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AN OPTIMIZATION FRAMEWORK FOR ADVANCED DISASSEMBLY/REPAIR-TO-ORDER SYSTEMS WITH REMAINING-LIFE ADJUSTMENT

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ABSTRACT

Due to environmental awareness and realization of cost savings, disassembly-to-order (DTO) concept has become popular. One of the main obstacles to making optimal DTO decisions is the uncertainty involved in end-of-life products (EOLPs). This uncertainty is due to the lack of information about the condition and the quantity of EOLPs returned. This uncertainty is removed by advanced disassembly/repair-to-order systems utilizing sensors to monitor the products in their life-cycle. Sensor technology enables remaining life estimation, thus allows advanced DTO models to deal with sophisticated component and product demands with remaining life adjustment.

This paper presents an optimization framework for advanced disassembly/repair-to-order (ADRTO) systems. The method is compared with a TABU search based heuristic algorithm.

INTRODUCTION

An ADRTO system can be considered as an extension to traditional disassembly-to-order (DTO) system. DTO is a process, in which end-of life products (EOLPs) are disassembled in order to fulfill the demand for materials and reusable components. DTO systems recently became popular with the increased public awareness on environmental issues such as depletion of landfills, exhaustion of virgin resources, global warming etc. Environmental consciousness triggered the use of recycled materials and reusable components, and created a demand for them. Thus, traditional supply-demand balance problem was reproduced for used components and recycled materials that are recovered from EOLPs. DTO models address this very problem: optimal planning of disassembly operations. In other words, DTO models try to determine the optimal number of EOLPs to be disassembled in order to satisfy the system criteria (minimum cost, maximum profit, etc.). In fact, this process contains a lot of uncertainties because neither quality, nor the quantity of EOLPs is known before disassembly. Many academicians put a lot of efforts to address this limitation of traditional DTO systems'. For more information about DTO, uncertainties involved in DTO and solution approaches [1-11] can be useful.

Life-cycle data bring clarity to the EOL operations and are used to determine the remaining life of the components [12]. These data are captured using embedded sensors and radio frequency identification (RFID) tags. RFID has long been used to gather a history or trace of object movements [13]. RFID technology can be introduced as an enabler of product lifecycle management (PLM) business, by enhancing the traceability of the product throughout its value chain via automatic identification, enabling the collection of product usage information during its life cycle, and facilitating the integration of product lifecycle information and knowledge [14]. Ondemir and Gupta [15] proposed a mathematical DTO model utilizing life-cycle data in order to fulfill remaining life time based sophisticated component demands. In its follow up papers [16, 17], authors extended the model in order to meet the sophisticated product demands by using repair option, and presented economic justification of establishing advanced

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DTO systems in which sensor-embedded EOLPs are disassembled in order to fulfill sophisticated demands.

In this paper, an optimization framework for advanced disassembly/repair-to-order (ADRTO) systems with remaining-life adjustment is proposed.

PROBLEM DEFINITION

ADRTO concept involves disassembly and repair operations in order to fulfill sophisticated component and product demands as well as material demands. It is assumed that ADRTO accepts completely modular EOLPs in which RFID tags and sensors were embedded. By means of remaining-life adjustment, any over qualified components in a repaired product may (or may not) be replaced with a less good, yet satisfying component. In other words, if a product is repaired to have at least two years of remaining-life, any components having more remaining-life may be replaced with the ones having at least two years of life remaining. That way, the over qualified components may be used to fulfill the demands for components with longer remaining-life. This should decrease outside procurement costs since it is assumed that there is a positive correlation between the remaining-life and the procurement cost of a component. On the other hand, this adjustment may incur extra disassembly and assembly cost. Therefore, a replacement (adjustment) is only beneficial when saving obtained outweighs the extra cost.

