The Combination of Postponement Operations in a Supply Chain Network with Multi-level Product Differentiations

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Abstract—To study the problem about the optimal combination of postponement operations in the context of supply chain network, a decision-making model is developed. In the model two kinds of product differentiations and three types of postponement operations are considered. Then a procedure for solving this model is proposed. By using a numerical example, we analyze the effect of cost structure on the decision about postponement operations. The results show that if customizing cost is high, no customizing operation should be adopted, if the subassembly-related costs are large assembling directly the components is more sensible, as well as if lead time is tight and penalty cost is high, only manufacturing postponement should be adopted.

Index Terms—Multiple Product Differentiations; Postponement Strategy; Supply Chain Network

I. INTRODUCTION

In today’s competitive marketplace, the ability to meet the needs of the customer for variable products becomes more and more important. Postponement, for its advantage in managing product variety and achieving quick response, has been adopted by several enterprises. Postponement means delaying the commitment to a product’s characteristics until more information is available so that the decisions about the product can be made more accurately [1]. It has been regarded as a powerful way to enable cost-effective mass customization. Automobile, apparel and electronics industries are the prime fields that postponement has been implemented [2].

Postponement has several forms, such as labeling postponement, packaging postponement, assembly postponement, manufacturing postponement, time postponement, partial postponement, price postponement and so on [2] - [4]. Each form of postponement has different cost and benefit for different enterprises. As a result the critical step for a enterprise adopting postponement is to determine the structure and form of postponement [5]. Furthermore, in recent years, more and more enterprises have adopted more than one kind of postponement operation. For instance, in 1990s General Motors (GM) delayed software configuration and customization of ECU from suppliers to the end of the vehicle assembly process. GM also asked a lot of subassembly contractors to assemble components purchased from suppliers into subassemblies and ship them to the final GM assembly plant. It means that GM simultaneously adopted customizing and manufacturing postponements [1]. Therefore, the optimal combination of postponement operations has become an increasingly attractive research subject [6].

A number of papers in the literature deal with the problem of finding right forms of postponement among two or more alternatives. However all of them differ from our study in some vital aspects. Ref. [7] built a model based on the Queuing Theory and offered a comparative analysis between form postponement and time postponement according to the measure of total cost and customer waiting time. But it did not study the problem from the perspective of supply chain. Ref. [6] developed a mathematical model for the entire supply chain network involving manufacturing, packaging and logistics postponements to find the optimal combination of these postponement operations. But the model only considered one kind of product differentiation. Ref. [8] built a goal programming model to optimize the production planning problem, from which determining the quantities of finished products produced from raw materials directly (without postponement) and from semi-finished products (manufacturing postponement). However, it did not take product differentiations into consideration. Ref. [9] constructed a supply chain model to obtain the optimal price and quantity of products under uncertainty by applying fuzzy bi-level programming modeling method. However, it did not consider the combination of postponement operations. Ref. [10] proposed a multi-commodity and multi-stage supply chain network equilibrium model to work out the conditions that made the supply chain achieve equilibrium. However it focused on the network equilibrium rather than postponement.

The purpose of this study is to develop a mathematical model to find the optimal combination in the context of supply chain and multiple product differentiations. The rest of this paper is organized as follows. In Section II we introduce our model as a mixed integer programming problem. Section III proposes a procedure for finding the optimal solution to the model. The results of numerical examples are presented in Section IV. Section V discusses the effect of cost parameters on the decision of postponement operations and provides some managerial
insights. Section VI presents summary comments and discusses promising areas for future research.

II. MODEL FORMULATION

We consider a supply chain including purchasing, manufacturing, assembling, packaging and transporting. In order to simplify the complexity of supply chain, we have the following assumptions:

(1) The supply chain network has an assembler as the core enterprise, whose upstream is the supply system composed of all suppliers and subassembly contractors, whose downstream is the sales system composed of retailers and customers [11]. Consequently, the decision made by this core enterprise is necessarily accepted by the other participants in the supply chain network.

