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A technique for determining the optimum mix of logistics service providers of a make-to-order supply chain by formulating and solving a constrained nonlinear cost optimization problem

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A B S T R A C T

In this paper, a technique has been developed to determine the optimum mix of logistic service providers of a make-to-order (MTO) supply chain. A serial MTO supply chain with different stages/ processes has been considered. For each stage different logistic service providers with different mean processing lead times, but same lead time variances are available. A realistic assumption that for each stage, the logistic service provider who charges more for his service consumes less processing lead time and vice-versa has been made in our study. Thus for each stage, for each service provider, a combination of cost and mean processing lead time is available. Using these combinations, for each stage, a polynomial curve, expressing cost of that stage as a function of mean processing lead time is fit. Cumulating all such expressions of cost for the different stages along with incorporation of suitable constraints arising out of timely delivery, results in the formulation of a constrained nonlinear cost optimization problem. On solving the problem using mathematica, optimum processing lead time for each stage is obtained. Using these optimum processing lead times and by employing a simple technique the optimum logistic service provider mix of the supply chain along with the corresponding total cost of processing is determined. Finally to examine the effect of changes in different parameters on the optimum total processing cost of the supply chain, sensitivity analysis has been carried out graphically.

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1. Introduction

In last few decades, both practitioners and academicians have shown their interest to study supply chain management (SCM) and its related issues (Harland, 1996; Mentzeret al., 2008).Many researchers also conducted their research related to SCM problems and its concepts from different perspectives (Christopher et al., 1998; Cooper & Lambert, 2000; Ross, 1997). Unfortunately, there is little explanation of SCM or its activities in the literature (Tan, 2001).

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A supply chain can be observed as a complex network of suppliers, manufacturers, distribution intermediaries and end customers through which raw materials, finished products, and information flow. A supply chain may be understood as an integrated process starting from the procurement of raw material, its conversion to create utility and distribution of the end products to either retailers or customers (Cooper & Lambert, 2000; Min & Zhou,2002). Jukka et al. (2001) defined SCM as a customer-centric approach to provide goods and services at the lowest cost and highest service level. In general, a supply chain involves a number of independent and interconnected business entities that are located in different places (Zhang et al., 2010). The activities of these entities range from the supply of raw materials to the transformation process and delivery of finished products to the end customers, in gaining competitive advantage while optimizing the entire supply chain cost (Croom et al., 2000). Different entities in a supply chain have different sets of constraints and objectives despite the fact they depend on each other to attain the common supply chain objectives such as on-time delivery, quality assurance, and cost minimization. As a result, performance of the entire supply chain is influenced by interdependency, compliance and coordination among the entities within the supply chain (Swaminathan et al., 1998). Benita and Beamon (1998) identified two important processes:(i) the production planning and inventory control process and (ii) the distribution and logistics process in SCM as shown in Fig. 1.

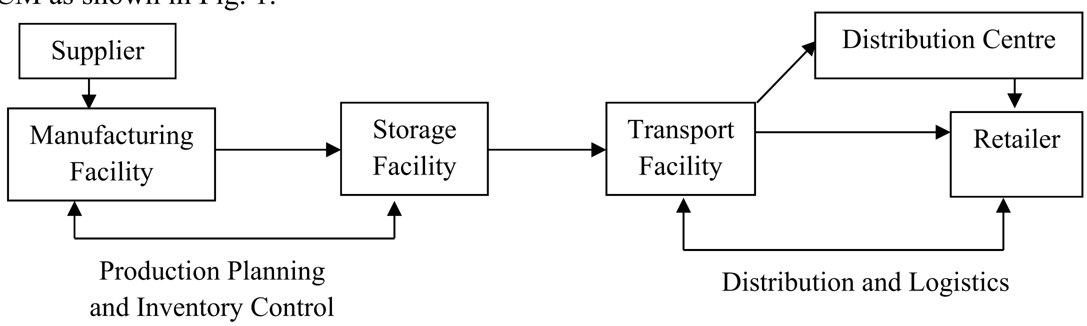

Fig. 1. Supply-chain process(Benita & Beamon, 1998)

