A Multi-criteria Model for Supplier Selection and Supply Chain Network Design

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ABSTRACT

Due to increased globalization and uncertainty in business environments, supply chains become more susceptible to disruptions. Therefore, risk management must be designed-in when making supply chain decisions. The objective of this study is to propose a multi-criteria, mixed integer, linear programming model to solve supplier selection and supply chain network-design decisions. We consider supply chain profit, supply dispersion, and supply resilience as objective functions. The proposed model is solved using a non-preemptive goal programming technique with multiple weight sets. We provided a numerical example to illustrate the usefulness of the model.

Keywords: Supply chain network design, Dispersion, Resilience, Goal programming, Multi-criteria decision making

INTRODUCTION

Supplier selection and supply chain network design are strategic and long-term decisions that are critical to an organization's success. Selecting the right facilities affects supply chain efficiency and profitability (Mendoza et al., 2008). Once these decisions have been made, disruptions can occur at any time due to several causes, such as bad weather conditions, economic crises, and natural disasters (Atoei et al., 2013). Due to increased globalization, the selection of countries or locations for facilities are important to business resilience (FMGlobal, 2015). Dispersion of facilities affects the likelihood and severity of a supply chain to disruptions (Falasca et al., 2008; Rienkhemaniyom and Pazhani, 2015). For these reasons, redundancy and/or flexibility in a network is important (Atoei et al., 2013). This paper develops a multi-criteria mathematical model to support supplier selection and supply chain network-design decisions with respect to profitability, supplier-based dispersion, and supplier resilience objectives.

MATERIALS AND METHODS

Literature review

Supplier selection and supply chain network-design decisions are strategic and long-term decisions that contribute to the competitive advantages of supply chains (Simchi-Levi et al., 2008). Once decisions have been made, they are difficult to alter. Due to dynamics, complexity, and uncertainty, selecting suppliers and designing a supply chain network should be resilient, in order to cope with potential disturbances (Mari et al., 2015)

The supplier selection problem usually determines which suppliers should be selected and the order quantity that should be assigned to them (Scott et al., 2015). Weber et al. (1991), De Boer et al. (2001), and Ho et al. (2010) have presented comprehensive reviews of criteria and methods supporting supplier selection problems. Supplier selection criteria that are widely used include price, delivery, quality, production facilities and capabilities, and geographical location (Meixell and Gargeya, 2005; Mendoza et al., 2008). For example, Ng (2008) proposed using weighted linear programming for a multi-criteria supplier selection problem. The author considered supply variety, quality, distance, delivery, and price as selection criteria. Wu (2009) presented a supplier selection model using integrated data envelopment analysis (DEA), decision tree, and neural network techniques. The author considered quality management practices and systems, documentation and self-audit, process and manufacturing capability, management of firm, design and development capabilities, and cost reduction capability as input criteria, while quality, price, delivery, cost reduction performance, economic environment, and location were considered as output criteria. Recent supplier selection studies have increasingly emphasized lower supply risk and improved supply chain resilience (Scott et al., 2015). Additional criteria have been incorporated to address risk and resilience aspects. For example, Chan and Kumar (2007) developed a multi-attribute decision-making framework for global supplier selection considering cost, quality, service performance, supplier's profile, and risk factors as selection criteria. Risk factors include geographical location of supplier and its country, political stability, economy, and terrorism. The authors applied a fuzzy extended analytic hierarchy process (FEAHP) to solve the problem. Haldar et al. (2012) solved a supplier selection problem using an AHP-QFD (analytic hierarchy process-quality function deployment) approach. The authors rated suppliers' resilience based on five criteria:, supply chain density, supply chain complexity, responsiveness, node criticality, and re-engineering. Scott et al. (2015) proposed a decision support system for supplier selection and order allocation problem for a bioenergy industry. AHP-QFD and a chance-constrained optimization algorithm were used to select appropriate suppliers and allocate orders. The authors incorporated stakeholder requirements to address potential risk issues. Some of the supplier selection and order allocation studies have extended the models to handle uncertain information. For instance, Torabi et al. (2015) proposed a scenario-based, bi-criteria, possibillistic, mixed-integer, linear programming model to create a resilient supply base under operational and disruption risks. The authors incorporated the concept of a business continuity management system (BCMS) into the model. Several resilience strategies were integrated in this study, e.g., multiple sourcing, fortification of some suppliers, extra inventory, backup suppliers, and recovery levels of suppliers. Memon et al. (2015) proposed an integrated grey system theory and uncertainty theory approach to select the best suppliers and determine order quantities. The grey system theory was used to handle possible uncertainty due to a lack of information or lack of clearness about qualitative criteria, while the uncertain theory was used to handle uncertainty of quantitative criteria. The authors used goal programming technique to solve the problem under uncertain demand and lead time. Moghaddam (2015) proposed a fuzzy, multi-objective, mathematical model to rank suppliers and allocate the optimal number of new, refurbished, and final product for a reverse logistics network configuration. The author considered uncertainty in demand, suppliers' capacity, and percentage of returned products. Monte Carlo simulation and fuzzy goal programming were used to create a set of Pareto-optimal solutions.

A supply chain, network design problem usually determines the number, location of facilities, and flows between them. Traditional supply chain network design models emphasized cost/profit, customer responsiveness, and response time (Beamon, 1998; Min and Zhou, 2002). Relevant global risk issues that were incorporated in the models include tariffs and duties, exchange rate, and income tax (Meixell and Gargeya, 2005). Recent supply chain network design has broadened in scope beyond just cost efficiency. Major efforts have been devoted to developing supply chain network design models that consider disruptions (Snyder et al., 2006). Klibi and Martel (2012) proposed a three-phase risk modeling approach for supply chain network design under uncertainty. The authors characterized the future supply chain environment into hazards, vulnerability sources, and exposure levels. A Monte Carlo approach is used to generate plausible scenarios. Atoei et al. (2013) formulated a reliable capacitated supply chain network design model considering random disruptions at distribution centers and suppliers. The authors modeled disruptions using a scenario-based approach and allowed a different range of capacity disruption at suppliers and DCs. Garcia-Herreros et al. (2014) formulated a two-stage stochastic programming model to design a resilient supply chain network considering risk of facility disruptions. A scenario-based approach is used to describe disruption at potential DCs. The objective is to minimize the sum of investment cost and expected distribution cost. Mari et al (2014) presented a mathematical model for designing a sustainable and resilient supply chain network. This study considered four objective functions: cost, carbon emission, carbon footprint, and disruption cost. The model was solved using a weighted, goal-programming approach.

