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Askiner Gungor  
*Northeastern University*

Surendra M. Gupta  
*Northeastern University*

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## **Contact Information**

Dr. Surendra M. Gupta, P.E.  
Professor of Mechanical and Industrial Engineering and  
Director of Laboratory for Responsible Manufacturing  
334 SN, Department of MIE  
Northeastern University  
360 Huntington Avenue  
Boston, MA 02115, U.S.A.

(617)-373-4846 **Phone**  
(617)-373-2921 **Fax**  
gupta@neu.edu **e-mail address**

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

# DISASSEMBLY SEQUENCE PLANNING FOR COMPLETE DISASSEMBLY IN PRODUCT RECOVERY

Askiner Gungor, Northeastern University, Boston, MA 02115, (617)-373-7635  
Surendra M. Gupta\*, Northeastern University, Boston, MA 02115, (617)-373-4846  
(\*Corresponding author)

## ABSTRACT

Disassembly is a key element for retrieving the desired subassemblies and/or parts from a product. However, determining an efficient disassembly sequence plan (DSP) is an *NP*-complete problem. In this paper, we propose a methodology to generate a near optimum DSP for a product. The methodology is illustrated using an example.

## INTRODUCTION

Product recovery and waste management techniques are in popular demand as key elements of Environmentally Conscious Manufacturing as a result of fast depletion of virgin resources and increasing amount of waste [2], [4]. Product recovery generally offers two major options: recycling and remanufacturing. Recycling aims to recover the material content of retired products by performing the necessary disassembly, sorting, and chemical operations. Remanufacturing preserves the product's (or its part's) identity and performs the required disassembly, sorting, and refurbishing operations in order to bring the parts of the product to a desired level of quality.

Products arrive at a recycling or remanufacturing facility when they finish their useful lives (that is, when the product is no longer the customer's choice either because it does not function properly, or its lease has expired or it is out of fashion or outdated etc.) Disassembly is considered a key element for retrieving the desired parts and/or subassemblies from the products. Examples of disassembly objectives include:

- Recovery of valuable parts or subassemblies (in short supply) which are common to other products still being produced,
- Retrieval of parts or subassemblies of discontinued products to satisfy a sudden demand for these parts,
- Removal of hazardous parts,
- Increasing the purity of the remainder of the product,
- Extraction of the parts from the remainder of the product which will be sent to inventory for future use,
- Decreasing the amount of shredder residue and the amount to be sent to landfills, and
- Achieving environmentally friendly manufacturing standards (i.e. meeting the ratio of the use of recycled materials in production to new products).

The purpose of this paper is to present a methodology to obtain a near optimal DSP which satisfies a given set of constraints defined by the product being disassembled as well as by the disassembly system.

## DISASSEMBLY SEQUENCE PLANNING PROBLEM

By definition, a DSP is a sequence of disassembly tasks that begins with a product to be disassembled and terminates in a state where all the parts of the product are disconnected. We assume that every part of the product has a demand. We further assume that the product is in perfect condition (i.e., all parts of the product are free of defect) and no modification has been made to the structure of the product during consumer use.

Identifying DSP is not an easy task since DSP is an *NP*-complete problem [4]. The number of alternative DSPs increases exponentially with the number of parts in the product being disassembled. For example, a product with 3 parts may have up to  $3! = 6$  disassembly sequences, whereas a product with 10 parts may have up to a whopping  $10! = 3,328,800$  disassembly sequences. Even though the number of feasibility constraints may reduce the number of disassembly sequences required to be analyzed for optimality, this number is still expected to be large for a complex product which motivates the development of a heuristic for obtaining optimum DSP.

## PROPOSED METHODOLOGY

The proposed methodology consists of two major steps. They are described as follows:

### Step 1. Generation of Geometric Precedence Relationships (Feasibility Constraints)

In order to generate the feasibility constraints for a near optimum DSP, we assume the following:

- The product is anchored on the disassembly table such that neither the rotation of the table nor the rotation of the product is allowed,
- A part can be removed only in one disassembly direction. Disassembly directions are defined as

rectilinear movements (e.g., in a 2D plane, the rectilinear movements are  $x$ ,  $-x$ ,  $y$ ,  $-y$ ).