(2) The raw materials are obtained in a very short time, so this model does not consider purchasing lead time.

(3) The product differentiations are grouped into two levels, that is, first-level specification and second-level specification. Each specification has two kinds of differential components. As a result, four types of products need to be considered.

(4) There is a general component that can be customized into first-level specification with a low cost.

(5) The inventory exists in the form of component, subassembly, semi-finished and finished product. The inventories of suppliers are not taken into account.

(6) The finished product is composed of standard, crucial, first-level and second-level differential components. The subassembly is composed of first-level differential (or general) and standard components. The semi-finished product is composed of standard, first-level differential and crucial components.

(7) The postponement operation is performed in the BTO environment, so it does not consider safety stock.

(8) The subassemblies and semi-finished products are produced after purchasing the components. They are not purchased directly.

(9) By reason of economy, the transportation doesn’t take place until the assembly operation is finished. Thus, the customer’s orders for various products are fulfilled simultaneously.

Fig. 1 illustrates the supply chain network for postponement. Considering the practice of many enterprises, we investigate three types of postponement operations as follows:

(1) Manufacturing postponement

This study defines manufacturing postponement as to assemble the components into a modular subassembly. Fig. 1 illustrates that if the Assembler asks the Subassembly Contractor to assemble first-level differential (or general) and standard components into a subassembly at node 8, it means the products perform the manufacturing postponement. On the contrary, if the components directly go to the Assembler station at node 9, no manufacturing postponement has been implemented.

(2) Packaging postponement

This study defines packaging postponement as to delay the installation of second-level differential components from Assembler station at node 9 to the Retailer station at node 10. Fig. 1 illustrates that if the Assembler assembles the second-level differential components and other parts at node 9, it means packaging postponement does not take place. On the contrary, if the second-level differential components go to the Retailer station at node 10 and are installed there, it indicates that the packaging postponement is performed. For instance, nowadays more and more drivers would like to use GPS integrated with Speech Controlling Module (SCM), which is more expensive than GPS operated by hands [12]. Auto manufacturers ask their retailers to install GPS integrated with SCM according to customers’ actual demand.

(3) Customizing postponement

This study defines customizing postponement as to purchase general components and customize them at node 8 or at node 9 instead of procuring directly first-level differential components from nodes 1 and 2. If the general components are shipped to the Subassembly Contractor station and there assembled into general subassemblies which would be customized at Assembler, it means both manufacturing postponement and customizing at Assembler are performed. If the Subassembly Contractor customizes the general components and uses them to assemble first-level differential subassemblies, it means both manufacturing postponement and customizing at Subassembly Contractor are performed. If the general components are shipped to Assembler station, it means customizing at Assembler would take place.

