Disassembly-to-Order System Using Linear Physical Programming

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Abstract

One of the most responsible ways of processing end-of-life (EOL) products is to minimize their disposal to landfills by reusing, remanufacturing and/or recycling them. Often, this necessitates a certain level of disassembly. It is therefore necessary to plan disassembly processing efficiently so as to minimize costs and the amount of disposal as well as to maximize reuse, remanufacturing and recycling. In this paper, we present a disassembly-to-order system to determine the number of EOL products to process to fulfill a certain demand for products, parts and/or materials under a variety of objectives and constraints using a newly developed decision tool, called Linear Physical Programming. It addresses problems involving multiple objectives and constraints and allows the decision maker to express his/her value-system in a realistic manner for each objective of interest. The model also provides the number of items to be disassembled for remanufacturing, recycling, storage and disposal. A case example is also presented.

INTRODUCTION

In recent years, swift developments in technology have facilitated unprecedented use of electronic products worldwide. Today electronic products are not only more reliable, they generally have longer physical lives. Unfortunately, their technological lives have reduced significantly leading to quick turnovers and an increase in product obsolescence. The need to minimize the disposal of such products has created a motivation for processing EOL products in a responsible manner.

In this paper, we present a disassembly-to-order (DTO) system [5] to determine the number of EOL products to process to fulfill a certain demand for products, parts and/or materials under a variety of objectives and constraints using a newly developed decision tool, called Linear Physical Programming (LPP) Messac et al. [7]. LPP addresses problems involving multiple objectives and constraints and allows the decision maker to express his/her value-system in a realistic manner for each objective of interest. The model also provides the number of items to be disassembled for remanufacturing, recycling, storage and disposal. A case example is presented to illustrate the methodology.

LITERATURE REVIEW

Many researchers have emphasized the importance of product recovery and EOL processing and have proposed models for disassembly systems.

Gupta and Taleb [4] presented an algorithm for scheduling the disassembly of a discrete, well-defined product structure. The algorithm determines the disassembly schedule for the components such that the demands for those components are satisfied. In their subsequent papers, Taleb et al. [13] and Taleb and Gupta [12] improved the methodology to include components/materials commonality as well as the disassembly of multiple product structures. Veerakamolmal and Gupta [14] employed mathematical programming to balance the lot sizes for the disassembly of multiple-products.


LINEAR PHYSICAL PROGRAMMING (LPP)

LPP is a recently developed optimization technique, which operates in the environment of multiple criteria and uses a utility function to represent the decision maker’s (DM) preference. The main difficulty associated with the formulation of a utility function is in determining the correct weights. The key distinguishing feature of LPP is that the DM is entirely removed from the process of choosing weights [7].

Within the physical programming procedure, the DM expresses his/her preferences with respect to each criterion using four different classes. The decision variable vector is denoted as \( x \), and the \( n \)-th generic criterion as \( g_n(x) \). The value of the criterion under consideration, \( g_n \), is on the horizontal axis, and the function that will be minimized for that criterion, \( z_n \), hereby called the class function, is on the vertical axis. A lower value of the class function is better than (more valuable than) a higher value thereof. The ideal
value of the class function is zero. Each class comprises two cases, hard and soft, referring to the sharpness of the preference. All soft class functions become constituent components of the aggregate objective function that is minimized. See Figure 1 for both the qualitative and quantitative depiction of each soft class function.

\[
\forall q \text{ in } 2S, 3S, 4S, q = 1, 2, \ldots, n_a, s = 2, \ldots, 5
\]
\[
g_p \leq t_{p,\text{max}} \quad \forall p \text{ in classes } 1H, p = 1, 2, \ldots, n_c
\]
\[
g_p \geq t_{p,\text{min}} \quad \forall p \text{ in classes } 2H, p = 1, 2, \ldots, n_c
\]
\[
g_p = t_{p,\text{value}} \quad \forall p \text{ in classes } 3H, p = 1, 2, \ldots, n_c
\]
\[
t_{p,\text{min}} \leq g_p \leq t_{p,\text{max}} \quad \forall p \text{ in classes } 4H,
\]
\[
p = 1, 2, \ldots, n_c
\]
\[
x_{\text{min}} \leq x \leq x_{\text{max}}
\]

where, \(n_a\) and \(n_c\) denote the number of soft and hard criteria.