Garg et al. (2006) explained supply chain as a collection of different stages of business processes interconnected to each other for the provision of goods and services. They stated that supply chain can be compared with a complex mechanical assembly in analyzing end-to-end delivery performance. In this context, they also identified two broad categories of supply chain network i.e. serial supply chain and converging-diverging supply chain. Traditionally, there are two types of supply chain viz "push" or Make-To-Stock (MTS) supply chain and "pull" or Make-To-Order (MTO) supply chain found in the market. In Make-To-Stock (MTS) supply chain, inventory is kept at each stage of the supply chain and the firms depend on forecasts to estimate the demand for determining the quantity to produce and stock. In Make-To-Order (MTO) supply chain, firms produce product based on customer order and keep no inventory at all. However, in this case, customers have to wait for delivery, which may lead to loss of competitiveness on the part of the firm.

In this paper, we address the problem of logistic service provider selection for individual stages of the MTO supply chain by minimizing the overall cost of supply chain. Optimization of the supply chain cost by order fulfillment time compression and business process synchronization is the broad objective of our study.

2. Related work

The order fulfillment process (OFP) has been recognized as a cyclic process that starts with acceptance of customer order and ends with the delivery of the final product to the customer. Traditionally, OFPs are controlled by the final producers of the product in a supply chain. However, it includes several activities such as receiving customer orders, processing orders, stock monitoring, selecting logistic partners, procurement planning, supplier selection, order delivery, etc. Lin and

Shaw (1998) stated that the order fulfillment process was a complex integrated process of demand and supply, which was accomplished by the different departments of an organization. Based on different supply chain systems (e.g. make-to-stock, make-to-order, engineer-to-order, and assemble-to-order), organizations follow different order fulfillment processes, though, the main objective of order fulfillment process of the organization is to deliver the products to satisfy customers' requirements at the right time, right place, right quantity, and right price (Christopher, 1992). Supply chain members of a firm nowadays handle order fulfillment process to optimize their own objectives. So firms reengineer their order fulfillment processes by integrating geographically scattered supply chain partners (Kritchanchai & MacCarthy, 1999; Waller et al., 1995). Zhang et al. (2010) stressed on the importance of reengineering of OFPs to take the advantages of sound integration between supply chain partners.

Song et al. (1999) stated that order fulfillment process of assemble to order (ATO)/ make to order(MTO) was crucial for the organizations to deliver the product quickly to market as compared to the traditional MTO inventory planning systems. Many of the important operational decisions related to MTO supply chain, like capacity planning, scheduling, etc., are initiated when an order fulfillment process starts. Make-to-order supply chain gains competitive advantage in the market if it has faster delivery time (Li & Lee, 1994). Guiffrida & Jaber (2008) defined delivery lead time as the elapsed time between the receipt of an order and the receipt of the final product by the customer in the supply chain. They also described that delivery lead time is the sum of internal lead times (i.e. manufacturing and processing time at each stage) and external lead times (i.e. distribution and transportation time between various stages)in a serial supply chain. In a MTO supply chain, lower delivery lead time can be attained by reducing the processing time of each process within the chain while assuming that the work in process inventory time is included in the processing time. Handfield & Pannesi (1995) argued that longer delivery lead time of MTO supply chain could not produce value added product resulting in low market share and less brand loyalty. According to them, MTO supply chain is likely to receive orders more frequently if it serves its customers before the scheduled/desired date. Therefore, delivery lead time depends on each of the activities and processes within MTO supply chain and all activities must be dealt with reasonably well despite some cost constraints at each stage in order to optimize the performance of the supply chain. Gunasekaran et al. (2001) identified that two important supply chain performance measures i.e. delivery performance and delivery reliability can be measured in financial as well as non-financial terms. They claimed that on-time delivery is a crucial issue of delivery performance and if it can not be measured finnancialy then it has adverse effect on the buyer–supplier relationship and capital budgeting process.