A. Notations

1. Indexes and parameters

\( d, g, l, m, s \): set of first-level differential, general, second-level differential, standard, crucial components, respectively; \( h \): index for first-level differentiations, \( h \in \{d, g\} \); \( v \): index for second-level differentiations, \( v \in \{l, m, s\} \); \( Y^v, Z^h, F^{h,v} \): types of subassemblies, semi-finished products, finished products, respectively, \( w \in \{d, g\} \); \( X \), \( Y \), \( Z \), \( F \): set of types of components, subassemblies, semi-finished products, finished products, respectively, \( X = \{d, g, l, m, s\} \), \( Y = \{Y^v\} \), \( Z = \{Z^h\} \), \( F = \{F^{h,v}\} \); \( x \):
index for components, $x \in X$; $k$ : index for materials, $k \in X, Y, Z, F$; $f$ : index for finished products, $f \in F$; $n$ : index for process sequenceings, $n=1$ represents assembling $Y^s$ from $g$ and $m$ , $n=2$ represents assembling $g$ and $m$ into subassembly and then customizing it into $Y^d$, $n=3$ represents assembling $Y^d$ from $d$ and $m$, $n=4$ represents assembling $Z^s$ from $d$, $m$ and $s$, $n=5$ represents assembling $g$, $m$ and $s$ into semi-finished product and then customizing it into $Z^d$, $n=6$ represents assembling $Y^f$ and $s$ into semi-finished product and then customizing it into $Z^f$, $n=7$ represents assembling $Z^d$ from $s$ and $Y^d$, $n=8$ represents assembling $F^{di}$ from $d$, $m$, $s$ and $l$ into finished product and then customizing it into $F^{df}$, $n=10$ represents assembling $Y^f$, $s$ and $l$ into finished product and then customizing it into $F^{df}$, $n=11$ represents assembling $F^{di}$ from $s$, $l$ and $Y^f$, $n=12$ represents assembling $F^{df}$ from $l$ and $Z^d$; $N^*$: set of nodes for component Suppliers, $x \in X$; $i^M$, $i^N$, $i^O$, $i^P$: set of nodes for Subassembly Contractor, Assembler, Retailer and Customer, respectively; $C_i$: unit purchasing cost for component $x$, $x \in X$; $C_{it}^{rh}$: unit processing cost for sequencing $n$; $C_{it}$: unit cost for customizing $g$ into $d$; $C_{ik}^{ih}$: unit inventory cost for material $k$ at node $i$; $C_{ik}^{nh}$: unit transport cost for material $k$ between $Arc(i,j)$; $C_{ij}$: unit penalty cost for product $f$ per unit per day, $f \in F$; $t^r$: processing time with process sequencing $n$; $l_{ij}$: transport time between $Arc(i,j)$; $D_i^f$: demand of customer $i$ for product $f$, $f \in F$; $l_i^f$: lead time of customer $i$ for finished products; $\alpha^{rh}$, $\alpha^{zh}$, $\alpha^{yf}$: required quantity of material $k$ for producing unit $Y^r$, $Z^h$ and $F^{zh}$, respectively; $T_i^{f-o}$: delay in receiving finished product $f$ for customer $i$, $f \in F$; $T_i^f$: the total time for customer $i$ receiving the finished products; $B$: extremely positive value.

2. Decision variables

$Y^{in}$, $Z^{nh}$, $F^{rh}$: quantity of subassemblies, semi-finished products, finished products produced with sequencing $n$, respectively; $q_{ij}^{k}$: flow of material $k$ between $Arc(i,j)$; $l_i^f$: inventory of material $k$ at node $i$. The subsequent decision variables are binary. $\delta_{ij}^k$: if material $k$ ships through $Arc(i,j)$; $\delta^n$: if process sequencing $n$ is adopted, $n=1, \ldots, 12$; $\delta^d$: if component $d$ is purchased; $\delta^f$: if customizing postponement takes place; $\delta_u$: if manufacturing postponement takes place; $\delta_{ij}^*$: if customizing takes place at Subassembly Contractor; $\delta_{ij}^d$: if component $g$ is used at Subassembly Contractor; $\delta_{ij}^o$: if customizing takes place at Assembler; $\delta_{ij}^o$: if component $d$ is used at Assembler; $\delta_{ij}^f$: if component $g$ is used at Assembler. For each binary variable above, if the answer is yes, its value is one. Otherwise, the value is zero.

B. Mathematical Model

In this model we take purchasing, processing, customizing, inventory and transport costs into account. The objective is to determine the optimal combination of postponement operations to minimize the total cost in the supply chain network. The objective function is given as following.

$$
CT = \sum_{i,j} \sum_{f} q_{ij}^k C_i^{rh} + \sum_{i,j} \sum_{f} q_{ij}^k C_i^{nh} + \sum_{i \in N^f} \sum_{h=d,2,3,4,5,6,7} Y_{ih}^{f} C_i^{zh} + \sum_{i \in N^r} \sum_{h=d,2,3,4,5,6,7} Z_{ih}^{r} C_i^{rh} + \sum_{i \in N^o} \sum_{h=d,2,3,4,5,6,7} I_{ih}^{f} C_i^{o} + \sum_{i \in N^m} \sum_{f} q_{ij}^k C_i^{m} + \sum_{i \in N^c} \sum_{f} \sum_{j} T_i^{f-o} D_{ij}^{f} C_i^{p}
$$