EOLPs dealt with are completely modular products consisting of a chassis and a number of different types of components based on their models. All components are assembled on the chassis and no interconnection exists among the components. An EOLP may be repaired to make a product of a certain model that is different from its original model. Therefore, some components may be extra (unnecessary). A repair operation involves disassembly of broken, under-qualified (remaining-life deficit) and extra components, and assembly of necessary components that satisfy remaining-life requirements. When an EOLP is to be repaired, repair plan is populated from the data set stored in RFID tags and there is no variability in the repair plan. In other words, repair operations (disassembly and assembly) are not decision variables. On the other hand, remaining-life adjustment is indeed a decision option and cost of this option is dependent on initial repair decision. This dependency is what makes the problem nonlinear.

Nonlinearity makes hard-to-solve pure integer problem even harder-to-solve. For easy computation, a two-stage linear program is developed. This method yields a near optimal solution.

TWO-STAGE OPTIMIZATION FRAMEWORK MODEL

Although generic ADRTO model is a linear deterministic model [16], remaining-life adjustment renders the problem non-linear. Non-linearity occurs in the objective function because of the structure of the EOLPs. Therefore, as a simplified method, a two-stage linear program reducing the problem to two linear sub-problems is developed. Then, as a second approach, a TABU search based heuristic algorithm is developed and the results of these two methods are compared. As conclusions, pros and cons of the two techniques are evaluated and a numerical example is considered to illustrate both approaches.

The goal of the model is to determine which EOLPs to disassemble, repair, or recycle and which components to replace for remaining life adjustment purposes. The model is constructed for completely modular products. In other words, all components are assumed to be independently assembled on a base (chassis). The mathematical model for stage 1 is shown below.

$$\min z_1 = \sum_{i \in I, j \in J} [ind1_i (\bar{x}_i c_{1j} a_{ij} + (\bar{x}_i + \bar{y}_i) c_3 f_{ij}) + (cd_j \sum_{t \in T} (ext_{itj} \sum_{m \in M} y_{itm}) + ca_j \sum_{t \in T} (mis_{itj} \sum_{m \in M} y_{itm}) + (cd_j + (cd_j + cd_j)) + (cd_j + (cd_j + cd_j)) + (cd_j + (cd_j)) + (cd_j + (cd_j)) + (cd_j + (cd_j)) + (cd_j) + ($$

$$ca_{j} \sum_{t \in T, m \in M} def_{itmj} y_{itm}] + \sum_{i \in l, t \in T, [j \in J], j \leq V} [f_{ij} \cdot \sum_{m \in M} ch_{itm} y_{itm} + \sum_{m \in M} ch_{itm} def_{itmj} y_{itm} + ext_{itj} \sum_{m \in M} ch_{itm} y_{itm} + mis_{itj} \sum_{m \in M} (chm_{itm} - (1 - ind_1)ext_{itj} cd_j + def_{itmj} (cd_j + ca_j)) y_{itm}] + \sum_{j \in J, b \in B} c_{jb} l_{jb} + \sum_{j \in J} cr_j (\sum_{i \in I} f_{ij} (\bar{x}_i + \bar{y}_i) + \sum_{b \in B} r_{jb})$$
to, $\bar{x}_i + \bar{y}_i \leq 1, \forall i$ (2)
 $\sum_{b \in B} x_{ijb} = \bar{x}_i, \forall i, j$ (3)
 $\sum_{t \in T, m \in M} y_{itm} = \bar{y}_i, \forall i$ (4)
 $\sum_{i \in I} y_{itm} \geq dp_{tm}, \forall t, m$ (5)
 $\sum_{\{i \in I \mid cin_{ijb} = 1\}} [a_{ij} x_{ijb} + \sum_{t \in T} (ext_{itj} \sum_{m \in M} y_{itm}) + \sum_{t \in T, m \in M} def_{itmj} y_{itm}] - \sum_{i \in I} (\sum_{t \in T, m \in M} (rep_{itmj} b)) + l_{jb} - r_{jb} \geq dc_{jb}, \forall b, j$ (6)
 $\sum_{i b \in B \mid b \geq m} rep_{itmjb} = y_{itm} (mis_{itj} + def_{itmj}), \forall i, j, t, m$ (7)
 $\sum_{j \in J} g_{jk} (rb_j + \sum_{b \in B} r_{jb}) \geq dm_k, \forall k$ (8)

$$rb_j \le \sum_{i \in I} f_{ij}(\bar{x}_i + \bar{y}_i), \forall j$$
(9)