Managing cost in supply chains is a key elementin providing competitive advantage. Borsodi (1927) pointed out that the visibility of cost in business processes and the supply chain should be increased. The importance of the cost of different supply chain activities were studied by several researchers (Develin, 1999; Pohlen et al., 1994). Lalonde and Pohlen (1996) found the requirement for linking performance measurement with cost in supply chain management. Ellram (2002) also stated that cost management in supply chain was difficult without proper performance measures. Lancioni (2000) mentioned in his study that firms require paying attention in optimization of supply chain cost to improve their performances. Guiffrida & Nagi (2006) argued that cost-based performance measures are crucial and capable of being used across various processes and stages of the supply chain. They identified the fact that cost-based measures had impact on the capital budgeting processes that helped the firm to get investment in supply chain improvement initiatives. In another article they discussed how time-based delivery performance measures were converted into financial based delivery performance metrics through cost-based models that enhance the delivery process (Guiffrida & Nagi, 2006). Ballou et al. (2000) acknowledged that supply chain cost performance depends on the cost performance of the channel members of serial supply chain. They stressed that measuring performance in terms of cost and uncertainty must be considered as a tool for continuous improvement of activities in supply chain. In the context of delivery performance, Bushuev and Guiffrida (2012) introduced the concept of delivery window and related cost measures. They defined delivery window as the difference between the earliest acceptable delivery date and the latest acceptable delivery date. They also pointed out the fact that early and late deliveries had an impact on the supply chain cost. Early deliveries contribute to excess inventory holding costs, while late deliveries may contribute to production stoppages costs, lost sales and loss of goodwill. Delivery windows are able to accomplish the purpose of developing cost based performance model for untimely delivery and the model helped to measure the delivery performance in financial term (Gunasekaran et al., 2001).

In this paper, we try to find the optimum cost of supply chain with respect to a delivery window. We also share the same view that cost optimization is important for supply chain planning, control and performance improvement because the metric of cost is easily measured and controlled by management. We have developed a cost optimization model of a serial make-to-order supply chain. The solution of the model helps us to find the optimal logistic service provider mix associated with minimum end to end delivery lead time within a specified delivery window. We consider the make-to-order supply chain as a collection of several processes which are serially connected. Processes of supply chain can be actuated by the placing of customer orders. Each process has several logistic service providers and each of them quotes his processing lead time along with cost of service to accomplish all tasks related with the process. A logical assumption that the logistic service provider who performs all tasks of a process with higher mean processing lead time charges lower price and vice versa has been made. The lead time variability of the service providers of a particular process are assumed to be the same. For each process/stage, we fit a polynomial function of processing cost in terms of processing lead time by using the pairs of values of processing lead time and processing cost provided by the service providers. After computing the cost function for each process we develop a nonlinear cost optimization problem with the consideration of suitable constraints arising out of timely delivery. To solve this problem Mathematica software has been used. The solution of the problem provides the optimum processing lead time for each process. Now out of all the available times given by the service providers for each process, two service providers' times which are nearer to the optimal processing lead time (obtained by solving the above mentioned problem) are selected. With the help of two service providers' times for each stage, different alternatives of logistic service provider mix are constructed and out of these, only for those alternatives which satisfy the model constraints, the total processing cost of supply chain are computed. The alternative for which the total processing cost of supply chain is minimum, is the one which provides the optimal combination of service providers of supply chain. Finally, the model has been illustrated with a numerical example and sensitivity analysis has been carried out to investigate the effect of different parameters on optimum total processing cost of supply chain.

3. Assumptions and notations

The following assumptions and notations are used in developing the proposed model.

3.1.Assumptions

(i) A serial make-to-order supply chain with no elapse time allowed between consecutive stages is considered.

