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Coordination of Collection and Disassembly Planning for End-of-Life Product [⋆]

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Abstract: This work proposes a formulation for coordinating between collection and disassembly planning for an End-of-Life (EOL) product. The coordination deals with the balance between the number of products collected, the inventory level and the number of products disassembled. The objective function aims to minimize the total cost including the disassembly cost, the penalty cost, the holding cost and the running cost of vehicle. Two strategies with and without coordination were compared via numerical experiments. The results obtained show that the coordinated strategy allows total cost reducing.

Keywords: Disassembly Process, Vehicle Routing, Inventory Control, End-of-Life Product, Coordination, Reverse Supply Chain.

1. INTRODUCTION

The public awareness and economical interest in reverse supply chain (RSC) are currently growing due to the environmental legislation, customers' attention to the environmental impact of products and the potential benefit of End-of-Life (EOL) products. To deal efficiently with growing amount of EOL products, the disassembly process is required to be implemented.

The disassembly process is defined as a set of activities for disassembling the EOL product in order to harvest its precious and/or hazardous components. However, it requires the support of other processes such as the collection of EOL products from suppliers, the distribution of disassembled components for recycling etc. Henceforth, this process has to be treated align with other activities in the reverse supply chain (RSC) of EOL product.

According to Fleischmann et al. (2000), the supply side of such RSC is exogenously determined since the number of sources of EOL products is fairly large compared to the number of supply points in a forward supply chain. This paramount difference has to be taken into account while coordinating the collection and disassembly process of EOL product.

This paper is organized as follows. Section 2 analyzes the existing literature related to the integrated function on RSC corresponding to disassembly process. Section 3 describes the mathematical model for the coordinating formulation proposed. The decoupled formulation is presented in section 4. An illustrative example and the results of numerical experiments are provided in section 5. Section

6 gives conclusion based on the results obtained as well as the future research directions.

2. LITERATURE REVIEW

Since processing EOL products is time consuming and expensive (Ilgin and Gupta, 2011), the integration of several processes in RSC is important for implementing economically viable solutions. This section presents the existing literature dealing with coordination of decision making in RSC for EOL products.

Özceylan et al. (2014) and Özceylan and Paksoy (2014) worked on strategic–tactical decision integration by combining network design of closed-loop supply chain and the disassembly line balancing problem. These works dealt with the decisions of product flows between supply chain's actors and the number of disassembly workstations.

As far as our knowledge, none of previous works dealing with EOL products has considered the integration of collection and disassembly processes. The majority of works focused on the disassembly line balancing for minimizing the number of workstations required to reach a given cycle time (Battaïa and Dolgui, 2013; Bentaha et al., 2013, 2014a,b). However, there is a number of studies addressing this point in forward supply chain. Chandra and Fisher (1994) initiated the work on coordination of production and distribution planning where there is an inventory between. This work has drawn attention of researchers in the last two decades (Boudia and Prins, 2009; Bard and Nananukul, 2010; Armentano et al., 2011; Amorim et al., 2012).

Adapting the work of Chandra and Fisher (1994), this work aims to coordinate the collection and disassembly

processes in a RSC through an inventory in order to minimize the total cost. The scheme of the RSC considered is depicted in Fig. 1. Specifically, the collection process adapts the capacitated vehicle routing problem while the disassembly process deals with the determination of the number of products disassembled. The inventory is used to balance those processes.

3. FORMULATION

A number of EOL items of a given product is dispersed in a number of suppliers. The term "item" is used in order to distinguish with "product" because the model considers one type of product only. A fleet of capacitated vehicles is used to pick them up into a capacitated inventory. The number of vehicles available is assumed unlimited. The vehicle is allowed to not visit all suppliers but once a supplier visited, the whole number of EOL products has to be picked up.

Each item is assumed to posess all corresponding components released by disassembly. The capacity of disassembly line is obtained by dividing the working hours in a period with the cycle time. The unsold components are discarded while the inventory of EOL products incurs the holding cost. The penalty cost is induced by the unfulfilled demands.
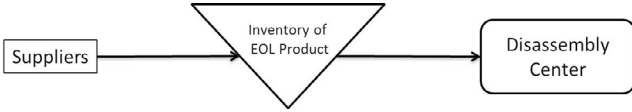

Fig. 1. Reverse Supply Chain Considered

The demand of components, the availability of EOL product in suppliers, the initial inventory level and the distance between the depot and the suppliers are deterministic and given. Because the items are collected into an inventory, multi-period is considered into the problem. The problem of coordination between the collection and disassembly process is formulated as follows:

Parameters:

