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Disassembly scheduling: literature review and future research directions

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Disassembly scheduling, one of the important operational problems in disassembly systems, can be generally defined as the problem of determining the quantity and timing of the end-of-use/life products while satisfying the demand of their parts over a planning horizon. This paper presents a literature review on this planning problem in disassembly systems. First, the basic form of the problem is defined with a mathematical formulation. To characterize the differences between assembly and disassembly processes, the effects of the divergence property are also explained with respect to the zero inventory property, indispensable surplus inventory, and mathematical representation. Then, we review the existing research articles on the basic problem and its generalizations. A systematic scheme for classifying problems is also suggested. Finally, we suggest several future research directions.

Keywords: Disassembly; Planning; Literature review; Research directions; Environmental studies

1. Introduction

Environmental issues have become increasingly important for manufacturing and service firms since legislation pressures and customer recognitions are increasing to protect the environment, imposing on remanufacturing firms the responsibility to collect, re-use, remanufacture, recycle, and even dispose of their products and services in an environmentally conscious way. This is followed by the originator-principle, i.e. he or she who inflicts harm on the environment should pay for fixing the damage. Some representative examples are EuP (Eco-design requirements for Energy using Products), WEEE (Waste Electrical and Electronic Equipment), RoHS (Restriction of the use of certain Hazardous Substance in electric and electronic equipment), and ELV (Directives for End-of-Life Vehicle). Among the environmental issues, those for worn-out products are very important since shortage of dumping sites and waste-incineration facilities reminds us that products do not merely disappear after disposal (Güngör and Gupta 1999). This leads to considerable attention to the effects of the environmental costs of manufacturing and service to both individual firms and to society as a whole.

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For environmental and economic reasons the significance of the disassembly process has been widely recognized in theoretical and practical terms. Disassembly, which can be defined as a systematic method for separating a product into its parts, subassemblies or other groupings, is performed to reduce materials harm to the environment as well as to obtain valuable parts or subassemblies from end-of-use/life products. In fact, the disassembly process is known to be one of the basic activities in product and material recoveries such as re-use, remanufacturing, and recycling. However, an *ad hoc* disassembly process without planning is prevalent in most remanufacturing and recycling firms, which results in serious cost pressures (Wiendahl *et al*. 1999). As in the case of the assembly process, therefore, appropriate planning and scheduling tools are needed to manage disassembly operations more economically.

As in assembly systems, various research areas are introduced and studied in disassembly systems (Jovane *et al*. 1993, O'Shea *et al*. 1998, Güngör and Gupta 1999, Lee *et al*. 2001, Santochi *et al*. 2002, Lambert 2003, Lambert and Gupta 2005, Kang and Xirouchakis 2006). Among them, we focus on the planning problem, called disassembly scheduling in the literature. In general, disassembly scheduling can be defined as the problem of determining the quantity and timing of disassembling end-of-use/life products and their subassemblies in order to satisfy the demand of their parts or components. In other words, from the solution of the problem, we can determine which products or subassemblies, how many, and when to disassemble used or end-of-life products in order to satisfy the demand of their parts or components. From the theoretical point of view, disassembly scheduling is known to be a reversed version of the lot-sizing problem in assembly systems (see Karimi *et al*. 2003 and Brahimi *et al*. 2006 for more details of the lot-sizing problem).

A number of research articles have been published since Gupta and Taleb (1994) described the basic form of the disassembly scheduling problem. Therefore, it is now time to review the previous research articles with respect to problem classes as well as their solution approaches. Based on this motivation this paper presents a state-of-the-art literature review on disassembly scheduling (to the best of our knowledge, there is no review paper totally devoted to disassembly scheduling). Before reviewing the articles, the main differences between lot-sizing in assembly systems and disassembly scheduling in disassembly systems are explained. One of the main differences is called the convergence (for assembly) and divergence (for disassembly) properties in the literature (Brennan *et al*. 1994). That is, in the assembly environment parts/components converge to a single demand source of the final product, while in the disassembly environment products diverge to its multiple demand sources of parts/components. This explains why the existing lot-sizing algorithms cannot be used directly to solve the disassembly scheduling problems. Finally, several further research directions are also summarized for the interested readers.

The remainder of this paper is organized as follows. The following section describes the basic problem with a mathematical formulation. The effects of the divergence property of disassembly scheduling are also explained to characterize the differences between assembly and disassembly processes. The literature review on the basic problem as well as its generalizations is presented in section 3. In section 4, several future research directions are suggested and finally, section 5 concludes the paper.

2. Basic problem description and effects of divergence property

This section describes the basic form of the disassembly scheduling problem with a mathematical formulation. Then, the effects of the divergence property of disassembly scheduling are explained to characterize the differences between assembly and disassembly systems.

2.1 *Definition of the basic problem*

Before defining the basic problem, the disassembly structure is explained first. In the structure, the root item represents the product to be disassembled and the leaf items are the parts or components to be demanded and not to be disassembled further. A child item denotes an item that has at least one parent and a parent item is an item that has at least one child item. Figure 1 shows an example of a disassembly structure. In the disassembly structure, item 1 is the root item and items 4 to 7 are leaf items. The numbers in parentheses represent the yield of the item when its parent is disassembled, e.g. one unit of item 3 is disassembled into two units of item 6 and two units of item 7. Here, item 3 is called the parent item, while items 6 and 7 are called the child items.

Given the disassembly structure, the disassembly scheduling problem can be generally defined as follows:

> For a given disassembly structure, the problem is to determine the quantity and timing of disassembling all parent items (including the root item) while satisfying the demand of leaf items over a given planning horizon with discrete time periods.

