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Solution Methodology for Synchronizing Assembly Manufacturing and Air Transportation of Consumer Electronics Supply Chain

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ABSTRACT

In this paper, we study the problem of synchronization of air transportation and assembly manufacturing to achieve accurate delivery with minimized delivery cost. This problem is observed in PC assembly manufacturing industry. There are two integrated decisions involved in the research problem and they are (1) optimal allocation of orders to various flights in the planning period and (2) an appropriate release time for each order to complete the assembly to match the first decision. We propose two solution methodologies for the research problem. An Integer Linear Programming model is developed for the first decision, backward scheduling logic for the second decision in solution methodology 1 and forward scheduling logic for the second decision in solution methodology 2. The computational experiments indicate that the proposed solution methodologies can achieve excellent average performance in comparison with an existing industry practice heuristic. Furthermore, the solution methodology with backward scheduling logic for determining orders' release time works better than the solution methodology with forward scheduling logic. The computational results demonstrate the effectiveness of our methodologies over a wide range of problem instances. Finally, managerial implications of the proposed methodology are presented.

JEL: *C61, R41*

Keywords: *Consumer electronics supply chain; Air transportation; Assembly manufacturing; Synchronization; Backward scheduling logic*

I. INTRODUCTION

Consumer electronics products, which contribute a major share in many nations' GNP, are playing an important role in our daily life. Almost every home has one of the consumer electronics products such as a videocassette recorder, a compact disk player, or a digital videodisk player (Han et al. 2001). Thirty years ago, electronic calculators were beginning to penetrate mass markets in rich countries. Today, around half a billion people are using consumer electronics products (Ayres and Williams, 2004). Most of consumer electronics products are knowledge-intensive goods with high value-to-weight ratios, which comprise a growing share of global trade (Bowen, 2004). All these indicate that consumer electronics is a booming industry.

Today's consumer electronics manufacturing companies have to face the challenge of volatile demand, shorter product life cycles, product customization, and time to market and cost reduction. To meet these challenges, companies are moving toward global manufacturing network. Cooperation with all the participants within the network and effective utilization of global resources benefit the manufacturers to gain competition advantages. Operation in this global manufacturing network requires co-ordination of a global network of manufacturing units, warehouses or distribution points; the optimization of routings and logistics (Azevedo and Sousa, 2000). Within the consumer electronics supply chain (CESC), synchronization of manufacturing with transportation is especially important for consumer electronics manufacturers to improve performance with lower cost.

Furthermore, the competition among the consumer electronics industries forces a kind of JIT manufacturing philosophy to avoid both earliness and tardiness. Costs or penalties are incurred by delivering an order either earlier or later than the due date. The delivery earliness costs could result from the need for storage and insurance. The delivery tardiness cost consists of customer dissatisfaction, contract penalties, loss of sales, and loss of reputation. Orders transferred to the airport ahead of departure times incur waiting penalties. The penalties are particularly for handling and storage of the goods in the airport. Unlike the basic assembly and transportation cost of the products, these penalty costs can be minimized by achieving better synchronization in CESC.

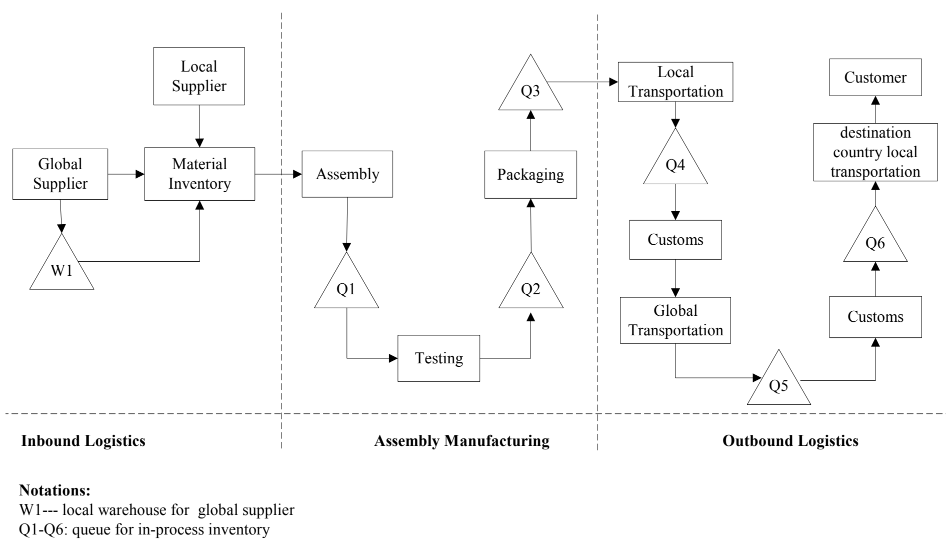
Different consumer electronics assembly manufacturers have different strategies to manage the supply chain. In general, there are three strategies. They are Make-to-Stock (MTS), Make-to-Order (MTO), and a hybrid of MTO and MTS (Rajagopalan, 2002). Generally, the MTS strategy with respect to CESC has significant weaknesses. This is due to the fact that the consumer electronics products' life cycle is short, demand variance is high and forecasting is difficult as the products are mostly customized. Recently researchers and industry practitioners started to pay more attention in developing MTO based supply chain management system, particularly in the consumer electronics industry.