From the review, it is important to incorporate a resilience aspect at both the firm and country level to enhance the resilience of supplier selection and supply chain network design decisions. This paper presents a multi-criteria mathematical model that integrates supplier selection and supply chain network decisions. The model consists of three objectives: supply chain profit, supply dispersion, and supply resilience. The consideration of supply dispersion in this study is motivated by the fact that supply chain network structure has an important relationship to supply chain disruptions (Falasca et al., 2008) and most studies do not explicitly incorporate supply network structure in their decisions. Recently, Rienkhemaniyom and Pazhani (2015) proposed a bi-criteria model to support a supply chain network design problem. The authors incorporated supply density as one of the objective functions. In this model, the number of suppliers to be selected is not limited. The results showed that a supply chain network that primarily emphasizes profit maximization tends to be centralized supplier-based, whereas a bi-criteria model tends to be decentralized supplier-based. In addition, a smaller number of suppliers were selected compared to a bi-criteria model. In this paper, we quantify supply dispersion based on a supply density proposed in Rienkhemaniyom and Pazhani (2015). We also limit the maximum number of suppliers to be selected. In terms of supply resilience, we incorporate the resilience index of the country where a supplier is located as a supplier resilience parameter. The supplier resilience parameter is based on the resilience index of FMGlobal (2015), which is quantified from three factors; economic, risk quality, and supply chain. Each factor has three corresponding drivers. The drivers of the economic factor are GDP per capita, political risk, and oil intensity. The drivers of the risk quality factor are exposure to natural hazards, quality of natural hazard risk management, and quality of fire risk management. The drivers of the supply chain factor are control of corruption, infrastructure, and local supplier quality. The scores are bound on a scale of 0 to 100. A high resilience index value is preferable.

The main contribution of this study for supplier selection and supply chain network design model compared to the published literature is its incorporation of supplier-based structure and country resilience into the design.

Mathematical model

This section discusses a multi-criteria mathematical model for an integrated supplier selection and supply chain network design. The research proposes a framework to support decision making as shown in Figure 1.

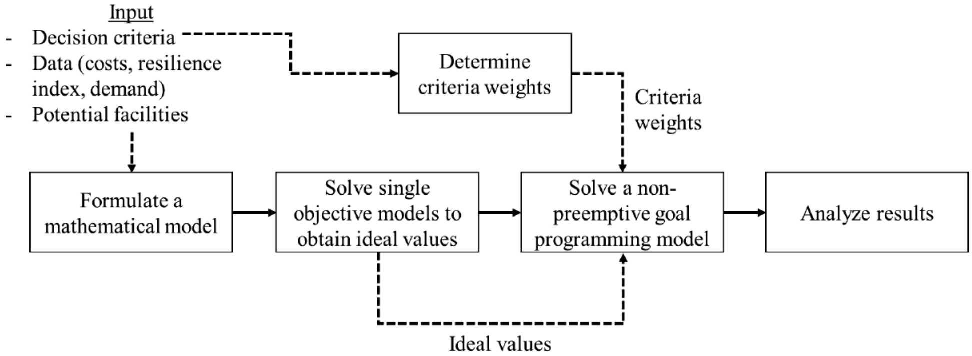

Figure 1. Supplier selection and supply chain network design framework.

Notations and model assumptions are as follows:

Indices

s	Index of suppliers s = 1,2,..., S
m	Index of manufacturing plants m = 1,2,..., M
w	Index of warehouses w = 1,2,..., W
c	Index of retailers c = 1,2,..., C
l	Index of warehouse capacity levels l = 1,2,..., L
i	Index of origin facilities $i \in S \cup M \cup W$
j	Index of destination facilities $j = M \cup W \cup C$

Parameters

cap_m	Production capacity at manufacturing plant m
cap_s	Capacity at supplier s
cap_w^l	Capacity of warehouse w of size l
d_c	Demand for products at retailer c
dis_{ij}	Distance between facilities i and j in the supply chain
msm	Minimum shipping quantity from suppliers to manufacturers
p_{sm}	Purchasing cost of material from suppliers by plant m
tr_{mw}	Transportation cost per unit from plant m to warehouse w
tr_{wc}	Transportation cost per unit from warehouse w to retailer c
pc_m	Production cost for a product at plant m
np	Price of a product
f_w^l	Fixed cost of opening a warehouse w of capacity level l
ls_c	Lost sales cost at retailer c
$svar_s$	Resilience factor of supplier s
mas	Maximum number of suppliers to be selected

Decision variables

QSM_{sm}	Quantity of raw material purchased from supplier s by plant m
QMW_{mw}	Quantity of products shipped from plant m to warehouse w
QWC_{wc}	Quantity of products shipped from warehouse w to retailer c
LD_c	Quantity of sales lost at retailer c
σ_s	Flow weight of supplier s
$S\alpha_{sm}$	Binary parameter = 1 if supplier s supplies raw material to plant m, = 0 otherwise
δ_w^l	Binary parameter = 1 if warehouse w of capacity level l is selected, = 0 otherwise
$S\beta_{ss'm}$	Binary parameter = 1 if suppliers s and s' supply raw material to plant m, = 0 otherwise
$S\beta'_{ss'm}$	Binary parameter = 1 if either one of suppliers s and s' supplies raw material to plant m, = 0 otherwise
SUP_s	Binary parameter = 1 if suppliers s is selected, = 0 otherwise

The following are the assumptions considered in this research:

- demands at the retailers are deterministic.
- the candidate suppliers and warehouses are predetermined.
- transportation cost from supplier to plant is included in the purchasing cost.

Objective functions. The proposed supply chain network design model considers three criteria: maximizing supply chain profit, maximizing supply dispersion, and maximizing supply resilience. The objective functions are formulated as follows:

Supply chain profit (z_1): supply chain profit is the difference between revenue and total cost, which consists of purchasing cost, fixed cost for opening warehouses, production cost, transportation cost between plants and warehouses, transportation cost between warehouses and retailers, and lost sales cost. It can be formulated as Equation (1).

$$\begin{aligned} z_1 = np\left(\sum_{w\in W}\sum_{c\in C} QWC_{wc}\right) - \left(\sum_{s\in S}\sum_{m\in M} p_{sm}QSM_{sm}\right) - \left(\sum_{w\in W}\sum_{l\in L} f_w^l \delta_w^l\right) \\ - \sum_{m\in M} pc_m\left(\sum_{w\in W} QMW_{mw}\right) - \left(\sum_{m\in M}\sum_{w\in W} tr_{mw}QMW_{mw}\right) \\ - \left(\sum_{w\in W}\sum_{c\in C} tr_{wc}QWC_{wc}\right) - \left(\sum_{c\in C} ls_c LD_c\right) \end{aligned} \tag{1}$$

