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A graph theoretic-based heuristic algorithm for responsive supply chain network design with direct and indirect shipment

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ABSTRACT

The configuration of the supply chain network has a strong influence on the overall performance of the supply chain. A well designed supply chain network provides a proper platform for efficient and effective supply chain management. The supply chain network should be designed in the way that could meet the customer needs with an efficient cost. This paper studies the responsive, multi-stage supply chain network design (SCND) problem under two conditions: (1) when direct shipment is allowed and (2) when direct shipment is prohibited. First, two mixed integer programming models are proposed for multi-stage, responsive SCND problem under two abovementioned conditions. Then, to escape from the complexity of mixed integer mathematical programming models, graph theoretic approach is used to study the structure of the SCND problems and it is proven that both of SCND problems considered in this paper could be modeled by a bipartite graph. Finally, since such network design problems belong to the class of NP-hard problems, a novel heuristic solution method is developed based on a new solution representation method derived from graph theoretic view to the structure of the studied problem. To assess the performance of the proposed heuristic solution method, the associated results are compared to the exact solutions obtained by a commercial.

1. Introduction

Today's competitive business environment leads to many changes in production and distribution systems. One of these important changes goes back to the competition among the supply chains instead of companies. An efficient and responsive supply chain helps firms to satisfy the two polar needs of customers including low delivery time and low price. Supply chain is a network of suppliers, manufacturers, warehouses, and retailers organized to produce and distribute merchandise at the right quantities, to the right locations, and at the right time, in order to minimize total costs while satisfying service level requirements [1]. As a traditional objective, efficiency of the supply chain network is the main objective considered by the researchers and practitioners in supply chain network design. Usually the network efficiency is translated and modeled as cost minimization (e.g. [2,3]) or profit maximization (e.g. [4]) in supply chain network design literature.

Another aspect that should be considered besides cost efficiency is the customer service level. Chopra [5] mentioned that the performance of supply chain network should be evaluated along two dimensions: (1) customer needs and (2) cost of meeting customers need. "On time delivery" plays an important role in customer satisfaction. The ability of supply chain to satisfy the customer's expected delivery time called "supply chain responsiveness" and helps firms for being the order winner in their product-markets [6,7]. According to this point a number of authors have proposed models for optimizing the supply chain network considering cost efficiency and network responsiveness simultaneously (e.g., [6,8]). However, these researches limited themselves to only considering direct shipment or indirect shipment mechanism (see for example [6,8,9]) and no one address both of these shipment mechanisms together and let the model to select the best mechanism as an output decision.

Most of supply chain network design problems can be reduced to capacitated facility location problem (CFLP) which is known to be NP-complete [10]; therefore, most of supply chain network design problems are NP-hard. To cope with the complexity of supply chain network design problems many heuristic algorithms (e.g. [3,11,12]) and metaheuristics such as genetic algorithm (e.g. [8,13]), simulated annealing (e.g. [14,15]), tabu search (e.g. [16,17]), memetic algorithm (e.g. [6]) and scatter search (e.g. [9]) are developed and used by authors in the recent decade. However, still this area needs efficient solution approaches, especially, when real-life features are incorporated in the network design model (e.g., the consideration of network responsiveness and/or indirect shipment besides direct shipment) and the complexity of the resulting model increased.

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The need of more efficient solution approaches overcoming more complex network design models have recently been emphasized by Melo et al. [18] in their comprehensive review article.

Based on the aforementioned descriptions, this paper proposes a network design optimization model as well as an efficient solution method for multi-stage, single product, responsive supply chain network design problem considering both direct and indirect shipment. The proposed graph theoretic-based heuristic algorithm can also be used in a number of problems in other domains (see [19]) such as telecommunication network design (see [20]), facility location and transportation network problems (see [21]) and multi-stage process planning in manufacturing systems (see [22]) with some little modifications.

