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Product Recovery Using a Disassembly Line: Challenges and Solution

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Abstract—Disassembly plays an important role in product recovery by allowing selective separation of desired parts and materials. The disassembly line is the best choice for automated disassembly of returned products, a feature that will be essential in the future. It is, therefore, important that the disassembly line be designed and balanced so that it works as efficiently as possible. In this paper, we address the disassembly line balancing problem and the challenges that come with it.

I. INTRODUCTION

Disassembly plays an important role in product recovery by allowing selective separation of desired parts and materials [5], [6]. A thorough review of the literature reveals that, so far, no one has formally talked about the disassembly line balancing problem (DLBP) [3]. The DLBP may sound similar to the assembly line balancing problem (ALBP); they are, in fact, very different. DLBP can be defined as follows. Given a finite set of disassembly tasks, each having individual performance times, and a set of precedence relationships which specify the permissible ordering of the tasks, the problem is to assign the tasks to an ordered sequence of workstations such that the precedence relationships are satisfied and some other measure of performance is optimized.

The disassembly of returned products can be performed at a single workstation, in a disassembly cell or on a disassembly line [11], [12]. Even though a single workstation or the disassembly cell provides the most flexible environment for sorting parts according to their quantity and quality, the disassembly line provides the highest productivity rate. The disassembly line setting is most suitable for the disassembly of large products [8] or small products in large quantities and is the best choice for automated disassembly process, a feature that will be essential in the future disassembly systems [9], [10].

In this paper, we address the disassembly line balancing problem and the challenges associated with it. We also present a methodology to solve a simple DLBP (DLBP-S). An example is considered to illustrate the use of the methodology.

II. CHALLENGES

A disassembly system encounters many challenges. For example, it has serious inventory problems because of the disparity between the demand for certain parts or subassemblies and their yield from disassembly. The flow process is also peculiar. As opposed to the normal "convergent" flow in regular assembly environment, in disassembly, the flow process is "divergent" (a single product is broken down into many subassemblies and parts) [1]. There is also a high degree of uncertainty in the structure and the quality of the returned products. The conditions of the products received are usually unknown and the reliability of the components is a suspect. In addition, some parts of the product may cause pollution or may even be hazardous. These parts tend to have a higher chance of being damaged and hence may require special handling, which can also influence the utilization of the disassembly workstations. Various types of demand sources may also lead to difficulties in the DLBP solution. Let us take a closer look at various kinds of challenges associated with DLBP.

Challenges Associated with the Product

Changing characteristics of products complicate the operations on a disassembly line. Balancing the disassembly line used in such cases can be very complex. Such a line may be balanced for a group of products yet may become unbalanced when a new type of product is received.

Challenges Associated with the Disassembly Line

Various line configurations may be possible. They are proposed to cope with the irregularities and product variability in the disassembly system. One important consideration is the line speed. It can be dynamically modified to minimize the effects of varying demands for subassemblies and/or parts on the disassembly line.
Challenges Associated with the Parts

Quality of Incoming Products: There is a high level of uncertainty in the quality of the products received and their constituent parts. They may be either physically defective or functionally defective or both.

Quantity of Parts in Incoming Products: Due to upgrading or downgrading of the product during its use, the actual number of parts in it may be more or less than expected when the product is received.

Operational Challenges

Variability of Disassembly Task Times: The disassembly task times may vary depending on several factors that are related to the condition of the product and the state of the disassembly workstation (or worker). Dynamic learning is possible, which allows systematic reduction in disassembly times.

Early Leaving Work-pieces (EWP): If one or more (not all) tasks of a work-piece, which have been assigned to the current workstation, cannot be completed due to some defect (that might be related to one or more of the tasks), the work-piece might leave the workstation early. We term this phenomenon as the early-leaving work-piece (EWP). Due to EWP, the workstation experiences an unscheduled idle time for the duration of the tasks that causes the work-piece to leave early.

Self-Skipping Work-pieces (SSWP): If all tasks of a work-piece, which have been assigned to the current workstation, are disabled due to some defect of their own and/or precedence relationships, the work-piece leaves the workstation early without being worked on. We term this phenomenon as self-skipping work-piece (SSWP).

Skipping Work-pieces (SWP): At workstation \( m \), if one or more defective tasks of a work-piece directly or indirectly precede all the tasks of workstation \( m+1 \) (i.e., the workstation immediately succeeding workstation \( m \)), the work-piece “skips” workstation \( m+1 \) and moves on to workstation \( m+2 \). We term this phenomenon as skipping work-piece (SWP). In addition to unscheduled idle time, both SSWP and SWP experience added complexities in material handling and the status of the downstream workstation.