Due to the high value of consumer electronics products and to meet the promised short delivery time, air transportation is commonly used in consumer electronics products distribution (Bowen, 2004). Regarding the features of relative fixed route, fixed departure time and stable transportation time, air transportation scheduling is different from the vehicle routing scheduling problems classified by Destrochers et al.

(1990). Furthermore, the problem of synchronization of assembly manufacturing and air transportation receives less attention in the literature, but effective solution of this problem is significantly important for a consumer electronics manufacturer to be competitive.

This study is motivated by a large MTO based PC assembly manufacturer who faces challenges in synchronizing the supply chain. The material flow through the supply chain is depicted in Figure 1. Components manufacturing is outsourced to local and global suppliers. Procured components are stored in inventory before assembly. When an order is received, the components are transferred into assembly flow shop. After three major modules of assembly processes that consist of assembly, test and packaging, finished products are transferred from assembly plant to airport by local transportation. Then, the products reach the destination country airport through global air transportation. Finally, destination country local transportation delivers the products to customers. Due to the complexity of the supply chain, synchronization is a challenge. In this paper, we have provided two solution methodologies, which are expected to synchronize both assembly and outbound logistics efficiently and effectively.

Figure 1. Material flow through CESC



The remainder of the paper is organized as follows: section II discusses related work. Section III illustrates the research problem and existing industry practice. Section IV presents the solution methodologies. Section V details the computational experiment design. The computational results and the managerial implications are discussed in section VI. Conclusions and the further work are discussed in the last section.

II. LITERATURE REVIEW

To the best of our knowledge, there is no research reported to date, which addresses the problem of synchronization of assembly manufacturing and air transportation for outbound logistics. However, there has been some discussion on synchronization of production and road transportation, which put emphasis on vehicle routing scheduling problem. Blumenfeld et al. (1991) examined the cost-effectiveness to synchronize production and transportation schedules on a production network which consists of one origin and many destinations. The trade-offs between production setup, freight transportation, and inventory costs on the network are analyzed and synchronized schedules are developed. Fumero and Vercellis (1999) proposed an integrated optimization model for production and distribution planning with the aim of optimally coordinating important and interrelated logistics decisions such as capacity management, inventory allocation, and vehicle routing.

Ruiz-Torres and Tyworth (1997) investigated the interaction of production scheduling and routing/transportation on a logistic network by simulation. The results indicate that low manufacturing-logistics cost and a high customer service level can both be maintained by an appropriate combination of scheduling and routing rules. Chen (2002) addresses the problem of integrating production and transportation scheduling in a MTO environment with the aim of minimizing the total cost which consists of transportation cost, tardiness penalty cost and overtime production cost. Sarmiento and Nagi (1999) reviewed work on integrated analysis of production-distribution systems.

From the above brief review on the related work, the following important observations can be obtained and these would highlight the significance of the research problem considered in this paper:

- The research on synchronizing the production and distribution is mainly carried out in MTS systems (Sarmiento and Nagi, 1999).
- The transportation used for the outbound logistics considered so far in literature focuses on land transportation and the issue related to outbound logistics was formulated as vehicle routing scheduling problem (Blumenfeld et al. 1991; Fumero and Vercellis, 1999).

Two solution methodologies are proposed in this paper in order to synchronize assembly manufacturing and outbound logistics in CESC. Both the methodologies take into account delivery earliness and tardiness penalties in addition to the normal shipping cost of air transportation in the outbound logistics.

III. THE RESEARCH PROBLEM AND EXISTING INDUSTRY PRACTICE

This study discusses the observations made by a major PC assembly manufacturer who is facing a challenge in its performance of on time delivery. The company has its major assembly plant in Singapore[1]. The observed industry receives their orders through many sources including email, World Wide Web, fax and phone. Orders come randomly, and the company commits the delivery time to the customers. Air transportation is commonly used for the distribution of high value MTO consumer electronics products to global customers and in general, commercial cargo flights are often used. The important dynamic factors, which dictate the outbound logistics of CESC are (a) the number of available flights for the distribution planning horizon, (b) the departure and arrival time of the flights, (c) the designated capacity and the corresponding transportation cost, and (d) the possible special capacity in each flight with the corresponding freight cost.