Function (1) represents the total cost under a supply chain network. Items 1-3 are the purchasing costs of differential, general, standard, crucial components. Items 4 and 5 are the costs of assembling subassemblies that are the quantities of subassemblies with different process sequencing times unit corresponding processing costs. Item 6 is the cost of assembling semi-finished products that is the quantity of semi-finished products times unit corresponding processing cost with corresponding process sequencing. Item 7 is the cost of assembling finished products that is the quantity of finished products times unit corresponding processing cost. Item 8 is the total inventory cost for components, subassemblies, semi-finished products and finished products. Item 9 is the total transport cost of components, subassemblies, semi-finished products and finished products. Item 10 is the penalty cost if the products are not delivered to the customer in the required time.

Constraints:

1. Process in Subassembly Contractor

$$
q_{ij}^{k} = l_i^f, \forall x \in d, g, m, \quad i \in N^M
$$

2. Processing in Subassembly Contractor

$$
I_i^f = \alpha^{rh} Y_{ih}^{f} + \sum_{h=d,2,3,4,5,6,7} \alpha^{rh} Y_{ih}^{zh}, \forall i \in N^M
$$

3. Processing in Subassembly Contractor

$$
I_i^h = \alpha^{zh} Y_{ih}^{zh}, \forall i \in N^M, h \in d
$$

4. Processing in Subassembly Contractor

$$
I_i^m = \alpha^{zh} Y_{ih}^{zh} + \sum_{n=2,3,4,5,6,7} \alpha^{mzh} Y_{ih}^{zh}, \forall i \in N^M
$$
\[
\sum_{i=1,2,3} Y_{ij}^{\text{in}} = \sum_{j} q_{ij}^{\text{in}}, \forall i \in N^g, w \in g, d \tag{6}
\]

Constraint (2) represents the inventories of components at Subassembly Contractor are equal to the flows from Suppliers to Subassembly Contractor. Constraints (3)–(5) represent the inventories of general, first-level differential and standard components are equal to the quantities of the materials required to produce the subassemblies at Subassembly Contractor. Constraint (6) represents the flow of subassembly shipped from node \( i \) to \( j \) is equal to the total amount assembled at node \( i \).

(2) Process in Assembler
\[
\sum_{j} q_{ij}^b = I_i^b, \forall k \in X, Y, \ i \in N^a \tag{7}
\]

\[
I_i^b + \alpha^{by} I_i^y = \sum_{n=4,7} \beta^{by} Z_i^{nh} + \sum_{n=8,11} \sum_{j} \gamma^{byh} F_{ij}^{nhv}, \forall i \in N^c
\]

\[
\alpha^{by} I_i^y = \sum_{n=5,6,7} \beta^{by} Z_i^{nh} + \sum_{n=9,10,11} \sum_{j} \gamma^{byh} F_{ij}^{nhv}, \forall k \in m, s, i \in N^a \tag{8}
\]

\[
I_i^y = \sum_{n=5,6,7} \sum_{j} \gamma^{byh} F_{ij}^{nhv}, \forall v \in l, i \in N^a
\]

\[
\sum_{n=4,7} Z_i^{nh} + \sum_{n=8,10,11} F_{ij}^{nhv} = \sum_{j} (q_{ij}^b + q_{ij}^y), \forall i \in N^a, h \in d, v \in l
\]

Constraint (7) indicates that the inventories of components and subassemblies are equal to the total flows from Suppliers and Subassembly Contractor to Assembler. Constraints (8)–(11) indicate the total inventories of components and subassemblies are equal to the quantities of the materials required to complete the finished products or semi-finished products at Assembler. Constraint (12) represents the flow of semi-finished products or finished products shipped from node \( i \) to \( j \) is equal to the total amount produced at node \( i \).

