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# OKP Supply Chain Scheduling

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**Abstract:** In one-of-a-kind production (OKP), a firm usually keeps zero stock for some components of which the demand is unstable. In this work, we model the scheduling problem for the OKP firm who promises due-date-guaranteed delivery to its customers. The firm schedules its jobs to minimize its total cost concerning the constraint of components delivery from its supplier. We develop a pair-wise scheduling algorithm to model. The simulation test shows that the proposed pair-wise scheduling algorithm can find the near optimal solution.

Keywords: one-of-a-kind production, supply chain scheduling, pair-wise algorithm

## 1. INTRODUCTION

Nowadays, increasing uncertainties in customer demand drives manufacturing firms to undertake appropriate management strategies in their production planning. One-of-a-kind production (OKP) is one such strategy that allows local firms to provide highly customized products, and at the same time to meet the customer's leadtime requirement. Comparing to mass customization, OKP is featured as a "once" successful approach on the product development and production according to specific customer requirements, i.e., no prototype or specimen will be made<sup>[1]</sup>. Thus, OKP manufacturer usually does not keep inventory of some inputs (e.g., parts) and only makes orders on demand. Concerning the leadtime of the parts delivered by the suppliers, the OKP manufacturer's production scheduling is further complicated, especially when the manufacturer's customers has specific requirements on due date. In this research, we study the supply chain described as follows.

This work relates to the literature of supply chain scheduling, which was initiated by [2]. Due to the complexity, most authors study either the supplier-manufacturer (or supplier-assembler) integration, or the manufacturer-deliverer integration.

In the research of supplier-manufacturer integration, [3], [4] and [5] has proved that the integrative scheduling between suppliers and manufacturers can significantly increase the supply chain's responsiveness and lower the total incurred cost. Moreover, they also studied the mechanism which enables the integration between the manufacturer and the suppliers. In the operational level, numbers of works studied the supply chain scheduling under different special conditions. A common method to study the supply chain scheduling is to assume the suppliers and/or the manufacturers as separated machines. [6] studied the case where one supplier serves multiple manufacturers. They reduce their problem to a single machine scheduling problem with deadlines, where the supplier is the machine and all the products manufactured for the same manufacturer belongs to the same product family. They developed the algorithm for the supplier to find the optimal schedule to minimize total setup cost. Both [7] and [8] studied a single-supplier-single-manufacturer supply chain. [7] optimizes the integrative schedule by minimizing the interchange cost and buffer storage cost, where the interchange cost measures the different between the supplier's or the manufacturer's own ideal schedule and the global optimal schedule.

As for the research in manufacturer-deliverer integration, [9] and [10] can be refereed for detail review. We present the works by [11] and [12], which is most related to our work. They both studied a problem in which the 3PL quotes a pricing schedule which maps the shipping time and the price, and the manufacturer sequences the

production of orders with different committed due dates, such that the transportation cost are minimized. According to our definition, this type of integration is weak integration. That is, the manufacturer does not know the detail scheduling within the deliverer. However, through the price schedule, the manufacturer's production schedule is automatically induced to the one which benefits the deliverer. When the manufacturer managed to balance the total transportation cost and the efficiency of delivery, the scheduling of the manufacturer and the deliverer is therefore coordinated, indirectly. To solve the computational complexity problem, [11] developed heuristics to find near optimal solution, and [12] improved their algorithm with worst-case concerns. However, they do not consider the constraints incurred by the delivery time from the supplier of the parts.

To our best knowledge, there is no research in the literature considering both the supplier's and the manufacturer's pricing schedule when studying the manufacturer's scheduling problem. In our present work, we first formulate a basic model, by which the manufacturer minimizes the total procurement cost and the total delivery cost. We propose the heuristics so that the near optimal solution can be obtained. Second, we study a case in which a single supplier serves multiple manufacturers, and the supplier and the manufacturers are weakly integrated. In this case, the manufacturers share the demand information from their own customers, i.e. the quantity of the orders and the urgency level of each order. Based on this information, the supplier formulates the pricing schedule mapping the leadtime to the price.