The methodologies to support assembly and transportation are different in industry. One of the popular industry based practice heuristic (termed by us 'EDD+FCFS') is given below in terms of step-by-step procedure:

Step 1: Earliest Due Date (EDD) policy plus zone group for assembly. The markets all over the world are divided into different zones. Orders come from the same zone with similar due date are grouped together. The order groups corresponding to the planning period are assigned into assembly manufacturing based on their due dates and released by EDD policy.

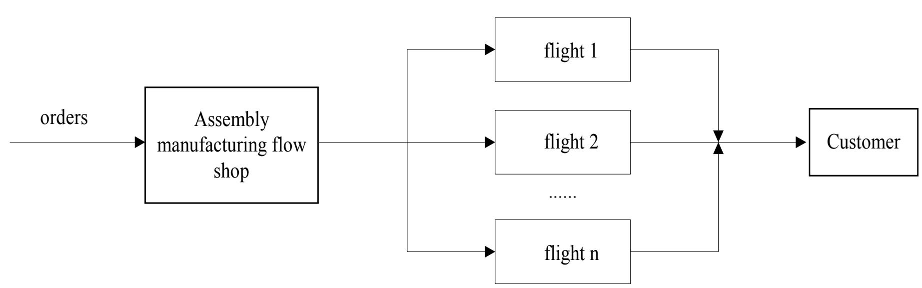
Step 2: First Come First Serve (FCFS) rule for transportation. Within the planning period, when the completed products transferred to airport, they are allocated to the flight based on FCFS rule.

The 'EDD+FCFS' heuristic is easy for implementation. However, it appears that the heuristic does not consider synchronization of assembly and transportation efficiently. In CESC, final delivery is carried out by air transportation. Thus, the transportation allocation should be decided based on final delivery due date information and assembly scheduling be decided based on transportation allocation. In contrast, the 'EDD+FCFS' heuristic determines the assembly schedule following EDD rule, which is based on final delivery due date instead of transportation allocation information, while transportation allocation is decided by assembly scheduling. Therefore, the performance of this method is not effective in industry. In order to improve the efficiency and the effectiveness of synchronizing assembly and outbound logistics, we propose two methodologies in this paper.

IV. SOLUTION METHODOLOGIES

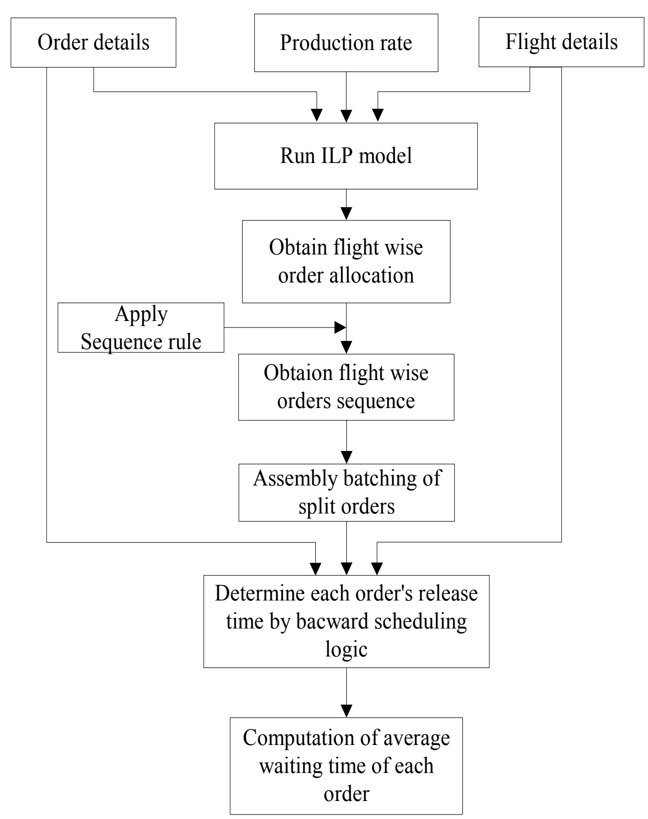
We propose two solution methodologies, which have two phases for the decision problem. A network representation of the two-stage decision model is shown in Figure 2.

Figure 2. Two stage decision model in CESC



In the first phase, the proposed Integer Linear Programming (ILP) model will run for the transportation issues of the outbound logistics assuming that the number of completed-customers'-orders are available and the production rate of assembly manufacturing is fixed and known. In the second phase, using the above optimal decision obtained for the outbound logistics, i.e., the flight wise customers' orders movement strategy, an efficient release control policy is decided for the assembly manufacturing based on the available assembly capacity. In the proposed two solution methodologies, only the procedure for obtaining an efficient release control policy varies, and they are based on backward scheduling and forward scheduling respectively. The flow diagram of the methodology containing backward scheduling is illustrated in Figure 3.

