03 | 105 | .60 | 550 | 100 | .90 |

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Table 2. Linear Programming and Fuzzy Goal Programming Results

| ***Function*** | ***LP*** | | | | | ***FGP*** |
|---|---|---|---|---|---|---|
| | **max *TPR*** | **max *NRC*** | **max *RMS*** | **min *CDI*** | **min *NDIS+NSTR*** | **min $(\mu_1+\mu_2+\mu_3+\mu_4)$** |
| ***TPR*** | 692305.2 | 15.9 | 1.7 | 657308 | 657308 | 550000 |
| ***NRC*** | 25523 | 516007 | 516007 | 2307 | 2307 | 30000 |
| ***CDI*** | 6012.1 | 41212 | 41212 | 342.2 | 657308 | 9200 |
| ***NDIS*** | 860 | 5765 | 5765 | 629 | 629 | 1202 |
| ***NSTR*** | 290 | 290 | 290 | 290 | 290. | 7678 |
| ***RMS*** | 56077.3 | 1176977 | 1176977 | 18097.7 | 18097.7 | 32039.7 |
| ***RPS*** | 820250 | 820250.0 | 820250.0 | 820250 | 820250 | 820250 |
| ***TB*** | 69510 | 935070 | 935096 | 69510 | 69510 | 114946 |
| ***CTRCF*** | 23014 | 369238.0 | 369232.0 | 23014 | 23014 | 37282 |
| ***CTRFS*** | 1160 | 1160 | 1160 | 1160 | 1160 | 30712 |
| ***CTRFCUS*** | 43392.5 | 45974.8 | 45974.79 | 43297.51 | 43297.5 | 43333.8 |
| ***CTRFD*** | 4303.7 | 28827.9 | 28827.9 | 3142.9 | 3142.9 | 6007.5 |
| ***CAC*** | 8573 | 152833.0 | 152827.0 | 8573 | 8573 | 13755 |
| ***CDD*** | 10180.50 | 201325.0 | 201325.2 | 1427.6 | 1427.6 | 11214 |
| ***CNDD*** | 6583.2 | 6583.177 | 6583.2 | 22287.7 | 22287.7 | 19848.5 |
| ***CRC*** | 10374. 8 | 214069.9 | 214069.9 | 3366.6 | 3366.6 | 5859.2 |
| ***CST*** | 918.3 | 918.3 | 918.3 | 918.3 | 918.3 | 10131.7 |
| ***NRES*** | 8650 | 8650 | 8650 | 8650 | 8650 | 8650 |
| ***ARC*** | 4204.6 | 77777.2 | 77777.2 | 1415.1 | 1415.1 | 2451.9 |
| ***TS*** | 3061.1 | 3061.1 | 3061.1 | 3061.1 | 3061.1 | 33772.4 |

From eq. (1), the second subproblem related to the priority level –2 becomes:

$$\max f(\mu) = \mu_3$$

$$s.t. \qquad \mu_3 \le \frac{11{,}500 - CDI}{2{,}300}$$

$\mu_1 = 1$ and $\mu_2 = 1$

$\mu_3 \le 1$ and $\mu_3 \ge 0$;

and eq. (2-27)

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The solution for the priority level–2 is found to be totally satisfied with achievement level $\mu_3 = 1$. The cost of disposal is obtained as, $CDI$ = \$ 9,200. Since this result is satisfactory we define the new set of goals with the third priority level.

From eq. (1), the third subproblem related to the priority level –3 becomes:

$$\max f(\mu) = \mu_4$$

$$s.t. \qquad \mu_4 \le \frac{(9{,}580) - (NDIS + NSTR)}{700}$$

$$\mu_1 = 1,\ \mu_2 = 1 \text{ and } \mu_3 = 1$$

$$\mu_4 \le 1 \text{ and } \mu_4 \ge 1.$$

and eq. (2-27)]

The solution for the priority level–3 is found to be totally satisfied with the achievement level $\mu_4 = 1$. The sum of the number of disposed and stored components is found to be ($NDIS$+$NSTR$) = 10,280 units. Since this result is satisfactory and there is no other goal left for consideration, we stop. According to the results, 1,916 units of Product I, 565 units Product II and 878 units Product III should be ordered for disassembly.

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