It is assumed that a disassembly structure is given in advance from the corresponding disassembly process plan that specifies all parts/subassemblies of a given product and the necessary disassembly operations. See O'Shea *et al.* (1998), Lee *et al.* (2001), Santochi *et al.* (2002), Lambert (2003) and Lambert and

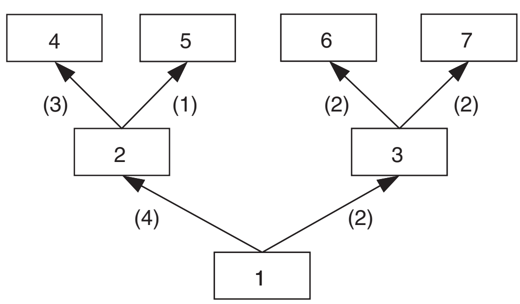

Figure 1. Diassembly structure: an example.

Gupta (2005) for views on disassembly process planning. Other assumptions made in the basic problem are as follows:

(a) demands of leaf items are given and deterministic;
(b) backlogging is not allowed, i.e. demands should be satisfied on time;
(c) parts/components are perfect in quality, i.e. no defective parts/components are considered; and
(d) each disassembly operation is performed in one and only one period and cannot extend over two or more periods.

Two types of objective functions are considered in the literature. They are:

(a) minimizing the number of products to be disassembled; and
(b) minimizing the costs related with the disassembly process.

In the basic problem, we consider the cost-based objective first. Note that Lee (2005) emphasizes the importance of considering cost factors in disassembly scheduling. More specifically, let the objective be the minimization of the sum of setup and inventory holding costs, which is commonly used for lot-sizing in assembly systems. The setup cost implies the cost required for preparing the corresponding disassembly operation. It is assumed that the fixed setup cost occurs in a period if any disassembly operation is performed in that period. Also, the inventory holding cost occurs if items are stored to satisfy future demand, and they are computed based on the end-of-period inventory.

To clarify the basic problem, we present an integer programming (IP) model that will be extended for more general problems. In the formulation, without loss of generality, all items are numbered by integers $1, 2, \ldots, i_l, i_l + 1, \ldots, N$, where 1 is the index for the root item and i_l is the index for the first leaf item which implies that indices greater than or equal to i_l represent leaf items. The notations used are summarized below.

Indices

- i Index for items, $i = 1, 2, \ldots, N$.
- t Index for periods, $t = 1, 2, \ldots, \mathrm{T}$.

Parameters

- s_i Setup cost of (parent) item i.
- h_i Inventory holding cost of item i.
- d_{it} Demand of (leaf) item i.
- a_{ij} Yield (number of units) of item j obtained from disassembling one unit of item i.
- I_{i0} Initial inventory of item i.
- $\varphi(i)$ Parent of item i.
- $H(i)$ Set of children of item i.
- M Arbitrary large number.

Decision variables

- X_{it} Disassembly quantity of item i in period t.
- Y_{it} $= 1$ if there is a setup for item i in period t, i.e. $X_{it} > 0$, and 0 otherwise.
- I_{it} Inventory level of item i at the end of period t.

The IP model (for the cost-based objective) is given below.

$$[\mathbf{P1}]\ \text{Minimize} \sum_{i=1}^{i_l-1}\sum_{t=1}^{T} s_i \cdot Y_{it} + \sum_{i=2}^{N}\sum_{t=1}^{T} h_i \cdot I_{it}$$

subject to

$$I_{it} = I_{i,t-1} + a_{(i),i} \cdot X_{(i),t} - d_{it} \quad \text{for } i = i_l, i_l+1, \ldots, N \text{ and } t = 1, 2, \ldots, T \tag{1}$$

$$I_{it} = I_{i,t-1} + a_{(i),i} \cdot X_{(i),t} - X_{it} \quad \text{for } i = 2, 3, \ldots, i_l - 1 \text{ and } t = 1, 2, \ldots, T \tag{2}$$

$$X_{it} \le M \cdot Y_{it} \quad \text{for } i = 1, 2, \ldots, i_l - 1 \text{ and } t = 1, 2, \ldots, T \tag{3}$$

$$Y_{it} \in \{0, 1\} \text{ and } X_{it} \ge 0 \text{ and integer} \quad \text{for } i = 1, 2, \ldots, i_l - 1 \text{ and } t = 1, 2, \ldots, T \tag{4}$$

$$I_{it} \ge 0 \quad \text{for } i = 2, 3, \ldots, N \text{ and } t = 1, 2, \ldots, T \tag{5}$$

The objective function denotes the sum of setup and inventory holding costs. Note that the other objective of minimizing the number of products to be disassembled can be represented as

$$\text{Minimize} \sum_{t=1}^{T} X_{1t}$$

Constraint (1) represents the inventory balance for leaf items. That is, the inventory level at the end of the current period equals the remaining quantity after the demand is satisfied with the previous inventory as well as the disassembly quantity of its parent multiplied by its yield from its parent item. Constraint (2) represents the inventory balance for parent items that should be disassembled further, which is represented by replacing the demand quantity in constraint (1) by the disassembly quantity. The inventory balance constraint for the root item is not needed since its surplus-inventory results in unnecessary cost increase. Constraint (3) guarantees that a setup cost in a period is incurred if any disassembly operation is performed in that period. Finally, the other constraints (4) and (5) are the conditions on the decision variables.

2.2 *Effects of divergence property*

To characterize the disassembly scheduling problem described above, this subsection explains the effects of the divergence property of a disassembly process. As stated earlier, the divergence property implies that the product diverges to their multiple demand sources of parts. In this paper, its effects are explained with regard to the following three aspects:

(a) the well-known zero inventory property (for ordinary lot-sizing) cannot be applied to disassembly scheduling and hence the existing lot-sizing algorithms cannot be used directly to solve the disassembly scheduling problem;
(b) the disassembly process results in indispensable surplus inventories for leaf items while satisfying their demands; and
(c) the disassembly scheduling problem should be formulated as an IP model even without binary setup variables Y_{it}.