A set of component index: $a = \{1, 2, \cdots, A\}$;
N set of nodes $i, j = \{1, 2, \cdots, N\}$ where 1 is depot;
T planning horizon $t = \{1, 2, \cdots T\}$;
n_a number of component a in the product;

q_{at} demand of component a at period t;
I_0 initial inventory level;
S_{it} number of items available at supplier i at period t;
C vehicle capacity;
IC inventory capacity;
DC disassembly line capacity;
CD disassembly cost of a product

CH holding cost for EOL product;
CP_a penalty cost for component a;
CF fixed vehicle cost;
C_{ij} traveling cost from i to j;

Decision variables:

Y_{it} load of the vehicle after visiting i at period t;
I_t inventory of EOL product's items at period t;
P_t number of products disassembled at period t;
SO_{at} stockout of component a at period t;
x_{ijt} $\begin{cases} 1 & \text{if } j \text{ is visited after } i \text{ directly at period } t \text{ ;} \\ 0 & \text{otherwise.} \end{cases}$

Mixed Integer Programming (MIP)

$$Min \sum_{t \in T} \{ CD \cdot P_t + CH \cdot I_t + \sum_{a \in A} CP_a \cdot SO_{at}$$
$$+ \sum_{j \in N, j > 1} CF \cdot x_{1jt} + \sum_{i \in N} \sum_{j \in N} C_{ij} \cdot x_{ijt} \}; \tag{1}$$

s.t.

$$\sum_{j \in N, i \neq j} x_{ijt} \leq 1, \forall i \in N \setminus \{1\}, \forall t \in T; \tag{2}$$

$$\sum_{i \in N, i \neq v} x_{ivt} = \sum_{j \in N, j \neq v} x_{vjt}, \forall v \in N, \forall t \in T; \tag{3}$$

$$Y_{it} \leq C - (C - S_{it}) \cdot x_{1it}, \forall i \in N \setminus \{1\}, \forall t \in T; \tag{4}$$

$$Y_{jt} \geq Y_{it} + S_{jt} - C + C \cdot x_{ijt}$$
$$+ (C - S_{jt} - S_{it}) \cdot x_{jit}, \tag{5}$$
$$\forall i \in N', \forall j \in N \setminus \{1\}, i \neq j, \forall t \in T;$$

$$I_t = I_{t-1} + \sum_{j \in N} \sum_{i \in N, i \neq j} S_{it} \cdot x_{ijt} - P_t, \forall t \in T; \tag{6}$$

$$n_a \cdot P_t + SO_{at} \geq q_{at}, \forall a \in A, \forall t \in T; \tag{7}$$

$$\sum_{j \in N, i \neq j} x_{ijt} \cdot S_{it} \leq Y_{it} \leq \sum_{j \in N, i \neq j} x_{ijt} \cdot C, \tag{8}$$
$$\forall i \in N, \forall t \in T;$$

$$0 \leq I_t \leq IC, \forall t \in T; \tag{9}$$

$$0 \leq P_t \leq DC, \forall t \in T; \tag{10}$$

$$SO_{at} \geq 0, \forall a \in A, \forall t \in T; \tag{11}$$

$$x_{ijt} \in \{0, 1\}, \forall i \in N, \forall j \in N, \forall t \in T; \tag{12}$$

The objective function (1) minimizes the total cost by considering the cost of disassembly, the unfulfilled demands, the inventory level of EOL products and the collection cost. The constraints (2)–(5) correpond to the collection of items while the constraints (6) bridge them with the contraints (7) corresponding to the demand of components. The constraints (2) set a single departure from a supplier. The constraints (3) guarantee that a vehicle has to leave a node after visiting it. The constraints (4) calculate the load after visiting the first supplier. Meanwhile, the constraints (5) are the well-known subtour avoidance constraints. The constraints (6) balance between the inventory level, the number of products collected and the number of products disassembled. For determining the number of demands unfulfilled, the constraints (7) are required. The constraints (8)–(12) define the domain as well as the nature of decision variables.

4. DECOUPLED FORMULATION

This section presents the formulations of disassembly and distribution without coordination. The disassembly

scheduling determines the number of products disassembled as well as the inventory level. Using this information, the collection is planified. The decision variable $Collection_t$ is introduced to determine the number of items intended for being collected in the collection scheduling.