Figure 3. Flow diagram of proposed methodology



The proposed solution methodologies are based on the following assumptions:

- The assembly flow shop is treated as a single machine (as shown in Figure 2).
- Setup time is included in the processing time of assembly manufacturing.
- Total assembly manufacturing time of an order is directly proportional to the order's quantity.
- Each flight has a normal capacity area with normal transportation cost and a special capacity area with special transportation cost for orders that exceed normal capacity. Normal capacity can be considered as the forecasted capacity, while special capacity can be taken as maximum extension from the forecasted capacity in the planning period.
- Orders released into assembly flow shop for the planning period are delivered within the same planning period, which means no assembly backlog.
- In general, order received in one period will be released into assembly flow shop in the next period.
- All the packed products are the same weight and same dimension.
- There are multiple flights in the planning period.
- Business processing time and cost together with load time and load cost of each flight are included in the transportation time and transportation cost.
- Local transportation time and cost are included in assembly time and assembly cost.
- Order fulfillment is considered to be achieved when the order reach destination airport on time.
- Orders can be split and allocated into more than one flight and delivered separately.
- Orders can be split and processed at assembly flow shop separately.

A. Methodology 1: Synchronization using Backward Scheduling (SBS)

The step-by-step details of the proposed solution methodology 1 are discussed below:

Step 1: Assuming all the orders are ready for transportation, together with the information of production rate and flight details, run the proposed ILP model to determine the optimal allocation of orders to all the flights. The proposed ILP model is detailed in section A.1.

Step 2: Use the sequence rule of LPT (Longest Processing Time[2]) to sequence the orders that optimally allocated in step 1 for each flight.

Step 3: Assembly batching of split orders (ABSO): Some orders may be split and allocated to different flights in step 1. This step is used to combine the split orders in a batch for assembly so that split orders in transportation can be treated as a whole order in assembly. This step is applied in the situation that when one order is split and allocated into two adjacent flights. If the first proportion of the split order is sequenced to be the last one in the order sequence of the first flight, the next proportion of the split order which allocated to the second flight is adjusted to be the first one in the second flight's order sequence. This is to keep the continuity of the assembly processing of an order.

Step 4: Calculate each order's release time by backward calculation using the backward scheduling logic starting from the last order of the last flight. The pseudo code illustration for the backward scheduling logic is given in section A.2.

Step 5: Measure the performance of various sequencing rules used in step 2 of this algorithm by computing the average waiting time of each order between assembly and transportation.

The working mechanism of the solution methodology 1 is demonstrated using a numerical example and it is presented in Appendix.

A. 1 ILP Model for Decision 1 of the Research Problem

The ILP model is one of the most important parts of the two methodologies. It is used to allocate orders into available flights optimally in order to synchronize with assembly. Synchronization is incorporated into the ILP model by constraining flight allocation using production rate. In order to propose the ILP model, we define the following notations:

i order index, i=1, 2, …. M

j flight index, j=1,2,……N

D_j departure time of flight j at the local place where the manufacturing plant locates

A_j arrival time of flight j at the destination

NC_j transportation cost for per unit product, which allocated to normal capacity area of flight j

SC_j transportation cost for per unit product, which allocated to special capacity area of flight j

$NCap_j$ available normal capacity of flight j

$SCap_j$ available special capacity of flight j

TQ_i quantity of order i

α_i delivery earliness penalty cost (/unit/hour) of order i

β_i delivery tardiness penalty cost (/unit/hour) of order i

d_i due date of order i

p_i priority of order i

WT_i waiting time of order i between assembly manufacturing and transportation

PE_{ij} per unit delivery earliness penalty cost for order i when it is transported by flight j

$$PE_{ij} = \mathrm{Max}(0, d_i - A_j) * \alpha_i \quad (1)$$

PL_{ij} per unit delivery tardiness penalty cost for order i when it is transported by flight j

$$PL_{ij} = \mathrm{Max}(0, A_j - d_i) * \beta_i \quad (2)$$

Z_{ij} quantity of order *i* allocated to flight *j*

X_{ij} the quantity of the portion of order *i* allocated to flight *j*'s normal capacity area

Y_{ij} the quantity of the portion of order *i* allocated to flight *j*'s special capacity area

PR production rate of assembly manufacturing

The model is expressed as follows:

$$\text{Min} \quad \sum_i \sum_j NC_j X_{ij} + \sum_i \sum_j SC_j Y_{ij} + \sum_i \sum_j PE_{ij} Z_{ij} + \sum_i \sum_j PL_{ij} Z_{ij} \tag{3}$$