Equation (1) defines the objective function by minimizing the sum of total disassembly cost, total recycling cost and total outside component procurement cost, respectively. Equation (2) represents the constraints that assure that EOLP in the inventory can be disassembled, repaired or left untouched. Equation (3) represents constraints that assure complete disassembly. Equation (4) represents constraints that make sure that an EOLP is repaired to produce only one product and that product is evaluated in only one product life-bin. Equation (5) is the set of constraints that ensure that the sophisticated product demand is satisfied by repaired EOLPs. Equation (6) sets a set of constraints to make sure the component demand is met. Constraints defined in Eq. (7) assure all missing and time-deficit components are replaced. Material demand is satisfied by recycling broken and, if necessary, good components. Recycled broken components cannot be more than disassembled broken components. These are defined in Eq. (8) and (9). All variables are non-negative.

The mathematical model for stage 2 is shown below.

subject

$$\min z_{2} = z_{1} + \sum_{i \in I, j \in J} \left((cd_{j} + ca_{j})(1 - ind2_{i}) \sum_{b \in B} opt_{ijb} \right) + \sum_{b \in B, j \in J} c_{jb} \sum_{i \in I} (opt_{ijb} - oq_{ijb})$$

$$(10)$$

subject to, $\sum_{\{b \in B | b < lifebin_{ij}\}} opt_{ijb} \le \overline{y}_i, \forall i, j$ (11)

$$\sum_{b \in B} opt_{iib} \le 1, \forall i, j \tag{12}$$

 $\sum_{b \in B} opt_{ijb} \le soq_{ijm}, \forall i, j \tag{13}$

 $\sum_{b \in B} oq_{ijb} = \sum_{b \in B} opt_{ijb}, \forall i, j$ (14)

$$\sum_{\{b \in B \mid b < m\}} oq_{ijb} = 0, \forall i, j \text{ and } for \{m \in M \mid \sum_{t \in t} y_{itm} = 1\}$$
(15)

Equation (10) defines the objective function stage 2 by minimizing the sum of cost calculated in stage 1, total optional replacement cost and savings obtained by remaining life adjustment, respectively. Equation (11) represents the constraints that assure that remaining life adjustment is performed on repaired EOLPs only. Equation (12) represents constraints that assure that an over qualified component is evaluated in one component life-bin only. Equation (13) represents constraints that make sure that only over qualified components are disassembled. Equation (14) is the set of constraints that ensure that disassembled over qualified components are replaced. Equation (15) sets a set of constraints to make sure assembled components have a remaining life that is suitable with resulting product's life-bin. All variable are non-negative.

TABU SEARCH BASED HEURISTIC ALGORITHM

A TABU search based heuristic algorithm is developed in MATLAB programming language to solve the original non-linear ADRTO problem with remaining life adjustment. The algorithm starts from a basic feasible solution and randomly visits 100 neighboring feasible solutions in each iteration. Termination criteria are two folds. Algorithm stops when it either reaches the 100th iteration or observes 25 non-improving iterations in a row.

NUMERICAL EXAMPLE

To illustrate the methodology, an example involving modular EOLPs is considered. There are 10 different models of a product and 17 components that the model deals with. Each product model is made of a different combination of these components. Original configuration of each product type and the list of components are given in Table 1. Three remaining-life-bins are defined for components. First life-bin holds those components having a remaining-life time of 2 years or less, second life-bin holds those components whose remaining-life are between two and three years. The last bin holds the other components (having 3 years or more remaining life). Same remaining life time ranges are used to define three product life-bins.