**Case Example**

Consider a case example in which four workstations (hereby called Product I, Product II, Product III, and Product IV) are available as EOL products (see Figure 2 for their Product Structures). Tables 1 and 2 exhibit the data related to the case example. Note that the four products are made up of various combinations of 17 different items. Table 1 displays the component commonality data \(Q_{ij}\) for each item \(j\) in product \(i\). For each item \(j\), Table 1 also shows its resale item value, volume, weight, item demand as part, disposal cost, recycling cost, non-destructive disassembly time and destructive disassembly time respectively.

**Table 1. Economics and Production Data**

<table>
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<th>(j)</th>
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</tbody>
</table>

*Adapted from [13].*

Additional data is given as follows: Demand for recycling (DRE) is 100 units/item. Recycling percentage (PRC) is 100% for each item \(j\). Recycling price (PM) is $1/\text{unit}$ for each item \(j\). Take back cost for each product \(UTR_b = $35, 48, 37, 40/\text{product}$ respectively. Unit transportation cost for each product from collectors to facility \(UCTRCF = $10, 20, 10, 15/\text{product}$ respectively. Unit transportation cost for each item from facility to old recyclers \(UCTRFD = $15/\text{item}$.

Unit transportation cost for each item from facility to storage \(UCTRFS = $19/\text{item}$.

Unit preparation cost for each product \(UCAC = $5, 4, 5, 4/\text{product}$ respectively.
$\text{cdd} = $12.5/hour and $\text{cd} = $14.59/hour. Available Space (AS) is given as 500,000 cu. in.

**Figure 2. EOL Product Structures**

**Table 2. Initial EOL Data for Products**

<table>
<thead>
<tr>
<th>$j$</th>
<th>$\text{uned}_j$</th>
<th>$\text{ueby}_j$</th>
<th>$\text{ucby}_j$</th>
<th>$\text{uqby}_j$</th>
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<td>M (5)</td>
<td>L (1)</td>
<td>H (10)</td>
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</table>

Note: L=Low, M=Medium, H=High, N/A=Not Allowed

We consider four intangible measures as follows:

**Degree of Environmental Damage** (a function of hazardous material content in each item ($\text{uned}_j$)).

**Degree of Environmental Benefit** (a function of environmental benefit from recycling of each item ($\text{ueby}_j$)).

**Degree of Customer Satisfaction** (a function of the technological sophistication and other physical characteristics of each item ($\text{ucby}_j$)).

**Degree of Quality Achievement** (a function of reusability of each item over time ($\text{uqby}_j$)).

Table 2 exhibits the intangible factors and their corresponding weights in parentheses based on a ten-point scale regardless of the product type.

We define goals 1, 2, 3, 4, 5, and 8 as Class-2S type (i.e. "Larger is Better"). Hence,

$g_1 - d_{1j}^x \leq t_{1j}(s-1); d_{1j}^x \geq 0; g_1 \leq t_{1j}^x, s=2,...,5$  

$g_2 - d_{2j}^x \leq t_{2j}(s-1); d_{2j}^x \geq 0; g_2 \leq t_{2j}^x, s=2,...,5$  

$g_3 - d_{3j}^x \leq t_{3j}(s-1); d_{3j}^x \geq 0; g_3 \leq t_{3j}^x, s=2,...,5$  

$g_4 - d_{4j}^x \leq t_{4j}(s-1); d_{4j}^x \geq 0; g_4 \leq t_{4j}^x, s=2,...,5$  

$g_5 - d_{5j}^x \leq t_{5j}(s-1); d_{5j}^x \geq 0; g_5 \leq t_{5j}^x, s=2,...,5$  

$g_6 - d_{6j}^x \leq t_{6j}(s-1); d_{6j}^x \geq 0; g_6 \leq t_{6j}^x, s=2,...,5$  

Goals 6 and 7 are defined as Class-4S type (i.e. "Range is Better"). Hence,

$g_6 - d_{6j}^x \leq t_{6j}^+ (s-1); d_{6j}^x \geq 0; g_6 \leq t_{6j}^+, s=2,...,5$  