Subject to:

$$X_{ij} + Y_{ij} = Z_{ij} \quad \text{for all } i, j \tag{4}$$

$$\sum_i X_{ij} \le NCap_j \quad \text{for all } j \tag{5}$$

$$\sum_i Y_{ij} \le SCap_j \quad \text{for all } j \tag{6}$$

$$\sum_j (X_{ij} + Y_{ij}) = TQ_i \quad \text{for all } i \tag{7}$$

$$\sum_{j=1}^{j} \sum_i (X_{ij} + Y_{ij}) \le D_j PR \quad \text{for all } j \tag{8}$$

The decision variables are: X_{ij}, Y_{ij}, and Z_{ij}. All decision variables are non-negative integer variables. The objective is to minimize total cost which consists of total transportation cost for orders allocated into normal flight capacity, total transportation cost for orders allocated into special flight capacity, total delivery earliness penalty cost and total delivery tardiness penalty cost. Constraint (4) ensures that the quantity of the proportion of order *i* allocated into flight *j* consists of quantities of the proportion of order *i* allocated into normal capacity area of flight *j* and the proportion of order *i* allocated to special capacity area of flight *j*. Constraint (5) ensures that the normal capacity of flight *j* is not exceeded. Constraint (6) ensures that the special capacity of flight *j* is not exceeded. Constraint (7) ensures that order *i* is completely allocated. Constraint (8) ensures that allocated orders do not exceed production capacity. It ensures that allocated quantity can be supplied based on assembly manufacturing capacity. The output of this model is the order allocation. Once an order's transportation allocation is decided, its transportation departure time is determined. Since local transportation time is assumed to be included in the assembly processing time, the order's due date of assembly manufacturing is determined.

A.2 Backward Scheduling for Decision 2 of the Research Problem

Another main part of methodology 1 is the backward scheduling logic. The pseudo code description of the logic is presented below:

If (job *i* is the last job in flight *j*) **then**

If (flight *j* is the last flight) **then**
Release time(job *i*, flight *j*) =Departure time(flight *j*) –
Processing time(job *i*, flight *j*)
Else
If (Release time (the first job, fight *j*+1) is earlier than
Departure time(flight *j*)) **then**
Release time (job *i*, flight *j*) **=**Release time (the first job,
flight *j*+1) – Processing time(job *i*, flight *j*)
Else
Release time (job *i*, flight *j*) =Departure time (flight *j*) –
Processing time (job *i*, flight *j*)
End if

End if

Else
Release time (job *i*, flight *j*) =Release time (job *i*+1, flight *j*) –
Processing time (job *i*, flight *j*)
End if

B. Methodology 2: Synchronization using Forward Scheduling (SFS)

Methodology 2 follows the steps of solution methodology 1 except the step 4. Therefore, only the modified step 4 for the methodology 2 is given below:

Step 4: Calculate each order's release time by forward calculation using the forward scheduling logic starting from the first order of the first flight.

In forward scheduling, the whole order sequence consists of each flight's order sequence is important regardless of which order is allocated to which flight. If order *i* is the first order in the whole order sequence, then its release time equals zero. Else, its release time equals the release time of order *i*-1 plus assembly processing time of order *i*-1.

V. EXPERIMENTAL DESIGN

The methodologies presented in the previous section can provide important managerial implications for making decisions of assembly scheduling and transportation allocation. In order to validate the efficiency of the methodologies, a series of computational experiments were carried out using randomly generated test problems. Table 1 shows the experimental design.

Table 1
Experimental design used in random problems generation

Problem Parameter	No. of classes	Values
Number of orders M	1	10
Number of flights N	1	3
Production rate PR	3	80,100,120
Order quantity TQ_i	2	Uniform[50,200], Uniform[100,200]
Order due date d_i	1	Uniform[5,24]
Order Priority p_i	1	Uniform[1,3]
Normal capacity $NCap_j$	1	Uniform[350,450]
Special capacity $SCap_j$	1	Uniform[60,120]
No. of configurations	6	1*1*3*2*1*1*1*1
Instance/configuration	5	
Total problems	30	

In this study, we fixed the number of orders and the number of flights. The early and late delivery penalty (per unit per hour) is given for each instance. Flights' departure times and arrival times are also given in this research. Other parameters are generated from uniform distribution. The range of uniform distribution for each parameter is also fixed. We therefore have a total of 6 parameter combinations. We generate 5 instances for each parameter combination, which gives a total of 30 test problems. Each problem is solved using the proposed solution methodologies.