(ii) Each stage of the supply chain is a work process like procurement of raw materials, manufacturing, transportation, packaging, etc. and the processing time at each stage i.e. lead time at each stage contributes to the overall delivery lead time. Therefore, the end to end delivery lead time is the summation of the processing lead times of the stages of supply chain.

(iii) There is no inventory at any intermediate stage of the supply chain and an interface time (if any) can be included into the lead time of any stage among two consecutive stages.

(iv) There are different types of logistic service providers who can perform a particular job at a particular stage of the supply chain and they charge differently for their services. The service provider who performs the job of a stage with higher mean lead time charges lower price and vice versa. It is also assumed that the quality of the job performed is same for all the service providers.

(v) The processing lead time of each stage is a random variable and it follows normal distribution. So it is realistic to assume that the end to end delivery lead time also follows normal distribution with its mean equal to the sum of the different mean processing lead times of the different stages and its variance equal to the sum of the different lead time variances of the different stages i.e. the processing lead time $X_i \sim N(\mu_i, \sigma_i)$ where μ_i, σ_i^2 are known, therefore it is obvious that the end to end delivery lead time of the supply chain Y is normally distributed i.e. $Y \sim N(\mu \ , \sigma \ )$ where $Y = \sum_{i=1}^{n} X_i$, $\mu = \sum_{i=1}^{n} \mu_i$ and $\sigma^2 = \sum_{i=1}^{n} \sigma_i^2$, because Y is the sum of n independent normally distributed random variables.

(vi) The lead time variances of the service providers of a particular stage are same and is equal to the constant lead time variance of that particular stage i.e. for a particular stage $i\,(i = 1,2,3,\ldots n)$, $\sigma_{ij}{}^2 = \sigma_i{}^2$ *for all* j .

(vii) The customers prefer to receive the order through a delivery window (i.e. difference between the earliest acceptable delivery time and the latest acceptable delivery time).

Notations

n	Number of stages in the serial supply chain
m	Number of logistics service provider in each stage of the serial supply chain
i	Index of stages ranging from 1 to n i.e. $(i = 1,2,3,\ldots n)$
j	Index of service providers ranging from 1 to m i.e. $(j = 1,2,3\ldots m)$
X_i	A random variable which denotes the processing lead time at stage i
μ_i	Mean processing lead time at stage i
σ_i^2	Variance of processing lead time at stage i
L_{ij}	j th logistics service provider at stage i
μ_{ij}	Mean processing lead time of j th service provider at stage i
σ_{ij}^2	Lead time variability of j th service provider at stage i
Y	A random variable which denotes end to end delivery lead time
μ	Mean end to end delivery lead time
σ^2	Variance of end to end delivery lead time
θ	Amount of time for which a customer is willing to wait after placing the order
T	Tolerance time specified by customer.
(θ, T)	Customer delivery window
Z_i	Processing cost per unit product at stage i of the supply chain $(\forall\ i = 1,2,3,\ldots n)$
C_{ij}	Per unit processing cost quoted by the j th service provider at stage i
TC	Total processing cost of the serial supply chain
μ_i^*	Optimum mean processing lead time at stage i

4. Mathematical model description

A serial make-to-order (MTO) supply chain with n stages has been considered as shown in Fig.2.The supply chain deals with a single product. Business processes in each stage of supply chain can be triggered by the customer orders and the customers receive the delivery from the nth stage of the supply chain.

