Tabu search-based heuristic for the selection of manufacturing and transportation partners in supply chain

Chang Seong Ko * and Jae Jeung Rho **

A proper selection of collaboration partners is recognized as a critical success factor in supply chain management. In the past, partners for outsourcing production were selected within a closed group of candidates due to the limited information and location of partners. The wide use of Internet and development of e-marketplace make it possible that the partners be selected regardless of their location or nationality. In this study, we propose an analytical approach for the selection of transportation partners as well as manufacturing partners for supply chain management. A mathematical model is developed to show how to minimize the sum of the operation and transportation costs in the presence of alternative production process plans. A heuristic algorithm based on tabu search is developed since the model belongs to a class of NP-hard problems. An example problem is solved to demonstrate the solution procedure.

Keywords: Supply Chain Management, Manufacturing and Transportation Partners, Tabu Search

1. Introduction

A proper selection of partners is a major success factor in supply chain management (SCM). In the past, partners for outsourcing production were selected within a closed group of candidates due to the limited information and location of partners. Also, the concept of partners was limited to the provider of manufacturing resources. In SCM of these days, transportation companies as well as manufacturing companies need to be included as collaboration partners, in order for the increasing portion of transportation cost out of total cost to be minimized and the on-time delivery rate between manufacturers to be maximized. The wide use of Internet and the development of e-marketplace make it possible that the partners capable of providing the optimal cost and service level are selected regardless of their location or nationality.
There is no doubt that the globally distributed manufacturing system can be integrated by virtue of easy access to Internet, global telecommunication infrastructure, and wireless communication system. The potential for the ubiquitous interconnectivity among globally distributed design and manufacturing centers enables the collaboration and cooperation for the development of a new product and for the sharing of manufacturing resources. The rapid evolution of the information technology and electronic commerce has resulted in new opportunities and challenges in SCM environment. Imbedded within such opportunities are the challenges associated with sharing and coordination of complex, concurrent activities among geographically disparate facilities. The efforts for the collaboration among distributed partners have been pursued in many research works [1, 6]. Recently, Ko et al. [4] formulated a mathematical model for the problem of selecting manufacturing partners in a distributed manufacturing. Their research effort was mainly focused on the selection of process planning and manufacturing partners with the objective of minimizing the sum of operation and transportation costs when some parts are manufactured by outsourcing partners. In their model, transportation costs were assumed to be the same for every transportation partners. However, the identical transportation costs may result in inappropriate decision making due to the possibility of empty or half-loaded returning vehicles.

In order to make the decision process more realistic, we consider the existence of multiple alternatives for transportation costs as well as manufacturers. It is assumed that each part to be manufactured is associated with a number of alternative process plans based on manufacturing costs (machining times, processing sequences), manufacturing resources (machines, jigs/fixtures, tools) and transportation cost (the cost of moving around manufacturing resources). Then for each part a most applicable process plan is selected among those alternative process plans. Rajamani et al. [9] developed a mathematical model for the generation of alternative process plans when the part families and machine groups are formed simultaneously. Alternative approaches appeared in the literature to tackle this NP-complete problem. Tabu search heuristics [5, 8], a hybrid of Hopfield neural network and genetic algorithm [7] are a few of the new approaches in this respect.

Most companies in mass production system are equipped with all the necessary manufacturing resources, such as special purpose machines and operators to achieve a higher production rate. As the manufacturing paradigm is shifted to customized, flexible, lean and cellular manufacturing, the
utility rate of expensive special purpose machines is dropped to lower level, which imposes financial burden to the companies. With the advent of Internet technology, those companies become interested in sharing production technology and resources to reduce fixed cost and to overcome duplicated investment.

In this research, we propose the collaboration partner selection procedure in SCM, where manufacturing partners with surplus capacity and transportation partners with empty space travel can be chosen to accomplish the assigned task. The main headquarter company takes a role of production engineering by designing a new product and developing a most applicable process plan. Actual manufacturing processes are performed by the exterior partners connected to the main system through Internet. Figure 1 shows the overall scheme for collaboration partner selection process in SCM.