## 2. MATHEMATICAL MODEL

In the future  $T$  periods, the manufacturer has  $J$  jobs to be processed, each of which is indexed by  $j: j \in \{1, 2, \dots, J\}$ . In this work, we treat a manufacturer as a one-machine production system. Thus, the manufacturer's target is to form a job sequence for production. We use  $i \in \{1, 2, \dots, J\}$  to index the  $i$ 's job in the sequence.

The starting time for the production of job  $j$  is constrained by the arriving time of its part from the supplier. For the purpose of simplicity, we assume that the manufacturer's starting time for processing job  $j$  is constrained by only one part. This is true in practice when the part is the last one to be delivered and therefore becomes the bottleneck for scheduling job  $j$ . In this work, we study the case where the supplier offers optional delivery time option for any single part, and the supplier can only deliver the part at the end of each period. If the manufacturer requires  $a_j: a_j \in N$  as delivery time for the part of job  $j$ , then the supplier will charge the manufacturer at expense  $\gamma_j(a_j)$ .

When the manufacturer finished the processing of job  $j$ , job  $j$  is ready for shipment to the final customer. We study the case that for any job  $j$ , the customer has a particular requirement for delivery due date, denoted by  $d_j$ . In this work, we assume that the customer is indifferent about the delivery time if the delivery is within the same period. Thus,  $d_j$  can be treated as positive integer, i.e.,  $d_j \in N$ . The finished job is shipped to the final customers by the third-party logistics provider (3PL). The shipping cost charged by the 3PL is a function of the order's weight, the distance to the order's destination and the shipping mode. We denote the order's weight and the distance to the order's destination by  $w_j: w_j \in R^+$  and  $r_j: r_j \in R^+$ , respectively. Following to [12], job  $j$ 's shipping mode is represented by its shipping time, which is denoted by  $l_j: l_j \in N$ .

Given  $w_j$ ,  $r_j$  and  $l_j$ , the manufacturer can compute the cost charged by the 3PL, denoted by  $\Phi(l_j, w_j, r_j)$ .

We assume that the 3PL only picks up the finished products at the end of each period, and  $\Phi(l_j, w_j, r_j)$  is

decreasing in  $l_j$  but increasing in  $w_j$  and  $r_j$ . If the delivery of the finished product is later than the required

due date, then a penalty is incurred to the manufacturer. In this work, we assume that the penalty is a function of the order's weight and the amount of tardiness. Saying that the tardiness for delivering job  $j$  is  $\Delta_j$ , then the

cost incurred for the penalty is denoted by  $\Psi(\Delta, w_j)$ , which is non-decreasing in  $\Delta$ . In this work, the

manufacturers we studied are minimizing the total cost which includes the cost charged by the supplier, the cost charged by the 3PL and the penalty for late delivery. The following mathematical model computes the optimal

production sequence of the orders under the constraints of supplier's delivery time and the 3PL's shipping time.

Similar as the NPD in [11], in the model, we use three status variable defined as follows:

- $f'_j$ :  $f'_j \in R^+$ . The finishing time of job  $j$ .
- $f_i$ :  $f_i \in R^+$ . The finishing time of the  $i$ th job in the scheduled job sequence.
- $y_{jt}$ :  $y_{jt} \in \{0,1\}$ . 1 if job  $j$  finishes in day  $t$ ; otherwise 0.

The manufacturer's problem, MP, is formed as:

$$\min \sum_{j=1}^J [\gamma(a_j) + C_w(f'_j - a_j) + \Phi(l_j, w_j, r_j) + \Psi(t_j + l_j - d_j)] \quad (1)$$

$$\text{Subject to: } \sum_{i=1}^J x_{ij} = 1, \quad i = 1, 2, \dots, J \quad (2)$$

$$\sum_{j=1}^J x_{ij} = 1, \quad j = 1, 2, \dots, J \quad (3)$$

$$f_0 = 0 \quad (4)$$

$$f_{i-1} + \frac{\sum_{j=1}^J s_j x_{ij}}{c} \leq f_i \quad i = 1, 2, \dots, J \quad (5)$$