Details of each effect are explained below.

2.2.1 Zero inventory property. In the basic lot-sizing problem for assembly systems, the solution space can be reduced using the well-known zero inventory property of Wagner and Whitin (1958). That is, this implies that there exists an optimal solution that satisfies $I_{i,t-1} \cdot X_{it} = 0$ for all i and t. Unlike the lot-sizing problem, this property does not hold in disassembly scheduling in itself, i.e. there may exist an optimal solution such that $I_{i,t-1} \cdot X_{it} > 0$.

For example, consider a problem with two planning periods, i.e., $T = 2$, for the disassembly structure given in figure 1. The other data are: $d_{it} = 10$ for $i = 4, 5$ and $t = 1, 2$, $h_i = 10$, $I_{i0} = 0$ for all $i = 2, 3, \ldots, 7$, and $s_i = 0$ for all $i = 1, 2, 3$. The optimal solution, which can be obtained from solving the integer program [P1] directly, is as follows:

$$X_{1,1} = 3, X_{1,2} = 2, X_{2,1} = 10,\ X_{2,2} = 10, X_{3,1} = 5, X_{3,2} = 5,$$
$$I_{2,1} = 2, I_{3,1} = 1,\ I_{4,1} = 20, I_{4,2} = 40,$$

and the others equal zero.

It can be seen from the optimal solution that the zero inventory property does not hold, e.g. $I_{2,1} \cdot X_{2,2} > 0$ and $I_{3,1} \cdot X_{3,2} > 0$.

Instead of the ordinary zero inventory property for assembly systems, Kim *et al.* (2006d) provided an extended property for disassembly scheduling under the following assumption

$$h_i \le \sum_{k \in H(i)} h_k \cdot a_{ik} \quad \text{for all } i = 2, 3, \ldots, i_l - 1,$$

which implies that the inventory holding cost of one unit of parent item i is not greater than the sum of the inventory holding costs of its child items. Theorem 1 shows the extended zero inventory property (see Kim *et al.* 2006d for more details).

Theorem 1: *For the disassembly scheduling problem [P1], there exists an optimal solution that satisfies*

$$X_{it} \cdot \min_{k \in H(i)} \left\lfloor \frac{I_{k,t-1}}{a_{ik}} \right\rfloor = 0 \quad \textit{for } i = 1, 2, \ldots, i_l - 1 \quad \textit{and} \quad t = 1, 2, \ldots, T$$

where $\lfloor \bullet \rfloor$ *gives the largest integer that is less than or equal to* $\bullet$.

2.2.2 Indispensable surplus inventories. Theorem 1 implies that in an optimal solution, if item i is disassembled in period t, i.e. $X_{it} > 0$, its child items should satisfy $\min_{k \in H(i)} \lfloor I_{k,t-1}/a_{ik} \rfloor = 0$. From this, we can obtain the following property related to the disassembly quantity (the proof is given in the appendix):

Theorem 2: *In an optimal solution of the disassembly scheduling problem [P1],*

$$X_{it} = 0 \textit{ or } \left\lceil \max_{k \in H(i)} \frac{\sum_{j=t}^{p} Q_{kj} - I_{k,t-1}}{a_{ik}} \right\rceil \textit{for } i = 1, 2, \ldots, i_l - 1 \quad \textit{and} \quad \textit{some } p, t \le p \le T,$$

where $\lceil \bullet \rceil$ *gives the smallest integer that is more than or equal to* $\bullet$ *and* $Q_{kt} = X_{kt}$ *if* k *is a parent item and* d_{kt} *if* k *is a leaf item.*

Theorem 2 implies that all the requirements of its child items can be satisfied automatically if the disassembly quantity is set according to Theorem 2. However, we can see that this optimal policy may result in indispensable surplus inventories of the child items. More formally, the surplus inventory of child item k can be specified as

$$I_{kt} = a_{ik} \cdot X_{it} - \sum_{j=t}^{u} Q_{kj} + I_{k,t-1} \quad \text{for } u = t, t+1, \ldots, p,$$

Note that the existence of the indispensable surplus inventories is one of the main differences between assembly and disassembly systems. In general, the surplus inventories are stored to satisfy future demands (or disposed of) and hence results in a huge amount of inventory in product and material recovery firms.

2.2.3 Mathematical representation. This difference considers the aspect of mathematical models. As stated earlier, the disassembly scheduling problem should be formulated as an IP model even without the binary setup variables Y_{it}, while the lot-sizing can be formulated as a linear programming model; the reason is as follows: according to Theorem 2, the optimal disassembly quantities can be obtained by rounding up fractions. Therefore, the direct implementation of the linear programming model without the integrality constraint (for X_{it}) does not give integer values for the decision variables. This cannot guarantee the optimality of the solution obtained from the linear programming relaxation. Also, without the integrality constraint, it is needed to modify the real-valued solutions to integer ones that satisfy the demand requirements. This is not an easy procedure and may result in low quality solutions (Kim *et al.* 2003). On the other hand, the ordinary lot-sizing problem does not require any integer restrictions on decision variables. That is, the problem can be solved using the linear programming model. See Maes *et al.* (1991) for the linearity of the lot-sizing problem.