The main contributions of this paper that differentiate it from the existing ones in the related literature can be summarized as follows:

- Proposing a supply chain network design mathematical model that is able to determine the least cost configuration of the supply chain network considering the network responsiveness as well as both direct and indirect shipment mechanisms. To the best of our knowledge there is no research paper considering both of the abovementioned features in a single model. Also, the proposed model considers penalty cost for non-utilized capacity at opened facilities (i.e., plants and distribution centers) in the objective function.
- Applying a graph theoretic approach to study the structure of the concerned SCND problems and proving that both of the studied problems can be converted to a bipartite graph.
- Proposing an efficient heuristic solution approach for the concerned problem, based on a new solution representation method derived from graph theoretic view to the structure of the studied problem, which is able to generate high quality solutions in a reasonable time.

In the next section the problem is described and possible structures for the studied supply chain networks are classified based on a graph theoretic approach. A novel solution method is proposed to determine the optimal design for the responsive supply chain network in Section 3 and a numerical example and the related results are given in Section 4. Finally a summary of work and some possible future works are given in Section 5.

2. Problem description and formulation

The considered supply chain network is a single product, multi-stage supply chain including plants, distribution centers and customers. As shown in Fig. 1, this network is organized to produce new products in plants and distribute the finished products to customers through distribution centers or directly from plants to customers.

All of the demand of customers should be satisfied and the location of customers are fixed and pre-defined. Also, all the products should be delivered to customers in an allowable delivery time to assure the appropriate supply chain responsiveness level and as a result the customer satisfaction. The maximum allowable delivery time is determined based on the customer's expected delivery time. The main issues to be addressed by this study are to choose the location and determine the number of plants, distribution centers and the quantity of flow between facilities and to choose the best strategy among direct and indirect shipment strategies. Design of this supply chain network may involve a trade-off relationship between the total fixed cost and the total variable cost.

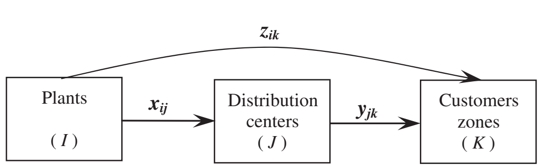

Fig. 1. Structure of the considered supply chain network.

2.1. Problem formulation

The following notation is used in the formulation of the considered supply chain network design model.

Indices

I	Index of candidate locations for plants $i = 1, \ldots, I$
J	Index of candidate locations for distribution centers $j = 1, \ldots, J$
K	Index of fixed locations of customers $k = 1, \ldots, K$

Parameters

d_k	Demand of customer k
f_i	Fixed cost of opening plant i
g_j	Fixed cost of opening distribution center j
a_{ij}	Unit transportation cost from plant i to distribution center j
b_{jk}	Unit transportation cost of from distribution center j to customer k
c_{ik}	Unit transportation cost from plant i to customer k
p_i	Production cost per unit of product at plant i
e_j	Material handling cost per unit of product at distribution center j
h_i	Maximum capacity for plant i
m_j	Maximum capacity for distribution center j
θ_i	Penalty cost per unit of non-utilized capacity at plant i
β_j	Penalty cost per unit of non-utilized capacity at distribution center j
td_{jk}	Delivery time from distribution center j to customer k
ts_{ik}	Delivery time from plant i to customer k
τ_k	Maximum allowable delivery time for customer k (which are determined based on the corresponding customer's expected delivery time)

Variables

X_{ij}	Quantity of products shipped from plant i to distribution center j
Y_{jk}	Quantity of products shipped from distribution center j to customer k
Z_{ik}	Quantity of products shipped directly from plant i to customer k
W_i	$= \begin{cases} 1 & \text{if a plant is opened at location } i, \\ 0 & \text{Otherwise} \end{cases}$
V_j	$= \begin{cases} 1 & \text{if a distribution center opened at location } j, \\ 0 & \text{Otherwise} \end{cases}$

In terms of the above notation, the considered supply chain network design problem can be formulated as follows.