$$\sum_{j=1}^J a_j x_{ij} + \frac{\sum_{j=1}^J s_j x_{ij}}{c} \leq f_i \quad i = 1, 2, \dots, J \quad (6)$$

$$f'_j - f_i \leq M[1 - x_{ij}] \quad i, j = 1, 2, \dots, J \quad (7)$$

$$f_i - f'_j \leq M[1 - x_{ij}] \quad i, j = 1, 2, \dots, J \quad (8)$$

$$f'_j \leq t_j \quad j = 1, 2, \dots, J \quad (9)$$

$$x_{ij}, y_{ij} \in \{0, 1\}, t_j, a_j \in N \cup \{0\} \quad i, j = 1, 2, \dots, J \quad (10)$$

(1) is the object function which minimizes the total cost, i.e., procurement cost, transportation cost, and tardiness penalty. (2) and (3) describe the job's position in the scheduled sequence. (5) regulates that the  $i$ th job in the sequence has to start after when  $i-1$ th job finishes. (6) regulates that the  $i$ th job in the sequence has to start after when its part arrives. (7) and (8) regulate that if job  $j$  is the  $i$ th job in the sequence, then  $f_i = f'_j$ . (9) regulates that an order is shipped at the end of the day when it is produced.

Since Stecke and Zhao has proved that NPD is a NP-hard problem, then we can conclude that our problem is also NP-hard. Stecke and Zhao developed heuristics for problem NPD to find the near optimal solution, and [12] developed an alternative heuristics to improve the worst case solution. Since they do not consider the impact of the supplier's delivery, then we develop a new problem specific heuristics in the next subsection.

### 3. HEURISTICS DEVELOPMENT

We propose a pair-wise algorithm to search the near optimal solution of the model presented in Section 2. In the heuristics, we try to find the optimal solution by iteratively swapping each pair of neighbor jobs. We first find the optimal schedule supposing the firm only have one job. Suppose that the firm only have job  $j$ , then there exists an optimal schedule in which job  $j$  starts at the beginning of  $t_j$ , such that

$$t_j = \arg \min_{t \in N} C_j(t), \quad (11)$$

where

$$C_j(t) = \Gamma_j(t-1) + \Phi(\max\{d_j - (t-1 + \lceil s_i/c \rceil), \underline{l}(r_j)\}, w_j, r_j) \\ + \Psi(\max\{0, (t-1 + \lceil s_i/c \rceil) + \underline{l}(r_j) - d_j\}).$$

We define  $C'_j(t)$  as  $C'_j(t) = C_j(t+1) - C_j(t-1)$ . Without loss of generality, we set that for any  $j$ ,

$C_j(0) = M$  where  $M$  is a large positive number. Then, we can have a sequence of jobs, denoted by  $Q_u$ . In

$Q_u$ , jobs are sequenced non-decreasingly in  $t_j$ . Our pair-wise heuristics (PWH) for is developed has follows:

**PWH:**Input:  $Q_u$ Output:  $Q_u$ 

```

for  $\bar{i} \leftarrow |Q_u|$  to 2 step -1 do
  SWAPPED  $\leftarrow False$ ;
  for  $i \leftarrow 1$  to  $\bar{i}-1$  do
    if  $Q_u(i)$  starts and  $Q_u(i+1)$  ends in the same period then
      if  $C'_{Q_u(i)}(t) < C'_{Q_u(i+1)}(t)$  then
        Swap  $Q_u(i)$  and  $Q_u(i+1)$ ;
        SWAPPED  $\leftarrow True$ ;
      end if
    else
      if Swap  $Q_u(i)$  and  $Q_u(i+1)$  can reduce the total cost then
        Swap  $Q_u(i)$  and  $Q_u(i+1)$ ;
        SWAPPED  $\leftarrow True$ ;
      end if
    end if
  end for
  if SWAPPED = False then
    STOP;
  end if
end for

```

The proposed heuristics can be regarded as a modified bubble sorting algorithm. The algorithm's complexity is  $O(n^2)$  in worst case, and is  $O(n)$  in best case.