MIP of Disassembly Scheduling

$$Min \sum_{t \in T} \{CD \cdot P_t + CH \cdot I_t + \sum_{a \in A} CP_a \cdot SO_{at}\}; \quad (13)$$

s.t.

$$I_t = I_{t-1} + Collection_t - P_t, \forall t \in T; \quad (14)$$

$$\text{Constraints (7), (9)–(11)}$$

$$Collection_t \geq 0, \forall t \in T; \quad (15)$$

The following formulation presents the collection scheduling:

MIP of Collection Scheduling

$$Min \sum_{t \in T} \{\sum_{i \in N} \sum_{j \in N} C_{ij} \cdot x_{ijt} + \sum_{j \in N, j>1} CF \cdot x_{1jt} + \sum_{a \in A} CP_a \cdot SO_{at}\}; \quad (16)$$

s.t.

$$Collection_t \geq \sum_{j \in N} \sum_{i \in N, i \neq j} S_{it} \cdot x_{ijt}, \forall t \in T; \quad (17)$$

$$n_a \cdot \sum_{i \in N, i \neq j} S_{it} \cdot x_{ijt} + SO_{at} \geq q_{at}, \forall a \in A, \forall t \in T; \quad (18)$$

$$\text{Constraints (2)–(5), (8) and (12)}$$

The objective function (16) aims to minimize the collection and the penalty costs. The collection cost consists of distance cost and fixed vehicle cost. The penalty cost is induced when the amount of items targeted in disassembly scheduling is not respected. The number of products collected is less than $Collection_i$ since it is only the amount demanded is disassembled (Constraints 17). Constraints (18) are required for calculating the penalty cost for stockout of component.

5. NUMERICAL EXPERIMENTS

Numerical experiments were carried out in order to test our model as well as to observe the impact of certain parameters on the results and computational time. To this aim, 108 instances were generated using different number of nodes, number of periods, number of components, the relative percentages of demands-supplies and the value of the disassembly capacity.

For the number of nodes, 5, 10 and 25 nodes were considered where the first node is depot. The system run in 5, 10 and 20 periods. Concerning the number of components, we have two types of products consisting of 5 and 10 components, respectively.

The coordinates of nodes are generated using uniform distribution between 0 and 100. The supplies are generated uniformly between 9 and 11 for each suppliers (the depot has no supply). The demands are generated using uniform distribution between 40 % - 60 % and 90 % - 110 % of the supplies. The instances are divided into three categories namely unconstrained, less constrained and constrained where each category has different value of the disassembly

capacity: infinitive, 200 % of average demands and 118 % of average demands. The value of 200 % and 118 % come from the assumption that the average demands in all periods are equal to 50 % and 85 % of disassembly capacity (based on the data used in Chandra and Fisher (1994)).

The supplies in all periods were generated using uniform distribution between 9 and 11. The vehicle capacity was determined as two times the average supply in all nodes and periods. The disassembly and holding costs were 10 and 1, respectively. The fixed vehicle cost was fixed to 10 and the vehicle running cost was equal to 1. The penalty cost was fixed to 4 for each unfulfilled demand.

Table 1. Benefit of coordinated strategy

N	T	A	Demand	Cost reduction (in %)		
				Unconsd*	Less Consd*	Consd*
5	5	5	40%-60%	47	47	47
			90-110%	24	24	24
		10	40%-60%	64	64	64
			90-110%	7	7	7
	10	5	40%-60%	47	47	47
			90-110%	13	13	13
		10	40%-60%	65	65	65
			90-110%	8	8	8
	20	5	40%-60%	47	47	47
			90-110%	20	20	20
		10	40%-60%	66	66	66
			90-110%	9	9	9
10	5	5	40%-60%	45	45	45
			90-110%	24	24	24
		10	40%-60%	63	63	63
			90-110%	11	11	11
	10	5	40%-60%	47	47	47
			90-110%	23	23	23
		10	40%-60%	65	65	65
			90-110%	16	16	16
	20	5	40%-60%	48	48	47
			90-110%	22	22	22
		10	40%-60%	65	65	64
			90-110%	15	16	15
25	5	5	40%-60%	49	49	49
			90-110%	18	18	18
		10	40%-60%	66	66	66
			90-110%	10	10	10
	10	5	40%-60%	49	49	49
			90-110%	12	14	14
		10	40%-60%	67	66	67
			90-110%	11	13	11
	20	5	40%-60%	48	47	48
			90-110%	11	11	10
		10	40%-60%	66	65	65
			90-110%	5	8	3

*consd = constrained

The model was implemented in java JDK 7 using ILOG CPLEX 12.6 on a PC with processor Intel®Core™i7 CPU 2.9 GHz and 4 Go RAM under Windows 7 Professional. Each instance was executed within 10 minutes. Table 1 and 2 show the results obtained.

Based on the results presented in Table 1, we can conclude that the model with coordiantion allows reducing the total cost from 7 % to 66 %.

Fig. 2–4 provides the difference between the corresponding costs for the converged instances shown in Table 2.