(3) Process in Retailer
\[
\sum_{j} q_{ij}^f = I_i^f, \forall k \in l, Z, F, \ i \in N^c \tag{13}
\]

\[
I_i^f = \sum_{l} \xi^{zh} F_{ij}^{zhv}, \forall h \in d, i \in N^c \tag{14}
\]

\[
I_i^f = \sum_{l} \xi^{zh} F_{ij}^{zhv}, \forall v \in l, i \in N^c \tag{15}
\]

\[
I_i^{13h} + F_{ij}^{13h} = \sum_{j} q_{ij}^{13v}, \forall i \in N^c, h \in d, v \in l \tag{16}
\]

\[
\sum_{i} q_{ij}^{13v} = D_j^f, \forall f \in F
\]

Constraint (13) indicates that the inventories of semi-finished products and second-level differential components are equal to the total flows from Assembler and Suppliers to Retailer. Constraints (14) and (15) represent that the total inventories of semi-finished products and second-level differential components are equal to the materials required to complete the finished products at Retailer. Constraint (16) represents the flow of finished products shipped from node \( i \) to customer \( j \) is equal to the amount assembled plus the inventory at node \( i \). Constraint (17) indicates the total amounts of finished products are equal to the customer’s demands.

(4) Service time in the entire supply chain
\[
T^R_s = \sum_{i} (Y_i^{t1} + \sum_{n=8,9,10} \sum_{l} F_{ij}^{nhv} t_v + \sum_{n=8,9,10,11} \sum_{l} F_{ij}^{12hv} t_{12} + \sum_{n=8,9,10,11} \sum_{l} I_{ij}^{13hv} (\delta_{ij}^{13} + \delta_{ij}^{12} + \delta_{ij}^{11} + \delta_{ij}^{10}))
\]

\[
T^R_s = \max(0, (T^R_s - L^R)), \forall f \in F
\]

Constraint (18) represents that the total time is equal to the total processing time plus the delivery time of subassemblies, semi-finished products and finished products. Constraint (19) represents that the delay time is equal to the positive value of the difference between the total time and the lead time of the customer.

(5) Postponed process
\[
\delta^l \leq \delta^s \tag{20}
\]

\[
\delta^l + \delta^m = 1 - \delta^s \tag{21}
\]

\[
\delta^s + \delta^m = 1 \tag{22}
\]

\[
\delta^s + \delta^m = \delta^s \tag{23}
\]

\[
\delta^3 + \delta^m = \delta^3 \tag{24}
\]

\[
\delta^3 + \delta^m = \delta^s \tag{25}
\]

\[
\delta^4 + \delta^3 = \delta^4 \tag{26}
\]

\[
\delta^4 + \delta^3 = \delta^3 \tag{27}
\]

\[
\delta^2 = \delta^m \tag{28}
\]

\[
\delta^4 + \delta^3 = \delta^3 \tag{29}
\]
Constraints (36)~(48) determine the transport route of components, subassemblies, semi-finished products and finished products. Constraints (49)~(51) assure that if a certain process sequencing is not chosen, no subassemblies, sub-finished products and finished products could be assembled by applying this sequencing. Constraint (52) indicates that if the material is not shipped through an arc, no flow takes place there.

### III. Solution Procedure for the Model

It is obvious that the model we have presented is a Mixed Integer Programming (MIP) model, which can be solved by OR software packages, such as CPLEX and LINGO. If the size of MIP problem is not large and only a finite number of feasible solutions exist, we can use some kind of enumeration procedure for finding the optimal solution. The solution procedure can be summarized as follows.

**Step 1:** Note that the decision variables \( \delta^0, \delta_x, \delta_{\lambda}, \delta_{\lambda}^{\tilde{u}}, \delta^{x} \) determine the forms of postponement operations. Thus, we can firstly enumerate all the combinations of the values of these five decision variables that satisfy (20) and (21).

**Step 2:** Insert all the combinations of the values of \( \delta^0, \delta_r, \delta_{\lambda}^{\tilde{u}}, \delta^{x} \) to (22)~(35) and solve the system of equations consisting of (22)~(35) to find the values of \( \delta^{\tilde{a}} \) (for \( n = 1, \cdots, 11 \)), \( \delta_1^{\tilde{u}}, \delta_2^{\tilde{u}}, \delta_{\lambda}^{\tilde{u}}, \delta_{\lambda}^{\tilde{u}} \).