$g_6 - d_{6j}^x \leq t_{6j}^- (s-1); d_{6j}^x \geq 0; g_6 \leq t_{6j}^-, s=2,...,5$  

$g_7 - d_{7j}^x \leq t_{7j}^+ (s-1); d_{7j}^x \geq 0; g_7 \leq t_{7j}^+, s=2,...,5$  

$g_7 - d_{7j}^x \leq t_{7j}^- (s-1); d_{7j}^x \geq 0; g_7 \leq t_{7j}^-, s=2,...,5$  

Goal 9 is defined as Class-1S, (i.e. "Smaller is Better"). Hence,

$g_9 - d_{9j}^x \leq t_{9j}(s-1); d_{9j}^x \geq 0; g_9 \leq t_{9j}^x, s=2,...,5$  

The first goal ($g_1$) is for average customer satisfaction (CS), which is a ratio of total customer satisfaction (TCS) and the number of reused items (NRES) plus recycled items (NRC). Therefore, we can write:

$$CS = \frac{TCS}{NRES + NRC}$$  

where TCS is the sum of customer satisfaction levels for each item reused and recycled ($\Sigma \text{ucby}_j$). Therefore:

$$TCS = \sum_{ij} \text{ucby}_j$$  

$$NRES = \sum_i NRES_i \forall j$$  

$$NRC = \sum_i NRC_i \forall j$$  

where $X_j$ and $R_j$ are the quantities of disassembled items ($j$) for resale and recycling from products ($i$), respectively. The second goal ($g_2$) is for average quality achievement (Q4), which is a ratio of total quality achievement (TQA) and the number of reused items. Therefore, we can write:

$$Q4 = \frac{TQA}{NRES}$$  

where, $TQA$ is the sum of quality achievement levels for each item reused ($\Sigma \text{uqby}_j$). Therefore:

$$TQA = \sum_{ij} \text{uqby}_j$$
\[ TQA = \sum_{y} u \cdot q_{y} \]  
(25)

The third goal \((g_3)\) is for resale revenue \((RPS)\), which is a function of the number of item type \(j\) reused \((\sum x_{ij})\) and the unit sale price for item type \(j\) \((PM_j)\). Therefore:

\[ RPS = \sum_{j=1}^{n} \sum_{i} x_{ij} \cdot PRM_j \]  
(26)

The fourth goal \((g_4)\) is for the recycling revenue \((RMS)\), which is a function of the amount of materials sold and the market value of material obtained from each item type \(j\) \((PM)\). The amount of materials sold is a function of the number of item \(j\) recycled \((\sum R_{ij})\), the weight of item \(j\) \((W_j)\) and the percentage of marketable material obtained from item \(j\) \((PRC)\). Therefore, by summing the revenue over all items, \(RMS\) can be obtained as follows:

\[ RMS = \sum_{j=1}^{n} \sum_{i} R_{ij} \cdot W_j \cdot PRC_j \cdot PM_j \]  
(27)

The fifth goal \((g_5)\) is for total profit function \((TPR)\), which is the difference between all the revenues and all the costs considered in the model. Therefore, \(TPR\) can be written as follows:

\[ TPR = RMS - RPS - TB - CTRF - CTRF \cdot CTRFD - CTRFS - CAC - CDD - CND - CRE - CST - CDD \]  
(28)

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

\[ TB = \sum_{i=1}^{n} Y_i \cdot UTB_i \]  
(28)

\(CTRCF\) 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,

\[ CTRCF = \sum_{i=1}^{n} Y_i \cdot UCTRCF_i \]  
(29)

\(CTRF\) is a function of the number of items sent to the recycling facility \((\Sigma R_{ij})\) and the transportation cost per unit from the facility to the recycling facility \((UCTRF_i)\). Therefore,

\[ CTRF = \sum_{i=1}^{n} \sum_{j} R_{ij} \cdot UCTRF_i \]  
(30)