Figure 1 Conceptual diagram for collaboration partner selection process

2. Mathematical model

In this section we present a mathematical model for selecting manufacturing and transportation partners in supply chain. In the model, a machine represents one of manufacturing partners. To facilitate model formulation, the following assumptions are postulated:

1. Information for each part such as demand rate, process characteristics, and size is known.
2. The available capacity of each machine type is known.
3. Operation time and cost on each machine for each process plan are known.
4. Transportation costs between machines of each company are known and only one transportation company is selected for each demand.
5. The demand for each part is smoothed before the due date.
6. Collaborating partners satisfy the quality level and technology requirements.

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requirement.

The following notations are also introduced to formulate the problem:

- \( i = 1, 2, ..., m \)  \( \) machines
- \( j = 1, 2, ..., n \)  \( \) parts
- \( p = 1, 2, ..., p_l \)  \( \) process plans for part \( j \)
- \( k = 1, 2, ..., K(j, p) \) operations for part \( j \) with process plan \( p \)
- \((k)\): sequence of process which represents \( k^{th} \) operation
- \((j, p)\): combination where part \( j \) can be produced in the process plan \( p \)
- \( d_j \): daily demand of part \( j \)
- \( cu_j \): unit volume of part \( j \)
- \( V \): volume of container
- \( N_j \): number of containers where part \( j \) is loaded,

\[
\sum_j cu_j \cdot \frac{d_j}{V}
\]

- \( Y_{ik}(j,p) \):
- \[
1 \text{ when } k^{th} \text{ operation is assigned to machine } i \text{ in } (j, p) \\
0 \text{ otherwise}
\]

- \( Z_{jp} \):
- \[
1 \text{ when part } j \text{ is produced under process plan } p \\
0 \text{ otherwise}
\]

- \( X_q \):
- \[
1 \text{ when transported by company } q \\
0 \text{ otherwise}
\]

- \( a_i(k) \):
- \[
1 \text{ when } k^{th} \text{ operation is assigned to machine } i \\
0 \text{ otherwise}
\]

- \( b_j(j,p) \):
- \[
1 \text{ when } k^{th} \text{ operation is active in } (j,p) \\
0 \text{ otherwise}
\]

- \( tc_q(i_1, i_2) \): transportation cost of company \( q \) for moving a container from
machine $i_1$ to machine $i_2$

c_1$: discount rate of operation cost

c_2$: penalty rate of operation cost

e_1$: proper coefficient of operation capability for each machine

e_2$: marginal coefficient of operation capability for each machine

$rt_i$: total operation time for machine $i$,

where $rt_i = \sum_{j,p} d_j \cdot Y_{(j,p)} \cdot pt_{i(j,p)}$

$at_i$: operational capacity of machine $i$

$oc_{i(k)}(j, p)$: operation cost of $k^{th}$ process in the $(j, p)$

$pt_{i(k)}(j, p)$: operation time of $k^{th}$ process in the $(j, p)$

$s$: starting point of raw material for machine operation

t: terminal where finished parts should be delivered

We formulate a mathematical model as the following:

Minimize

$$
Z = \sum_{j,p,k} d_j \cdot Y_{(j,p)} \cdot oc_{i(k)}(j, p) + \sum_{i,j,p,q,t} c_q(s,t) \cdot X_q \cdot Y_{(i(k),j,p)}(j, p) \cdot N_j
$$

subject to

$$
oc_{i(k)}(j, p) = \begin{cases} 
oc_{i(k)}(j, p) : \quad rt_i < e_1 \cdot at_i \
\c_1 \cdot \c_{i(k)} : \quad e_1 \cdot at_i \leq rt_i < at_i \
\c_2 \cdot \c_{i(k)} : \quad at_i \leq rt_i \leq e_2 \cdot at_i \
M \cdot \c_{i(k)} : \quad e_2 \cdot at_i \leq rt_i \
\end{cases}$$

