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Multiple sourcing under supplier failure risk and quantity discount: A genetic algorithm approach

P.L. Meena [a], S.P. Sarmah [b,*]

[a] Institute of Management Technology, Ghaziabad, UP 201 001, India
[b] Department of Industrial Engineering & Management, Indian Institute of Technology Kharagpur, WB 721 302, India

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A B S T R A C T

This paper investigates an order allocation problem of a manufacturer/buyer among multiple suppliers under the risks of supply disruption. A mixed integer non-linear programming (MINLP) model is developed for order allocation considering different capacity, failure probability and quantity discounts for each supplier. We have shown that the formulated problem is NP-hard in nature and genetic algorithm (GA) approach is used to solve it. The model is illustrated through a numerical study and the result portrays that the cost of supplier has more influence on order quantity allocation rather than supplier's failure probability.

1. Introduction

In today's global business market, sourcing decision is one of the major challenges faced by the buying firms and it has received wide attention from both academicians as well as practitioners. Sourcing decision includes selection of right number of suppliers and order quantity allocation among the selected suppliers (Chopra and Meindl, 2005). The problem of sourcing becomes more crucial when there is a possibility of occurrence of disruptions in the supply which may be natural or created by man. Generally, supply disruptions are caused by the occurrence of high profile catastrophic events such as 9/11, Hurricane and Katrina, in 2004, and tsunami in India in 2004. These events can seriously affect the profitability and performance of the entire supply chain. The largest automaker company of the world, Toyota had to suspend the production at its 12 assembly plants in March 2012 because of the devastating earthquake and tsunami in Japan and estimated a production loss of 140,000 cars (Kim and Reynolds, 2011). For more examples on supply disruption, one can see the study of Kleindorfer and Saad (2005), Ellis et al. (2010), and Wakolbinger and Cruz (2011).

In the literature, many authors (for example, Wu et al., 2007; Yang and Yang, 2010; Ellis et al., 2010) have proposed different strategies to mitigate the effects of supply disruptions. Hou et al. (2010) have defined supply disruption as the sudden non-availability of supplies due to the occurrence of an unexpected event making one or more supply sources totally unavailable. Tomlin (2006) has suggested supply diversification is an efficient strategy to cope with the risk of supply disruptions and avoid the dependence on single supplier. Under multiple sourcing, the major issue before the buyer is the optimal allocation of demand among the selected set of suppliers when the suppliers are exposed to the risk of supply disruptions. There is a paucity of literature on optimal allocation of order among the suppliers under supply disruptions risk.

* Corresponding author. Tel.: +91 3222 283735.
E-mail addresses: plmeena1@yahoo.co.in (P.L. Meena), spsarmah@iem.iitkgp.ernet.in (S.P. Sarmah).

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Notation

D	total demand of the buyer in a given period
C_P	base price of the item offered by each suppliers (mu) where, mu – monetary units
d_{ij}	discount in percentage given by ith supplier in jth price break
b	per supplier management cost (mu/supplier)
n	number of potential suppliers
s	number of price breaks
L	loss per not obtained unit due to the supplier failure (mu)
Q_{bi}	actual capacity of individual supplier
Q_i	order quantity allocated to the ith supplier
p^*	probability of occurrence of super-event that would fail all suppliers
p_i	probability of occurrence of unique-event that fails the ith supplier
K_i	compensations of supplier(s) that don't fail, where $K_i = (Q_{bi} - Q_i)$
$A^{(i)}$	set of suppliers who fail
$Q_{\min}$	minimum quantity ordered to each selected supplier
Q_{lot}	lot size of any supplier
h	integer multiple which is used to get equal to Q_{lot} from $Q_{\min}$ (i.e. $Q_{\min} = hQ_{lot}$)
k_i	integer multiple required to reach from Q_i to Q_{lot}, for example, $Q_i = k_iQ_{lot}$
H	integer multiple required to reach from Q_{lot} to D, i.e. $D = HQ_{lot}$
S	set of suppliers
$p(S)$	power set of S

In this paper, we have developed a mixed integer non-liner programming (MINLP) model to determine the optimal order allocation among multiple suppliers when the suppliers are exposed to the risk of failure due to man-made or natural disruptions. We have shown here that the formulated problem is NP-*hard* in nature, and genetic algorithm (GA) is used to solve it. The reason of using GA is that it has been proven to excel in solving combinatorial optimization problems in comparison to traditional optimization techniques (Goldberg, 1998; Steiner and Hruschka, 2002).

The remainder of the paper is organized as follows: Section 2 provides a brief review of literature related to order allocation problem. Description of the problem and development of the model are presented in Section 3. The problem complexity is discussed in Section 4. Section 5 presents the GA approach to find the solution. Numerical experiments are conducted in Section 6 and sensitivity analysis of different parameters is performed in Section 7. Finally, conclusions and future scope of the work are presented in Section 8.

2. Literature review

A large number of studies are available in the literature on supplier selection and order allocation problems. Here, a brief review of literature related to order allocation problem is discussed only. The research pertaining to order allocation can broadly be classified into the following two categories:

(i) Order allocation without the consideration of supply disruptions risk.
(ii) Order allocation under supply disruptions risk.

2.1. Order allocation without the consideration of supply disruptions risk

Considerable amount of literature is available in this stream, and to the best of our knowledge, Sculli and Wu (1981) are the frontrunners to study the order allocation problem. They have shown that in comparison to single sourcing, the mean and variance of the lead time and demand distribution are reduced under dual sourcing. Further, they have shown that probability of stock out is less in dual sourcing as compared to single sourcing. Many authors have extended the work of Sculli and Wu (1981) in different directions in the last two decades (for example, Sculli and Shum, 1990; Pan, 1989; Ramasesh et al., 1991; Chaudhry et al., 1991; Lau and Zhao, 1993; Chiang and Benton, 1994; Sedarage et al., 1999; Basnet and Leung, 2005; Kawtummachai and Hop, 2005). Instead of discussing these studies in details, we refer the readers to Minner (2003) and Thomas and Tyworth (2006) who have provided an extensive review on order splitting. In recent years, many authors (for example, Burke et al., 2008a, 2008b; Wang et al., 2008; Qi, 2007; Che and Wang, 2008; Yu and Tsai, 2008; Tsai and Wang, 2010; Cheng and Ye, 2011) also have studied the similar problem. However, all the aforementioned studies have ignored the risks of supply disruption.