$$\min \quad Z = \sum_i f_i W_i + \sum_j g_j V_j + \sum_i \sum_j (p_i + a_{ij}) X_{ij} + \sum_j \sum_k (e_j + b_{jk}) Y_{jk} + \sum_i \sum_k (p_i + c_{ik}) Z_{ik} \sum_{i \in I} \theta_i \left[W_i h_i - \left(\sum_{j \in J} X_{ij} + \sum_{k \in K} Z_{ik} \right) \right] + \sum_{j \in J} \beta_j \left[\left(V_j m_j - \sum_{k \in K} Y_{jk} \right) \right] \tag{1}$$

$$\sum_i Z_{ik} + \sum_j Y_{jk} = d_k \quad \forall k \tag{2}$$

$$\sum_i X_{ij} = \sum_k Y_{jk} \quad \forall j \tag{3}$$

$$Y_{jk} td_{jk} \leqslant Y_{jk} \tau_k \quad \forall j, k \tag{4}$$

$$Z_{ik} ts_{ik} \leqslant Z_{ik} \tau_k \quad \forall i, k \tag{5}$$

$$\sum_k Z_{ik} + \sum_j X_{ij} \leqslant W_i h_i \quad \forall i \tag{6}$$

$$\sum_i Y_{jk} \leqslant V_j m_j \quad \forall j \tag{7}$$

$$W_i, V_j \in \{0, 1\} \quad \forall i, j \tag{8}$$

$$X_{ij}, Y_{jk}, Z_{ik} \geqslant 0 \quad \forall i, j, k \tag{9}$$

Objective function (1) minimizes the total cost including fixed opening costs, processing and transportation costs and penalty costs for non-utilized capacities at plants and distribution centers. Constraint (2) assures that all the demands of customers are satisfied. Constraint (3) ensures the flow balance at distribution centers. Constraints (4) and (5) ensure that all the products are delivered to customers in the maximum allowable delivery time. Constraints (6) and (7) are capacity constraints on plants and distribution centers. Constraints (8) and (9) are related to the binary and non-negativity restrictions on the corresponding decision variables.

In some cases direct shipment is not possible. If direct shipment is prohibited in the supply chain network the model could be rewritten as follows:

$$\begin{aligned} \min \quad Z = {} & \sum_i f_i W_i + \sum_j g_j V_j + \sum_i \sum_j (p_i + a_{ij}) X_{ij} + \sum_j \\ & \times \sum_k (e_j + b_{jk}) Y_{jk} + \sum_{i \in I} \theta_i \left[W_i h_i - \sum_{j \in j} X_{ik} \right] \\ & + \sum_{j \in J} \beta_j \left[\left(V_j m_j - \sum_{k \in K} Y_{jk} \right) \right] \end{aligned} \tag{10}$$

$$\sum_j Y_{jk} = d_k \quad \forall k \tag{11}$$

(3) and (4)

$$\sum_j X_{ij} \leqslant W_i h_i \quad \forall i \tag{12}$$

(7)–(9)

2.2. Graph theoretic view

In this subsection graph theoretic approach is used to study the structure of the two abovementioned problems.

Definition 1 (Diestel [23]). A graph $G = (V, E)$ is called r-partite ($r \geqslant 2$) graph if V admits a partition into r classes such that every edge has its end in different classes, i.e., vertices in the same partition class must not be adjacent.

It is obvious from this definition that the structure of the considered problem – when direct shipment is allowed – could be presented by a tripartite graph that plants, distribution centers and customers constitute the three disjoint set of vertices (see Fig. 2). As a potential structure, all the edges are presented in Fig. 2, therefore the presented graph is a complete tripartite graph. However, in the final solution some edges and vertices may not be existed.

Also, the structure of the studied problem when direct shipment is prohibited is illustrated in Fig. 3. It can be proven that this graph is a bipartite graph.

Lemma 1. *When direct shipment is prohibited the structure of the considered supply chain network can be presented by a (I + K) by (J) bipartite graph (K_{I+k}, J).*

Proof. Since every graph is bipartite if and only if it is 2-colorable, the lemma can be proven by labeling (coloring) the graph illustrated in Fig. 3 with two labels (or colors) as illustrated in Fig. 4. It should be noted that a coloring of a graph means a labeling of the graph's vertices with colors such that no two vertices sharing the same edge have the same color and a graph that can be colored by k colors is k-colorable. □

Finally it can be proven that the tripartite structure of the considered supply chain network – when direct shipment is allowed – can be converted to a bipartite graph.