$$
\sum_{p,j} Z_{j,p} = 1 \quad j = 1, 2, \ldots, n
$$

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In the model, $Y_{i(k)}(j, p)$, $Z_{jp}$ and $X_q$ are decision variables, and $a_{ik}$ and $b_{ik}(j, p)$ are coefficients used in the formulation. The variable $X_q$ is added to the model of Ko, et al. [4], in order to include transportation partner selection process. The objective function (1) is to minimize the total cost which is composed of both operation cost and transportation cost. The discount policy (2) is also applied to the operation cost according to total workload time for each machine. The constraint (3) shows the uniqueness property implying that one part is assigned to only one process plan uniquely. The constraint (4) specifies the relationship between each part and multiple alternative process plans. The constraint (5) also shows the uniqueness property for transportation partners. If it is possible to select multiple transportation partners, this constraint may be relaxed. But, in the real world problem, the selection of multiple transportation partners is not recommended for the purpose of efficient management. The model is a nonlinear binary-integer programming model for a class of typical NP-hard problems. Therefore, heuristic search algorithm is required for the large-sized problem in the real world. This paper presents an exploratory algorithm based on tabu search that has shown optimal or near optimal solutions in the combinatorial problems [2, 3, 10].

3. Heuristic algorithm based on tabu search

In order to find optimal or near-optimal solutions to the model established in the previous section, a heuristic algorithm is developed. Among the combinations of process plans for each part, a process plan was chosen randomly. Thereafter, manufacturers, a transportation company and corresponding process plan were chosen with minimum total cost composed of operation and transportation cost. To help this process, tabu search algorithm was adopted which has been applied in previous research for the similar problems [4, 5, 9].

Tabu search is a general heuristic procedure for augmenting search
process to obtain good solutions in complex solution spaces. The tabu search algorithm starts with an initial feasible solution and moves successively at each iteration to its best neighboring solution even though it is not an improving one. In such a way it converges to an optimal or near-optimal solution. An important feature of tabu search is the tabu list that consists of those solution states not permitted at the current iteration. Since the tabu list contains only the modifications made to a solution state, an aspiration level (AL) function is used to provide an added flexibility in overruling the tabu status of a move. The aspiration level is initially set equal to the total cost of the initial feasible solution. A tabu-move becomes admissible, if the aspiration level is attained. A simple aspiration level function often used is to override the tabu status of a move, if it gives an objective value strictly better than the best obtained thus far. Two other lists are also adopted. The index list (IL) contains the local optima evaluated as the search progresses and the candidate list (CL) consists of potential configurations chosen to perform future perturbations. A configuration refers to a solution point.

Based on the tabu search algorithm, a heuristic algorithm is proposed for the given problem as follows.

Step 1. For each part, arrange all the possible operating cost in the non-decreasing order.
Step 2. Determine the initial feasible solution that corresponds to the minimum operating cost for each part and to a transportation company.
Step 3. Estimate the total cost composed of operating cost for all parts and transportation cost between operating machines.
Step 4. Put the initial feasible solution as the first configuration in CL. The CL forms process plans for each part that will be changed afterwards. The total cost of the initial feasible solution, corresponding to the first local optimum, is set equal to the AL.
Step 5. Search the process plan with minimum total cost as Step 3 by changing single process plan. If the total cost from this process plan is less than AL, insert it in the CL by assigning '*', then revise AL with the lower value. When multiple process plans with minimum cost exist, choose all of them. In this case, the element corresponding to the changed part is underlined ('_') by inserting the element in the tabu, implying that it was the last part perturbed to create this configuration.
Step 6. During the search process, if the process plan with total minimum cost resulted in bigger value than that of AL, replace
the new AL as this value, and insert the previous process plan in the IL as local optimum by assigning ‘**’.

Step 7. Repeat the search process until a specified number of local optima are tested or a specified CPU time is reached. The best solution with a minimum total cost can be obtained among the local optima in the IL.

4. An Example Problem

An example problem used in previous research by Rajamani et al. [9], Logendran et al. [5], and Ko et al. [4] was adopted to illustrate the steps associated with the algorithm. The problem considered four parts, three machines, and three operations (4P*3M*3O).