Disappearing Work-pieces (DWP): If a defective task disables the completion of all the remaining tasks on a work-piece, the work-piece may simply be taken off the disassembly line before it reaches any downstream workstation. In another words, the work-piece “disappears”. Therefore, we term this phenomenon as the disappearing work-piece (DWP). DWP may result in starvation of subsequent workstations leading to a higher overall idle time.

Revisiting Work-pieces (RWP): Work-piece currently at workstation \( w \), may revisit a preceding workstation \( (w-a) \), where \( (w-a) \geq 1 \) and \( a \geq 1 \) and integer, to perform task \( f \) if the completion of current task \( i \) enables one to work on task \( f \) which was originally assigned to workstation \( (w-a) \), and was, however, disabled due to the failure of another preceding task. We term this revisiting work-pieces (RWP). An RWP results in overloading one of the previous workstations.

Exploding Work-pieces (EWP): A work-piece may split into two or more work-pieces (subassemblies) as it moves on the disassembly line because of the disassembly of certain parts that hold the work-piece together. Each of these subassemblies acts as an individual work-piece on the disassembly line. We term this phenomenon as the exploding work-pieces (EWP). The EWP complicates the flow mechanism of the disassembly line.

Demand Challenges

In disassembly, the following demand scenarios are possible: Demand for one part only (single part disassembly - a special case of partial disassembly); demand for multiple parts (partial disassembly); and demand for all parts (complete disassembly). Possible physical and functional defects on the demanded parts or the parts preceding the demanded parts may complicate the situation further.

Assignment Challenges

Certain tasks must be grouped and assigned to a specific workstation for reasons such as requirement of similar operating conditions for them and availability of special machining and tooling at certain workstations.

Other Challenges

There are additional uncertainty factors associated with the reliability of the disassembly workstations. For example, hazardous parts may require special handling, which can also influence the utilization of the workstations. Some of the assembly line balancing factors, which are presented by Ghosh and Gagnon [2] in their comprehensive literature survey, can also be important in the disassembly line balancing case.

A comparison of the assembly and the disassembly lines both from technical and operational points of view is given in Table 1. It clearly demonstrates that there is a need for developing unique techniques and modifying the existing line balancing techniques to improve the disassembly lines. Obviously, the experience gained and the body of knowledge developed in addressing the problems encountered in assembly lines over the last four decades may provide some very helpful guidelines.

III. A SIMPLE DLBP (DLBP-S)

The DLBP-S is defined as follows: A paced disassembly line is utilized to disassemble one type of product into its constituent parts and subassemblies. We assume that there is an infinite supply of products. The configuration of each product received is identical which means that the exact
quantity of the parts in each product received is known. For simplicity, the disassembly times are assumed to be deterministic and known. We target the complete disassembly under the assumption that every part in the product has an associated demand. The demand parameters are deterministic and known. The parts disassembled are accepted by the demand source in their current conditions. The objective of the DLBP-S is to utilize the resources of the disassembly line as efficiently as possible while meeting the demand. There are precedence relationships among the tasks which must be satisfied while assigning them to the stations. These types of relationships also exist in the traditional ALBP. However, the precedence relationships in the ALBP are limited to the simple AND types [2]. In the assembly case, these relationships are developed considering the physical and functional constraints, because the objective of the assembly process is to create a stable and functional end product. However, in the disassembly case, the parts are removed from the product without any concern of their interrelated functionality (only physical constraints are important). The relationships, which are important in the disassembly case, are AND, OR and complex AND/OR [7]. The precedence relationships are represented using a matrix called the disassembly precedence matrix (DPM) [4]. The DPM is denoted by \( R = \{ r_{ij} | i, j = 1, \ldots, n \} \); where \( n \) is the number of tasks; \( r_{ij} = 0 \) if task \( i \) does not precede task \( j \); \( r_{ij} = 1 \) if task \( i \) AND precedes task \( j \); \( r_{ij} = d \) if task \( i \) OR precedes task \( j \); \( d \) is used to denote the disassembly movement directions (\( x, y, \) or \( z \)), \( d \in D = \{ x, -x, y, -y, z, -z \} \).

### IV. Notation

The following notations are used in rest of the paper.