Lemma 2. *In the case that direct shipment is allowed, the tripartite structure of the considered supply chain network can be converted to a (I + K) by (J + I) bipartite graph ($K_{I+k,\ J+I}$).*

Proof. To convert the tripartite graph presented in Fig. 2, first we have inserted some dummy distribution centers (nodes) in the network as illustrated in Fig. 5.

The number of inserted dummy distribution centers is equal to number of potential plants. These dummy distribution centers are always open and have no fixed costs, material handling costs and non-utilized capacity penalty costs ($g = 0$, $\beta = 0$, $e = 0$). Also the transportation costs/delivery times from them to customers are also equal to transportation cost/delivery time of direct shipment from the corresponding plants to customers. It should be mentioned

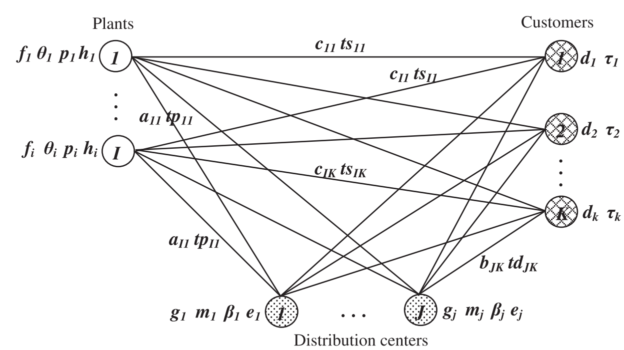

Fig. 2. The graph of the studied supply chain network when direct shipment is allowed.

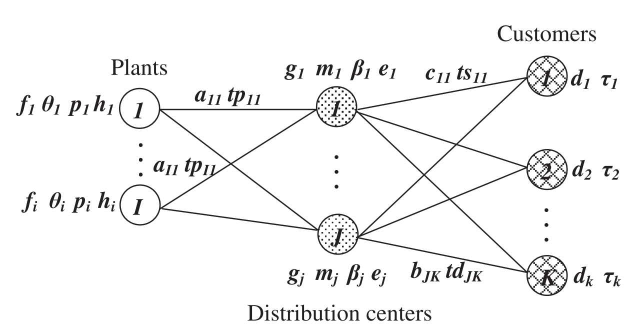

Fig. 3. The graph of the studied supply chain network when direct shipment is prohibited.

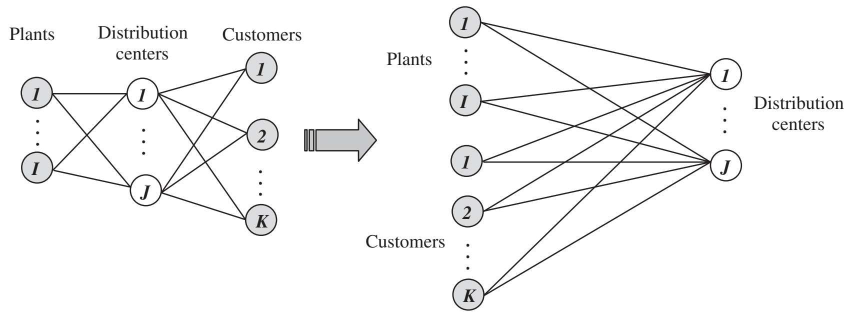

Fig. 4. Bipartite graph of the studied supply chain network when direct shipment is prohibited.