3. Literature review

This section presents a literature review on the basic disassembly scheduling problem [P1] and its generalizations. To show an overview of the review, a summary of the relevant articles is given in table 1. As shown in this table, the disassembly scheduling problem can be basically classified as uncapacitated and capacitated ones. Here, the capacitated models incorporate the resource capacity restriction, i.e., there is a restriction on resources or capacities of manpower, equipment, machines, budget, etc. Also, each category can be further classified according to the product structure, i.e. assembly structure without parts commonality and general structure with parts commonality. Here, the parts commonality implies that a product or subassembly shares its parts and/or components, and hence makes the problem more complex since it may result in two or more alternative procurement sources for each common part and create additional interdependencies between parts/components.

3.1 *Basic problem [P1]: uncapacitated problem with assembly structure*

Gupta and Taleb (1994) consider the basic problem [P1] without explicit objective function and suggest an algorithm that is a reversed version of material requirement

Table 1. Summary of previous research articles on disassembly scheduling.

Problem class		Articles	Objective function	Solution method	
Assembly structure		Gupta and Taleb (1994)	N†	Reverse MRP (optimal)	
		Lee and Xirouchakis (2004)	C‡	Heuristic	
		Kim *et al*. (2006d)	C	Branch and bound	
	Two-level	Kim *et al*. (2006c)	C	Polynomial algorithm	
General structure	Single product type	Taleb *et al*. (1997)	N	Heuristic	
		Neuendorf *et al*. (2001)	N	Petri-net model	
	Multiple product types	Taleb and Gupta (1997)	C	Heuristic	
		Kim *et al*. (2003)	C	Heuristic	
		Langella (2005)	C	Heuristic	
		Kim *et al*. (2006a)	C	Heuristic	
		Veerakamolmal and Gupta (1998)	C	Non-linear programme	Single period
		Lambert and Gupta (2002)	C	IP model	Single period
		Kongar and Gupta (2002)	C	Goal programme	Single period
Capacity: assembly structure		Kim *et al*. (2006e)	N	Optimal algorithm	
		Lee *et al*. (2002)	C	IP model	
		Kim *et al*. (2006b)	C	Heuristic	
Uncertainty		Kongar and Gupta (2006)	C	Fuzzy goal programme	Single period
	Two-level	Inderfurth and Langella (2006)	C	Heuristic	Single period

†Number of products disassembled.
‡Cost-based.

planning (MRP). This is because the ordinary MRP cannot be directly applied to disassembly systems due to the divergence property described earlier. Their algorithm works as follows: the demand of leaf items (external demand) is translated into an equivalent demand (internal demand) for parent items. By continuing this routine to the root item, the disassembly schedule for all parent items is determined in such a way that the external demand of the leaf items and the internal demand of parent items are satisfied. This paper has a contribution in that it defines the disassembly scheduling problem.

Lee and Xirouchakis (2004) consider the cost-based objective that minimizes the sum of purchase, setup, disassembly operation, and inventory holding costs and suggest a two-stage heuristic algorithm: an initial solution is obtained using the algorithm of Gupta and Taleb (1994) and it is improved using the backward move, i.e. some disassembly quantity is moved backward considering cost changes. They show from a computational experiment that the two-stage algorithm can give near optimal solutions within a reasonable amount of computation time. Recently, Kim *et al*. (2006d) analysed the complexity of the basic disassembly scheduling problem [P1] and proved that it is NP-hard by transforming its special case into the joint replenishment problem of Arkin *et al*. (1989). To solve the problem, they suggest a branch and bound algorithm using Theorem 1. The lower and upper bounds are obtained with the Lagrangean relaxation technique. Here, the Lagrangean dual problem can be decomposed into single-item lot-sizing problems that can be solved in polynomial time. Another property, called an extension of the nested property of Crowston and Wagner (1973), is also used in the algorithm. This can be explained as follows (Kim *et al*. 2006d for its proof).

Theorem 3: *For the basic disassembly scheduling problem* [*P1*], *there exists an optimal solution in which* $X_{it} > 0$ *for* $i = 1, 2, \ldots, i_l - 1$ *implies that* $Q_{kt} > 0$ *for some* $k \in H(i)$, *where* $Q_{it} = X_{it}$ *for* $i = 2, 3, \ldots, i_l - 1$ *and* d_{it} *for* $i = i_l, i_l + 1, \ldots, N$.

Unlike these, Kim *et al*. (2006c) consider a special case of the basic problem [P1], called the two-level disassembly structure, for the objective of minimizing the sum of setup and inventory holding costs. The two-level disassembly structure implies that the disassembly structure has a direct relationship between the root item and leaf items without intermediate non-root parent items. In this paper, they suggest a polynomial optimal algorithm with $O(N \cdot T^3)$ using Theorems 1 and 2. The basic idea, which is similar to that of Wagner and Whitin (1958), is that the problem can be decomposed into sub-problems and hence formulated as a dynamic programming model.

3.2 *Generalizations*

This subsection reviews the articles on the problems that generalize the basic one [P1]. There may be various types of generalizations that can be obtained from relaxing the assumption(s) of the basic problem [P1]. Among them, three cases are mainly considered in the literature. They are:

(a) uncapacitated problems with general structure;
(b) capacitated problems with assembly structure; and
(c) problems with uncertainty.

3.2.1 Uncapacitated problems with general structure. The first class of generalization relaxes the assumption of assembly product structure, i.e. the general structure with parts commonality is considered. As stated earlier, the parts commonality implies that a product or subassembly shares its parts and/or components, and hence increases the problem complexity significantly since it may result in alternative procurement sources for each common part and create additional interdependencies among parts. In general, the articles in this class can be classified as those for single product type (Taleb *et al*. 1997, Neuendorf *et al*. 2001) and multiple product types (Taleb and Gupta 1997, Veerakamolmal and Gupta 1998, Kongar and Gupta 2002, Lambert and Gupta 2002, Kim *et al*. 2003, Langella 2007, Kim *et al*. 2006a), and our review is done under this classification.