2.2. Order allocation under supply disruptions

As supply chains are expanding globally, buying firms are allocating their business to foreign suppliers and in turn it is increasing the risk of supply disruptions. Anupindi and Akella (1993) studied the problem of quantity allocation between two uncertain suppliers and its effect on inventory policies of the buyer. They developed three models for different delivery process from the suppliers. However, they did not consider quantity discount in their model. As far as we are aware, Ruiz-Torres and Mahmoodi (2006) are the frontrunners who have studied the demand allocation problem under the risk of supplier(s) failure. They developed a model considering the risk of supply delivery failure similar to Berger et al. (2004). The authors incorporated output flexibility parameter in the model to consider the ability of suppliers to increase their output when one or more supplier(s) fails to deliver. Output flexibility is defined as the ability of a supplier to increase its delivery during a supply cycle. They used decision tree approach to solve the problem and stated that low output flexibility resulted in an equal allocation across the suppliers, even when some suppliers offered a discount. Conversely, high output flexibility resulted significantly higher allocation to the suppliers with higher risk but they have not considered different capacity for different suppliers.

Burke et al. (2009) developed a model to compare single sourcing and multiple sourcing under stochastic supplier reliability and stochastic demand. Their results show that when mean of the demand is low, single sourcing is a good strategy whereas multiple sourcing is a good strategy when mean of the demand is high. They considered only partial failure of suppliers to supply. However, they ignored quantity price discounts and risk of disruptive events that make suppliers completely unavailable to supply. Burke et al. (2008a) mentioned that quantity discounts often complicate the order allocation problem under multiple sourcing. They considered various quantity discounts such as linear discount pricing, incremental units discount pricing and all units discount pricing in order allocation models, but they ignored the supply disruptions risk. Benton and Park (1996), Munson and Rosenblatt (1998) and Dolan (1987) have extensively discussed about different quantity discounts models.

The detailed review of literature shows that there is a dearth of studies pertaining to order allocation under the risks of supply disruptions. Here, a mathematical model is developed to determine the optimal allocation of order quantity among the selected suppliers. In the development of the model, we have considered that each supplier has different capacity, failure probability and quantity discounts to represent more realistic situation, which are absent in the earlier work and is considered as the main contribution of this paper. Further, a compensation potential parameter is also incorporated in the model. The problem description, model and GA approach for order allocation are discussed in the next section.

3. Problem description

The buyer procures single item from n multiple suppliers in a single period. It is assumed that the demand of the buyer is known and constant, and a set of suppliers is already selected based on certain criteria (e.g. quality, service, delivery, maintenance, etc.) of the buyer and each supplier offers different price discounts based on order quantity. All suppliers have different capacity, failure probability and compensation potential. Further, we have considered that each supplier supplies order quantities in lots. The allocated order quantity to a supplier must be equal to or some integer multiple of lot size of the supplier and this type of situation is very much prevalent in actual business scenario.

Two different types of disruptive events namely unique event and super event are considered here similar to the study of Berger et al. (2004) and Meena et al. (2011). The occurrence of unique-event leads to complete failure of a single particular supplier to supply. Two or more suppliers may also fail simultaneously, if unique events occur at the same time at respective suppliers end. On the other hand, due to the occurrence of a super event, all the suppliers fail completely to supply the negotiated order quantity to the buyer. Our aim here is to determine the amount of order quantity to be allocated to each selected supplier, while minimizing the expected total cost of the buyer. The expected total cost includes purchasing, supplier management and expected total loss costs. The following notation are used in the development of the model.

3.1. The model

The objective is to optimally allocate the total demand of the buyer among the multiple suppliers keeping expected total cost minimum. The problem is formulated as given below.

$$\text{Minimize } ETC(Q) \tag{1a}$$

$$\text{Subject to } Q_{\min} \leqslant Q_i \leqslant Q_{bi} \tag{1b}$$

$$Q_i \leqslant D - (n-1)Q_{\min} \tag{1c}$$

$$Q_i = k_i Q_{lot} \tag{1d}$$

$$\sum_{i=1}^{n} Q_i = D \tag{1e}$$

$$k_i \in \mathbb{N}_1 \quad \text{and} \quad i = 1, 2, \ldots, n \tag{1f}$$

where k_i is an integer number and $\mathbb{N}_1$ is set of integer numbers and Q is allocated order quantity vector, $Q = [Q_1, Q_2, Q_3, \ldots, Q_n]$.

Constraint (1b) ensures that allocated order quantity to any supplier must be greater than or equal to the minimum order quantity of the supplier and less than the capacity of supplier and it implies that the order quantity has lower and upper bounds. In reality, the buyer has to allocate a certain fraction of total order to a supplier to retain that supplier for future business. Constraint (1c) shows the maximum possible order allocation to a specific supplier. Further, constraint (1d) shows that order allocation to a specific supplier must be an integer (k_i) multiple of the lot size of the supplier. Finally, constraint (1e) ensures that the sum of the allocated order quantities among all the selected suppliers must be equal to the total demand of the buyer. The expected total cost equation $ETC(Q)$ can be written as follows:

$$ETC(Q) = PC(Q) + SMC + ETL(Q) \tag{2}$$

where $PC(Q)$, SMC and $ETL(Q)$ are the purchasing, supplier(s) management and supplier(s) failure loss costs respectively.

3.1.1. Purchasing cost

In most of the practical cases, it is found that a buyer procures material from multiple suppliers where the suppliers may offer different price discounts to encourage a larger order quantity. Here, we have considered only all-unit quantity discount with three price breaks as shown in Fig. 1.