VI. COMPUTATIONAL RESULTS AND MANAGERIAL IMPLICATIONS

Managerial implications are derived from the performance comparison of the proposed methodologies with the industry practice heuristic as well as the relative performance of SBS and SFS. The result of each computational experiment is presented in terms of average value of the five instances for each experiment configuration.

As SBS and SFS are different only on affecting assembly manufacturing performance, they are only needed to be measured by average waiting time (AWT) between assembly and transportation. Table 2 and Table 3 show the solution quality of SBS and SFS for different production rate (PR) and order quantity configurations with the three sequence rules: LPT, Weighted Priority (WP) and Shortest Processing Time (SPT).

According to the computational results, SBS works better than SFS with all the sequence rules under any PR and order quantity configuration. With the increasing of PR, SBS can achieve decreased AWT while AWT is increased when using SFS. An insight can be obtained that SBS has the ability to control AWT effectively when there is gap between available assembly capacity and total workload while SFS does not have this ability in this scenario. Here, workload refers to the total quantity of product to be assembled. Another insight provided by Table 2 and Table 3 is the performance of different sequence rules used in SBS and SFS. It is stated in note 2 that the performance of the LPT rule needs to be compared with other sequence rules. Table 2 and Table 3 shows that the AWT is minimized by LPT rule for all configuration of PR and order quantity. It means that LPT performs the best in combination with the process of ABSO according to the results of this computational study.

Table 2
Performance of SBS and SFS with order quantity = Uniform [50,200]

	AWT due to						Relative AWT reduction of SBS compared to SFS due to sequence rule of (%)		
	LPT		WP		SPT				
PR	**SBS**	**SFS**	**SBS**	**SFS**	**SBS**	**SFS**	**LPT**	**WP**	**SPT**
80	1.81	2.25	1.93	2.36	2.71	3.15	19.56	18.39	14.00
100	1.16	3.64	1.9	4.38	1.25	3.73	68.13	56.62	66.49
120	0.98	4.73	1.61	5.35	1.06	4.79	79.28	69.91	77.87
Average	1.32	3.54	1.81	4.03	1.67	3.89	55.66	48.31	52.79

Table 3
Performance of SBS and SFS with order quantity = Uniform [100,200]*

PR	AWT due to						Relative AWT reduction of SBS compared to SFS due to sequence rule of (%)		
	LPT		WP		SPT				
	SBS	**SFS**	**SBS**	**SFS**	**SBS**	**SFS**	**LPT**	**WP**	**SPT**
100	1.61	2.47	1.72	2.58	2.30	3.16	34.82	33.33	27.22
120	1.29	3.74	1.39	3.83	1.87	4.32	65.51	63.71	56.71
Average	1.45	3.105	1.555	3.205	2.085	3.74	53.30	51.48	44.25

* The configure of PR=80 is too small to satisfy randomly generated orders from Uniform [100,200]. The comparison is carried out with PR=100 and PR=120.

We compare the performance of proposed methodologies with the industry practice heuristic to identify the advantage of our methodology. Since SBS is found to be better than SFS from the above comparison, SBS will be compared with the existing industry practice heuristic (based on ‘EDD+FCFS’), which is detailed in section III. Using the same data with the configuration of PR=80 and order quantity=uniform[50,200] in the former experiments but scheduled following the ‘EDD+FCFS’ heuristic, the results of costs and AWT are collected. The performance of SBS and ‘EDD+FCFS’ heuristic are compared in terms of total cost and AWT. Out of the five instances, one instance produced infeasible solution when we used the 'EDD+FCFS' heuristic. It is because one order cannot be delivered within the same planning period which breaks the assumption of no assembly backlog. The comparison between the 'EDD+FCFS' heuristic and the SBS based on the results of the four instances are illustrated in Table 4.

Table 4
Performance of SBS and 'EDD+FCFS' heuristic

	AWT	Total cost
SBS (1)	1.67	21104.18
'EDD+FCFS' Heuristic (2)	2.46	22739.74
Reduction of (1) to (2)	32.14%	7.19%

Compared to the 'EDD+FCFS' heuristic, SBS significantly reduce the AWT by 32.1% and reduce the total cost by 7.2%. Furthermore, since there is one infeasible solution by applying 'EDD+FCFS' heuristic, it is suggested that SBS provides better performance in reducing backlog thus to improve delivery accuracy.

The proposed methodology of SBS and the computational results can provide several management implications. Firstly, once the orders to be transported in a planning period are decided, the transportation allocation can be obtained by the ILP model. This is helpful for daily transportation capacity planning. The worst situation of no flight capacity to transport finished orders can be avoided. It is due to the fact that the transportation capacity is always larger than the order quantity to be transported, which are the inputs to the ILP model. Then, the unallocated flight capacity can be handled in advance. The allocated special capacity of each flight could be negotiated with airlines in advance and possibly obtained by a lower cost.