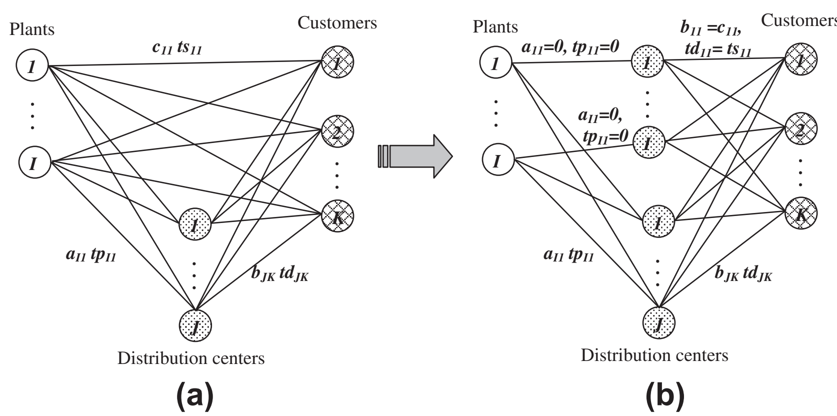

Fig. 5. Converting the tripartite structure to a bipartite graph.

that the transportation costs/delivery times between plants to dummy distribution centers is equal to zero and the capacity of dummy facilities is equal to the corresponding plants. The resulted graph, Part (b) of Fig. 5, is a bipartite graph. The proof is straight forward by using Lemma 1. It should be noted that shipment is only allowed from plant i to dummy distribution center j that $i = j$, but for non-dummy distribution centers there is no limitation. □

3. Heuristic solution approach

In this section a heuristic solution method is developed based on the graph theoretic view discussed in the previous section.

3.1. Solution representation

As the body of literature shows, many different methods have been developed for solution representation in heuristic and meta-heuristic solution methods (e.g. [24,25]). One of these methods that has been applied for supply chain network design problem is the matrix method attributed to Michalewicz et al. [25]. In this method, the solution is represented by a $|K| \cdot |J|$ matrix in which $|J|$ denotes the number of sources and $|K|$ represents the number of depots. Gen and Cheng [26] developed a spanning tree method that uses Prüfer numbers for solution representation. In this method, solutions are presented by arrays of size $|K| + |J| - 2$. Since this method may result in infeasible solutions, repair mechanisms are developed to avoid infeasibility. As an alternative, Gen et al. [27] proposed a priority-based encoding method that does not need a repair mechanism. In this approach, solutions are presented as arrays of length $|K| + |J|$, in which the value in cells represents the priorities and the position of each cell represents the sources and depots.

As it was shown in the previous section, both of the SCND problems considered in this paper can be presented by a bipartite graph. Based on this result, a $|J|$ by $|I + K|$ matrix is used to represent the solution. Which $|J|$ denoted the number of potential distribution centers and $|I|$ and $|K|$ represent the number of potential plants and customers respectively. It is obvious that when direct shipment is allowed the solution can be presented by a $|I + J|$ by $|I + K|$ matrix (i.e., $|J_{new}| = |I + J|$). An illustrative example for this representation method is given in Fig. 6.

		Plants (I)		Customers (K)		
		1	2	1	2	3
Distribution centers (J)	1	200	0	100	0	100
	2	0	0	0	0	0
	3	150	0	0	150	0

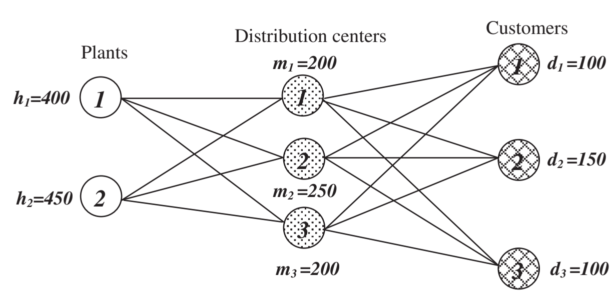

Fig. 6. A sample of SCND problem and its encoding.

To find a feasible solution for the SCND problem, we divide the problem into two sections: (1) customers-distribution centers section and (2) distribution centers-plants section. The following algorithm is used to generate a feasible solution for each of the sections.

Algorithm 1: Solution generation algorithm.