Munson and Rosenblatt (1998) have mentioned that maximum number of price breaks offered by a supplier normally does not exceed more than four in most of the real situations. The purchasing cost with quantity discount is formulated as follows:

$$PC(Q) = C_P \sum_{i=1}^{n} Q_i (1 - d_{ji}) \quad \text{where,} \quad j = 1, 2, \ldots, s \tag{3}$$

where d_{ji} is the discount in percent on price offered by ith supplier in jth price break.

The discounts provided by suppliers are as shown in Eq. (3.1), where d_{ji} is the discount in percent on price offered by ith supplier in jth price break and $0 < Q_1 < Q_2 < Q_3$ are the order quantities for the ith supplier at which price-breaks occurs, and $0 < d_1 < d_2 < d_3$ are the associated price discounts.

$$d_{ji} = \begin{cases} d_1 & \text{for } Q_1 \leqslant Q_i < Q_2 \\ d_2 & \text{for } Q_2 \leqslant Q_i < Q_3 \\ d_3 & \text{for } Q_3 \leqslant Q_i \end{cases} \tag{3.1}$$

3.1.2. Supplier management cost

The supplier management cost linearly increases as the number of supplier increases and it includes cost of negotiation, managing a supplier contract, and monitoring the quality, etc. and one can write this cost as follows:

$$SMC = b(n) \tag{4}$$

3.1.3. Expected total loss cost

The buyer may face a significant economic loss if the supplier(s) fails to deliver or supply the negotiated order quantity. Here, we have considered the case of compensation from the un-failed supplier(s). When a particular or set of supplier(s) fails to supply then the other set of un-failed supplier(s) compensate the shortfall that occurs due to the supplier(s) failure by supplying extra quantity. It is assumed that the extra quantity supplied by the non-failed suppliers come at no extra cost. Therefore under the risk of supply disruptions, the minimum order quantity received by the buyer from the given set of suppliers in a particular period can be written as

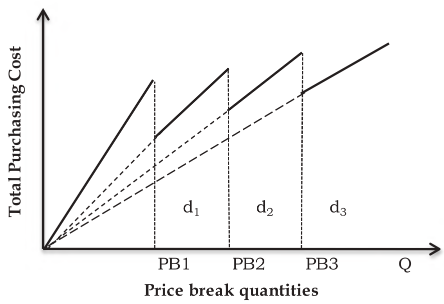

Fig. 1. All unit quantity discount pricing.

$$\min\left(D, \sum_{l\in\{S/A^{(i)}\}} Q_l + \sum_{l\in\{S/A^{(i)}\}} K_l\right)$$

where K_l is the compensation provided by the supplier(s) who does not fail.

Finally, expected total loss because of the supplier(s) failure due to the occurrence of the unique and super-event can be formulated as follows:

$$\begin{aligned} ETL(Q) &= LDp^* + (1-p^*)L\sum_{i\in p(S)}\left(\prod_{j\in A^{(i)}} p_j \prod_{l\in\{S/A^{(i)}\}}(1-p_l)\right)\left[D - \min\left(D, \sum_{l\in\{S/A^{(i)}\}} Q_l + \sum_{l\in\{S/A^{(i)}\}} K_l\right)\right] \\ &= LDp^* + L(1-p^*)\sum_{i\in p(S)}\left(\prod_{j\in A^{(i)}} p_j \prod_{l\in\{S/A^{(i)}\}}(1-p_l)\right)\left[D - \min\left(D, \sum_{l\in\{S/A^{(i)}\}} Q_{bl}\right)\right] \end{aligned} \quad (5)$$

The above formulated problem is an integer programming problem, where, Q_i's and k_i's are the decision variables and integer number. From Eq. (1e), one can determine the value of k_i as follows:

$$\sum_{i=1}^{n} k_i = \frac{D}{Q_{lot}} \quad (6)$$

By considering only k_i's, one can reduce the problem. Now, from Eqs. (1b) and (1c), one gets

$$\begin{aligned} &Q_{\min} \leqslant k_i Q_{lot} \leqslant D-(n-1)Q_{\min} \\ &\frac{Q_{\min}}{Q_{lot}} \leqslant k_i \leqslant \frac{D-(n-1)Q_{\min}}{Q_{lot}} \end{aligned} \quad (7)$$

For a practical situation $Q_{\min}$ must be equal to Q_{lot} or some integer multiple of Q_{lot} (i.e. $Q_{\min} = hQ_{lot}$) and as k_i's are integers, so, from Eq. (6), it is found that D must be some integer multiple of Q_{lot} (i.e. $D = HQ_{lot}$). In order to get any feasible solution of the problem, the condition $H > h$ must be satisfied. Precisely from Eq. (7), one gets $H-(n-1)h \geqslant h$. Therefore, the condition $H \geqslant nh$ must also be satisfied to get any feasible solution of the problem. Now, Eq. (1f) reduces to $k_i \in \Omega \subset \mathbb{N}_1$, where $\Omega = \underbrace{\{h, h+1, h+2, \ldots, H-(n-1)h\}}_{|\Omega|}$.According to problem situation, the number of steps required to find the optimal solution is given by $|\Omega|^n$, where $|\Omega|$ represents the cardinality of the set Ω and is defined as the total number of elements present in that set and n represents the number of suppliers. Here, we have not considered the constraint part of Eq. (6) (i.e. $\sum_{i=1}^{n} k_i = H$) for calculating the complexity of the problem. Now, if we omit the situation $H = nh$ (i.e. Ω is not a singleton set, $|\Omega| \geqslant 2$) then the complexity of the problem greater than $O(2^n)$, which represents, it is a NP-hard problem.