Before presenting the literature review, an example of general structure with multiple product types is shown in figure 2. In this figure, the shaded item 4 denotes the common item that has more than one parent, i.e. item 4 can be obtained from either item 1 or 2.

The IP model for the problem with multiple product types is given below. Note that this model can be obtained by modifying the constraints (1), (2), and (5) of [P1] so that parts commonality can be additionally represented. That is, each item is obtained by summing over quantities resulting from disassembling the set of its parents, which is denoted in constraints (1a), (2a), and (5a) in the following IP model. (See Lee *et al*. (2004) for more details of the model.) In the IP model, $\Phi(i)$ and i_r denote the set of parents of item i and the number of root items, respectively. Therefore, the special case of single product type can be obtained by setting $i_r = 1$.

$$[\mathbf{P2}]\text{Minimize} \sum_{i=1}^{i_l-1} \sum\nolimits_{t=1}^{T} s_i \cdot Y_{it} + \sum_{i=1}^{i_l-1} \sum_{t=1}^{T} p_i \cdot X_{it} + \sum_{i=i_r+1}^{N} \sum_{t=1}^{T} h_i \cdot I_{it}$$

subject to

$$I_{it} = I_{i,t-1} + \sum_{k \in \Phi(i)} a_{ki} \cdot X_{kt} - d_{it} \quad \text{for } i = i_l, i_l+1, \ldots, N \quad \text{and} \quad t = 1, 2, \ldots, T \tag{1a}$$

$$I_{it} = I_{i,t-1} + \sum_{k \in \Phi(i)} a_{ki} \cdot X_{kt} - X_{it} \quad \text{for } i = i_r+1, i_r+2, \ldots, i_l-1 \quad \text{and} \quad t = 1, 2, \ldots, T \tag{2a}$$

$$I_{it} \geq 0 \text{ and integer for } i = i_r+1, i_r+2, \ldots, N \quad \text{and} \quad t = 1, 2, \ldots, T \tag{5a}$$

and (3) and (4)

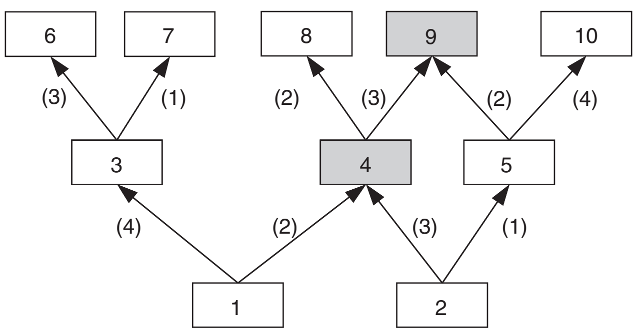

Figure 2. General product structure: an example.

For the problem with single product type, i.e. $i_r = 1$, Taleb *et al.* (1997) suggest a heuristic algorithm for the objective of minimizing the number of products to be disassembled. The basic idea is to transform the general structure into the assembly structure by decomposing each common item into imaginary items so that the reverse MRP algorithm of Gupta and Taleb (1994) can be used. Here, the yield from the root item is used when the demand of each common item is distributed to the corresponding imaginary items. Later, Neuendorf *et al.* (2001) suggest a Petri-net based algorithm that consists of two main steps: the first step computes the minimal number of the root items to meet the total demands of all leaf items over the planning horizon and the second step determines the detailed disassembly schedule of the root item so that the demand in each period can be satisfied. They show, using the example of Taleb *et al.* (1997), that their Petri-net based algorithm gives a better solution than the existing MRP-like heuristic algorithm.

For the problem with multiple product types, i.e. $i_r \geq 1$, Taleb and Gupta (1997) suggest a heuristic algorithm for the objective of minimizing the disassembly cost. The heuristic algorithm consists of two steps: the first step computes the quantity of each root item to satisfy the total demand of the relevant leaf items over the planning horizon and the second step fixes the disassembly schedule of each root item by allocating the corresponding disassembly quantities to each period. Here, the disassembly schedules of root items are used to determine those of non-root parent items. However, as noted in Langella (2007), this algorithm may result in infeasible solutions. A more general cost-based objective, minimizing the sum of setup, disassembly operations and inventory holding costs, is considered by Kim *et al.* (2003) that suggest a linear programming (LP) relaxation based heuristic algorithm. In this algorithm, the IP model is solved directly after relaxing the integrality constraints of decision variables and the real-valued LP solution is rounded down to the integer one. Then, the rounded-down solution is modified to satisfy all the original constraints while considering the resulting cost changes. Computational experiments show that the LP relaxation based heuristic algorithm does not work well for the cases where the setup cost is large. Note that the setup cost is generally large in disassembly processes due to inherent manual operations (Kang *et al.* 2001, 2002, 2003). Therefore, Kim *et al.* (2006a) extend the algorithm of Kim *et al.* (2003) to cope with high setup costs. In this algorithm, an initial solution is obtained using the algorithm of Kim *et al.* (2003) and then it is improved by the dynamic programming approach.