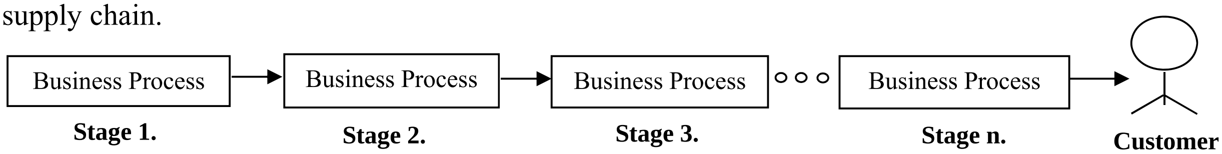

Fig. 2. Serial Supply Chain (Garg et al., 2006)

When a customer places an order, the supply chain starts processing from first stage and continues work processes through the successive stages till the final delivery is received by the end customer from the stage n. At any stage $i\,(i = 1, 2, 3, \ldots n)$, we may get the different prices for the different mean lead times for processing offered by the different service providers to accomplish the job. For example, there may be several third party logistic providers (3PL) who can package the product and different service providers charge different prices to complete the packaging process because of differences in their processing lead times, though their lead time variance is equal to fixed lead time variance for a particular stage $i\,(i = 1, 2, 3, \ldots n)$. The customer delivery window (θ, T) indicates that a customer is prepared to wait for a maximum period of $\theta + T$ and also, the customer does not want the delivery to occur before $\theta - T$. C_{ij} , the per unit processing cost quoted by the service provider j at stage i being known for all i and j, the pairs (μ_{ij}, C_{ij}) for a particular stage i (where $j = 1, 2, 3, \ldots m$) can be used to derive a polynomial function which expresses the Z_i in terms of μ_i. The objective of our model is to find out the optimum value of processing lead time at each stage of the supply chain (and thus finding the best logistics service provider at each stage) such that delivery lead time of the supply chain attained for a specified delivery window leads to minimum total cost of processing per unit product of the supply chain. The solution of the model helps us to select best mix of logistics service providers.

Decision variables

The decision variables of our model are μ_i for $i = 1, 2, 3, \ldots n$

Objective function

Our objective is to minimize the overall processing cost of supply chain. For any stage ***i***, the processing cost is a function of μ_i i.e. $Z_i = f(\mu_i)$ .The total processing cost of supply chain is given by $TC = \sum_{i=1}^{n} Z_i$, where Z_i is the cost of processing at stage $i\,(i = 1, 2, 3, \ldots n)$. Therefore, the objective function of the model is as follows:

$Min\ TC = Min(\sum_{i=1}^{n} Z_i) = Min\sum_{i=1}^{n}(a_{i0} + a_{i1}\mu_i + a_{i2}\mu_i^2)$,where a_{i0}, a_{i1}, a_{i2} are constants whose values are obtained by polynomial curve fitting.

Constraints

We earlier assumed that the processing lead time X_i at stage $i\,(i = 1, 2, 3, \ldots\ldots n)$ is a random variable and $X_i \sim N(\mu_i, \sigma_i)$ where μ_i, σ_i^2 are known. We know that 99.73% of all observations of X_i lies within the $\mu_i \pm 3\sigma_i$ by a well-known characteristic of Normal distribution. In our model the overall processing lead time must be within Customer delivery window (θ, T). Therefore the constraints of the model are as follows:

$\mu + 3\sigma \le \theta + T$ and $\mu - 3\sigma \ge \theta - T$; where $\mu = \sum_{i=1}^{n} \mu_i$ and $\sigma = \sqrt{\sum_{i=1}^{n} \sigma_i^2}$

4.1.Mathematical model

Our model is a non-linear optimization problem which can be written as follows:

$$\min \ TC = Min(\sum_{i=1}^{n} Z_i) = Min \sum_{i=1}^{n} (a_{i0} + a_{i1}\mu_i + a_{i2}\mu_i^2) \quad (1)$$

subject to

$$\mu + 3\sigma \le \theta + T \quad (2)$$

$$\mu - 3\sigma \ge \theta - T \quad (3)$$

and $\mu_i \ge 0 \quad \forall i = 1, 2, 3, ..., n$; where $\mu = \sum_{i=1}^{n} \mu_i$ and $\sigma = \sqrt{\sum_{i=1}^{n} \sigma_i^2}$

5. Solution procedure

In order to solve the non-linear optimization problem presented in section 4.1, the following steps are followed:

Step 1: Collect the values of all known parameters of the problem. This includes collecting the values of θ, T *and* σ .