When one considers the constraint part of Eq. (6), then set Ω changes with the choice of supplier given by

$$\Omega_1 = \{h, h+1, h+2, \ldots, H-(n-1)h\} \quad (8a)$$

$$\Omega_2 = \{h, h+1, h+2, \ldots, H-(n-2)h-k_1\} \quad (8b)$$

$$\vdots$$

$$\Omega_i = \left\{h, h+1, \ldots, H-(n-i)h-\sum_{j=1}^{i-1} k_j\right\} \quad (8c)$$

$$\vdots$$

$$\Omega_{n-1} = \left\{h, h+1, \ldots, H-h-\sum_{j=1}^{n-2} k_j\right\} \quad (8d)$$

$$\Omega_n = \left\{h, h+1, \ldots, H-\sum_{j=1}^{n-1} k_j\right\} = \{k_n\} \quad (8e)$$

Depending upon the situations, we have multiple choice for k_i's, and Eq. (6) restricts our choice to only k_n for the case $i = n$. Now, $|\Omega_i|$ is given by $m_i = 1 + \sum_{j=1}^{n}(k_j - h)$. For the case $i = 1$

$$m_1 = H - nh + 1 = \left(\frac{H}{h} - n\right)h + 1 = (N-n)h + 1 \geqslant 2$$

Cardinality must be a whole integer $\frac{H}{h} = N \in \mathbb{N}_1$ and $(N-n) \geqslant 1$, if we consider the situation $H \geqslant nh$. Similarly, for the case i, $m_i \geqslant 2$ also arises because of $H \geqslant nh$. So for at least one j, $k_j - h > 0$ and k_j and h are integers, $k_j - h \geqslant 1$ coming straight forward. Therefore, numbers of choices are given by $\prod_{i=1}^{n}|\Omega_i| = \prod_{i=1}^{n} m_i \geqslant 2^{n-1}$.

Now, the original problem can be reduced to the form given by (P),

$$\begin{aligned} &\text{Minimize}\, f(k_i) \\ &\text{Subject to} \sum_{i=1}^{n} k_i = H \\ &\qquad h \leqslant k_i \leqslant H - (n-1)h \\ &\qquad k_i \text{ is an integer and } i = 1,2,\ldots,n \\ &\qquad \text{where}, f(k_i) \text{ is } PC(Q) + SMC + ETL(Q) \end{aligned}$$

4. Problem complexity

In this section, it is shown that the above discussed problem is NP-*hard* in nature.

Definition PARTITION. Given n positive integers $a, w_1, w_2, \ldots, w_n$, c, is there a subset $S \subseteq \mathbb{N}_1 = \{1, 2, \ldots, N\}$ such that $\sum_{i \in S} w_i = \sum_{i \in \mathbb{N}_1/S} w_i$? is a basic NP-complete problem, originally treated in Karp (1972). One can refer the work of Martello and Toth (1990) for the same proof.

Lemma 1. SUBSET-SUM is NP-hard.

Proof. *Consider R (SUBSET-SUM)*: Given $n + 2$ positive integers $a, w_1, w_2, \ldots, w_n, c$, is there a subset $S \subseteq \mathbb{N}_1 = \{1, 2, \ldots, N\}$ such that $\sum_{i \in S} w_i \leqslant c$ and $\sum_{i \in S} w_i \geqslant a$?

If we consider set $c = a = \sum_{j \in \mathbb{N}_1} \frac{w_i}{2}$ then any instance I of PARTITION can be polynomially transformed into an equivalent instance I_1. □

Lemma 2. 0–1 KNAPSACK is NP-hard.

Proof. Consider 0–1 KNAPSACK:

$$\begin{aligned} &\text{Maximize} \sum_{i=1}^{n} c_i x_i \\ &\text{Subject to} \sum_{i=1}^{n} w_i x_i \leqslant W \\ &\qquad x_i = \{0, 1\}, \quad i = 1, 2, \ldots, n. \end{aligned}$$

when $c_i = w_i$ for $j \in \mathbb{N}_1$, *SUBSET-SUM* is the particular case of 0–1 KNAPSACK. □

Lemma 3. BOUNDED KNAPSACK is NP-hard.

Proof. Consider BOUNDED KNAPSACK:

$$\begin{aligned} &\text{Maximize} \sum_{i=1}^{n} x_i \\ &\text{Subject to} \sum_{i=1}^{n} w_i x_i \leqslant W \\ &\qquad 0 \leqslant x_i \leqslant b_i, \quad i = 1, 2, \ldots, n, \\ &\qquad x_i \text{ is integer} \quad i = 1, 2, \ldots, n. \end{aligned}$$

0-1 KNAPSACK is the particular case of BOUNDED KNAPSACK when $b_i = 1\ \forall i \in \mathbb{N}_1$. □

Claim 4. (*P*) is NP-hard.

Proof. Consider (*P*):

$$\text{Maximize } -f(k_i)$$

$$\text{Subject to } \sum_{i=1}^{n} k_i = H$$

$$h \leqslant k_i \leqslant H-(n-1)h, \quad i=1,2,\ldots,n,$$

$$k_i \text{ is integer and } \quad i=1,2,\ldots,n.$$

BOUNDED KNAPSACK is the particular case of (*P*) when $b_i = H-(n-1)h \quad \forall i \in \mathbb{N}_1$, lower limit is defined by h and k_i is treated as x_i. Note that in the capacity constraint, we impose equality sign instead of inequality and the maximization condition can be implemented by putting negative sign before the objective function. □

5. Solution methodology

Here, genetic algorithm (GA) is used to solve the problem. GA is one of the non-traditional search techniques and it differs from traditional optimization techniques in various ways such as it uses an encoding of the parameter rather than parameters themselves; GA search from one population of solutions to another rather than from individual to individual; it uses fitness function information to guide themselves through the solution space, not derivatives and it uses probabilistic transitions rules instead of deterministic rules. Further, comparing with traditional optimization techniques, GA has been proven to excel in solving combinatorial optimization problems. Considering the aforementioned merits, we have employed GA to solve the problem.