**Step 3:** Insert all the values obtained above into (36)~(48) and solve them to obtain the values of \( \delta_{i,j}^{x} \) for \( k \in \{ X, Y, Z, F \} \).

**Step 4:** Start with the quantities of finished products that are equal to the demands and work backward toward the components to calculate the quantities of different types of semi-products, subassemblies and components. According to (49)~(51), calculate the real quantities of materials.

**Step 5:** Insert the values obtained in preceding steps into (1) and work out the corresponding total cost \( CT \). Compare all \( CT \)’s to find the optimal combination whose \( CT \) is minimal.

### IV. Numerical Examples

**TABLE I. BILL OF MATERIALS AND PURCHASING COST**

<table>
<thead>
<tr>
<th>Parameter for component</th>
<th>Component $k$</th>
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<tbody>
<tr>
<td>$d_{i,j}$</td>
<td>$g$</td>
</tr>
<tr>
<td>$m$</td>
<td>$s$</td>
</tr>
<tr>
<td>$l_1$</td>
<td>$l_2$</td>
</tr>
</tbody>
</table>

| $a_{i,j}$               | 4             |
| $a_{i,j}^\text{ext}$    | 0             |
| $a_{i,j}^\text{ext}$    | 4             |
| $y_{i,j}$               | 4             |

\( C_j^\text{S} \) (\( $ \))

In this section we consider a supply chain with 11 nodes, consisting of 7 Suppliers, 1 Subassembly Contractor, 1 Assembler, 1 Retailer and 1 Customer, see Fig. 1. Four types of products \( F_{i,j}^{a,b}, F_{i,j}^{a,b}, F_{i,j}^{a,b}, F_{i,j}^{a,b} \) can be provided to the customer. According to the
Due to having assembled the materials required together finished product and finished product are listed in Table I.

The costs are given as 100, 200, 300, respectively. Lead time of the customer for products $L^8$ is 5 days. Penalty costs are given as $C_p^{\prod} = 243$ $\$, $C_p^{\prod} = 245$ $\$, $C_p^{\prod} = 248$ $\$, $C_p^{\prod}$ = 250 $\$ per unit per day. The unit purchasing cost for general, standard, and differential components and the required quantities of components for producing unit subassembly, semi-finished product and finished product are given in Table I. Due to having assembled the materials required together to form a unit of subassembly or semi-finished product, we have $\beta^{\prod} = \gamma^{\prod} = l(k \in Y) \ , \ \gamma^{\prod} = l(k \in Z)$ . The other parameters are listed in Table II to Table IV.

Our model is solved by applying the procedure described in Section III. With the parameters above, we can obtain the optimal solution for ten scenarios, as shown in Table V. Here each scenario indicates a certain combination of postponement operations. Note that $\delta^g$, $\delta_M$ and $\delta^{i2}$ are the decision variables determining whether customizing, manufacturing and packaging postponement are adopted, respectively. If customizing