Inputs:
- *J:* Set of sources
- *K:* Set of depots
- d_k: Demand on depot *k*
- Ca_j: Capacity of source *j*
- $Value_{jk}$: Value of arc (*j*, *k*) that is determined according to fixed opening cost, processing cost and transportation costs (see Algorithm 2 for detail).
- *TB:* Set of arcs that products cannot shipped through them, because their delivery times violate the maximum allowable delivery time

Outputs:
- v_{jk}: Amount of shipment between nodes
- Y_j: Binary variable shows the opened facilities

Step 1: $v_{jk} = 0 \quad \forall j \in J, k \in K$

While $\sum_k d_k \geqslant 0$

Step 2: Select a node from set of active depots and sources randomly. Active depots are depots that have nonzero demands and active sources are sources that have nonzero capacities.
$l = \text{select random}\{I + J | if\ \ l \in j,\ \ Ca_j \neq 0$
$\&\ if\ l \in k,\ \ d_k \neq 0\} \forall j \in J, k \in K$

Step 3: $j^* = \arg\min\{Value_{jk} | (j,k) \notin TB\ \&\ Ca_j \neq 0\}$
else $j^* = l$ and select a depot with minimum value
$k^* = \arg\min\{Value_{jk} | (j,k) \notin TB\ \&\ d_k \neq 0\}$

Step 4: $v_{j^*k^*} = \min(Ca_{j^*}, d_{k^*})$
Update demands and capacities
$Ca_{j^*} = Ca_{j^*} - v_{j^*k^*}, d_{k^*} = d_{k^*} - v_{j^*k^*}$

end of loop

Step 5: **For** *1 to J*
if $\sum_{k \in K} v_{jk} \geqslant 0$, ***then*** $Y_j = 1$

End

To form a complete solution for SCND problem, Algorithm 1 should be run twice. First, the algorithm should be run for distribution centers and customers and secondly, it should be run for distribution centers and plants. In addition to simplicity of the solution representation method, this method also ensures the feasibility of the generated solution.

3.2. Heuristic algorithm

According to the above descriptions, the proposed heuristic algorithm is outlined as follows:

Algorithm 2: Heuristic algorithm for SCND problem.

Step 1: If direct shipment is allowed in the considered SCND problem, convert the problem structure into a bipartite graph by using Lemma 2 ("*J*" represent the number of distribution centers including both dummy and non-dummy distribution centers).

Step 2: Determine $TB = \{(j,k) | td_{jk} > \tau_k, j \in J, k \in K\}$ which represents the list of arcs that products cannot shipped through them because their delivery time violate the maximum allowable delivery time.

Step 3: Calculate the value of arcs between plants (*I*) and distribution centers (*J*) using the following equation.
$Value(i,j) = f_i/h_i + a_{ij} + p_i \quad \forall i \in I, j \in J$
Calculate the value of arcs between distribution centers (*J*) and customers (*K*) using the following equation.
$Value(j,k) = g_i/m_i + b_{ij} + e_i \quad \forall j \in J, k \in K$

Step 4: Form the initial solution ($X_{initial}$: a |*J*| by |*I* + *K*| matrix) using Algorithm 1 twice; first for distribution centers (*J*) and customers (*K*) and secondly for plants (*I*) and distribution centers (*J*).
$X^* = X_{initial}, f(X^*) = f(X_{initial})$

Step 5: **For** *it* = 1 to 50 + (*I* + *J* + *K*)/5 Form a solution (X_{temp}: a |*J*| by |*I* + *K*| matrix) using Algorithm 1 twice; first for distribution centers (*J*) and customers (*K*) and secondly for plants (*I*) and distribution centers (*J*).
For *jt* = 1–10 + (*J* + *K*)/10
Use Algorithm 1 for plants (*I*) and distribution centers (*J*) on X_{temp} and find a new solution (X_{new})
if $f(X_{new}) \geqslant f(X_{temp})$ then $f(X_{temp}) = f(X_{new})$, $X_{temp} = X_{new}$
if $f(X_{temp}) \geqslant f(X^*)$ then $f(X^*) = f(X_{temp})$, $X^* = X_{temp}$

Step 6: Return the final solution (X^*, $f(X^*)$)

With the aid of test problems, the parameters of the heuristic algorithm are tuned by changing their values and comparing the results. As is indicated in the abovementioned algorithm, the number of outer and inner loop iterations is determined according to the size of the SCND problem.