5.1. The optimal values of GA parameters

Srinivas and Lalit (1994) have mentioned that there is no perfect way for parameters setting in GA except for experimental training. The procedure adopted for determining the optimal values of GA parameters (population size, crossover probability p_c and mutation probability p_m and no. of generation Gen.) is briefly described here. The performance of a genetic-search depends on the amount of exploration (population diversity) and exploitation (selection process). To have an effective search, there must be proper balance between them and to ensure this, the values of GA parameters need to be selected in optimal sense. The following steps are followed as described by Pratihar (2008) to find the optimal values of GA parameters:

- First we varied $\mathrm{p_c}$ within its range (0.6–1.0), while keeping other parameters fixed at their respective mid values.
- Second, we fixed the values of $\mathrm{p_c}$, N and G respectively and varied the values of $\mathrm{p_m}$ from 0.01 to 0.2.
- Third, the values of $\mathrm{p_c}$, $\mathrm{p_m}$ and G are kept fixed and the population size is varied from 30 to 100.
- Finally, we varied the no of generation G in the range of 30–150 keeping the values of other parameters ($\mathrm{p_c}$, $\mathrm{p_m}$ and N) fixed.

5.1.1. Steps of GA for demand allocation

Here, binary GA is used to solve the allocation problem. The procedure of GA is as follows:

Generate an *initial population*,
Evaluate fitness of individual in the *population*,
repeat:
Select *parents* from the *population*,
Recombine (mate) parents to produce children,
Evaluate *fitness* of the *children*,
Replace some or all of the *population* by the *children*,
until a satisfactory solution have been found.

The demand allocation can be represented as follows:

$$\text{Minimize } ETC(n)$$

$$\text{Subject to } \sum_{z=1}^{N} Q_z = D$$

$$Q_{\min} \leqslant Q_z \leqslant Q_{\max} \quad z=1,2,\ldots,N$$

5.1.2. Genetic operators

This section provides brief explanation pertaining to different operators of genetic algorithm that have been utilized in solving the problem.

5.1.2.1. Selection. The traditional selection operator, the roulette wheel selection is used, generating the increase in the number of high quality individuals from generation to generation.

5.1.2.2. Crossover. The traditional crossover consists in choosing at random an index of variable and exchanging the bits on both sides of this point, as shown in the Fig. 2.

5.1.2.3. Mutation. The mutation operator acts in two phases. Initially it chooses the gene to be modified, i.e. the variation, then a particular bit of this variable as shown in Fig. 3. The problem in hand is an integer programming problem with bounded situation with the decision variables. Roulette-Wheel selection is used for reproduction and single point crossover and population is generated for only integer values. Initial population generated by binary GA is modified accordingly to get the feasible solution for the problem. Generated integer variables are converted to the nearest bound values to get a feasible solution.

5.1.2.4. The algorithm of repair operator for the constraints. The first constraint of the problem is handled by the repair operator. The repair operator consider here consists of two phases. The first phase called DROP phase, examines each variable in decreasing order of Q_z's and changes the variable from Q_z to $Q_z - \left(\sum_j^S Q_j - D\right)$ as long as feasibility is not violated with respect to lower bounds (LB_i's). The second phase called ADD phase, examines each variable in increasing order of Q_z's and changes the variable from Q_z to $Q_z + \left(\sum_j^S Q_j - D\right)$ as long as feasibility is not violated with respect to upper bounds (UB_i's). The aim of the repair operator is to obtain a feasible solution from an infeasible solution. Algorithm for the repair operator is given below:

DROP Phase
Set, Q_z's in decreasing order,
repeat:
Initialize $R := \sum_j^S Q_j - D$,
  If $Q_i - R \geqslant LB_i$ then $Q_i = Q_i - R$
  Else $Q_i = LB_i$ and set $R : = R - (Q_i - LB_i)$,
until $R := 0$.
ADD Phase
Set, Q_z's in increasing order,
repeat:
  Initialize $R := D - \sum_j^n Q_j$,,
  If $Q_i + R \leqslant LB_i$ then $Q_i = Q_i + R$,
  Else $Q_i = LB_i$ and set $R := R - (UB_i - Q_i)$,
until $R := 0$.

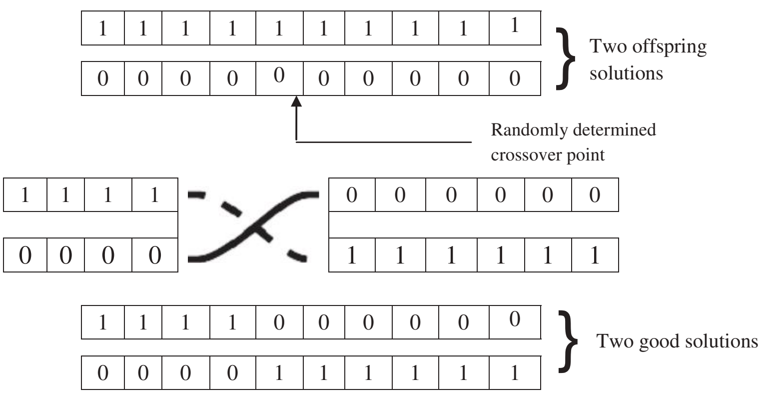

Fig. 2. Crossover.

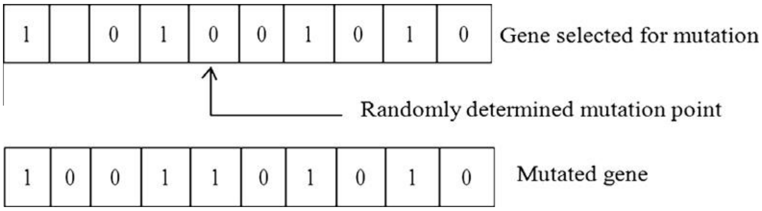

Fig. 3. A single point mutation.

In the DROP phase, variables with the highest Q_z is considered first, are successively decreased from the original value until a feasible solution is achieved. Similarly, in the ADD phase we consider the lowest Q_z at first, and increase the value until we found a feasible solution. The repair operator always produce a feasible solution from an infeasible solution is a greedy algorithm. In many scenarios in the literature, we find this kind of repair operators (see Chu and Beasley (1998) and Fox and Scudder (1985)).

6. Numerical experiments

In this section, numerical studies are conducted to illustrate the proposed mathematical model and GA for order allocation among multiple suppliers under the risk of supply disruptions. GA is coded in MATLAB 7.13 and the numerical experiments were executed on a personal computer equipped with a Core(TM)-2-Duo @ 2.93 GHz, with 1.49 GB of RAM, running on Windows XP. The total numbers of suppliers have been increased from small to large for enlarging the size of the problem. Thus, 10 problems of one, two, three, four, five, six, seven, eight, nine and ten suppliers are considered separately from a set of ten suppliers for evaluating the performance of the algorithm.