#### 4. PERFORMANCE OF THE PROPOSED HEURISTICS

In order to illustrate the efficiency of our heuristics, we compare the solutions obtained by our heuristics with the optimal solution obtained by CPLEX.

In order to obtain the optimal solution by CPLEX, we constrain the problem to  $J = 8$  and  $T = 10$ . The cost functions are generated based on the following forms, which is consistent with the monotone assumption.

$$\Gamma_j(a_j) = \begin{cases} \gamma_{1j} - \gamma_{2j}a_j & \text{if } a_j \leq \gamma_{3j} \\ \Gamma_j(\gamma_{3j}) & \text{if } a_j > \gamma_{3j} \end{cases}, \quad (12)$$

where  $\gamma_{1j}, \gamma_{2j}, \gamma_{3j} \in R^+$  are function parameters which vary between different jobs. In order to make sure that  $\Gamma_j(a_j) > 0$  for any  $a_j > 0$ , for each job  $j$ , we first randomly generate  $\gamma_{1j}$  and  $\gamma_{3j}$  from uniform  $U(50, 200)$  and  $U(1, T)$ , respectively. Then, we generate  $\gamma_{2j}$  from  $U(0, \gamma_{1j} / \gamma_{3j})$ .

$$\Phi(l_j, w_j, r_j) = \begin{cases} r_j w_j [\phi_1 - \phi_2 l_j] & \text{if } l_j \leq \phi_3 \\ \Phi(\phi_3) & \text{if } l_j > \phi_3 \end{cases}, \quad (13)$$

where  $\phi_1, \phi_2, \phi_3 \in R^+$  are function parameters. For all the jobs, the shipping cost is in the same form. Same as generating  $\Gamma_j(a_j)$ , we first randomly generate  $\phi_1$  and  $\phi_3$  from uniform  $U(10,40)$  and  $U(1,T)$ , respectively. Then, we generate  $\phi_2$  from  $U(0, \phi_1 / \gamma_3)$ .

$$\Psi_j(\Delta) = \begin{cases} 0 & \text{if } \Delta \leq 0 \\ \psi_j \Delta & \text{if } \Delta > 0 \end{cases} \quad (14)$$

where  $\psi_j \in R^+$  are function parameters. For any job  $j$ ,  $\psi_j$  is randomly generated from  $U(1,500)$

The other parameters used in the simulation are listed in Table 1. Note that in the simulation, the capacity and each job's processing time are both in job unit. Thus,  $c$  and  $s_j$  are both integers.

**Table 1. Parameter settings**

Parameter	Value
$c$	5
$d_j$	random integer from $U(1,T)$
$r_j$	random real from $U(1,2)$
$w_j$	random real from $U(1,5)$
$s_j$	random integer from $U(1,15)$

The simulating result is shown in Table 2. It can be observed that the gap can be constrained to around 1%. Our heuristics appears less efficient in speed and accuracy than the one introduced by [11] because we considered the supplier's delivery and the overdue of the final products. The complexity can be reflected by the CPU times consumed by CPLEX, which are much longer than the ones in [11]'s results.

**Table 2. Simulating results**

	Optimal solution CPU time (seconds)	Heuristics CPU time (seconds)	Average gap between optimal cost and heuristic cost(%)
1	16.64	0.92	0.97
2	17.07	0.86	1.03
3	17.01	0.88	1.08
4	16.73	0.89	0.92
5	17.01	0.88	1.02
6	17.06	0.91	0.96
7	17.11	0.85	1.03
8	16.41	0.90	1.04
9	16.86	0.88	0.91
10	16.35	0.88	1.00

## 5. CONCLUSIONS

In this work, we modeled the scheduling problem of an OKP manufacturer whose scheduling is constrained by its supplier's delivery. A pair-wised sequencing algorithm is proposed and the simulation test shows that the proposed algorithm can find the near optimal solution within a short computation time. The sequencing method proposed in this work can be easily extended to fit for various contexts by changing the objective function of the mathematical model.

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