Step 2: Obtain the values of the constants a_{i0}, a_{i1}, a_{i2} from the pairs (μ_{ij}, C_{ij}) for a particular stage i (where $j = 1, 2, 3, ...m$) to get a polynomial function Z_i in terms of μ_i by using SPSS 17.0.

Step 3:Formulate the nonlinear optimization problem which has been presented under section 4.4 with all known parameters and constants. Obtain the optimum solution of the problem using the software Mathematica 8.0.

Step 4:Here for each stage of supply chain, one logistic service provider whose lead time is nearest to the optimal lead time for that stage(as obtained from the optimum solution referred in Step 3)is spotted. The process is explained elaborately below.

The idea behind the solution of the problem is to execute Steps1–3 and get $\mu_1^*, \mu_2^*, ...\mu_n^*$ i.e. optimal values of mean lead time μ_i where $(\boldsymbol{i} = 1, 2, ..., \boldsymbol{n})$. Now consider stage *i*. If μ_i^* exactly coincides with the mean processing lead time of a logistic service provider for stage *i,* then that service provider is selected. Otherwise, out of all the available service providers for stage i, select two service providers $\boldsymbol{L_{ik}}$ (i.e. $\boldsymbol{j} = \boldsymbol{k}$) and $\boldsymbol{L_{iw}}$ (i.e. $\boldsymbol{j} = \boldsymbol{w}$) in such a way that the optimal processing lead time μ_i^* lies in the smallest available interval $[\mu_{ik}, \mu_{iw}]$ where μ_{ik} and μ_{iw} are the mean processing lead times of L_{ik} and L_{iw} respectively. After selecting two alternatives $\boldsymbol{L_{ik}}$ and $\boldsymbol{L_{iw}}$ for stage *i,* prepare logistics service provider mix of alternatives in 2^n ways and compute the total cost of supply chain for the alternative which satisfies the constraints of the model. Note that it may happen that μ_i^* is either less than all candidate processing lead time or greater than all candidate processing lead time. In both the cases, we choose the one that is closest to μ_i^* .After calculating these values, decide the optimal combination of service providers all along the supply chain at minimum total processing cost of supply chain.

6. Numerical Example

The proposed model is explained by considering the following example. The values of the model parameters considered in the numerical example are not selected from any case study, but the values considered here are all realistic. A serial make to order supply chain has been considered and the 4-Step approach for formulating and solving the logistic service provider selection problem has been applied. The assumed values of the parameters in the example are given below:

$m = 6$ for all stages; $\theta = 60$ days; $T = 11$ days; $n = 6$

$\sigma_1^2 = 0.78$ days; $\sigma_2^2 = 0.61$ days; $\sigma_3^2 = 0.72$ days; $\sigma_4^2 = 0.65$ days; $\sigma_5^2 = 0.64$ days; $\sigma_6^2 = 0.60$ days

Table 1
Processing lead times and cost for each service provider at different stages

Stage	Logistic service provider											
i	L_{i1}		L_{i2}		L_{i3}		L_{i4}		L_{i5}		L_{i6}	
	μ_{i1} (days)	C_{i1} (Rs./item)	μ_{i2} (days)	C_{i2} (Rs./item)	μ_{i3} (days)	C_{i3} (Rs./item)	μ_{i4} (days)	C_{i4} (Rs./item)	μ_{i5} (days)	C_{i5} (Rs./item)	μ_{i6} (days)	C_{i6} (Rs./item)
1	14	14,180	15	14,150	08	15,100	07	15,385	10	14,655	12	14,345
2	10	5,665	11	5,510	17	5,000	19	4,900	14	5,175	16	5,050
3	10	995	03	1,500	05	1,300	02	1,605	06	1,200	04	1,375
4	20	31,200	15	31,900	18	31,340	19	31,240	12	32,800	10	33,700
5	06	3,955	05	4,040	03	4,255	08	3,835	07	3,885	04	4,140
6	12	4,080	07	4,365	08	4,300	14	3,985	05	4,500	10	4,185

The processing cost of one unit of product at each one of the six business processes varies over the service providers as a function of processing lead times.