For the numerical study, it is considered that demand of the buyer is 100 units in a given period, base price of the item offered by all the suppliers is 10 mu per unit, management cost per supplier is 20 mu, loss per not received unit due to the supplier failure is 15 mu and the probability of occurrence of the super-event is 0.01. The values of other parameters such as capacity, failure probability, price breaks quantities and price discount percentage of each supplier is given in Table 1.

6.1. Computational results and discussion

To solve the problem with GA, first the optimal value of GA parameters (*Pop_size*, Pc, Pm and Gen) are determined, its program was ran for 20 iterations to find the better solution. The results of demand allocation for different problems with GA are shown in Table 2. For the problem of two suppliers (S1 and S2), there may be different combinations for allocating the total demand of the buyer between these two suppliers. After calculating ETC for all possible combinations, it is found that the allocation of 10 units to S1 supplier and 90 units to S2 supplier has minimum ETC. On the other hand, for three suppliers problem (S1, S2 and S3), the results show that the allocation of 10, 10, and 80 units among S1, S2 and S3 respectively has minimum ETC. Supplier S3 has received maximum order quantity in-spite of having higher failure probability. This has happened as supplier S3 provides higher discount as compared to the other suppliers. Similarly, for the rest of the problems, the results are presented in Table 2.

The results of all suppliers' problems reveal that best strategy for the buyer is to allocate maximum possible order quantity to a supplier that offer high discount, and keep rest of the suppliers into the supply base by allocating minimum possible order quantity. The computational results show that the supplier with high discount and low failure probability has received maximum order quantity as compared to the other suppliers. Moreover, if the price discounts of all suppliers are equal then the supplier with less failure probability will get the maximum order quantity. Since allocation of maximum order quantity to the highest discount providing supplier will reduce the expected total cost, the buyer can keep less failure probability sup-

Table 1
Data of capacity, unique-events probability and price discounts of each supplier.

Supplier no.	Supplier's capacity (units)	Unique-events probability	Price break quantities (units)			Associated price discounts (%)		
S1	70	0.13	30	45	60	0.11	0.22	0.31
S2	93	0.09	40	55	70	0.07	0.19	0.29
S3	110	0.15	35	45	50	0.09	0.18	0.33
S4	90	0.17	50	60	80	0.14	0.19	0.25
S5	105	0.12	30	40	45	0.10	0.15	0.27
S6	80	0.19	37	52	60	0.17	0.21	0.30
S7	95	0.05	30	45	55	0.13	0.23	0.35
S8	115	0.14	45	50	65	0.10	0.29	0.37
S9	100	0.11	40	55	60	0.15	0.25	0.35
S10	140	0.16	50	60	70	0.20	0.27	0.46

Table 2
GA results for order quantity allocation.

GA results							
No. of supplier	Suppliers	Optimal value of Pop_size, Pc, Pm and Gen.	Allocated order quantity	PC	SMC	ELC	Min. ETC
1	[S3]	30, 0.4, 0.05, 50	[100]	670	20	240.0	930.0
2	[S1, S2]	30, 0.4, 0.05, 50	[10, 90]	739	40	80.20	859.2
3	[S1, S2, S3]	30, 0.4, 0.05, 50	[10, 10, 80]	736	60	24.78	820.7
4	[S1, S2, S3, S4]	30, 0.4, 0.05, 50	[10, 10, 70, 10]	769	80	16.88	865.8
5	[S1, S2, S3, S4, S5]	30, 0.4, 0.05, 50	[11, 10, 60, 10, 10]	802	100	15.0	917.2
6	[S1, S2, S3, S4, S5, S6]	30, 0.41, 0.06, 50	[10, 10, 50, 10, 10, 10]	835	120	15.0	970.0
7	[S1, S2, S3, S4, S5, S6, S7]	30, 0.4, 0.05, 50	[10, 10, 10, 10, 10, 40, 10]	932	140	15.0	1087.0
8	[S1, S2, S3, S4, S5, S6, S7, S8]	30, 0.4, 0.05, 50	[10, 10, 10, 10, 10, 10, 30, 10]	961	160	15.0	1136.0
9	[S1, S2, S3, S4, S5, S6, S7, S8, S9]	30, 0.4, 0.05, 50	[10, 10, 20, 10, 10, 10, 10, 10, 10]	1000	180	15.0	1195.0
10	[S1, S2, S3, S4, S5, S6, S7, S8, S9, S10]	30, 0.4, 0.05, 50	[10, 10, 10, 10, 10, 10, 10, 10, 10, 10]	1000	200	15.0	1215.0

pliers as backup for emergency as the probability of disruptive events are very less. Furthermore, the results also indicate that as compared to single (sole) sourcing multiple sourcing is best strategy.

7. Sensitivity analysis

In this section, sensitivity analysis of various parameters is performed to investigate their impact on the final solution.

7.1. Sensitivity analysis of failure probability and quantity discounts

The values of failure probabilities and price discounts of the suppliers are varied at different levels keeping the other parameters value at their base value (as used in the previous numerical studies). Here, three suppliers (for example, S8, S9 and S10) problem was considered to perform the sensitivity analysis. The different values of failure probability and price discounts considered for these suppliers are given in Table 3. Three different levels such as low, medium and high are considered for the values of failure probability and price discounts of the suppliers. Further, it is considered that all suppliers provide price discounts at price breaks quantities of 30, 40, and 60 units and the minimum allocation to each supplier is considered as 10% of the total demand.

The results of sensitivity analysis for different values of failure probabilities and price discounts are presented in Table 4. In order to explore the effects of supplier's failure probability and price discounts on order allocation, first, we have considered that all suppliers have low failure probability and offers low discounts. Similar to the results in last section, here also the buyer has allocated maximum order quantity to the supplier who has provided high price discount though it has high failure probability as compared to other suppliers and retained reliable but expensive suppliers as backup by allocating minimum proportion of the total demand. From the results of the sensitivity analysis, it is observed that first priority for order quantity allocation is price discount rather than failure probability of the supplier.

