On the Profitability of the Disassembly Processes

L. Duta*, I. Caciula*, S. Addouche**

*Automation and Computer Science Department, Valahia University of Targoviste, 130065 ROMANIA (Tel: +40-723613305; e-mail: duta@valahia.ro; caciula@valahia.ro)
**Institut Universitaire de Technologie, 140 rue de la Nouvelle France, Montreuil, FRANCE (Tel: +331 48 70 34 60; e-mail: addouche@iut.univ-paris8.fr)

Abstract: Disassembly is part of reuse, recycling and disposal processes of the end-of-life manufactured products. Disassembly induces both costs and revenues. Costs are essentially determined by the line balancing and hence by the cycle time, while revenues are provided by the end-of-life values of the recovered parts and by the efficiency of the line. This work presents an optimization method that maximizes the income flow as well as the efficiency of the disassembly line. A case study on a multi-variant product is presented in the final part of the paper.

1. INTRODUCTION

Manufacturers are interested in recycling, refurbishing and remanufacturing of their own end of life products and seek to make these processes profitable. Disassembly is the central stage of the three-R processes referred as "product reconstruction" by (Pearce, 2009). It decomposes products into parts or subassemblies in view of their recovering or recycling. Economically speaking this process is not profitable if its implementation costs are higher than the end of life value of the recovered parts or materials. (Lambert and Gupta, 2005)

One has to evaluate the costs of the disassembly operations as well as its final revenues, so as to make this process profitable. The objective is to find the most profitable disassembly sequence, taking into account, on one hand - the parts end-of-life options and on the other hand - the operational times for a given assignment of the tasks on the disassembly line.

Costs of a disassembly process are essentially determined by the operational times and by the line balancing. An equal distribution of the disassembly tasks among workstations provides the lowest cycle time. The better the line is balanced, the lower the process cost is. All the other costs (e.g. tools costs, material and human resources costs) are considered to be independent from the disassembly process.

However, the maximal end-of-life value of the disassembled parts could be obtained using the optimal disassembly sequence resulted from different modeling methods (Lambert, 2003).

Line efficiency is another factor that can increase the profit of the disassembly process. Line efficiency is defined as the percentage utilization of the line (Grzechca, 2008). This item is also used as an indicator of how efficient the equipment is used in batch production. Moreover, while cost and revenues are natural and direct indicators of the process performance, the line efficiency is an indirect indicator.

One has to consider all these premises, mixing disassembly costs and revenues, line balancing and its efficiency, to obtain a profitable disassembly process. This is a typical multi-criteria optimization problem that can be solved in two steps: first by minimizing the costs and second by maximizing the process revenues. The aim of this paper is to present a method that schedules the tasks on a disassembly line so as to maximize the income flow and the efficiency of the process.

This paper is organized as it follows: the optimization problem is formulated in Section 2. Section 3 details the mathematical model and its linear constraints. In Section 4, the proposed method is implemented on a real case.

2. OPTIMIZATION PROBLEM STATEMENT

This section will present the mathematical model of the process profitability.

2.1. Assumptions and notations

While performing the optimization the following assumptions are taken into consideration:

- the disassembly line is paced and linear and the number of workstations is fixed;
- two types of operations are possible: a) proper disassembly and b) dismantling;
- both destructive and non-destructive operations can be accomplished on the same workstation;
- the flow of jobs on the line is continuous and the line can never be starved;
- we deal with a multi-variants product in the sense that variants of the same product can be processed on the same line (Duta et al, 2009);
• the cycle time has the same value for all product variants;
• a task is a disassembly operation.

The following notations are used in this paper:

\( n \) number of workstations;
\( m \) number of tasks (disassembly operations);
\( i \) index of a workstation;
\( j \) index of a task;
\( k \) index for a product component;
\( v \) index for a product variant;
\( t_{cy} \) cycle time;
\( W_i \) workstation \( i \);
\( t_{ij} \) operational time of the task \( j \) performed on the workstation \( W_i \);
\( t_j \) operational disassembly time of the task \( j \);
\( t'_j \) operational dismantling time of the task \( j \);
\( nop_i \) Total number of disassembly operations accomplished on \( W_i \).

2.2. Preliminaries

Disassembly process induces both costs and revenues. The cycle time is a parameter that has a high influence in calculating the process costs. Its value influences the balance of the line as well as its efficiency. The cycle time is defined as the operational time of the slowest workstation on the line (Nof, 1997; Gungor and Gupta, 1999).

\[
t_{cy} = \max_{W_i} \sum_j t_{ij}
\]

Line efficiency (LE) is expressed as a ratio between the sum of workstation operational times and the cycle time multiplied by the number of stations (Grzechca, 2008)

\[
LE = \frac{\sum_{i=1}^{n} ST_i}{n \cdot t_{cy}} \times 100 \text{ } \%
\]

Where \( ST_i \) is the total operational time of the workstation \( i \).