Table 1 shows the relationship among part, machine, and operation. It also includes information on demand and volume for each part. The volume is used to estimate the capacity of freight for calculating transportation cost. A big difference with the previous papers is that the operation sequence among the machines in each process is considered in this research. That is the reason why the number 1, 2 or 3 is shown within the matrix instead of 1 as in the papers. For example, part 4 (P4) in Table 1 has two process plans. The first process plan is composed of operations 1, 2, and 3, and the job sequence is also assigned in the same order. The second process plan requires operations 1 and 2 with the same job order. The data in Table 2 indicate that operation 1 can be performed on either machine 1 (M1) or M3, operation 2 on either M2 or M3, operation 3 either M1 or M2. Thus we have eight (2*2* 2) different ways of processing P4 for the first process plan. Likewise, there are four different ways how P4 can be processed by the second process plan.

Table 3 shows the operation time and cost. Table 4 indicates the cost for transporting containers between remote machines by each transportation company. The transportation cost within the same location is assumed to be no additional cost. We also assume that the discount rate of operation cost, \( c_1 = 0.9 \); the penalty rate of operation cost, \( c_2 = 1.5 \); the proper coefficient of operation capability for each machine, \( e_1 = 0.8 \); marginal coefficient of operation capability for each machine, \( e_2 = 2.0 \).

The total cost for each part with every process plan is evaluated as the product of the operation cost and transportation cost by the demand. The number of operation for part 4 is 12 that are composed of 8 from process plan 1 and 4 from process plan 2. Thus, the total combination of operation and transportation for four parts can be generated as 36,864 (=8*12*16*12*
3). The minimum total cost on every part is selected as the case corresponding to the initial feasible solution. The total cost is assigned as the aspiration level (AL). In this case, two other lists, the index list (IL) and the candidate list (CL) are also created. The IL contains the local optima evaluated as the search continues, while the CL consists of potential configurations chosen.

In the given example, the configuration (1,1,1,1;1) was chosen as the initial solution, in which the first four 1’s corresponding to the smallest total cost for each part, and the last 1 in the configuration represents a transporting company. Once the configuration (1,1,1,1;1) is chosen, the total cost for operation and transportation is calculated. The configuration is inserted in the CL, then * is assigned to this case because there is a chance that it can be a local optimal solution.

In the next stage, the search process continues for the adjacent process-transportation plan. Starting from the seed configuration (1,1,1,1;1), the adjacent configuration (2,1,1,1;1) is chosen as the next target. The element corresponds to P1(2) is underlined to indicate that it is now tabu, meaning that it was the last part perturbed to create this configuration. Therefore, the neighbor configuration constitute the available candidate such as (2,1,1,1;1), (1,2,1,1;1), (1,1,2,1;1), (1,1,1,2;1), (1,1,1,1;2). The total expected cost corresponds to 455, 422, 447 and 437 respectively. If the cost 412 for the (1,1,1,1;1) case is smaller than 422 for the (1,1,2,1;1) case in the second stage, it can be local optimal solution. A ‘**’ is assigned for the case because it is already a local optimum with a ‘*’ allocated to it. The configuration is inserted in the IL.

The above process continues until a given number of local optimal solutions are acquired. Table 5 shows the results of the algorithm based on the five partial optimal solutions. The solution obtained in this process was the one chosen from the third process-transportation plan (2,1,2,1;1), where the total cost was 405, which was identical with the optimal solution through enumeration in the solution space. The result implies that minimum cost can be obtained when part 1 and 3 are processed with the second process plan, part 2 and 4 are processed with the fourth process plan, and parts are transported by partner 1.

5. Conclusions

In the face of global competition, the challenges to reduce product costs, improve product quality, substantially shorten time to market and competitive response times have all forced manufacturing companies to consider...
all available new technology and management strategy. This paper proposed a framework of choosing potential manufacturing and transportation partners who were distributed remotely. The proposed algorithm was also proved using complicated problem similar to real world situation. The model proposed

| Table 1  Process Plan and Operation for Each Part |
|---------|---------|---------|---------|
| j=1     | j=2     | j=3     | j=4     |
| p=1     | p=2     | p=1     | p=2     | p=3     | p=1     | p=2     |
| (k) = 1 | 2       | 2       | 1       | 2       | 1       | 3       | 3       | 1       | 1       |
| (k) = 2 | 1       | 3       | 3       | 3       | 3       | 1       | 2       | 2       | 2       |
| (k) = 3 | 2       | 1       | 2       | 1       | 2       | 1       |
| Demand  | 10      | 10      | 10      | 10      |
| Volume  | 10      | 15      | 5       | 20      |