The second implication is derived from the cost saving of SBS over the 'EDD+FCFS' heuristic. Delivery earliness and tardiness penalties for each order can be assigned according to the priority of the customer. Then, optimal delivery is guaranteed by the ILP model. In other words, the total cost which consists of transportation cost and delivery penalty cost is minimized. Higher delivery penalty cost and higher transportation cost generally lead to larger gap between the results of ILP model and the result of 'EDD+FCFS' heuristic. Another viewpoint of cost saving is the reduction of AWT by SBS compared to 'EDD+FCFS' heuristic. The temporary finished goods inventory always leads to storage cost, insurance cost, capital opportunity cost, etc.

The third attractive managerial implication is the planning flexibility of the methodology. The methodology can be used to evaluate various decisions, which have different parameter values. The decision alternatives can be consideration of different flights, schedules, and acceptance of orders. The decision leading to lower cost can be selected for execution by the proposed methodology. This helps the planners for making decisions in volatile situation such as acceptance of an important emergency order, flight cancellation, order cancellation, and customer priority changing.

VII. CONCLUSION

The paper considered a consumer electronics supply chain synchronization problem that occurs in the context of a major PC assembly manufacturer. The company generally applies EDD rule for assembly manufacturing and FCFS rule for transportation. However, the delivery performance is poor. In order to improve the synchronization of both assembly and outbound logistics efficiently and effectively, we proposed two solution methodologies, namely SBS and SFS.

30 test problems are generated randomly based on experimental design and solved using the proposed solution methodologies to provide computational analysis. The results showed that SBS could effectively reduce order-waiting time between assembly and transportation compared to SFS. Furthermore, LPT rule performs better than the other sequence rules considered in this study in both solution methodologies: SBS and SFS. According to the analysis of the solution for the same test problems by applying the industry practice heuristic, the conclusion can be drawn that SBS can achieve good delivery performance with significantly reduced waiting time between assembly manufacturing and transportation. Finally, three managerial implications of the proposed methodology are illustrated.

This study indicates that combination of optimized transportation allocation, backward scheduling and proper sequence rule can achieve good delivery performance with reduced cost in complex consumer electronics supply chain. Even though the methodology was developed under the special application of a major PC assembly manufacturer, it can be easily adopted by other applications in context of fixed transportation departure time and arrival time in MTO supply chain.

This paper can be extended in several ways. One possible extension is to relax the assumption of single machine of assembly to parallel machine or multi-stage machine, as most of the assembly processes have more than one stage. Moreover, the relaxation of one transportation destination to multi-destination presents another practical application since a global manufacturer must face various markets scattered all over the world.

NOTES

1. Due to confidentiality, the name of the PC assembly manufacturer is not mentioned here.
2. The problem to determine release time of each order for assembly manufacturing is similar to the problem of single machine scheduling to minimize earliness without tardiness. Though LPT leads to the optimal sequence to the second problem mentioned above (Chand and Schneeberger (1988)), we have also studied other two sequence rules, Weighted Priority (WP) and Shortest Processing Time (SPT).

It is because sequence rule is combined with the process of assembly batching of split orders in this research. Each order's weighted priority equals its priority multiplied by its quantity. Orders are released from higher weighted priority to the lower one.

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APPENDIX

Demonstration of the solution methodology of SBS

A simple example is presented to demonstrate the proposed methodology of SBS step by step in this section.

Inputs:

a) Problem size:
   PR=80
   Number of flights = 3
   Number of orders = 10
   Planning period = 24 hours

b) Order details as shown in Table 5.

Table 5

Input of order details to SBS

Order	Quantity (TQ_i)[1]	Due date (d_i)[2]	Priority (p_i)[3]	Earliness penalty (α_i)	Tardiness penalty (β_i)
1	131	13.1	2	5	6
2	76	10.7	2	3	7
3	96	11.4	1	6	7
4	132	6.4	3	3	8
5	119	20.3	3	3	7
6	191	10.5	3	4	5
7	91	9.1	2	5	8
8	178	7.4	2	5	6
9	106	9.5	1	3	5
10	54	20.8	3	4	7

1. Order quantity is drawn from uniform distribution: TQ_i=Uniform[50,200].
2. Order due date is drawn from uniform distribution: d_i=Uniform[5,24]
3. Order priority is drawn from uniform distribution: p_i =Uniform[1,3]

c) Flight details as shown in Table 6.