- \( A_k \) set of tasks that have been assigned to station \( k \)
- \( c \) cycle time
- \( CA_k \) set of candidate tasks that can be assigned to station \( k \)
- \( d_i \) demand for part \( i \)
- \( F_i \) priority function value of task \( i, \) where \( i \in CA_k \)
- \( h_i \) task \( i \) hazardous or not (\( h_i = 1, \) if task \( i \) is hazardous; \( h_i = 0, \) otherwise)
- \( I \) cumulative idle time of all stations (idle time of the disassembly line)
- \( I_{ik} \) idle time of station \( k \) when task \( i \) is assigned to station \( k \)
- \( I_k \) idle time of station \( k \)
- \( KB \) index for disassembly workstations
- \( L \) duration (or the length) of the planning period (discretely incremented)
- \( M \) number of stations; i.e., \( k = 1, \ldots, M \)
- \( md_i \) disassembly direction change or not (\( md_i = 1, \) if direction changes from previous task; \( md_i = 0, \) otherwise)
- \( OG_{i,d} \) OR group, i.e., the set of tasks that OR precedes task \( i \) in direction \( d \)
- \( q_i \) number of same part \( i \) (i.e., quantity of part \( i \)) in the product
- \( R \) disassembly precedence matrix (DPM)
- \( R_{i} \) row \( i \) of \( R \)

**Table 1: Comparison of operational and technical considerations of assembly and disassembly lines**

<table>
<thead>
<tr>
<th>Line Considerations</th>
<th>Assembly Line</th>
<th>Disassembly Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>Dependent</td>
<td>Dependent</td>
</tr>
<tr>
<td>Demand sources</td>
<td>Single</td>
<td>Multiple</td>
</tr>
<tr>
<td>Demanded entity</td>
<td>End product</td>
<td>Individual parts/subassemblies</td>
</tr>
<tr>
<td>Precedence relationships</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Complexity related to precedence relations</td>
<td>High (physical and functional precedence constraints)</td>
<td>Moderate (mostly physical constraints)</td>
</tr>
<tr>
<td>Uncertainty related to quality of parts</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Uncertainty related to quantity of parts</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Uncertainty related to workstations and the material handling system</td>
<td>Low to Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Reliability of the workstations and the material handling system</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Multiple products</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Flow process</td>
<td>Convergent</td>
<td>Divergent</td>
</tr>
<tr>
<td>Line flexibility</td>
<td>Low to Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Layout alternatives</td>
<td>Multiple</td>
<td>Multiple</td>
</tr>
<tr>
<td>Complexity of performance measures</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Known performance measures</td>
<td>Numerous</td>
<td>N/A</td>
</tr>
<tr>
<td>Disappearing Work-pieces Phenomena (DWP)</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Exploding Work-pieces Phenomena (EWP)</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Required line robustness*</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Complexity of &quot;between workstation inventory&quot; handling</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Known techniques for line optimization</td>
<td>Numerous</td>
<td>None</td>
</tr>
<tr>
<td>Problem complexity</td>
<td>NP-hard</td>
<td>NP-hard</td>
</tr>
</tbody>
</table>

* e.g. resistance to dirt encountered during the disassembly process.
\( R_j \) column \( j \) of \( R \)
\( S_k \) station time of \( k \) (i.e., total processing time of tasks that have been assigned to station \( k \))
\( sr_i \) number of remaining tasks that task \( i \) precedes to
time necessary to perform task \( i \) (or operation time of
task \( i \))

V. THE APPROACH

The steps of the proposed approach are as follows:

Step 1: Input \( R, c, \) and \( KB \). Initialize the number of
stations (or open a station), i.e., \( k = 1 \); where:

\[
c = \left\lfloor \frac{L}{d_{\text{max}}} \right\rfloor
\]

[The number of products that need to be disassembled to meet the demand]

\( d_{\text{max}} = \max_{i=1,\ldots,N} \left\{ \frac{\text{Demand of part } i}{\text{Quantity of part } i \text{ in the product}} \right\} = \max_{i=1,\ldots,N} \left\{ \frac{d_i}{q_i} \right\} \]

Step 2: If all tasks have been assigned to stations then go
to Step 7.

Step 3: If \( I_k < t_i, i = 1, \ldots, n \), then open a new station, i.e.,
\( k = k + 1 \); where:

\[
I_k = c - S_k \\
S_k = \sum_{j \in A_k} t_j
\]

Step 4: Generate \( CA_k \). The tasks in the \( CA_k \) must satisfy
the following three conditions:

1. Task \( i \) must not have already been assigned to any
earlier station, i.e.,
\[
i \notin \bigcup_{m=1}^{k-1} A_m
\]

2. Task \( i \) must not have any incomplete predecessor, i.e.,

\[
\exists j, j \in A_m; m = 1, \ldots, k-1; \text{ and } f(j) = d \\
\exists j \in OG_i, d \subseteq \bigcup_{m=1}^{k-1} A_m; m = 1, \ldots, k-1.
\]

3. Operation time of task \( i \) must not exceed the cycle time
of the station, i.e.,

\[
S_k + t_i \leq c
\]

Step 5: Calculate the priority function value \( F_i \) as
follows:

\[
F_i = f(I_i) + f(d_i) + f(sr_i) + f(h_i) + f(md_i), \quad i \in CA_k
\]

where: \( f(I_i) \) is the priority value with respect to the idle
time of the stations; \( f(d_i) \) is the priority value with respect to
disassembly of highly demanded parts; \( f(sr_i) \) is the priority
value with respect to parts that are easily accessible and
precede many other parts (e.g., part \( i \) where \( R_j = 0 \) and \( R_k \)
contains the most number of nonzero entities); \( f(h_i) \) is the
priority value with respect to parts with hazardous
materials; and \( f(md_i) \) is the priority value with respect to
disassembly movement direction changes.