From the results of the sensitivity analysis, it is observed that under same failure probability and at low level discount, maximum order quantity is allocated to the highest capacity supplier. It is because the highest capacity supplier can provide more compensation compared to other suppliers. Further, the results depict that as the value of price discount percentage increases (i.e. at medium and high level), the allocation of order quantity among all suppliers comes closer or equal in-spite of having higher differences in failure probabilities of suppliers.

7.2. Sensitivity analysis of demand

To perform demand sensitivity analysis, values of demand is varied at six different levels with different failure probability and price discounts. The results of sensitivity analysis are given in Table 5.

The results presented in Table 5 depict that when the demand of the buyer is less and suppliers are having sufficient or large capacity, it is optimal to allocate maximum possible order quantity to one supplier and give minimum order quantity to other suppliers. Therefore, it can be concluded that when a supplier has enough capacity, it is an efficient strategy to order maximum order quantity to one supplier, and keep the rest of the suppliers engaged in relationship by allocating minimum possible order quantity.

7.3. Sensitivity analysis of suppliers' capacity

As consideration of different capacity of all suppliers is one of the contributions of this work; therefore, we have performed its sensitivity analysis to delve its effect on the final solution. To perform the sensitivity analysis, the values of de-

Table 3
Data set of suppliers for sensitivity analysis.

Supplier	Failure probability (p_i)			Discount percentage d_{ji}		
	Low risk (LR)	Medium risk (MR)	High risk (HR)	Low discount (LD)	Medium discount (MD)	High discount (HD)
S8	0.05	0.11	0.21	0.05, 0.09, 0.12	0.21, 0.25, 0.27	0.31, 0.33, 0.37
S9	0.05	0.11	0.21	0.05, 0.09, 0.12	0.21, 0.25, 0.27	0.31, 0.33, 0.37
S10	0.05	0.11	0.21	0.05, 0.09, 0.12	0.21, 0.25, 0.27	0.31, 0.33, 0.37

Table 4
Results of failure probability and price discount sensitivity analysis.

Demand	Supplier	Failure probability level		Discount percentage level		Allocated quantity	ETC
	S8		0.05		0.05, 0.09, 0.12	10	
100	S9	Low	0.05	Low	0.05, 0.09, 0.12	10	979.19
	S10		0.05		0.05, 0.09, 0.12	80	
	S8		0.11		0.21, 0.25, 0.27	40	
100	S9	Medium	0.11	Medium	0.21, 0.25, 0.27	30	851.00
	S10		0.11		0.21, 0.25, 0.27	30	
	S8		0.21		0.31, 0.33, 0.37	40	
100	S9	High	0.21	High	0.31, 0.33, 0.37	30	770.89
	S10		0.21		0.31, 0.33, 0.37	30	
	S8		0.05	Low	0.05, 0.09, 0.12	10	
100	S9	Low	0.05	Medium	0.21, 0.25, 0.27	10	779.19
	S10		0.05	High	0.31, 0.33, 0.37	80	
	S8		0.11	Low	0.05, 0.09, 0.12	10	
100	S9	Medium	0.11	Medium	0.21, 0.25, 0.27	80	781.00
	S10		0.11	High	0.31, 0.33, 0.37	10	
	S8		0.21	Low	0.05, 0.09, 0.12	10	
100	S9	High	0.21	Medium	0.21, 0.25, 0.27	10	792.89
	S10		0.21	High	0.31, 0.33, 0.37	80	
	S8	Low	0.05		0.05, 0.09, 0.12	10	
100	S9	Medium	0.11	Low	0.05, 0.09, 0.12	10	980.73
	S10	High	0.21		0.05, 0.09, 0.12	80	
	S8	Low	0.05		0.21, 0.25, 0.27	40	
100	S9	Medium	0.11	Medium	0.21, 0.25, 0.27	30	850.73
	S10	High	0.21		0.21, 0.25, 0.27	30	
	S8	Low	0.05		0.31, 0.33, 0.37	40	
100	S9	Medium	0.11	High	0.31, 0.33, 0.37	30	758.73
	S10	High	0.21		0.31, 0.33, 0.37	30	
	S8	Low	0.05	Low	0.05, 0.09, 0.12	10	
100	S9	Medium	0.11	Medium	0.21, 0.25, 0.27	10	780.73
	S10	High	0.21	High	0.31, 0.33, 0.37	80	

mand is considered 200 units and suppliers' capacity are varied at four different levels while keeping the rest of the parameters fixed at their base value. The results of sensitivity analysis are presented in Table 6.

The case 1 in Table 6, depicts that when suppliers have sufficient same capacity and same price break quantity, discount percentage and different failure probability, it allocates maximum possible order quantities to the supplier who has lower failure probability. In case 2, we have observed an interesting result that when all the suppliers have same price break quantity and discount percentage and different capacity and failure probability, it allocates more order quantity to the supplier that has large capacity inspite of its higher failure probability. The buyer can get more compensation from the higher capacity supplier. The case 3 shows that when suppliers' have different capacity, price breaks, failure probability and discount percentage, it is better to allocate maximum possible order quantity to the suppliers with high discount in spite of his/her high failure probability.

7.4. Sensitivity analysis of supplier management cost and loss per unit

Here, we have studied the effect of per supplier management and loss per units costs on demand allocation. To perform sensitivity analysis, we varied the value of both these parameters at different level, while keeping rest of the parameters at their base value. The sensitivity analysis results of both parameters are presented in Tables 7 and 8 respectively. The results show that both parameters don't have impact on demand allocation decision.

Table 5
Results of sensitivity of demand variation.