Supply dispersion (z_2): supply dispersion is the average distance among suppliers and plants per unit of demand, which is the sum of inter-stage distance between suppliers and manufacturing plants and the intra-stage among suppliers and plants, divided by total demand. To avoid the high concentration of suppliers, the higher average distance among suppliers and plants is preferred. Hence, we maximize the supply dispersion. We quantify supply dispersion as Equation (2).

$$z_2 = \frac{1}{\sum_{c\in C} d_c}\left(\sum_{s\in S}\sum_{m\in M} dis_{sm}S\alpha_{sm} + \sum_{m\in M}\sum_{s\in S}\sum_{\substack{s\prime\in S\\ s\neq s\prime, s<s\prime}} dis_{ss\prime}S\beta_{ss\prime m}\right) \tag{2}$$

Supply resilience (z_3): supply resilience is the total resilience score of suppliers. Countries, where suppliers are located, have different resilience levels to disruptions. If a supplier with a high resilience level accounts for a large amount of material flow, the resilience of the supply chain would be high. Hence, raw material should be allocated to each supplier such that the flow weighted resilience value of the whole supply chain is maximized. We quantify the supply resilience as shown in Equation (3).

$$z_3 = \sum_{s} svar_s \sigma_s$$

where
$$\sigma_s = \left(\sum_{m \in M} QSM_{sm} \right) \Big/ \left(\sum_{c \in C} d_c \right) \tag{3}$$

As mentioned above, the supplier resilience parameter ($svar_s$) can be obtained from the resilience index reported in FMGlobal (2015).

Constraints.

Supplier capacity: Equation (4) ensures that the quantity of raw materials supplied by suppliers to all the manufacturing plants should not exceed its capacity.

$$\sum_{m \in M} QSM_{sm} \leq cap_s \qquad \forall s \in S \tag{4}$$

Inter-stage flow: Equation (5) ensures that the shipment between a supplier and a manufacturing plant meets the minimum requirement and cannot exceed a supplier's capacity.

$$msmS\alpha_{sm} \leq QSM_{sm} \leq cap_S S\alpha_{sm} \quad \forall s \in S, m \in M \tag{5}$$

Inter-stage flow binary variable: Equations (6) and (7) relate to binary variables for the intra-stage flow of the supplier stage. If both suppliers *i* and *j* supply raw material to plant *m*, the binary variable $S\beta_{ijm} = 1$ and $S\beta'_{ijm} = 0$. If one of suppliers *i* and *j* supply raw material to plant *m*, then $S\beta'_{ijm} = 1$ and $S\beta_{ijm} = 0$. If none of suppliers *i* and *j* supply raw material to plant *m*, then $S\beta_{ijm}$ and $S\beta'_{ijm} = 0$. Equation (7) ensures that only one of the above three cases can be true.

$$2S\beta_{ijm} + S\beta'_{ijm} = S\alpha_{im} + S\alpha_{jm} \qquad \forall (i,j) \in S, i \neq j, m \in M \tag{6}$$

$$S\beta_{ijm} + S\beta'_{ijm} \leq 1 \qquad \forall (i,j) \in S, i < j, m \in M \tag{7}$$

Production capacity: Equation (8) ensures that the total shipment from plant m to all warehouses cannot exceed the plant capacity.

$$\sum_{w \in W} QMW_{mw} \leq cap_m \quad \forall m \in M \tag{8}$$

Material flow between suppliers and plants: Equation (9) ensures that the quantity of raw material shipped to plant m is equal to the quantity of products shipped out of that plant to warehouses.

$$\sum_{s\in S} QSM_{sm} = \sum_{w\in W} QMW_{mw} \quad \forall m \in M \tag{9}$$

Warehouse capacity: Equation (10) ensures that the quantity of products shipped to warehouse w does not exceed the warehouse storage capacity. Equation (11) ensures that only one level of warehouse capacity can be opened.

$$\sum_{m\in M} QMW_{mw} \le \sum_{l\in L} cap_w \delta_w \quad \forall w \in W \tag{10}$$

$$\sum_{l\in L} \delta_w^l \le 1 \quad \forall w \in W \tag{11}$$

Product flows between warehouses and retailers: Equation (12) ensures that the quantity of products shipped to warehouse w is equal to the amount of new products shipped out of that warehouse to retailers.

$$\sum_{m\in M} QMW_{mw} = \sum_{c\in C} QWC_{wc} \quad \forall w \in W \tag{12}$$

Demand requirement: Equation (13) ensures that the total quantity of products shipped to retailer *c* and the lost sales at the retailer *c* should be equal to the demand at that retailer.

$$\sum_{w\in W} QWC_{wc} + LD_c = d_c \quad \forall c \in C \tag{13}$$

Number of selected suppliers: Equation (14) ensures that the binary variable SUP_s is set to 1, when supplier *s* supplies raw material to plants. Note that M is a large positive number. Equation (15) ensures that the total number of selected suppliers cannot exceed the maximum limit.

$$\sum_{m\in M} QSM_{sm} \le MSUP_s \quad \forall s \in S \tag{14}$$

$$\sum_{s\in S} SUP_s \le mas \tag{15}$$

Non-negativity and binary conditions: Equations (16) and (17) describe non-negativity and binary conditions of the decision variables.

$$QSM_{sm}, QMW_{mw}, QWC_{wc}, LD_c \ge 0 \tag{16}$$

$$\delta_w^l, S\alpha_{sm}, S\beta_{ss'm}, S\beta'_{ss'm}, SUP_s \in \{0,1\} \tag{17}$$

Solution technique

This paper uses a non-preemptive goal programming (NPGP) approach, which is suitable for solving a model with multiple and conflicting objectives (Masud and Ravindran, 2008). In NPGP, numerical weights are used to indicate the relative importance of the objective functions. It is easy to solve, since all objective functions are optimized simultaneously as a single objective (Masud and Ravindran, 2008). However, the objectives must be scaled, due to the difference in units and magnitude of the objectives (Masud and Ravindran, 2008). The formulation of NPGP can be described as follows:

Additional Parameters

W_i Numerical weight of goal i for a non-preemptive GP formulation.

Z_i Objective functions *i* denoting supply chain profit, supply dispersion, and supply resilience.

$IDEAL_i$ Ideal value of objective *i*. The ideal value of objective *i* can be obtained by solving a single objective optimization problem (ignoring other objectives). For example, the ideal value of supply chain profit is obtained by solving the problem to maximize supply chain profit ignoring the other objectives.

$TARG_i$ Target value of objective *i*. This value is set by the decision maker based on the ideal value and whether the objective is to maximize or minimize. In this study, we set the target value equal to the ideal value.