Step 6: Find the best candidate task, say task \( b \), with the
minimum value of priority function. Assign task
\( b \) to station \( k \), i.e., \( A_k = A_k \cup b \). Go to Step 2.

Step 7: Print results; the number of stations, \( M = k \), and
the task assignment of the stations, \( A_m, m = 1 \) to
\( M \). STOP.

VI. EXAMPLE

Consider the disassembly of a personal computer (PC). The
tasks associated with the disassembly of a PC are presented
in Table 2. \( R \) is given in Figure 1 and the knowledge base
(KB) is presented in the Table 3.

<table>
<thead>
<tr>
<th>Task No. (n)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Removal of the top cover of the PC (TC)</td>
</tr>
<tr>
<td>2</td>
<td>Removal of the floppy drive (FD)</td>
</tr>
<tr>
<td>3</td>
<td>Removal of the hard drive (HD)</td>
</tr>
<tr>
<td>4</td>
<td>Removal of the back plane (BP)</td>
</tr>
<tr>
<td>5</td>
<td>Removal of PCI cards (PCI)</td>
</tr>
<tr>
<td>6</td>
<td>Removal of two RAM modules (RAM)</td>
</tr>
<tr>
<td>7</td>
<td>Removal of the power unit (PU)</td>
</tr>
<tr>
<td>8</td>
<td>Removal of the motherboard (MB)</td>
</tr>
</tbody>
</table>

**Figure 1:** R of disassembly tasks

\[
R = \begin{bmatrix}
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & x & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & -x & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix}
\]
In order to fulfill the demand levels given in Table 3, the number of products that need to be disassembled is calculated using step 1. In Table 3, RAM has the highest part level demand (750 units). However, since disassembly of each product yields two RAM modules, the actual requirement for the number of products to be disassembled in order to meet the demand for RAM is 375. Thus, demand for MB defines \( d_{\text{max}} \) that is 720. Assuming the planning horizon to be an 8-hour shift, \( L = 8 \times 60 \times 60 = 28800 \) seconds. Then, the cycle time is found using step 1, i.e., \( c = 28800/720 = 40 \) seconds.

<table>
<thead>
<tr>
<th>Part</th>
<th>( t_j ) (sec.)</th>
<th>( d_j ) (per day)</th>
<th>Hazardous content</th>
<th>Disassembly Movement Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC</td>
<td>14</td>
<td>360</td>
<td>No</td>
<td>-x</td>
</tr>
<tr>
<td>FD</td>
<td>10</td>
<td>500</td>
<td>No</td>
<td>x</td>
</tr>
<tr>
<td>HD</td>
<td>12</td>
<td>620</td>
<td>No</td>
<td>x</td>
</tr>
<tr>
<td>BP</td>
<td>18</td>
<td>480</td>
<td>No</td>
<td>( x, \sim x, y, \text{ or } y )</td>
</tr>
<tr>
<td>PCI</td>
<td>23</td>
<td>540</td>
<td>No</td>
<td>y</td>
</tr>
<tr>
<td>RAM</td>
<td>16</td>
<td>750</td>
<td>No</td>
<td>z</td>
</tr>
<tr>
<td>PU</td>
<td>20</td>
<td>295</td>
<td>Yes</td>
<td>( \sim x, x, \text{ or } y )</td>
</tr>
<tr>
<td>MB</td>
<td>36</td>
<td>720</td>
<td>No</td>
<td>z</td>
</tr>
</tbody>
</table>

*Identified during the analysis of the product to generate \( R \).*

Table 4 presents the step by step solution for the PC example. The number of stations, \( M \), found for the PC example is 4. The tasks have been assigned to stations as follows: \( A_1 = \{1, 3, 2\}; A_2 = \{5, 6\}; A_3 = \{8\}; \) and \( A_4 = \{7, 4\}. \) The idle times of the stations are: \( J_1 = 4; J_2 = 1; J_3 = 4; J_4 = 2 \) seconds per product respectively. The overall idle time of the disassembly line, \( I = 11 \) seconds. If each task were assigned to one station, then \( M \) would be equal to \( 8 \) and the overall idle time would be \( 171 \) seconds. This clearly demonstrates the importance of utilizing a systematic approach for the DLBP.

### References