In equation (2) the smaller the value of the cycle time is, the better the line is balanced and the higher the value of the line efficiency is. In case of perfect balancing, LE is equal to 100%.

Therefore, minimizing the function value of the equation (3) below, a maximal value for LE is obtained.

\[
f = n \cdot t_{cy} - \sum_{i=1}^{n} ST_i
\]

The ratio between the total profit obtained after performing a given disassembly sequence on one product and the corresponding cycle time, represents the income flow of the line (Duta et al, 2003):

\[
IF = \frac{\sum_k (r_k - c_k)}{t_{cy}}
\]

In equation above \( r_k \) is the end-of-life value of the \( k \)-th recovered/recycled component and \( c_k \) the cost of disassembly/dismantling operation performed to obtain the \( k \)-th component.

Taking into consideration the values of the two performance indicators (IF) and (LE), one can calculate the total profit of the disassembly process on a planned work horizon \( H \):

\[
P = \alpha \cdot LE \cdot IF \cdot H
\]

Where \( \alpha \in [0..1] \) is a coefficient which depends on the workstations’ availability and its value is taken into consideration when calculating the effectiveness of the line (Mainea et al, 2010).

In case of a single type of product (a product with one variant) the cycle time can be also defined as the ratio between the planned working horizon \( H \) and the quantity/number of products \( Q \) (Duta et al, 2009). Using this relation one could substitute \( H \) by \( Q \cdot t_{cy} \) and equation (5) becomes:

\[
P = \alpha \cdot LE \cdot Q \cdot \sum_k (r_k - c_k)
\]

This is the mathematical model of the disassembly process with respect to its profitability. Next paragraph will present how this profit can be maximized by balancing the disassembly line. This balance can be obtained by minimizing the function value of equation (3).
3. MULTI VARIANT PRODUCT CASE

In the recycling industry, products which arrive to a disassembly line are not structurally identical. Usually they are part of the product family. In (Duta et al., 2009) products with similar structure are called variants of the same product. Variants have optional components and differences among the secondary functions of the product. To justify its high implementation costs, a line dedicated to the disassembly of the end-of-life products must have the capacity to process a large variety of products from the same family (Ilgin and Gupta, 2010).

3.1. The objective function

Let’s note with \( Q_v \) the quantity from the \( v \)-th variant of a product and \( N_v \) the number of variants.

In the case of a product with \( N_v \) variants, the mean value of the line efficiency is then given in the equation (7):

\[
LE = \frac{\sum_{v=1}^{N_v} \left( Q_v \cdot \sum_{i=1}^{n} ST_i^v \right)}{\sum_{v=1}^{N_v} Q_v \cdot n \cdot t_{cy}} \times 100 \quad [\%]
\]

To maximize the line efficiency value, one has to find the best balancing of the line.

With these notations, the function from equation (3) becomes:

\[
f = \sum_{v=1}^{N_v} Q_v \cdot n \cdot t_{cy} - \sum_{v=1}^{N_v} \left( Q_v \cdot \sum_{i=1}^{n} ST_i^v \right)
\]

(8)

This is the objective function which value is to be minimized.

On the other hand, in the case of a multi variant product, taking into consideration both disassembly and dismantling operations, the total operational time on a workstation is given by the equation (9) (Duta et al., 2009):

\[
ST_i^v = \sum_{j=1}^{nop} \varphi_{ij}^v \left( \theta_j^v t_j^v + (1-\theta_j^v) t_{inop_j}^v \right)
\]

Where:

The decision coefficient \( \theta_j \) defines the operational performing manner: destructive or not (Duta et al., 2008).

\( \theta_j^v = 1 \) when the operation \( O_j \) is to be performed without damaging the variant \( v \) of the product

\( \theta_j^v = 0 \) when the operation \( O_j \) has to be performed in a destructive way

The assignment coefficient \( \varphi_{ij} \) defines the possible off-line assignment of the tasks to stations. It can take the following values:

\( \varphi_{ij}^v = 1 \), when the operation \( O_j \) on the \( v \) variant can be assigned to the \( i \)-th workstation.