Table 2. Average solver gap and computation time

| N	T	A	Demand	Solver gap	Computation time (in seconds)
5	5	5	40%-60%	Optimal	0
			90-110%	Optimal	0
		10	40%-60%	Optimal	0
			90-110%	Optimal	0
	10	5	40%-60%	Optimal	0
			90-110%	Optimal	0
		10	40%-60%	Optimal	0
			90-110%	Optimal	0
	20	5	40%-60%	Optimal	2
			90-110%	Optimal	4
		10	40%-60%	Optimal	3
			90-110%	Optimal	4
10	5	5	40%-60%	Optimal	0
			90-110%	Optimal	5
		10	40%-60%	Optimal	1
			90-110%	Optimal	8
	10	5	40%-60%	Optimal	16
			90-110%	3%	600
		10	40%-60%	Optimal	24
			90-110%	4%	600
	20	5	40%-60%	13%	603
			90-110%	13%	603
		10	40%-60%	14%	600
			90-110%	14%	604
25	5	5	40%-60%	Optimal	25
			90-110%	3%	600
		10	40%-60%	Optimal	85
			90-110%	5%	602
	10	5	40%-60%	12%	601
			90-110%	14%	605
		10	40%-60%	14%	612
			90-110%	15%	610
	20	5	40%-60%	20%	605
			90-110%	18%	605
		10	40%-60%	22%	619
			90-110%	20%	613
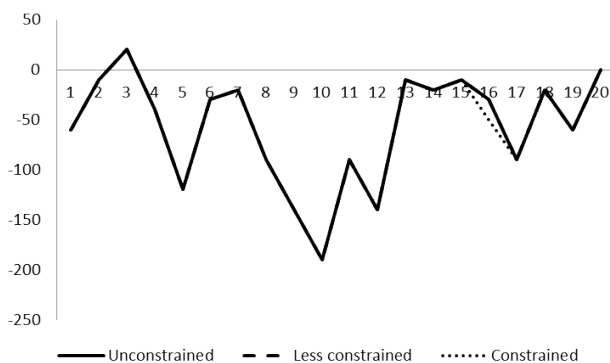
Fig. 2. Difference of Disassembly Costs

The values are obtained by substracting the costs of the coordinated and uncoordinated strategy.

Comparing the costs, the disassembly and penalty cost of the coordinated strategy are lower. However, for all instances, the coordinated strategy has more important holding costs than the uncoordinated strategy. For the majority of the instances having 90 % - 110 % demands of supplies, the transportation cost of the coordinated strategy is lower. Some instances have no difference in
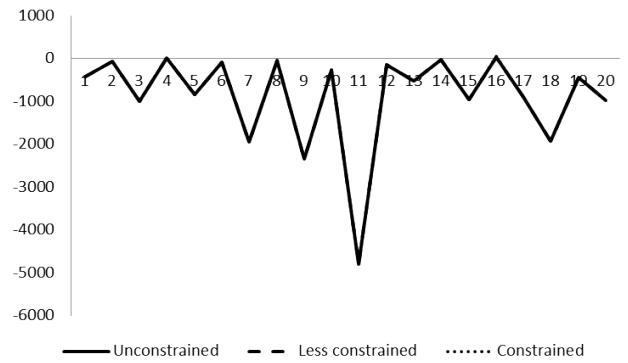

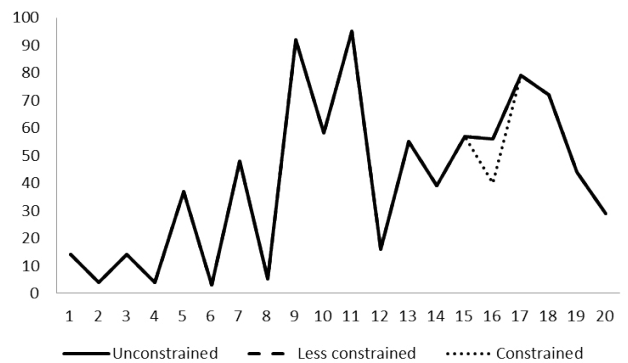Fig. 3. Difference of Penalty Costs

Fig. 4. Difference of Transportation Costs

transportation cost but their penalty and holding costs are lower resulting in lower total costs.

According to the results presented in Table 2, the computation time is more than 1 second for instances with 5 customers and 10 periods. About 44 % of the instances requires more than 10 minutes to converge starting from the instances having 5 components and 10 periods.

6. CONCLUSIONS

This work proposed a coordinated optimisation model for collection and disassembly activites in Reverse Supply Chains. The coordination is based on the balance between the number of products collected, the inventory level and the number of products disassembled with aim of fulfilling the demands of components. The results of numerical experiments showed that the coordinated strategy allowed the decision makers to reduce the total cost.

In our future research work, the uncertainty of the availability of EOL products at suppliers as well as of the number of components in products will be considered since such phenomena are major in reverse supply chains.

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