Additional Variables:

d_i^+ Positive deviation from target value of objective *i*

d_i^- Negative deviation from target value of objective *i*

Since all objective functions are maximization, the NPGP objective function should minimize the negative deviation from the target values of all objectives, as shown in Equation (18).

$$Min \quad W_1(d_1^-) + W_2(d_2^-) + W_3(d_3^-) \tag{18}$$

Subject to

(Supply chain profit) $$Z_1 - d_1^+ + d_1^- = TARG_1 \tag{19}$$

(Supply dispersion) $$Z_2 - d_2^+ + d_2^- = TARG_2 \tag{20}$$

(Supply resilience) $$Z_3 - d_3^+ + d_3^- = TARG_3 \tag{21}$$

$$W_1 + W_2 + W_3 = 1 \tag{22}$$

$$d_i^+, d_i^- \geq 0 \qquad i = 1,2,3 \tag{23}$$

To scale each objective, the objective equation is divided by the target value, so that the new right-hand-side value is 1. The scaled objective would be:

$$\frac{Z_i}{TARG_i} - d_i^+ + d_i^- = 1$$

Hence, the objective function of the NPGP formulation would be:

$$Min \qquad W_1(d_1^-) + W_2(d_2^-) + W_3(d_3^-)$$

subject to real constraints from Equations (4) – (17) and goal constraints from Equations (18) – (23).

Numerical example

This section provides a numerical example to illustrate the supplier selection and supply chain network design decisions of the proposed model. We refer to Rienkhemaniyom and Pazhani (2015) for a four-stage supply chain network, which consists of 20 candidate suppliers, 5 existing manufacturing plants, 25 candidate warehouses, and 100 retailers (see Table 1). The geographical locations of those facilities are presented in Figure 2.

Table 1. List of facilities (Rienkhemaniyom and Pazhani, 2015).

Region	Suppliers	Plants	Warehouses	Retailers
Region 1	S16	M3	W17	R65-R68
Region 2	S5, S8, S10, S11, S12, S15, S17, S18	M1, M2	W7, W9, W10, W11, W14, W15, W16, W19, W20, W21, W25	R25-R28, R33-R44, R53-R64, R73-R84, R97-R100
Region 3	S6, S7, S9, S14, S19	M4	W3, W4, W8, W13, W18, W22	R9-R16, R29-R32, R49-R52, R69-R72, R85-R88
Region 4	S4, S13, S14, S20	M5	W6, W12, W23	R21-R24, R45-R48, R89-R92
Region 5	S2	-	W2	R5-R8
Region 6	S1, S3	-	W1, W5, W24	R1-R4, R17-R20, R93-R96
Total	20	5	25	100

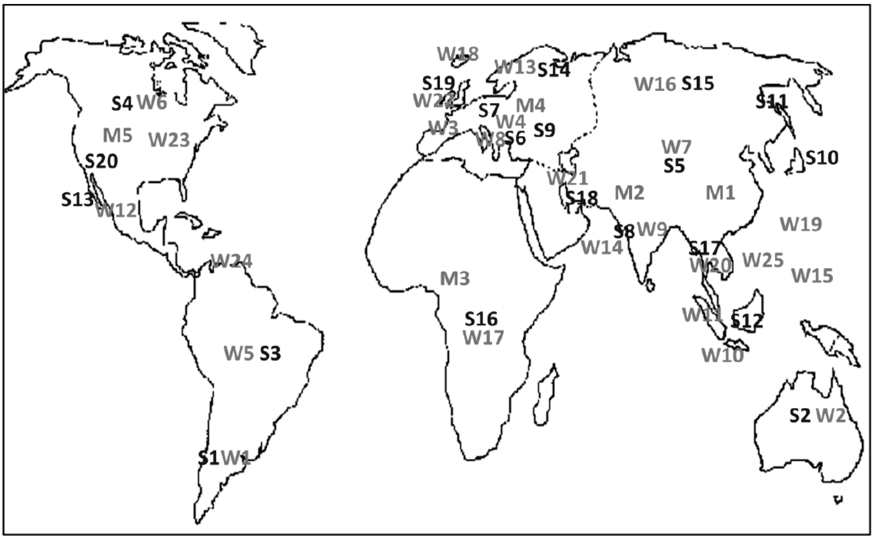

Figure 2. Geographical location of facilities (Rienkhemaniyom and Pazhani, 2015).

Demand at retailers is assumed to follow a uniform distribution between 500 and 700 units. The product price is $900 per unit. Transportation costs from warehouses to retailers are uniformly distributed between $63.75 and $71.25 per unit. Other parameters are summarized in Appendix A.

We first solve the single objective models to obtain the ideal values of the three objectives. Next, we assume that criteria weights are predefined by a decision maker. In this study, we solve the multi-criteria model with three weight sets, as shown in Table 2. Each case represents the preference towards objectives from a decision maker. For example, in Case 1, we assign the criteria weights to supply chain profit, supply dispersion, and supply resilience as 0.6, 0.2, and 0.2, respectively. It implies that a decision maker gives the highest preference to supply chain profit, and equal priority to supply dispersion and supplier resilience. The results of multi-criteria models are presented in the next section.

To solve the problem, the model is coded using optimization software LINGO 15.0 on a PC with INTEL(R) Core(TM) i5, Processor at 1.60GHz at and 4.0 GB RAM.

Table 2. Criteria weights for NPGP model.

NPGP model	(W1, W2, W3)
Case 1	W1=0.6, W2=0.2, W3=0.2
Case 2	W1=0.2, W2=0.6, W3=0.2
Case 3	W1=0.2, W2=0.2, W3=0.6

RESULTS

This section presents the results from a numerical example. Table 3 provides the objective values of the single objective models. For the supply chain profit maximization model (ignoring other objectives), the supply chain profit value is USD 13.1 million, while the supply dispersion and supply resilience are 22.2 miles/unit and 56.6, respectively. For the supply dispersion maximization model, the supply dispersion value is 241.6 miles/unit, while the supply chain profit is USD 10.6 million, and the supply resilience is 55.7. Maximizing the supply dispersion increases supply chain costs (e.g., purchasing cost, production cost, transportation cost, and fixed cost), which reduces supply chain profit (see Table 4). Similarly to the supply resilience maximization model, the supply resilience is 76.1, while the supply chain profit is USD 12.0 million, and the supply dispersion is 21.9 miles/unit.

The results above confirm that these three criteria are conflicting objectives. No supply chain network design solution simultaneously achieves all three decision criteria. Hence, we apply a NPGP approach to generate compromise solutions based on the pre-defined preferences of a decision maker. The last column of Table 3 provides the ideal values of the three objectives: USD 13.2 million, 241.6, and 76.1, respectively. They will be set as target values in the NPGP model.

Table 3. Ideal values from the single objective models.