Demand	Suppliers	Failure probability level	Discount percentage level	Allocated order quantities	ETC
	S8	0.14	0.05, 0.09, 0.12	08	
80	S9	0.11	0.23, 0.26, 0.28	64	695.75
	S10	0.16	0.22, 0.24, 0.26	08	
	S8	0.14	0.05, 0.09, 0.12	10	
100	S9	0.11	0.23, 0.26, 0.28	80	854.7
	S10	0.16	0.22, 0.24, 0.26	10	
	S8	0.14	0.05, 0.09, 0.12	15	
150	S9	0.11	0.23, 0.26, 0.28	60	1249.9
	S10	0.16	0.22, 0.24, 0.26	75	
	S8	0.14	0.05, 0.09, 0.12	20	
200	S9	0.11	0.23, 0.26, 0.28	100	1670.2
	S10	0.16	0.22, 0.24, 0.26	80	
	S8	0.14	0.05, 0.09, 0.12	25	
250	S9	0.11	0.23, 0.26, 0.28	100	2178.6
	S10	0.16	0.22, 0.24, 0.26	125	
	S8	0.14	0.05, 0.09, 0.12	90	
300	S9	0.11	0.23, 0.26, 0.28	90	2880.9
	S10	0.16	0.22, 0.24, 0.26	120	

Table 6
Results of sensitivity analysis of suppliers' capacity.

Case no	Suppliers	Suppliers' capacity	Failure probability	Price break quantity	Discount percentage level	Allocated order quantities	ETC
	S8	200	0.14	70 100 130	0.10, 0.29, 0.37	20	
1	S9	200	0.11	70 100 130	0.10, 0.29, 0.37	160	1534.2
	S10	200	0.16	70 100 130	0.10, 0.29, 0.37	20	
	S8	100	0.14	70 100 130	0.10, 0.29, 0.37	20	
2	S9	140	0.11	70 100 130	0.10, 0.29, 0.37	20	1553.8
	S10	160	0.16	70 100 130	0.10, 0.29, 0.37	160	
	S8	200	0.14	70 100 130	0.10, 0.29, 0.37	20	
3	S9	210	0.11	90 110 140	0.15, 0.25, 0.35	20	1473.4
	S10	250	0.16	100 130 150	0.20, 0.27, 0.39	160	
	S8	120	0.14	50 70 90	0.10, 0.29, 0.37	100	
4	S9	90	0.11	70 80 100	0.15, 0.25, 0.35	80	1595.9
	S10	110	0.16	60 90 100	0.20, 0.27, 0.39	20	

Table 7
Results of sensitivity analysis of per supplier management cost.

Per supplier management cost	Suppliers	Allocated order quantities	ETC
	S8	10	
10	S9	10	680.69
	S10	80	
	S8	10	
20	S9	10	710.69
	S10	80	
	S8	10	
40	S9	10	770.69
	S10	80	
	S8	10	
60	S9	10	830.69
	S10	80	
	S8	10	
80	S9	10	890.69
	S10	80	
	S8	10	
100	S9	10	950.69
	S10	80	

Table 8
Results of sensitivity analysis of loss per unit.

Loss per unit	Suppliers	Failure probability level	Discount percentage level	Allocated order quantities	ETC
15	S8	0.14	0.10, 0.29, 0.37	10	710.69
	S9	0.11	0.15, 0.25, 0.35	10	
	S10	0.16	0.20, 0.27, 0.46	80	
30	S8	0.14	0.10, 0.29, 0.37	10	729.39
	S9	0.11	0.15, 0.25, 0.35	10	
	S10	0.16	0.20, 0.27, 0.46	80	
45	S8	0.14	0.10, 0.29, 0.37	10	748.08
	S9	0.11	0.15, 0.25, 0.35	10	
	S10	0.16	0.20, 0.27, 0.46	80	
60	S8	0.14	0.10, 0.29, 0.37	10	766.78
	S9	0.11	0.15, 0.25, 0.35	10	
	S10	0.16	0.20, 0.27, 0.46	80	
75	S8	0.14	0.10, 0.29, 0.37	10	785.48
	S9	0.11	0.15, 0.25, 0.35	10	
	S10	0.16	0.20, 0.27, 0.46	80	

8. Conclusions

In this paper, we studied the optimal order allocation problem under supplier failure risk and quantity based price discounts. The specific contributions of this paper to the relevant literature are as follows. First, a mixed integer non-linear programming (MINLP) problem is developed considering different capacity, failure probability, price discounts and compensation potential for each supplier. As far as we are aware, no such study is present in the literature that has considered all the aforementioned parameters together. Consideration of all these parameters together has made the problem more realistic but also at the same time more complex. Next, we have proved that the formulated problem is NP-hard in nature. This type of problems is difficult to solve with any exact method for optimality. Therefore, non-traditional optimization technique genetic algorithm (GA) is used here to solve the problem. Finally, different numerical experiments are conducted to illustrate the model and GA to find the solution of the problem.

The results of numerical study portray that the cost of supplier has more influence on order quantity allocation rather than supplier's failure probability. The supplier's with high discount receives more order quantity as compared to other suppliers. Further, it is found that if the price discounts of all suppliers are equal then the supplier with less failure probability will get the maximum order quantity. The results suggest that allocation of maximum order quantity to one supplier of high price discount and allocation of minimum order quantity to rest of the suppliers is the best strategy. Allocation of maximum order quantity to the high discount providing supplier will reduce the cost and the buyer can keep lesser failure probability suppliers as backup for emergency.

The results of sensitivity analysis depict that as the value of price discount increases, the allocation of order quantity among all suppliers comes closer or equal in-spite of higher difference in failure probabilities of suppliers. It is found that when a supplier has large capacity, it is efficient to order more quantity from one supplier. The results also reveal that when all the suppliers have same price break quantity, the supplier with higher capacity receives maximum order quantity in spite of its higher failure probability. Further, it is observed that management cost and loss per unit have no impact on demand allocation decision.

In future, several interesting extensions are possible of this paper. Here, it is assumed that demand is deterministic. Consideration of stochastic demand will be an interesting problem for future study. Further, it is assumed that the compensation (i.e. extra quantity) provided by the supplier comes at no extra cost. However, in reality, supplier may charge higher cost for supplying extra quantity. Finally, one can extend the model developed here for multi-periods and multi-items environment.

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