Langella (2007) considers the problem with disposal option, such as landfill, incineration or selling to secondary markets, for the objective of minimizing the sum of purchase, disassembly operation, inventory holding, and disposal costs. Here, the disposal cost may be negative, i.e. revenues, since parts can be sold to secondary markets. In this case, the inventory balance constraints are modified to deal with the disposal option, and they can be represented as follows.

$$I_{it} = I_{i,t-1} + \sum_{k \in \Phi(i)} a_{ki} \cdot X_{kt} + B_{it} - W_{it} - d_{it} \quad \text{for } i = i_l, i_l + 1, \ldots, N \quad \text{and} \quad t = 1, 2, \ldots, T \tag{1b}$$

$$I_{it} = I_{i,t-1} + \sum_{k \in \Phi(i)} a_{ki} \cdot X_{kt} - W_{it} - X_{it} \quad \text{for } i = i_r + 1, i_r + 2, \ldots, i_l - 1 \quad \text{and} \quad t = 1, 2, \ldots, T \tag{2b}$$

$$I_{it} = I_{i,t-1} + B_{it} - X_{it} \quad \text{for } i = 1, 2, \ldots, i_r \quad \text{and} \quad t = 1, 2, \ldots, T, \tag{6}$$

where B_{it} and W_{it} denote the purchase and the disposed quantities of item i in period t, respectively. Also, the returns of end-of-use/life products are considered by limiting the number of purchasable root items from suppliers, i.e.,

$$B_{it} \le B_{it}^{\max} \quad \text{for } i = 1, 2, \ldots, i_r \quad \text{and} \quad t = 1, 2, \ldots, T,$$

where $B_{it}^{\max}$ denotes the maximum purchasable quantity of item i in period t. To solve this extended problem, Langella (2007) suggests a heuristic algorithm that modifies the algorithm of Taleb and Gupta (1997) with respect to the limited purchase quantity and disposal options.

Unlike the multi-period models described above, several papers consider similar problems with a single period. Veerakamolmal and Gupta (1998) consider the problem for the objective of maximizing profit, i.e. revenues subtracted by disassembly operation and disposal costs, and suggest a non-linear programming model where a constraint corresponding to the disassembly quantity is represented with a non-linear equation, and later, Lambert and Gupta (2002) suggest a linear constraint to represent the disassembly quantity. Note that the problem considered by Veerakamolmal and Gupta (1998) and Lambert and Gupta (2002) is a single period version of that of Langella (2007). Also, Kongar and Gupta (2002) suggest a goal programming model for an extended version (single period problem) of Veerakamolmal and Gupta (1998), in which more realistic factors are considered such as recycling, transportation, product returns, storage capacity of inventory, etc.

3.2.2 Capacitated problems: assembly structure. The second class of generalization considers the resource capacity constraint. As in the production planning problems in assembly systems, the resource capacity constraint is an important consideration in disassembly scheduling since it makes the resulting solution more applicable. In the previous research, the capacity restriction is considered in the form of a time limit for the disassembly operations performed in that period. That is, there is an upper limit on the available time in each period of the planning horizon, and each disassembly operation assigned to a period consumes a portion of the available time of that period. The capacity constraint is represented as

$$\sum_{i=1}^{i_{l-1}} g_i \cdot X_{it} \le c_t \quad \text{for } t = 1, 2, \ldots, T,$$

where g_i denotes the disassembly operation time to disassemble one unit of item i and c_t denotes the given time capacity in period t, and can be added to the IP models [P1] and [P2].

The previous research on the capacitated version considers the assembly structure. Lee *et al.* (2002) consider the problem for the objective of minimizing the sum of disassembly operation and inventory holding costs and suggest an IP model. A case study was done and its optimal solution was obtained with a commercial software package. Kim *et al.* (2006e) consider the problem for the objective of minimizing the number of disassembled product and suggest an optimal algorithm after showing that its optimal solution value is equal to that of the corresponding uncapacitated problem, i.e. the problem of Gupta and Taleb (1994).

The algorithm works as follows: an initial solution is obtained using the reverse MRP algorithm of Gupta and Taleb (1994), and then, the initial solution, which may be infeasible to the capacity constraint, is modified to satisfy the capacity constraint, i.e. the disassembly quantity overloaded in each period is moved to other periods. Recently, Kim *et al.* (2006b) consider the objective of minimizing the sum of setup and inventory holding costs and suggest a Lagrangean heuristic algorithm. Here, the Lagrangean dual problem is solved by decomposing it into the single item lot-sizing problems that can be solved in polynomial time and the feasible solutions are obtained by changing the Lagrangean dual solution while considering the cost trade-offs.

3.2.3 Uncertainty problems. The third class of generalization relaxes the assumption of deterministic parameters, i.e., stochastic disassembly scheduling. Like other decision problems in disassembly systems, uncertainties, such as defective parts, stochastic demands and lead times, etc., are important considerations in disassembly scheduling.

The previous research articles on this problem class consider various uncertainty factors. Kongar and Gupta (2006) consider the problem with stochastic cost factors and suggest an algorithm using fuzzy goal programming. In fact, this is a stochastic extension of Kongar and Gupta (2002) on the deterministic problem. Recently, Inderfurth and Langella (2006) considered the problem with two-level disassembly structure and random yields. The objective is to minimize the sum of expected disassembly operation, purchasing and disposal costs. The main assumption is that all needed leaf items are purchased from suppliers if the disassembly quantity is not enough to satisfy the demands, and all excesses of leaf items are disposed of, otherwise. Two heuristic algorithms, called one-to-one and one-to-many heuristics, are suggested in this paper. In the one-to-one heuristic, the entire disassembly structure is decomposed into those with single root and single leaf items so that each sub-problem becomes a single item problem with random yield. On the other hand, in the one-to-many heuristic, the decomposition is done to generate those with single root and multiple leaf items.

4. Future research directions

This section presents several further research directions on the disassembly scheduling problems considered in this paper. The research directions suggested in this paper are mainly classified as the issues on problem extensions, uncertainty, and integration with other decision problems.

4.1 *Problem extensions*

This direction is on extending the problems considered in the literature to more general ones, i.e. problems with capacity constraint and general structure, setup time, storage capacity, product returns, backlogging, etc. Details of each issue are explained below.