Objective function value	Single objective model			Ideal value
	Maximize supply chain profit	Maximize supply dispersion	Maximize supply resilience	
Supply chain profit (USD)	13,176,960	10,648,060	11,979,060	13,176,960
Supply dispersion (miles/unit)	22.2	241.63	21.90	241.63
Supply resilience	56.56	55.71	76.095	76.095

Table 4. Revenue and costs obtained from the single objective models.

Revenue and costs	Single objective model		
	Maximize supply chain profit	Maximize supply dispersion	Maximize supply resilience
Revenue	$53,607,600	$53,607,600	$53,607,600
Purchasing cost	$27,824,520	$28,787,200	$28,832,270
Production cost	$4,349,147	$4,592,646	$4,457,382
Transportation cost from plants to WHs	$2,580,571	$2,728,228	$2,638,662
Transportation cost from WHs to retailers	$3,907,431	$4,010,814	$3,929,887
Fixed cost	$1,768,967	$2,840,651	$1,770,334
Lost sales cost	$0.00	$0.00	$0.00
Supply chain profit	$13,176,960	$10,648,060	$11,979,060

Table 5 presents the list of suppliers and warehouses that are selected for each single objective model. Since we limit the maximum number of suppliers to 15, the profit maximization model and the supply resilience maximization model select 15 suppliers from 5 out of 6 regions. Both models select 3 warehouses. The supply dispersion maximization model selects 15 suppliers from all 6 regions and 7 warehouses from 2 regions. The supply dispersion maximization model completely decentralized the supplier base compared to the other two models.

Table 5. Selected suppliers and warehouses from single objective models.

Selected facilities		Single objective model		
		Maximize supply chain profit	Maximize supply dispersion	Maximize supply resilience
Suppliers	Region 1	S16	S16	S16
	Region 2	S8, S10, S11, S12, S15, S17, S18	S5, S8, S10, S11, S12, S17, S18,	S10, S11, S12, S17, S18
	Region 3	S6, S9, S14	S14	S14, S6, S7, S9, S19
	Region 4	S4, S13	S4, S13, S20	S4, S13, S20
	Region 5		S2	S2
	Region 6	S1, S3,	S1, S3	
Warehouses	Region 1			
	Region 2	W19	W7, W9, W10, W16	W9, W16
	Region 3	W4	W8, W13, W18,	
	Region 4			W23
	Region 5			
	Region 6	W5		

Tables 6 and 7 show the results of the non-preemptive goal programming model with different weight sets. Table 6 presents the objective function values and deviations from the target values. Case 1 represents a situation in which a decision maker gives the highest weight to supply chain profit and small equal weights to supply dispersion and supply resilience. Supply chain profit value is USD 12.2 million, which falls short of the target value by USD 1.0 million or 0.08%, while the supply dispersion and supply resilience fall short of their target values by 0.06% and 0.05%. In Case 2, a decision maker gives the highest weight to supply dispersion and small equal weights to supply chain profit and supply resilience. Supply dispersion value is 237.1 (0.02% below the target value), while the supply chain profit and supply resilience are USD 11.5 million and 68.1 (0.12% and 0.11% below their target values), respectively. In Case 3, a decision maker gives the highest weight to supply resilience and small equal weights to supply chain profit and supply dispersion. Supply resilience value is 74.1 (0.03% below the target value), while the supply chain profit and supply dispersion are USD 12.1 million and 229.8 (0.08% and 0.05% below their target values), respectively.

These three cases demonstrate how to obtain the best compromise solutions from the multi-criteria decision problem by varying numerical weights. In this numerical example, the NPGP approach provides compromise solutions that are close to the target values (the negative deviation variables are less than 1%).

Table 6. Objective function values and deviations from the NPGP models.

Goal programming models	Case1 (W1=0.6, W2=0.2, W3=0.2)	Case2 (W1=0.2, W2=0.6, W3=0.2)	Case3 (W1=0.2, W2=0.2, W3=0.6)
Supply chain profit	12,180,410	11,545,060	12,088,080
Supply dispersion	227.07	237.08	229.75
Supply resilience	72.35	68.12	74.06
d_1^-	1,001,449 (0.076%)	1,633,943 (0.124%)	1,093,687 (0.083%)
d_2^-	14.5 (0.060%)	4.59 (0.019%)	11.84 (0.049%)
d_3^-	3.73 (0.049%)	7.99 (0.105%)	2.05 (0.027%)

Table 7 presents the list of selected supplier and warehouse facilities from the NPGP models. In all cases, the models select 15 suppliers from all 6 regions. This is due to the non-zero weight given to the supply dispersion criterion. We observe that 10 suppliers were commonly selected across the three cases (e.g., S1, S2, S4, S6, S10, S12, S14, S16, S19, and S20). This is because their costs, distances, and resilience parameters are applicable to the decision criteria. The selection of warehouses were based on facility cost, transportation cost between plants and the selected warehouses, and transportation cost between the selected warehouses and customers. Figures 3 to 5 present geographical locations of selected suppliers and warehouses of the three weight sets. Tables 8 to 13 summarize material flows and product flows between facilities.

Table 7. Selected suppliers and warehouses of the NPGP models.

Goal programming models		**Case1 (W1=0.6, W2=0.2, W3=0.2)**	**Case2 (W1=0.2, W2=0.6, W3=0.2)**	**Case3 (W1=0.2, W2=0.2, W3=0.6)**
Selected suppliers	Region 1	**S16**	**S16**	**S16**
	Region 2	**S10**, S11, **S12**, S17	**S10**, **S12**, S15, S17	S5, **S10**, S11, **S12**
	Region 3	**S6**, S7, S9, **S14**, **S19**	**S6**, S8, **S14**, **S19**	**S6**, S7, S9, **S14**, **S19**
	Region 4	**S4**, S13, **S20**	**S4**, S13, **S20**	**S4**, **S20**
	Region 5	**S2**	**S2**	**S2**
	Region 6	**S1**	**S1**, S3	**S1**, S3
Selected warehouses	Region 1	W17	W17	
	Region 2		W7, W10, W19	
	Region 3		W13	W8
	Region 4	W12, W23		W12
	Region 5			
	Region 6			W24

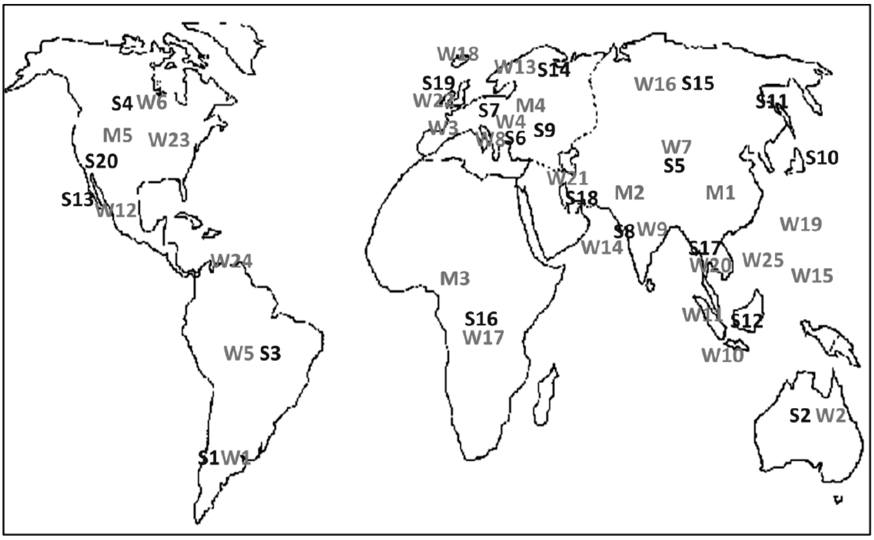

Figure 3. Geographical location of facilities from a multi-criteria model with criteria weights = (W1=0.6, W2=0.2, W3=0.2).