4. Computational results

To evaluate the performance of the proposed heuristic algorithm, the results of the heuristic algorithm are compared to the solutions obtained by LINGO 8.0 optimization software on five test problems. It should be noted that LINGO 8.0 solves the problems by branch-and-bound algorithm and guaranteed to find the global optimal solution. The sizes of the test problems are selected in the range of the test problems existed in the recent literature (e.g. [11,27]). The parameters in each size of test problems are generated randomly using uniform distributions specified in Table 1. Also, the heuristic algorithm is coded in MATLAB 7.0 and all the tests are carried out on a Pentium dual-core 1.60 GHz computer with 1 GB RAM.

To compare the optimal solutions obtained by LINGO 8.0 to the results of the heuristic algorithm, the percentage of error, that

Table 1
The values of the parameters used in test problem.

Parameter	Range
d_k	~uniform (550, 800)
f_i	~uniform (28,00,000, 35,00,000)
g_j	~uniform (22,00,000, 26,00,000)
$a_{ij}\ b_{jk}$	~uniform (8, 12)
c_{ik}	~uniform (10, 18)
p_i	~uniform (10, 15)
e_j	~uniform (8, 12)
h_i	~uniform (3000, 4500)
m_j	~uniform (2200, 3200)
θ_i	~uniform (40, 100)
β_j	~uniform (25, 50)
td_{jk}	~uniform (6, 12)
τ_k	~uniform (10, 12)
ts_{ik}	~uniform (10, 16)

Table 2
Computational results.

Problem size $I*J*K$	Heuristic objective value			Heuristic average time (s)	LINGO objective value	LINGO time (s)	Error (%)	Standard deviation	SD/obj. ave.
	Max	Min	Ave						
$5*15*10$	71,26,880	71,06,580	71,14,700	7	68,58,000	3	3.7	11118.77	0.0015
$10*30*50$	362,07,440	361,75,700	361,91,096	18	358,80,340	320	0.86	13,002	0.0003
$15*40*60$	397,75,820	395,62,180	396,48,032	35	390,84,420	1951	1.44	89049.85	0.0022
$20*50*80$	537,94,600	537,38,000	538,49,496	61	531,74,500[a]	43,256	1.26	100099.7	0.0018
$40*70*100$	645,90,000	644,12,740	644,97,876	143	634,35,900[a]	43,795	1.67	80920.64	0.0012

[a] Best objective function value obtained by LINGO after about 12 h.

shows the deviation of Z value (the value of the objective function) of the heuristic algorithm (H.Z) from the optimal value of Z obtained by LINGO (L.Z), is used as quality criterion. The percentage of error is calculated according to the following equation.

$$\%\text{error} = \frac{\text{H.Z} - \text{L.Z}}{\text{L.Z}} \times 100$$

For each test problem the heuristic algorithm is run for five times and the average of the corresponding Z values is used to calculate the error percentage. Also, the standard deviation of the heuristic algorithm per average of objective value is used to evaluate the stability of the proposed heuristic algorithm. The results of the comparison between heuristic algorithm and LINGO are reported in Table 2.

As the computation times show (see Table 2), LINGO takes about 1951 s to find the optimal solution for the test problem "$15*40*60$", and for problems "$20*50*80$" and "$40*70*100$" could not find the optimal solution in 12 h. Therefore, the results of the heuristic algorithm are compared to the best objective value obtained by LINGO in 12 h in the last two test problems (i.e., problems "$20*50*80$" and "$40*70*100$").