The following steps describe the procedure for generating the precedence relationships which are presented in a matrix form denoted by  $R$ :

**Step 1.1.** If all parts are analyzed (i.e.,  $i = n$ ) then STOP. Otherwise CONTINUE:

**Step 1.2.** Find a disassembly direction in which the least number of physically obstructing parts exist for disassembly of part  $j$ . If there are more than one such direction, then pick one of them randomly. The obstructing parts of the part  $j$  are required to be removed prior to the removal of  $j$ . This is called the AND relationship between the parts that obstruct and the part that needs to be removed. In another words, the obstructing parts in a disassembly direction are the predecessors of part  $j$ . Generate  $R$  according to the following assignment rules and Go to Step 1.1:

$$r_{ij} = \begin{cases} 1, & \text{if } j \text{ is obstructed by } i \text{ in the disassembly direction} \\ 0, & \text{otherwise} \end{cases}$$

where  $r_{ij}$  is the element of  $R$ ,  $1 \leq i, j \leq n$  and  $n$  is the number of parts in the product.  $R$  is a binary matrix in which '1' represents AND relationship between the parts and '0' symbolizes no relationship.

## Step 2. Identification of the (near) optimum DSP

In the heuristic, the feasibility will be satisfied by using the  $R$  matrix. However, this is just enough to identify the feasible DSPs (FDSPs). Our intention from the beginning is to create a near optimum DSP. When generating such a DSP, we use some qualitative and quantitative knowledge of the disassembly processes which have been acquired through a series of experimental studies reported in the literature [1], [2], [3]. These aspects may include:

- *Tool changes required during disassembly according to the DSP being utilized:* Tool changes are usually required depending on the physical characteristics of the parts (e.g., the joint type, dimensions, and weight of the part). It can be said that the lesser the tool changes required, the higher the expected efficiency of the DSP.
- *Movement directions of parts during disassembly operation:* Disassembly movement directions are defined according to free space (or direction) towards which there are no obstructing parts. These directions are identified during the generation of  $R$ . In a disassembly process, changes in disassembly movements introduce additional observation times and distances which are undesirable.

Besides the aspects related to disassembly process, characteristics of the individual parts are also important. For example, some parts may be hazardous, others may be very valuable and yet others may be fragile etc. In practice, sometimes it is necessary to assign priority for removal of these parts because the probability of contamination or breakage might increase if left too long in the assembly/subassembly.

We use the following notations:

$\mathbf{a}_1$	=	unit time per tool change
$\mathbf{a}_2$	=	unit time per disassembly direction change
$\mathbf{a}_3$	=	unit time of delaying the disassembly of a part with hazardous contents by one step in DSP
$\mathbf{a}_4$	=	unit time of delaying the disassembly of a part with high market value by one step in DSP
$n$	=	the number of parts of the product
$t_i$	=	disassembly time of part $i$

$\mathbf{a}_1$  and  $\mathbf{a}_2$  are determined according to the current part to be disassembled and the part that succeeds it in the DSP. If part  $i+1$  has a different tool type than part  $i$  in the DSP, then magnitude of  $\mathbf{a}_1$  is unchanged, otherwise  $\mathbf{a}_1$  is set to 0. Similarly, if part  $i+1$  has a different disassembly direction than part  $i$  in the DSP, then magnitude of  $\mathbf{a}_2$  is unchanged, otherwise  $\mathbf{a}_2$  is set to 0.  $\mathbf{a}_3$  and  $\mathbf{a}_4$  are position dependent (in DSP) and are defined according to the objectives of the disassembler.

We use the following definitions:

$IC$	=	a set consisting of the parts which are candidates for immediate disassembly
$DS$	=	a sorted list consisting of disassembled components
$TTD$	=	total time of disassembly

The steps for finding a near optimum DSP are as follows:

**Step 2.1.** (Initialize Variables)  $IC = \emptyset$ ;  $DS = \emptyset$

**Step 2.2.** By examining the columns of  $R$ , identify the columns with all '0's which represent the parts with no predecessor. These are the candidate parts for immediate disassembly. Insert them into  $IC$ .