Table 8. Material flow from suppliers to plants (Q_{SM}) from a multi-criteria model with criteria weights = (W1=0.6, W2=0.2, W3=0.2).

QSM	M1	M2	M3	M4	M5	Total
S1	500	500	500	500	500	2500
S2	500	3483	500	500	500	5483
S4	500	500	500	500	4295	6295
S6	500	500	500	3788	500	5788
S7	500	500	0	5400	500	6900
S9	500	500	500	500	500	2500
S10	500	500	500	500	500	2500
S11	500	500	500	500	500	2500
S12	500	500	500	500	500	2500
S13	500	500	500	500	500	2500
S14	500	500	1604	500	500	3604
S16	500	500	4597	500	500	6597
S17	500	500	500	500	500	2500
S19	500	500	2897	500	500	4897
S20	500	500	500	500	500	2500
Total	7500	10483	14598	15688	11295	59564

Table 9. Product flow from plants to warehouses (Q_{MW}) from a multi-criteria model with criteria weights = (W1=0.6, W2=0.2, W3=0.2).

QMW	W12	W17	W23	Total
M1	0	0	7500	7500
M2	0	0	10483	10483
M3	0	14598	0	14598
M4	9912	5082	694	15688
M5	11295	0	0	11295
Total	21207	19680	18677	7500

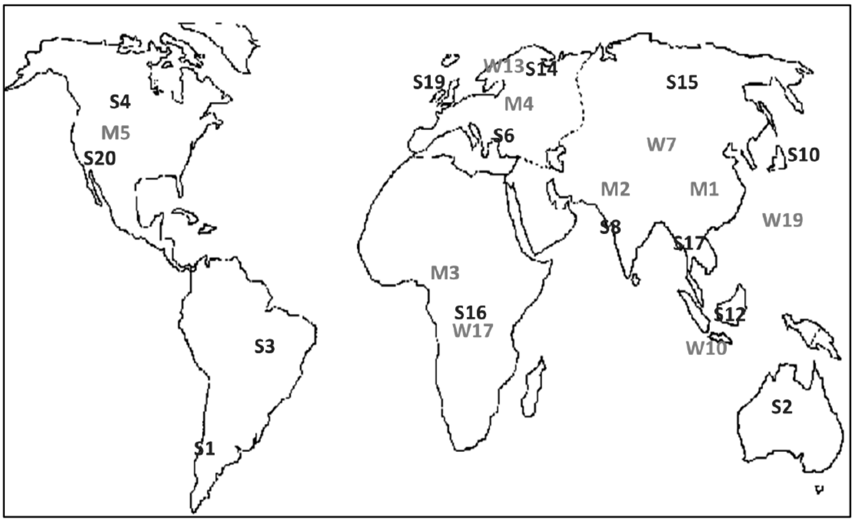

Figure 4. Geographical location of facilities from a multi-criteria model with criteria weights = (W1=0.2, W2=0.6, W3=0.2).

Table 10. Material flow from suppliers to plants (Q_{SM}) from a multi-criteria model with criteria weights = (W1=0.2, W2=0.6, W3=0.2).

QSM	M1	M2	M3	M4	M5	Total
S1	500	500	500	500	500	2500
S2	500	3483	500	500	500	5483
S3	500	500	500	500	500	2500
S4	500	500	500	500	4295	6295
S6	500	500	500	3788	500	5788
S8	500	500	500	500	500	2500
S10	500	500	500	500	500	2500
S12	500	500	500	2662	500	4662
S13	500	500	500	500	500	2500
S14	500	500	1604	500	500	3604
S15	500	500	500	500	500	2500
S16	500	500	4597	500	500	6597
S17	500	500	500	500	500	2500
S19	500	500	3057	500	500	5057
S20	500	500	2578	500	500	4578
Total	7500	10483	17336	12950	11295	59564

Table 11. Product flow from plants to warehouses (Q_{MW}) from a multi-criteria model with criteria weights = (W1=0.2, W2=0.6, W3=0.2).

QMW	W7	W10	W13	W17	W19	Total
M1	0	659	6841	0	0	7500
M2	0	0	0	0	10483	10483
M3	0	0	0	17336	0	17336
M4	4306	8644	0	0	0	12950
M5	1938	0	0	0	9357	11295
Total	6244	9303	6841	17336	19840	59564

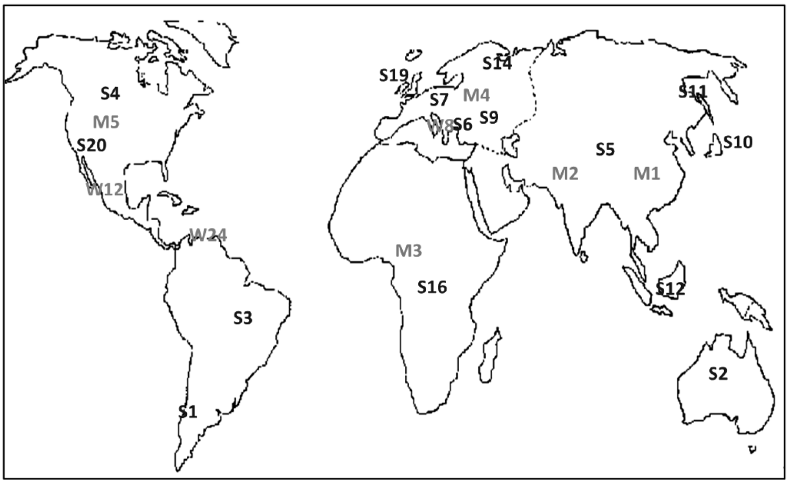

Figure 5. Geographical location of facilities from a multi-criteria model with criteria weights = (W1=0.2, W2=0.2, W3=0.6).