\( \varphi_{ij}^v = 0 \), otherwise

3.2. Constraints of the linear model

The linear model to optimize is formed by the objective function \( f \) of the equation (8) and the following linear constraints that have to be accomplished.

Every task is performed on a single workstation. A task cannot be divided between workstations. Formula (10) represents the non divisibility constraint.

\[
\sum_{i=1}^{n} \varphi_{ij}^v = 1 \quad \forall \ v = 1 \ldots N_v \quad a n d \quad j = 1 \ldots m
\]

(10)

If the cycle time is considered to be a positive sum then it is an upper bound for the workload assigned to each workstation.

\[
\sum_{j=1}^{nop} \varphi_{ij}^v \left[ \theta_j t_j^v + (1-\theta_j) t_{inop_j}^v \right] \leq t_{cy}
\]

(11)

If task \( x \) is to be done before task \( y \) then it cannot be assigned to a station downstream from task \( y \) (Rekiek and Delchambre, 2006); thus, the precedence constraint is obtained.

\[
\sum_{i=1}^{n} i \cdot \varphi_{ix}^v - \sum_{i=1}^{n} i \cdot \varphi_{iy}^v \leq 0
\]

(12)
Equations (8) and (9) together with constraints (10), (11) and (12) form the linear mathematical model to optimize.

4. EXAMPLE

4.1. Problem statement

The aim of this work is to maximize the profit of the process and hence the line efficiency. This can be accomplished if in the LE formula the parameter \( ST \) could be minimized. Hence, the optimization problem is reduced to the minimization of the objective function value from the equation (8) taking into consideration the constraints above. At the end, the maximal value of the line efficiency from equation (7) is calculated in view of model validation.

The case study is made on four variants of a notebook. The case of three years old variants is considered. Each variant structure and the corresponding disassembly sequences are given in figures 1 to 4. Operational times are given in Table 1, the quantity from each variant in Table 2, disassembly operational costs are given in Table 3, the end-of-life values and the reusable/recycling percentage are specified in Table 4. All data is taken from (Imtanavanich and Gupta, 2006; Imtanavanich and Gupta, 2007)

Components are named from A to O. The convention is that operational tasks are noted in the same way: A means the disassembly of the LCD monitor.

<table>
<thead>
<tr>
<th>Table 1. Operational times</th>
</tr>
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<tbody>
<tr>
<td>Components</td>
</tr>
<tr>
<td>[A] LCD Monitor Type I</td>
</tr>
<tr>
<td>[B] LCD Monitor Type II</td>
</tr>
<tr>
<td>[C] Motherboard Type I</td>
</tr>
<tr>
<td>[D] Motherboard Type II</td>
</tr>
<tr>
<td>[E] Processor</td>
</tr>
<tr>
<td>[F] Memory</td>
</tr>
<tr>
<td>[G] Hard drive 20Gb</td>
</tr>
<tr>
<td>[H] Hard drive 30Gb</td>
</tr>
<tr>
<td>[I] CD Drive</td>
</tr>
<tr>
<td>[J] Combo Drive</td>
</tr>
<tr>
<td>[K] Network Card</td>
</tr>
<tr>
<td>[L] Modem</td>
</tr>
<tr>
<td>[M] Keyboard</td>
</tr>
<tr>
<td>[N] Battery</td>
</tr>
<tr>
<td>[O] Power Adaptor</td>
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</tbody>
</table>

<table>
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<tr>
<th>Table 2. Variant quantity</th>
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<tbody>
<tr>
<td>Variant</td>
</tr>
<tr>
<td>N1</td>
</tr>
<tr>
<td>N2</td>
</tr>
<tr>
<td>N3</td>
</tr>
<tr>
<td>N4</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3. Operational costs</th>
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</thead>
<tbody>
<tr>
<td>Components</td>
</tr>
<tr>
<td>[A] LCD Monitor Type I</td>
</tr>
<tr>
<td>[B] LCD Monitor Type II</td>
</tr>
<tr>
<td>[C] Motherboard Type I</td>
</tr>
<tr>
<td>[D] Motherboard Type II</td>
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</tr>
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<td>[O] Power Adaptor</td>
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</tbody>
</table>

| Table 4. End of life values [reusable/recyclable percentage] |
|----------------|----------------|
| Components | Reusable value ($) | Recyclable value ($) |
| [A] LCD Monitor Type I | 60[65%] | 50[75%] |
| [B] LCD Monitor Type II | 50[61%] | 50[75%] |
| [C] Motherboard Type I | 35[69%] | 75[85%] |
| [D] Motherboard Type II | 28[64%] | 65[85%] |
| [E] Processor | 30[61%] | 180[90%] |
| [F] Memory | 30[65%] | 110[80%] |
| [G] Hard drive 20Gb | 25[65%] | 55[75%] |
| [H] Hard drive 30Gb | 35[58%] | 55[75%] |
| [I] CD Drive | 16[70%] | 25[70%] |
| [J] Combo Drive | 32[69%] | 50[70%] |
| [K] Network Card | 16[69%] | 50[80%] |
| [L] Modem | 6[64%] | 50[80%] |
| [M] Keyboard | 6[73%] | 15[65%] |
| [N] Battery | 25[61%] | 30[75%] |
| [O] Power Adaptor | 15[65%] | 25[70%] |