As the results show, the solution errors vary from 0.86% to 3.7% for different test problems. Usually the largest error for heuristic algorithms occurred on large-sized problems (see [14,28]), however the largest error for the proposed heuristic algorithm occurred on the smallest test problem (i.e., problem "$5*15*10$"). This result could be explained by the lack of search time in small-sized problems, causing the heuristic algorithm to find solutions with lower quality. On the other hand, on large-sized test problems, the heuristic algorithm generates high quality solutions with significantly lower computation times compared to LINGO computation times (see also Fig. 7). As illustrated in Fig. 7, for small-sized problems, the gap between computation times is not very significant, but the gap tends to widen as the problem size increases. An important characteristic of the proposed heuristic algorithm is the very low computation time of the algorithm, in which it takes only 143 s to find the near optimal solution for large-sized problem "$40*70*100$". In addition, the ratio of the standard deviations per averages of the objective values is less than 0.0022 in all of the test problems, thus, it seems that the heuristic algorithm generates stable range of solutions for each test problem.

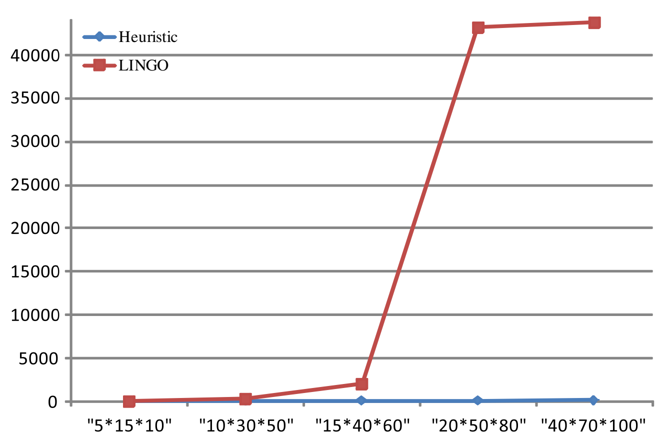

Fig. 7. Heuristic computation time vs. LINGO computation time.

Totally, it can be concluded that since the CPU times for the heuristic algorithm are significantly lower than the LINGO computation times, especially in large-sized problems, and the deviation of the heuristic solutions from the optimal value is narrow, using the heuristic algorithm is quite acceptable in the case of large-sized problems.

5. Conclusions

The design of the supply chain network is the most important strategic decision in supply chain management. This paper studies the responsive SCND problem under two conditions: (1) when direct shipment is allowed and (2) when direct shipment is prohibited. To this aim, first, two mixed integer programming models are developed. The proposed models are multi-stage, capacitated SCND models aimed at making a reasonable balance between fixed opening costs, variable transportation and processing costs and penalty costs for non-utilized capacity at opened facilities to determine the least cost configuration of the concerned supply chains. To escape from the complexity of mixed integer mathematical programming models, graph theoretic approach is used to study the structure of the SCND problem in this paper. Also, it is proven that SCND problems considered in this paper could be modeled by a bipartite graph. A heuristic solution method is proposed based on a new encoding method derived from the bipartite structure of the studied problems to solve the proposed responsive, multi-stage SCND models. The performance of the proposed heuristic solution method is investigated by comparing the associated results with the exact solutions obtained by a commercial solver in a set of problems.

To the best of our knowledge, this research is one of the primary works using graph theoretic approach for SCND problem and the literature considering this approach in SCND is still scarce. Therefore, many possible future research avenues can be defined in this context. For example using graph theoretic approach to study the closed-loop or multi-product SCND problems and to analyze the adaptability of the designed supply chain networks or taking into account the uncertainty in SCND problems that may results in stochastic or fuzzy optimization models are attractive future research avenues. Also, providing new efficient heuristic solution approaches based on graph theoretic view or extending the proposed solution method for multi-objective SCND problems is another attractive research line for future. As mentioned in Section 1, the structure of some other problems such as telecommunication network design, facility location and transportation network design and multi-stage process planning problems are somehow similar to the structure of the studied SCND problem. Therefore, the proposed heuristic method in this paper can be modified and extended to solve the abovementioned problems. Moreover, since tripartite graph structure while the time on edges are taken into account is connected with timetabling problems, this problem can also be considered as another potential area for further extensions.

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