**Step 2.3.** Assign priority to  $j \in IC$  from highest to lowest as follows: (1)  $\mathbf{a}_3$  and  $\mathbf{a}_4$  are present for part  $j$ ; (2)  $\mathbf{a}_3$  is present for part  $j$ ; (3)  $\mathbf{a}_4$  is present for part  $j$ ; and (4)  $\mathbf{a}_3$  and  $\mathbf{a}_4$  are NOT present for part  $j$ . If  $\mathbf{a}_3 < \mathbf{a}_4$  then exchange the order of (2) and (3). If all components in  $IC$  has the lowest priority of (4) then Go to step 2.4. Otherwise, insert  $j$  with the highest priority into  $DS$ . Then update the precedence matrix as follows:

Assign '0' to row  $j$  in  $R$  except the diagonal cell to which -1 should be inserted indicating that  $j$  has been disassembled. If all diagonal elements of  $R$  are -1, Go to Step 2.5. Otherwise Go to Step 2.2.

**Step 2.4.** Find a part  $j \in IC$  such that it has the lowest cumulative of  $\mathbf{a}_1$  and  $\mathbf{a}_2$  according to the  $j$ -1<sup>st</sup> part in  $DS$ . Then insert  $j$  into  $DS$  and update the precedence matrix as was done in Step 2.3. If all diagonal elements of  $R$  are -1, Go to Step 2.5. Otherwise Go to Step 2.2.

**Step 2.5.** Print out  $DS$  as the near optimum DSP for the product and calculate the associated  $TTD$  as follows:

$$TTD_{DSP} = \sum_{j=1}^n t_j + \sum [p_1 \times \mathbf{a}_1 + p_2 \times \mathbf{a}_2 + p_3 \times \mathbf{a}_3 + p_4 \times \mathbf{a}_4]$$

where:  $n$  is the number of parts;  $p_1$  and  $p_2$  are the number of tool and direction changes respectively;  $p_3$ , and  $p_4$  are the position numbers of hazardous and the high valued parts in the DSP, respectively. STOP.

The above heuristic assumes that the magnitudes of  $\mathbf{a}_3$  and  $\mathbf{a}_4$  are greater than the effects of  $\mathbf{a}_1$  and  $\mathbf{a}_2$ . However, the heuristic could be easily modified by correcting the priorities of  $\mathbf{a}$ 's even if this were not true.

### EXAMPLE

As an example, we select a simple product with 6 parts as shown in Figure 1. By analyzing the product based on the procedure defined in the Step 1 of the methodology,  $R$  is generated and given in Table 1.

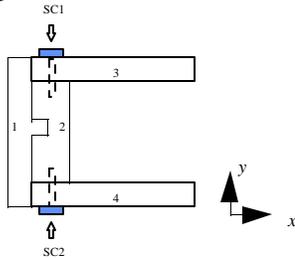


Figure 1: Sample Product

In order to perform the Step 2 procedures we need the following information: Let us assume that parts 3 and 4 require tool #1; part 1 requires tool #2; part 2 requires tool #3; and parts SC1 and SC2 require tool #4. As for the disassembly directions; 1 is removed towards -x; 2 towards x; 3 and SC1 toward y; and 4 and SC2 toward -y. These were identified in the Step 1. Further, we assume that part 2 is fragile and has an associated high value in the market. Similarly, assume that part 3 is a high-valued part with

	1	2	3	4	SC1	SC2
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
SC1	0	1	1	0	0	0
SC2	0	1	0	1	0	0

Table 1:  $R$  of sample product

hazardous contents. When this information was applied to Step 2 of the methodology, the methodology generated a near optimum DSP as follows: {1-SC1-3-SC2-2-4}. Note that we used  $\mathbf{a}_1 = \mathbf{a}_2$ ,  $\mathbf{a}_3 = \mathbf{a}_4$  and  $\mathbf{a}_1 < \mathbf{a}_3$ . However, when we assumed part SC2 as one of the high valued parts, the methodology produced the optimum result: {SC2-SC1-3-2-1-4}.

### CONCLUSIONS

We presented a methodology to determine a near optimum DSP for a complex product. The methodology dramatically simplifies the decision making process in a product recovery system. The proposed methodology suggests a systematic development of a geometrically-based precedence relationship matrix ( $R$ ) by examining the product. Then using  $R$  and some qualitative aspects of disassembly process as well as the individual characteristics of the product which influence the optimality measure (total time of disassembly -  $TTD$ ), a near optimum DSP is generated.

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