4.1.1 Capacitated problems with general structure. As stated earlier, most previous articles on the capacitated problem consider the assembly structure. Although Langella (2007) consider the capacitated problem for general structure, its cost-based objective does not include the setup cost, an important cost factor in disassembly systems (Kang *et al.* 2001). Therefore, it is needed to extend the existing problems to those with general structure as well as setup cost. However, these additional considerations increase the problem complexity significantly.

4.1.2 Capacitated problems with setup time. Although several previous articles on the capacitated problems consider the setup cost in the objective function, they do not consider the corresponding setup time required for preparing the disassembly operation. In general, the setup time is large, especially in manual disassembly operations, and hence should be incorporated in the capacity constraint. This makes the existing problem more realistic. For example, if the setup time is deterministic, the capacity constraint can be modified as

$$\sum_{i=1}^{i_{l-1}} (st_i \cdot Y_{it} + g_i \cdot X_{it}) \leq c_t \quad \text{for } t = 1, 2, \ldots, T,$$

where st_i is the setup time required for preparing the disassembly operation of item i and Y_{it} is equal to 1 if there is a setup for item i in period t, and 0 otherwise. However, we can easily see that this makes the problem much more difficult. Note that in the ordinary lot-sizing problem with setup time, even its feasibility problem is known to be NP-complete (Maes *et al.* 1991).

4.1.3 Problems with storage capacity. As stated earlier, one of the main differences between assembly and disassembly systems is that the disassembly process results in indispensable surplus inventories of parts and/or components. Therefore, methods to manage these inventories in disassembly scheduling are also important extensions. One of them is to restrict the storage capacity for inventories. For example, this constraint can be simply represented as

$$\sum_{i=i_r+1}^{N} q_i \cdot (I_{i,t-1} + a_{\varphi(i),i} \cdot X_{it}) \leq z_t \quad \text{for } t = 1, 2, \ldots, T,$$

where q_i and z_t represent the volume of item i and the storage capacity in period t, respectively. This constraint implies that in each period, the total volume of the remaining items from the previous period and the items obtained by disassembling the corresponding parent items should be less than or equal to the storage capacity.

4.1.4 Problems with product returns. In the previous research, it is assumed that there is no shortage of end-of-use/life products. That is, the end-of-use/life products required can be supplied whenever they are ordered. In the real disassembly systems, however, the product return is highly uncertain and hence cannot meet the requirement of end-of-use/life products. One of the approaches to deal with this situation is to set the limit on the available number of products, which requires modifications of the existing models.

4.1.5 Problems with backlogging. One of the basic assumptions of the existing problems is that backlogging is not allowed, i.e. the inventory level cannot be negative. As in the ordinary production planning problems, this assumption can be relaxed easily by modifying the inventory balance constraint and incorporating the relevant backorder cost into the objective function. For example, the inventory balance constraint can be extended as

$$I_{it}^{+} - I_{it}^{-} = I_{i,t-1}^{+} - I_{i,t-1}^{-} + a_{\varphi(i),i} \cdot X_{\varphi(i),t} - d_{it} \quad \text{for } i = i_l, i_l + 1, \ldots, N \text{ and } t = 1, 2, \ldots, T$$

where I_{it}^{+} and I_{it}^{-} are the inventory and backorder levels of item i at the end of period t, respectively. Although the existing IP models can be extended with these modifications, it is needed to analyse the complexity of the extended problems.

4.2 *Uncertainties*

As in other decision problems in disassembly systems, uncertainties are important considerations in disassembly scheduling. Although the previous research considers this issue (Kongar and Gupta 2006, Inderfurth and Langella 2006), it has not been well addressed. For example, it may be more practical to extend the single-period model of Inderfurth and Langella (2006) to multi-period ones. Other uncertainty issues are stochastic product returns and demands, defective parts and/or components, and stochastic disassembly operation time, etc. However, these issues also increase the problem complexity much more significantly.

4.3 *Integration with other decision problems*

Disassembly scheduling is closely related with other disassembly problems since it is one of the basic operational problems in disassembly systems. Therefore, to make the disassembly scheduling models more practical, it is needed to integrate the problem with other decision problems in disassembly systems. To deal with this issue, we suggest two integration problems in disassembly systems. They are:

(a) the integration with disassembly process planning and
(b) the integration with disassembly shop scheduling.

Also, another issue on integration with other activities in remanufacturing systems is provided to enlarge the system scope from disassembly systems to remanufacturing systems.

4.3.1 Integration with disassembly process planning. In general, disassembly process planning can be defined as the problem of determining the sequence of disassembly operations for a given product in such a way that the resulting disassembly sequence satisfies the constraints established by the product. That is, a disassembly process plan begins with a product to be disassembled and terminates in a state where the entire product or certain parts are disconnected. There are two additional decision variables, disassembly level and end-of-life options, in disassembly process planning. The disassembly level implies whether more disassembly operations are required or not at each stage of disassembling of a product, and the end-of-life option is about how parts and/or components, obtained from disassembling products, are dealt with, e.g. re-use, remanufacturing, disposal, etc.

There is a strong interdependence between disassembly process planning and disassembly scheduling. As stated earlier, one of the basic data for disassembly scheduling is the disassembly structure that can be obtained from the disassembly process plan. Therefore, we can easily integrate them in a hierarchical fashion. However, this may reduce the quality of disassembly schedule, especially when considering the resource capacity constraint, and hence certain methods to integrate disassembly process planning and disassembly scheduling are required as a further research direction. See Lee *et al.* (2001) for a detailed explanation of this issue.