Table 12. Material flow from suppliers to plants (Q_{SM}) from a multi-criteria model with criteria weights = (W1=0.2, W2=0.2, W3=0.6).

QSM	M1	M2	M3	M4	M5	Total
S1	500	500	500	500	500	2500
S2	500	3483	500	500	500	5483
S3	500	500	500	500	500	2500
S4	500	500	500	500	4295	6295
S5	500	500	500	500	500	2500
S6	500	500	500	3788	500	5788
S7	500	500	500	4900	500	6900
S9	500	500	500	500	500	2500
S10	500	500	500	500	500	2500
S11	500	500	500	500	500	2500
S12	500	500	500	2359	500	4359
S14	500	500	1604	500	500	3604
S16	500	500	500	500	500	2500
S19	500	500	3057	500	500	5057
S20	500	500	2578	500	500	4578
Total	7500	10483	13239	17047	11295	59564

Table 13. Product flow from plants to warehouses (Q_{MW}) from a multi-criteria model with criteria weights = (W1=0.2, W2=0.2, W3=0.6).

QMW	W8	W12	W24	Total
M1	7500	0	0	7500
M2	0	0	10483	10483
M3	12121	0	1118	13239
M4	0	9912	7135	17047
M5	0	11295	0	11295
Total	19621	21207	18736	59564

DISCUSSION

The multi-criteria model presented in this paper allows managers to make decisions with respect to supplier selection and supply chain network design. The manager can evaluate the impact of achievement levels by changing criteria weights, a flexibility offered by the goal-programming approach.

Unlike Rienkhemaniyom and Pazhani (2015), this study included an additional constraint to limit the maximum number of selected suppliers and an additional objective function that considers country resilience as an objective. Without restricting the number of suppliers to be selected, the proposed model in Rienkhemaniyom and Pazhani (2015) selected 13 suppliers for a supply chain profit maximization model, and selected all 20 suppliers for a bi-criteria model. In this study, we limited the number of suppliers to be selected to 15. Even though the solutions were different, we observed a consistency in choosing the same 10 suppliers (S1, S2, S4, S6, S10, S12, S14, S16, S19, and S20) in all three NPGP models. In addition, order quantities allocated to these 10 suppliers did not vary much (see Tables 7, 9, and 11). This insight implies the robustness of the solution for the GP model, which is a benefit of the additional constraint to limit the number of selected suppliers.

The NPGP solutions could be provided to the decision maker along with information regarding the achieved value for each objective (see Table 5). The results show that resilience can be designed-in when making supplier selection and network design decisions by incorporating them as decision criteria. This should provide the decision maker with good insights into possible alternatives for the final decision.

CONCLUSION

This paper presented a multi-criteria mathematical model to solve an integrated supplier selection and supply chain network design decision. We incorporated supplier-based structure and their countries' resilience as objective functions. This consideration allows supply chain managers to improve their supplier selection and supply chain network design decisions with respect to risk perspective. Non-preemptive goal programming was used to solve the proposed model. It is a widely used technique to handle multiple and conflicting objectives problems. A numerical example was presented to illustrate how to mitigate disruption risk through a supply chain re-design. We also discussed the tradeoffs among different solutions that obtained by varying a decision maker's preference on criteria weights.

In this paper, we considered a single product supply chain; future work may consider more realistic complexities, such as multiple products and multiple transportation alternatives. We also assumed that suppliers are located in different countries, hence the use of a country resilience index was reasonable. If suppliers were located in the same country, one may quantify suppliers' resilience based on company performance. Furthermore, the proposed model only focused on mitigating supplier-side risk; future work may apply the dispersion and countries' resilience to the whole network. Sustainability criterion could be incorporated to address environmental concerns in supply chain management.

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APPENDIX A

Table 1A. Purchasing cost of raw material from supplier to plant (p_{sm}), capacity of suppliers (cap_s), resilience index of suppliers ($svar_s$), capacity of plants (cap_m), production cost at plants (p_{cm}).

p_{sm}	M1	M2	M3	M4	M5	cap_s	$svar_s$
S1	508.777	514.717	474.866	503.673	477.979	3969	40.7
S2	486.661	476.616	494.57	515.108	497.156	5483	86.9
S3	496.181	502.996	481.708	489.274	503.19	3113	47.8
S4	482.217	502.976	486.836	481.184	461.25	6295	90.1
S5	466.21	486.012	492.102	489.029	479.461	5975	45.8
S6	498.06	485.635	505.89	472.896	473.148	5788	83.8
S7	505.114	497.65	490.101	474.558	481.142	6900	91.1
S8	494.945	458.172	491.423	511.329	521.516	6882	27.1
S9	492.79	485.13	476.75	489.09	499.792	6990	53.5
S10	462.624	490.695	503.805	490.966	496.661	3767	61.9
S11	453.202	486.089	492.614	500.564	483.085	3670	42.1
S12	495.562	492.78	509.745	478.512	485.356	5646	64.9
S13	516.55	491.807	491.992	479.304	465.883	6188	44.8
S14	486.668	490.826	472.783	493.416	490.512	3604	93.3
S15	490.159	470.873	496.627	482.149	502.005	4304	44.1
S16	508.984	472.372	457.842	506.448	519.294	6597	54
S17	482.129	469.718	504.407	505.412	496.629	3453	39
S18	490.385	491.911	501.769	497.736	481.536	4538	38.4
S19	495.061	498.614	488.26	494.264	486.261	5057	80.7
S20	516.219	494.487	488.887	484.912	493.265	4578	79.1
cap_m	17442	18262	16478	11029	12829		
pc_m	82.5633	76.6976	62.2423	76.5706	83.728		

Table 2A. Distance between suppliers and plants (dis_{sm}).

dis_{sm}	M1	M2	M3	M4	M5
S1	12143	9756	5466	5782	5338
S2	5502	6363	6417	8647	8803
S3	10471	8038	4446	5816	5383
S4	7043	7154	7428	2322	2129
S5	560	2947	7380	5915	6351
S6	5498	4264	5331	4932	4945
S7	5170	4055	5488	4912	4965
S8	2824	525	4405	8454	8791
S9	5519	4113	5076	5189	5195
S10	1442	4221	8639	5060	5513
S11	720	3580	7945	5774	6226
S12	8696	9262	7812	2435	1983
S13	8270	9904	8897	1997	1607
S14	5351	4236	5496	4822	4855
S15	1977	2589	6747	5545	5907
S16	7856	5121	704	9699	9324
S17	1356	2101	6038	7711	8152
S18	4533	2579	4387	6461	6562
S19	5446	4620	5919	4344	4377
S20	7373	7790	7838	1907	1619

Table 3A. Capacity at each level of warehouse (cap_{wl}).