With this data four precedence graphs were constructed.
4.2. Results

To run simulations, the XPRESS-MP software was utilized. This is a linear and integer programming optimizer which has been programmed to handle a broad range of optimization problems. The main advantage of this software is that the user works in the Console Mode and he can modify the code of the program to suit the data of the problem.

XPRESS optimizer uses Branch and Bound technique to solve linear integer programming problems. The relaxed problem is a linear programming problem and can be solved by exploring the tree of solutions using the cut-off value method (Dash, 2007).

The program was run on an Intel Core 2 Duo T7500 processor at 2.2 GHz and 2GB RAM.

The line was considered to be served by four disassembly workstations that can perform both destructive and non-destructive disassembly operations.

The applied method aims to minimize the value of the objective function and to obtain a good balance of the line. In this case, the cycle time value is not the minimal one but is very close to it. In exchange the method gives a good balance of the line and also the maximal value of the LE (97%). The tasks assignment on workstations and operations generated for each type of Notebook are given below.

**Notebook 1**
- Workstation 1: A d F nd (duration: 12 s)
- Workstation 2: M nd N d O d (duration: 13 s)
- Workstation 3: G d I nd K d (duration: 12 s)
- Workstation 4: C e E d (duration: 13 s)

**Notebook 2**
- Workstation 1: A nd M d (duration: 12 s)
- Workstation 2: H d N nd O nd (duration: 13 s)
- Workstation 3: F d I d J d L nd (duration: 13 s)
- Workstation 4: D d E d (duration: 13 s)
Notebook 3
Workstation 1: M nd N nd (duration: 13 s)
Workstation 2: B d J d O d (duration: 13 s)
Workstation 3: F d G d I d K nd (duration: 13 s)
Workstation 4: C d E d (duration: 13 s)

Notebook 4
Workstation 1: B nd M d (duration: 12 s)
Workstation 2: H d N nd O nd (duration: 13 s)
Workstation 3: F d G d I d K nd (duration: 13 s)
Workstation 4: C d E d (duration: 13 s)

Cycle time: 13 s

Notation significance is:
nd – non destructive operation
d – destructive (dismantling) operation.

One can notice that all precedence relationships between tasks are fulfilled. Results are generated in 180 seconds.

Aggregating these results with values from Table 3 and Table 4, one can calculate the total profit using equation (6). Considering $\alpha=1$ and values given in Table 2, the process profit is calculated and then given in Table 5.

Table 5. Process profit

<table>
<thead>
<tr>
<th>Variant</th>
<th>Profit ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>0.97 x 241 x 374.20</td>
</tr>
<tr>
<td>N2</td>
<td>0.97 x 261 x 475.48</td>
</tr>
<tr>
<td>N3</td>
<td>0.97 x 400 x 521.17</td>
</tr>
<tr>
<td>N4</td>
<td>0.97 x 321 x 329.12</td>
</tr>
<tr>
<td>Total</td>
<td>512 546</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

Results confirm the fact that is more profitable to operate a destructive operation on components like motherboards, processors and batteries, instead of dismantling other components like LCD monitors, network cards or keyboards. One can notice that the disassembly/dismantling operational costs are practically negligible comparative to components end-of-life values. Instead, the disassembly process costs are essentially determined by the balance of the line.

After having performed a number of simulations, one could notice that by increasing the number of variants the line efficiency decreases but not with a significant value (with maximum 5%). At the same time, the number of product variants determines a proportional grow of the income flow. This means that the profit of the disassembly process is higher if more than one variant (type) of product is processed once on the line.

Another conclusion is that between 1/4 and 1/3 of the Notebook’s initial value is recovered using the proposed approach.

Future work aims to study the influence of other factors on the profitability of the disassembly process (as the human factor, the quality of the recovered components, the reuse percentage, and the energy consumption). An application of the method in the automotive industry is also under study.

REFERENCES