<table>
<thead>
<tr>
<th>TABLE II. PROCESSING COST AND TIME WITH VARIOUS SEQUENCING</th>
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<tbody>
<tr>
<td>Process sequencing $n$</td>
</tr>
<tr>
<td>$C^i$ ($)</td>
</tr>
<tr>
<td>$C_Z^i$ ($)</td>
</tr>
<tr>
<td>$t^i$ (s)</td>
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<tr>
<th>TABLE III. UNIT TRANSPORT COST $C_{ij}^{\prod}$ (AND INVENTORY COST $C_{ij}^{\prod}$) IN DOLLARS</th>
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<tbody>
<tr>
<td>$d_i$</td>
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<td>$d_j$</td>
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<td>$y_i$</td>
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<td>$y_j$</td>
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<td>$Z_i$</td>
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<td>$Z_j$</td>
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<tr>
<td>$F_{i1}^{\prod}$</td>
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<tr>
<td>$F_{j1}^{\prod}$</td>
</tr>
<tr>
<td>$F_{i2}^{\prod}$</td>
</tr>
<tr>
<td>$F_{i3}^{\prod}$</td>
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<tr>
<td>$F_{j3}^{\prod}$</td>
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<tr>
<td>$T_{i1}^{\prod}$ (day)</td>
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<tr>
<td>$T_{j1}^{\prod}$ (day)</td>
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<td>$CT (10,000 $)$</td>
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<thead>
<tr>
<th>TABLE IV. TRANSPORT TIME BETWEEN I AND J IN DAYS</th>
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<tbody>
<tr>
<td>$j$</td>
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<tr>
<td>$i$</td>
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<td>9</td>
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<td>10</td>
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<td>11</td>
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<table>
<thead>
<tr>
<th>TABLE V. THE RESULT OF VALIDATION</th>
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<tbody>
<tr>
<td>Scenario</td>
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<tr>
<td>1</td>
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<td>10</td>
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postponement is used, \( \delta^1 \) and \( \delta^0 \) determine where it takes place. According to Table V, the optimal combination of postponement operations is Scenario 1, which means adopting customizing postponement and implementing it at Assembler.

V. THE EFFECT OF COST PARAMETERS ON THE DECISION OF POSTPONEMENT OPERATIONS

In this section we would investigate the effect of cost parameters on the decision of postponement operations through the sensitive analysis of parameters.

(1) The influence of customizing cost

![Figure 2. The influence of customizing cost.](image)

Note that customizing operation could happen at Subassembly Contractor or Assembler. Thus, we would compare the scenarios not using packaging postponement, that is, Scenarios 1, 3, 5, 7 and 9. Fig. 2 shows how the total cost changes with different values of unit customizing cost for various scenarios.

From Fig. 2 it can be seen that when customizing cost is low, purchasing general components and customizing them at Assembler can lead to the lowest cost (see Scenario 1). However, once customizing cost increases beyond a certain value, directly purchasing first-level differential component is better (see Scenarios 7 and 9), which means not adopting customizing postponement.

(2) The influence of subassembly-related costs

![Figure 3. The influence of subassembly-related cost.](image)

Note that subassembly-related costs consist of processing, transport and inventory costs of subassembly. For convenience, we only compare the scenarios not using packaging postponement and introduce a variable \( \alpha \) denoting the ratio of various subassembly-related costs that change in the same direction to the costs listed in Section IV. Fig. 3 shows how the total cost changes with \( \alpha \) for various scenarios.

From Fig. 3 we can see that if the subassembly-related costs are low, adopting manufacturing postponement is reasonable (see Scenario 3 and 5). Otherwise, assembling directly the components at Assembler is more sensible (see Scenarios 1 and 7).

(3) The influence of lead time and penalty cost

![Figure 4. The influence of lead time with high penalty cost.](image)

From Fig. 4 we can see that if the lead time is tight manufacturing postponement is a good option due to it can shorten the total time (see Scenarios 3 and 5). However if we adopt manufacturing postponements accompanying other operations (see Scenarios 4 and 6), the total cost would be larger than that without any postponement (Scenario 7). This shows that if lead time is tight, as well as penalty cost is high, only manufacturing postponement should be implemented.

VI. CONCLUSION

In this paper we develop a supply chain model with postponement and propose a solution procedure for solving this model. Three types of postponement are considered, namely, manufacturing, packaging, and customizing postponement. Effects of customizing cost, subassembly-related cost, penalty cost and lead time on total cost are explored. The results of a numerical example show that if customizing cost is high no customizing operation should be adopted, if the subassembly-related costs are large, assembling directly the components at Assembler is more sensible, as well as if lead time is tight and penalty cost is high, only manufacturing postponement should be implemented. There are several possibilities for furthering our research on this topic area. First, one could research the impact of the correlation between the demands for the different types of products on the decision. Second, one could consider this kind of decision-making question about postponement in an environment of uncertainty.

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