cap_{wl}	L1	L2	L3
W1	10704	13972	20815
W2	9221	16831	18571
W3	11475	16286	23349
W4	8217	16900	20054
W5	7982	14727	20575
W6	8451	13892	18241
W7	6244	16988	22484
W8	10030	15965	19621
W9	5969	17592	22075
W10	9303	14467	21678
W11	10930	15089	19982
W12	8310	17200	21207
W13	6841	17675	22429
W14	10844	15275	21700
W15	11362	17524	19656
W16	7181	12708	20022
W17	7347	17101	21393
W18	8648	15305	19381
W19	9152	14547	23218
W20	7691	14665	22235
W21	6931	16977	23565
W22	10637	12036	21585
W23	9518	13224	18677
W24	7578	15985	19037
W25	8287	17718	18519

Table 4A. Fixed cost of opening warehouse at each level (f_{wl}).

f_{wl}	L1	L2	L3
W1	429710	484574	599472
W2	404814	532581	561788
W3	442658	523435	642000
W4	387955	533729	586685
W5	384007	497248	595437
W6	391883	483239	556251
W7	354828	535214	627484
W8	418406	518043	579420
W9	350216	545354	620613
W10	406197	492889	613955
W11	433503	503333	585475
W12	389518	538780	606052
W13	364853	546755	626558
W14	432061	506460	614329
W15	440753	544214	580012
W16	370575	463363	586151
W17	373362	537118	609170
W18	395190	506954	575390
W19	403661	494239	639801
W20	379137	496211	623307
W21	366364	535030	645632
W22	428585	452082	612395
W23	409799	472028	563570
W24	377227	518368	569619
W25	389135	547476	560910

Table 5A. Distance between suppliers ($dis_{ss'}$).

$dis_{ss'}$	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
S1	100000	7076	1972	5164	11636	6868	7190	9852	6865	10714
S2	7076	100000	8645	10928	6037	10626	10389	5842	10470	5797
S3	1972	8645	100000	4207	10041	5008	5340	8316	4966	10400
S4	5164	10928	4207	100000	6484	3044	3168	7674	3264	6243
S5	11636	6037	10041	6484	100000	5033	4701	2999	5077	1278
S6	6868	10626	5008	3044	5033	100000	333	4786	261	5688
S7	7190	10389	5340	3168	4701	333	100000	4580	471	5361
S8	9852	5842	8316	7674	2999	4786	4580	100000	4631	4236
S9	6865	10470	4966	3264	5077	261	471	4631	100000	5801
S10	10714	5797	10400	6243	1278	5688	5361	4236	5801	100000
S11	11450	5514	10686	6759	765	5706	5373	3543	5772	744
S12	3459	9185	3456	2130	8189	5031	5215	9787	5211	7482
S13	3873	8150	4452	2921	7871	5963	6084	10367	6177	6876
S14	7004	10579	5167	3011	4877	193	193	4760	421	5506
S15	10346	7446	8538	5370	1503	3531	3200	2915	3573	2418
S16	4846	6226	4050	7502	8050	5791	5985	5057	5547	9290
S17	11372	4878	10129	8078	1805	5847	5556	1819	5780	2758
S18	7942	8909	5971	4788	4231	1752	1630	3087	1562	5288
S19	6876	10868	5138	2572	4939	600	602	5145	862	5424
S20	4808	10323	4163	664	6827	3708	3831	8305	3927	6395

$dis_{ss'}$	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
S1	11450	3459	3873	7004	10346	4846	11372	7942	6876	4808
S2	5514	9185	8150	10579	7446	6226	4878	8909	10868	10323
S3	10686	3456	4452	5167	8538	4050	10129	5971	5138	4163
S4	6759	2130	2921	3011	5370	7502	8078	4788	2572	664
S5	765	8189	7871	4877	1503	8050	1805	4231	4939	6827
S6	5706	5031	5963	193	3531	5791	5847	1752	600	3708
S7	5373	5215	6084	193	3200	5985	5556	1630	602	3831
S8	3543	9787	10367	4760	2915	5057	1819	3087	5145	8305
S9	5772	5211	6177	421	3573	5547	5780	1562	862	3927
S10	744	7482	6876	5506	2418	9290	2758	5288	5424	6395
S11	100000	8176	7618	5539	2214	8574	2014	4995	5548	6991
S12	8176	100000	1226	5040	7374	7497	9973	6773	4643	1543
S13	7618	1226	100000	5931	7513	8468	9624	7708	5484	2256
S14	5539	5040	5931	100000	3379	5968	5750	1777	479	3675
S15	2214	7374	7513	3379	100000	7451	2710	2869	3473	5854
S16	8574	7497	8468	5968	7451	100000	6613	5019	6356	7807
S17	2014	9973	9624	5750	2710	6613	100000	4432	5990	8526
S18	4995	6773	7708	1777	2869	5019	4432	100000	2232	5452
S19	5548	4643	5484	479	3473	6356	5990	2232	100000	3233
S20	6991	1543	2256	3675	5854	7807	8526	5452	3233	100000

Table 6A. Transportation cost from plants to warehouses (tr_{mw}).

tr_{mw}	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13
M1	46.4306	45.4446	45.1535	42.8091	45.7801	42.5164	47.1381	45.2137	46.3152	43.8955	44.1664	47.7301	44.7159
M2	45.2025	47.9236	46.1244	46.2808	44.8141	42.4194	45.8174	45.4689	42.0915	46.7668	45.96	45.8926	43.6354
M3	46.0289	46.148	44.6857	42.5782	47.6694	47.9686	44.1258	41.4747	44.9678	46.9837	42.1279	43.8814	43.3931
M4	48.3195	43.0533	47.5829	44.1247	44.1676	46.133	42.6247	45.317	48.5296	41.4583	44.0427	41.5479	45.9888
M5	45.1728	43.1804	47.873	44.9753	47.2407	43.6173	43.5183	45.789	45.1061	47.6135	44.938	41.3338	45.9368

tr_{mw}	W14	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24	W25
M1	46.6847	42.0969	45.7886	47.5534	47.3003	48.4279	41.965	47.7948	45.5137	43.5188	47.5169	47.9702
M2	45.5641	42.9373	43.6747	43.9873	48.2008	41.2939	45.3576	43.0883	46.0264	42.0409	42.5602	43.5751
M3	43.1888	45.3815	44.9673	42.1334	43.0287	45.739	48.2326	44.2227	47.7081	44.1899	43.6826	42.7663
M4	45.0974	46.1625	43.7934	44.6226	43.6817	47.2324	45.1223	45.1071	44.7863	42.9681	41.8047	47.5509
M5	46.2839	46.1457	42.8871	46.8026	48.1062	43.5188	44.3696	44.0854	43.9256	44.9555	44.7539	43.8353

none