\(CTRF\) is a function of the number of items sent to disposal \((NDIS)\) and the transportation costs per unit from facility to the disposal site \((UCTRFD)\). The number of items sent to disposal includes the non-demanded items \((L_{ij})\). Therefore:

\[ NDIS = \sum_{j=1}^{n} L_{ij} \]  
(31)

and

\[ CTRFD = \sum_{i=1}^{n} \sum_{j} L_{ij} \cdot UCTRFD_i \]  
(32)

\(CTRF\) is a function of the number of items sent to storage \((NSTR)\) and the transportation cost per unit from the facility to the storage location \((UCTRF)\). Therefore:

\[ NSTR = \sum_{j=1}^{n} \sum_{i} V_{ij} \]  
(33)

and

\[ CTRFS = \sum_{j=1}^{n} \sum_{i} V_{ij} \cdot UCTRF \]  
(34)

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

\[ CAC = \sum_{i=1}^{n} Y_i \cdot UCAC_i \]  
(35)

\(CDD\) is the cost of destructive disassembly (considered for the items that are recycled for their material content or the items that are sent to landfills for proper disposal) and is a function of number of items to be recycled and disposed \((\Sigma \{R_{ij} + L_{ij}\})\), the cost per hour \((cdd)\) and the time of disassembling each item \((ddj)\). Therefore:

\[ CDD = \sum_{j=1}^{n} \sum_{i} \{R_{ij} + L_{ij}\} \cdot cdd \cdot ddj \]  
(36)

\(CND\) is the cost of non-destructive disassembly (considered for the items that are reused or the items that are sent to storage) and is a function of number of items to be reused and stored \((\Sigma \{X_{ij} + V_{ij}\})\), the cost per hour \((cnd)\) and the time of disassembling each item \((dtj)\). Therefore:

\[ CND = \sum_{j=1}^{n} \sum_{i} \{X_{ij} + V_{ij}\} \cdot cnd \cdot dtj \]  
(37)

\(CRE\) is a function of the number of items recycled in plant \((\Sigma R_{ij})\) and the corresponding unit recycling cost \((UCRE)\). Therefore:

\[ CRE = \sum_{i=1}^{n} R_{ij} \cdot UCRE_i \]  
(38)

\(CST\) is a function of the number of stored items \((\Sigma V_{ij})\) and the corresponding unit holding cost \((h_j)\). Therefore:

\[ CST = \sum_{i=1}^{n} \sum_{j} V_{ij} \cdot h_j \]  
(39)

\(CDI\) is a function of the number of disposed items \((\Sigma L_{ij})\) and the unit disposal cost \((UCDI)\). Therefore:

\[ CDI = \sum_{i=1}^{n} \sum_{j} L_{ij} \cdot UCDI_j \]  
(40)

The sixth goal \((g_6)\) is the average environmental damage \((ED)\), which is a ratio of total environmental damage \((TED)\) and the number of disposed items \((NDIS)\). Therefore:

\[ ED = \frac{TED}{NDIS} \]  
(41)

where, \(TED\) is the sum of all environmental damage levels \((\Sigma \{ned_{ij}\})\) for all disposed items. Therefore:

\[ TED = \sum_{i} \{ned_{ij}\} \]  
(42)

\[ NDIS = \sum_{i} \sum_{j} L_{ij} \cdot \forall j \]  
(43)
The seventh goal \((g_7)\) is the average environmental benefit (EB), which is a ratio of total environmental benefit (TEB) and the number of recycled items (NRC). Therefore:

\[
EB = \frac{TEB}{NRC}
\]

where, TEB is the sum of all environmental benefit levels (\(\sum_{ji} weby_j\)) for all recycled items. Therefore:

\[
TEB = \sum_{ji} weby_j
\]

\[
NRC = \sum_{i} \sum_{j} R_{ij} \forall j
\]

The eight and goals \((g_8, g_9)\) are for the number of recycled items (NRC) and the number of disposed items (NDIS) respectively.