Table 6
Input of flight details to SBS

Flight	Departure time (D_j)	Arrival time(A_j)	Normal area: Capacity ($NCap_j$)	Normal area: Unit cost (NC_j)	Special area: Capacity ($SCap_j$)	Special area: Unit cost (SC_j)
1	5	7	377	13	83	12
2	10	12	422	8	103	14
3	15	17	369	13	118	10

Outputs:
a) The optimal order allocation to existing flights that are summarized in Table 7

Table 7
Optimal order allocation

Order	Flight 1: Quantity in normal area	Flight 1: Quantity in Special area	Flight 2: Quantity in normal area	Flight 2: Quantity in Special area	Flight 3: Quantity in normal area	Flight 3: Quantity in Special area	Total allocated quantity
1	0	0	0	0	131	0	131
2	0	0	76	0	0	0	76
3	0	0	96	0	0	0	96
4	132	0	0	0	0	0	132
5	0	0	0	0	119	0	119
6	0	0	191	0	0	0	191
7	67	23	1	0	0	0	91
8	178	0	0	0	0	0	178
9	0	0	36	0	65	5	106
10	0	0	0	0	54	0	54

The details of capacity allocation for each flight can also be derived from this table. The capacity allocation indicates the remaining free normal capacity or the allocated special capacity of each flight. The result facilitates transportation capacity planning which is demonstrated in section VI of this paper.

b) Flight wise order sequence. As shown in Table 8, only LPT and WP rules are applied in this example.

Table 8
Flight wise order sequence

Flight	Orders in normal capacity area	Orders in special capacity area	Flight wise order sequence	
			LPT [1]	WP
1	4, 7(67)*[2], 8	7(23)*	8, 4, 7*	4, 8, 7*
2	2, 3, 6, 7(1)*, 9(36)*		7*, 6, 3, 2, 9*,	7*, 6, 2, 3,9*
3	1, 5, 9(65)*, 10	9(5)*	9*, 1, 5, 10	9*, 5, 1, 10

1. Sequence by LPT with the process of ABSO. In the following illustration, rule name means the rule with ABSO.
2. * means a proportion of an order. The number in the bracket is the quantity of the proportion of the order that allocated into the corresponding flight.

c) Determined release time as shown in Table 9.

Table 9
Determined release time

Order	Determined release time	
	LPT	WP
1	11.20	12.69
2	8.60	7.40
3	7.40	8.35
4	2.23	0
5	12.84	11.20
6	5.01	5.01
7(90)	3.88	3.88
7(1)	5.00	5.00
8	0	1.65
9(36)	9.55	9.55
9(70)	10.32	10.32
10	14.33	14.33

d) The waiting time, earliness and tardiness as shown in Table 10.

Table 10
The waiting time, earliness and tardiness

Rules	Order	Priority	Delivery time	Due date	Earliness	Tardiness	Waiting time	Weighted waiting time[1]
By LPT	8	2	7	7.4	0.4		2.78	5.55
	4	3	7	6.4		0.6	1.13	3.38
	7	2	7	9.1	2.1		0.00	0.00
	7	2	12	9.1		2.9	4.99	9.97
	6	3	12	10.5		1.5	2.60	7.80
	3	1	12	11.4		0.6	1.40	1.40
	2	2	12	10.7		1.3	0.45	0.90
	9	1	12	9.5		2.5	0.00	0.00
	9	1	17	9.5		7.5	3.80	3.80
	1	2	17	13.1		3.9	2.16	4.33
	5	3	17	20.3	3.3		0.68	2.03
	10	3	17	20.8	3.8		0.00	0.00
total					**9.6**	**20.8**	**19.97**	**39.15**
Average							**1.67**	**1.57**
By WP	4	3	7	6.4		0.6	3.35	10.05
	8	2	7	7.4	0.4		1.13	2.25
	7	2	7	9.1	2.1		0.00	0.00
	7	2	12	9.1		2.9	4.99	9.97
	6	3	12	10.5		1.5	2.60	7.80
	2	2	12	10.7		1.3	1.65	3.30
	3	1	12	11		0.6	0.45	0.45
	9	1	12	10		2.5	0.00	0.00
	9	1	17	9.5		7.5	3.80	3.80
	5	3	17	20.3	3.3		2.31	6.94
	1	2	17	13.1		3.9	0.68	1.35
	10	3	17	20.8	3.8		0.00	0.00
Total					**9.6**	**20.8**	**20.95**	**45.91**
Average							**1.75**	**1.84**

1. Weighted waiting time = Waiting time * Priority

e) Performance measure as shown in Table 11.

Table 11
Performance measure

Sequence Rule	AWT	Weighted AWT[1]
LPT	1.67 Hour	1.57Hour
WP	1.75Hour	1.84Hour

1. $$\text{Weighted AWT} = \frac{\sum_{i} (\text{Waiting time}(i) * \text{Priority}(i))}{\sum_{i} \text{Priority}(i)}$$