4.3.2 Integration with disassembly shop scheduling. Disassembly shop scheduling is the problem of allocating resources in disassembly systems over time to perform a collection of disassembly operations, i.e. sequence and timing of disassembling operations over a scheduling period. That is, it is the scheduling problem in disassembly systems. Although there are several previous research articles on this problem (Kisilkaya and Gupta 1998, Stuart and Christina 2003, Rios and Stuart 2004), none of them address the integration with the planning problems, such as the disassembly scheduling problem considered in this paper.

As in the ordinary production planning and scheduling problems in assembly systems, there is a close relationship between the planning and scheduling problems in disassembly systems. Therefore, the models and algorithms to integrate them can be important research directions. For example, disassembly shop scheduling is ready to be done after obtaining the disassembly schedule. In this case, the top-down procedure may not guarantee that a feasible shop schedule exists for the generated disassembly schedule (Lasserre 1992), and hence other methods such as iterative approaches may be needed to integrate them more effectively.

4.3.3 Integration with other activities in remanufacturing systems. The last integration issue suggested in this paper is that of remanufacturing systems. In general, remanufacturing can be defined as an industrial process in which worn-out products are restored to like-new condition (Lund 1984). That is, through a series of industrial processes, an end-of-life/use product is partially or completely disassembled. Among the disassembled parts or subassemblies, usable ones are cleaned, refurbished, and put into inventory. Then, the new product is reassembled from both old and, where necessary, new parts to produce a unit equivalent and sometimes superior in performance and expected lifetime to the original new product.

When the system scope is extended to the remanufacturing systems, the disassembly scheduling problem can be regarded as the lot-sizing problem with remanufacturing options. Several existing articles consider this extended planning problem. For example, see Clegg *et al.* (1995), Richter and Sombrutzki (2000), Richter and Weber (2001), Golany *et al.* (2001), Yang *et al.* (2005) and Li *et al.* (2006). However, most of them simplify the disassembly process as an aggregated activity within the remanufacturing systems, i.e. remanufacturing encompasses the

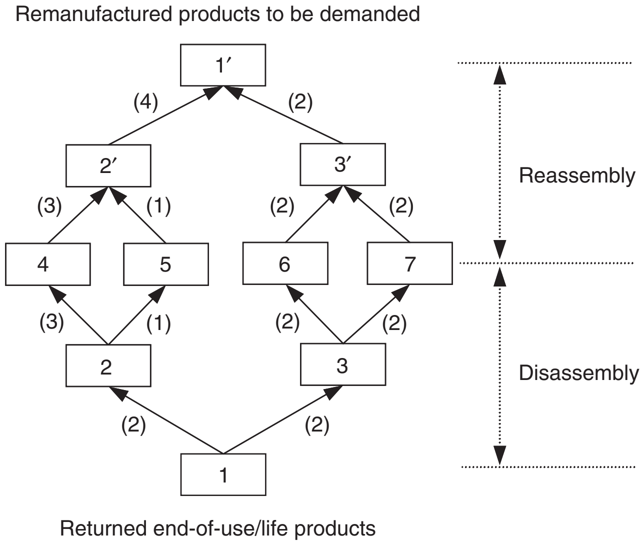

Figure 3. Example of a product structure with disassembly and reassembly.

disassembly and reassembly processes. Instead, to make the integrated models more precise, it is needed to consider the disassembly process in the form of the disassembly structure explained in this paper. For example, when the disassembly scheduling problem considers the reassembly activity, the corresponding product structure can be represented as figure 3.

5. Concluding remarks

This paper considered the problem of determining the quantity and timing of end-of-use/life products while satisfying the demand of their parts over the planning horizon. This problem, called disassembly scheduling in the literature, is one of the important planning problems in disassembly systems, and hence from the solution of the problem we can determine how much, and when, to disassemble the end-of-use/life products, i.e. basic operational information in disassembly systems.

In this paper, we reviewed the research articles on this problem and suggested several further research directions. First, the basic form of the problem was presented with a mathematical formulation. To characterize the differences between assembly and disassembly systems, the effects of the divergence property of disassembly scheduling are summarized with respect to the zero inventory property, the indispensable numerous inventories, and mathematical representation. Then, a literature review was done on the basic problem as well as its generalizations. An appropriate scheme for problem classification was also suggested. Finally, we suggested several future research directions for interested readers.

Appendix: proof of Theorem 2

According to Theorem 1, there are two possible cases for item i in period t in an optimal solution:

$$\min_{k \in H(i)} \left\lfloor \frac{I_{k,t-1}}{a_{ik}} \right\rfloor > 0, \tag{a}$$

and

$$\min_{k \in H(i)} \left\lfloor \frac{I_{k,t-1}}{a_{ik}} \right\rfloor = 0 \tag{b}$$

In case (a), $X_{it} = 0$ from Theorem 1. In case (b), the requirement (demand or disassembly quantity) of all child items of item i from period t to p should be satisfied by disassembling item i in period t. Therefore, the requirement (demand or disassembly quantity) of any child item $k \in H(i)$ becomes

$$\sum_{j=t}^{p} Q_{kj} - I_{k,t-1},$$

and hence the corresponding disassembly quantity becomes

$$\mathrm{X_{it}} = \left\lceil \max_{k \in H(i)} \frac{\sum_{j=t}^{p} Q_{kj} - I_{k,t-1}}{a_{ik}} \right\rceil$$

since all the requirements (of child items) can be satisfied if parent item i is disassembled by the maximum requirement amount of those of its child items. Then, the inventory level in period $t-1$ satisfies $\min_{k \in H(i)} \lfloor I_{k,t-1}/a_{ik} \rfloor = 0$, which results in Theorem 1. □

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