The model also involves some constraints as follows:

The total space \((TS)\) occupied by the stored items have to be less than or equal to the total available space in the warehouse \((AS)\). \(TS\) is a function of the number of stored item \(j (\sum_{i} Y_{ij})\) and its corresponding volume \((v_j)\). Therefore:

\[
TS = \sum_{j} (\nu_j \times \sum_{i} Y_{ij})
\]

and

\[
TS \leq AS
\]

There is also a limit on the number of items that can be disassembled in the facility. This constraint can be expressed mathematically as:

\[
\sum_{i} (X_{ij} + R_{ij} + L_{ij} + W_{ij}) \leq DCA
\]

Where, \(X_{ij}\), \(R_{ij}\) and \(W_{ij}\) are the quantities of disassembled items \((j)\) for resale, recycling and disposal from products \((i)\), respectively. \(DCA\) denotes the disassembly capacity.

The number of items retrieved from EOL products ordered \((\sum_{i} Y_{ij}Q_{ij})\) has to be greater than or equal to the number of demanded items \((D_j)\). Therefore:

\[
\sum_{i} Y_{ij}Q_{ij} \geq D_j \forall j
\]

where

\[
D_j \leq \sum_{i} X_{ij} \forall j
\]

The total number of disassembled items \((\sum_{i} Y_{ij}Q_{ij})\) should be equal to the items that are reused \((\sum_{i} X_{ij})\), recycled \((\sum_{i} R_{ij})\), stored \((\sum_{i} V_{ij})\) and disposed \((\sum_{i} L_{ij})\), where \(Q_{ij}\) is the multiplicity factor. Therefore:

\[
\sum_{i} Y_{ij}Q_{ij} = \sum_{i} (X_{ij} + R_{ij} + V_{ij} + L_{ij}) \forall j
\]

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

\((\nu_j), (X_{ij}), (R_{ij}), (V_{ij}), (L_{ij}) \geq 0 \text{ and integer; for all } i \text{ and } j\).
Table 5. LPP and LP Model Results for the Goals

<table>
<thead>
<tr>
<th>#</th>
<th>Goal</th>
<th>LPP</th>
<th>LP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CS</td>
<td>9.851565</td>
<td>5.122206</td>
</tr>
<tr>
<td>2</td>
<td>QA</td>
<td>9.410876</td>
<td>9.410876</td>
</tr>
<tr>
<td>3</td>
<td>RPS</td>
<td>402,700</td>
<td>402,700</td>
</tr>
<tr>
<td>4</td>
<td>RMS</td>
<td>13,408</td>
<td>8,520</td>
</tr>
<tr>
<td>5</td>
<td>TPR</td>
<td>250,000</td>
<td>366,382</td>
</tr>
<tr>
<td>6</td>
<td>ED</td>
<td>4.75</td>
<td>6.75</td>
</tr>
<tr>
<td>7</td>
<td>EB</td>
<td>6</td>
<td>2.191176</td>
</tr>
<tr>
<td>8</td>
<td>NRC</td>
<td>3,356</td>
<td>1,405</td>
</tr>
<tr>
<td>9</td>
<td>NDIS</td>
<td>10</td>
<td>270</td>
</tr>
</tbody>
</table>

It is clear from Table 5 that the DTO system is highly sensitive to the introduction of the targets. Of the nine goals, only two of them remained unchanged in the LPP model. Quality Achievement (QA) and Revenue from Product Sales (RPS) remained unchanged. Revenue from Material Sales (RMS) however, increased about 60% even though the LPP provides a lower overall profit (TPR). This is because the related cost values also increase while trying to achieve higher recycling material sale revenue (such as transportation, disassembly cost etc).

Customer Satisfaction (CS) has increased to 9.852 (high) from 5.122 (medium). Intangible variables reflect the effect of the LPP programming more clearly than the tangible ones. Environmental Damage (ED) resulted in 4.75 points on a ten point scale and is in the ideal range for a Class – 4S function. Environmental Benefit (EB) has also been raised up to 6 from 2.191 points, reaching the ideal range.

The number of EOL products to be disassembled also varies depending on the model. As for the LPP model, 124, 0, 195 and 412 units of EOL products I, II, III and IV should be taken-back respectively. The corresponding values are 90, 5, 145 and 50 units respectively for the LP model. As expected, the total profit also varies depending on the solution methodology. The LPP results in a $250,000 profit while LP provides a higher profit of $366,382. The revenue from the material sales (RMS) are $13,408 and $8,520 for LPP and LP respectively.

REFERENCES