	Components	Α		B		C			D		E							
		1	2	3	1	2	3	1	2	3	4	1	2	1	2	3	4	5
Models	1	X			Х			Х				Х		Х				
	2		Х		Х			Х				Х		Х				
	3			Х		Х		Х				Х			Х			
	4		Х		Х					Х			Х				Х	
	5	Х					Х		Х					Х				
	6	Х				Х					Х	Х			Х			
	7			Х		Х				Х					Х			
	8			Х	Х					Х				Х		Х		
	9		Х				Х		Х			Х					Х	
	10			Х			Х				Х		Х					Х

TABLE 1: ORIGINAL CONFIGURATION

There are 200 EOLPs (daily return quantity) in the inventory. Non-operable and operable components in EOLPs and remaining life associated with each operable component are recorded into the EOLP database.

Disassembly and procurement costs differ by component groups. Disassembly costs for component groups A, B, C, D, and E are \$0, \$0.50, \$2.00, \$1.00, and \$1.50, respectively. Procurement costs also depend on the remaining life of the components and are given in Table 2. Recycling costs are 20 Cents for each component in group C and 10 Cents for the others.

	Components	Α		В			С			D		E						
	Components	1	2	3	1	2	3	1	2	3	4	1	2	1	2	3	4	5
ins	1	20	40	60	15	15	15	12	18	22	24	5	8	10	30	45	60	75
	2	40	30	70	20	20	20	18	22	24	30	7	9	15	40	55	65	94
B	3	50	60	75	25	25	25	24	26	30	32	10	12	25	60	75	80	105

TABLE 2: PROCUREMENT COSTS

Demands for each type of component and product are shown in Table 3 and Table 4, respectively

TABLE 3: SOPHISTICATED										
COMPONENT DEMANDS										
	Remaining-life-bins									
Components	Bin 1	Bin 2	Bin 3							
A1	3	9	9							
A2	3	3	6							
A3	0	0	15							
B1	3	6	12							
B2	0	3	6							
B3	0	6	6							
C1	3	3	12							
C2	3	3	15							
C3	6	3	6							
C4	3	3	12							
D1	3	3	15							
D2	9	15	15							
E 1	3	6	9							
E2	3	3	9							
E3	3	0	15							
E4	0	3	15							
E5	0	0	21							

TABLE 4: SOPHISTICATED PRODUCT DEMANDS

	Remaining-life-bins							
Models	Bin 1	Bin 2	Bin 3					
1	1	6	1					
2	1	3	4					
3	3	3	3					
4	1	4	6					
5	1	3	12					
6	1	3	3					
7	1	4	7					
8	3	5	3					
9	3	3	3					
10	2	6	6					

RESULTS AND COMPARISON OF THE METHODS

Programs were run on a host computer featuring 1.80 GHz Intel Core2 Duo processor and 3GB memory. Two-stage optimization framework was solved using LINGO 11.0 and obtained a solution costing \$6935 in the first stage and remaining life adjustment (stage 2) decreased the cost to \$6169. Stage 1 and stage 2 calculations took 262 and 6 seconds, respectively. On the other hand, the TABU search algorithm found a solution with a total cost of \$4581.40, but the calculation took 971.32 seconds. Algorithm stopped because maximum number of iterations was reached.

CONCLUSIONS

In this paper, a two-stage optimization framework for advanced disassembly/repair-to-order (ADRTO) systems is presented and compared with a TABU search based heuristic algorithm developed for the

same problem. According to the obtained results, TABU search algorithm found a significantly better solution in a longer time. Calculation time is highly dependent on the features of the host computer, programming language and the programming skills of the programmer. Besides, search parameters may affect the calculation time as well.

As a conclusion, the TABU search algorithm developed for this problem was found to be superior to the two-stage optimization framework despite its calculation time drawback.

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