| Table 2  Machine i and Its Capacity for Operation k |
|---------|---------|---------|
| i=1     | i=2     | i=3     |
| (k)=1   | 1       | 1       |
| (k)=2   | 1       | 1       |
| (k)=3   | 1       | 1       |
| Capacity| 100     | 100     | 100     |

| Table 3  Operation Time and Cost Corresponding to Process Plan, Operation, and Machine of Each Part |
|---------|---------|---------|---------|---------|---------|
| p=1     | p=2     | p=1     | p=2     | p=3     | p=1     | p=2     |
| (k)=1   | i=1     | 5.3     | 3.4     | 4.2     | 2.2     | 1.2     | 8.1     | 1.2     | 9.7     |
| (k)=1   | i=3     | 7.2     | 4.3     | 7.5     | 2.2     | 2.4     | 9.2     | 2.1     | 8.9     |
| (k)=2   | i=2     | 3.5     | 9.8     | 7.8     | 3.3     | 5.9     | 2.3     | 9.8     |
| (k)=2   | i=3     | 4.3     | 7.9     | 7.7     | 2.3     | 3.10    | 2.4     | 10.9    |
| (k)=3   | i=1     | 8.8     | 10.9    | 6.5     | 4.7     | 11.7    | 7.4     | 3.5     |
| (k)=3   | i=2     | 7.7     | 8.9     | 6.6     | 3.2     | 8.8     | 9.5     | 2.6     |

in this paper can select transportation partners as well as manufacturers in
order to make the model more appropriate to the SCM environment with emphasis on the importance of transportation efficiency. As future research, the model developed in this paper should be expanded to include warehousing facilities as well as manufactures and transportation companies.

Table 4  Cost for Transporting Containers between Remote Machines by Each Transportation Company

<table>
<thead>
<tr>
<th>O-D</th>
<th>Transportation company</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>a-1</td>
<td>2</td>
</tr>
<tr>
<td>a-2</td>
<td>2</td>
</tr>
<tr>
<td>a-3</td>
<td>3</td>
</tr>
<tr>
<td>1-2</td>
<td>0</td>
</tr>
<tr>
<td>1-3</td>
<td>5</td>
</tr>
<tr>
<td>2-3</td>
<td>7</td>
</tr>
</tbody>
</table>

Note that ‘a’ can be either a starting point or terminal point.

Table 5  Results of The Algorithm

<table>
<thead>
<tr>
<th>No</th>
<th>Combination</th>
<th>Total cost</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1,1,1;1:1)</td>
<td>412</td>
<td>**</td>
</tr>
<tr>
<td>2</td>
<td>(1,1,2;1:1)</td>
<td>422</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(2,1,2;1:1)</td>
<td>405</td>
<td>**</td>
</tr>
<tr>
<td>4</td>
<td>(2,1,2;2:1)</td>
<td>415</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(2,2,2;2:1)</td>
<td>435</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>(3,2,2;2:1)</td>
<td>465</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(4,2,2;2:1)</td>
<td>433</td>
<td>**</td>
</tr>
<tr>
<td>8</td>
<td>(4,2,2;2:2)</td>
<td>497</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>(4,2,2;2:3)</td>
<td>457</td>
<td>**</td>
</tr>
<tr>
<td>10</td>
<td>(4,3,2;2:3)</td>
<td>524</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>(4,3,2;3:3)</td>
<td>501</td>
<td>*</td>
</tr>
<tr>
<td>12</td>
<td>(4,3,2;3:3)</td>
<td>495</td>
<td>**</td>
</tr>
<tr>
<td>13</td>
<td>(4,4,2;3:3)</td>
<td>504</td>
<td></td>
</tr>
</tbody>
</table>

*: Candidate list, **: Index list
Acknowledgement

This research has been supported in part by Kyungsung University in 2002.

References