Step 1

The parameters for the problem are provided explicitly in the given problem. The values of the parameters, which will be needed in further calculations are as follows

$$\sigma^2 = \sum_{i=1}^{6} \sigma_i^2 = 4; \sigma = \sqrt{\sum_{i=1}^{6} \sigma_i^2} = 2; \theta = 60 \text{ days}; T = 11 \text{ days}$$

Step 2

The values of the constants a_{i0}, a_{i1}, a_{i2} can be obtained by fitting a second order polynomial curve for the given six pairs $(\mu_{i1}, C_{i1}), (\mu_{i2}, C_{i2}), (\mu_{i3}, C_{i3}), (\mu_{i4}, C_{i4}), (\mu_{i5}, C_{i5})$ and (μ_{i6}, C_{i6}) considering each stage i. The values of the coefficients a_{i0}, a_{i1}, a_{i2} for each stage i, obtained by using SPSS 17.0 are tabulated in Table 2. It may be noted here that for each curve fitting, the goodness of fit is pretty high (satisfactory) indicating that the second degree polynomial is capable of explaining the relationship between the cost and mean processing lead time.

Table 2
Cost coefficients for the problem

Stage i	a_{i0}	a_{i1}	a_{i2}	Stage i	a_{i0}	a_{i1}	a_{i2}
1	18332.64	−546.19	17.82	4	40671.84	−923.53	22.49
2	7736.08	−274.22	6.60	5	4699.10	−171.69	7.49
3	1881.57	−148.06	5.93	6	4888.92	−85.26	1.48

Z_i i.e. processing cost per item at each stage i is as follows:

$\boldsymbol{Z}_1 = 17.82\mu_1^2 - 546.19\mu_1 + 18332.64;$
$\boldsymbol{Z}_2 = 6.60\mu_2^2 - 274.22\mu_2 + 7736.08;$
$\boldsymbol{Z}_3 = 5.93\mu_3^2 - 148.06\mu_3 + 1881.57;$
$\boldsymbol{Z}_4 = 22.49\mu_4^2 - 923.53\mu_4 + 40671.84;$
$\boldsymbol{Z}_5 = 7.94\mu_5^2 - 171.69\mu_5 + 4699.10;$
$\boldsymbol{Z}_6 = 1.48\mu_6^2 - 85.26\mu_6 + 4888.92;$

Step 3

Now the optimization problem can be formulated as follows

$$\min \ \boldsymbol{TC} = (17.82\mu_1^2 - 546.19\mu_1 + 18332.64) + (6.60\mu_2^2 - 274.22\mu_2 + 7736.08) + (5.93\mu_3^2 - 148.06\mu_3 + 1881.57)$$
$$+ (22.49\mu_4^2 - 923.53\mu_4 + 40671.84) + (7.94\mu_5^2 - 171.69\mu_5 + 4699.10) + (1.48\mu_6^2 - 85.26\mu_6 + 4888.92)$$

Subject to

$\mu + 3(2) \le 60 + 11 \Rightarrow \mu \le 65$ and $\mu - 3(2) \ge 60 - 11 \Rightarrow \mu \ge 55$ and $\mu_i \ge 0 \quad \forall i = 1,2,3,...,6$;

where $\mu = \sum_{i=1}^{6} \mu_i$

Applying the software Mathematica 8.0, the following solution is obtained:

Minimum total processing cost of supply chain i.e. $Minimum \ TC =$ Rs. 60,179.90

Optimum values of $\mu_i \ (i = 1,2,3,4,5,6)$ are

$\mu_1^* = 13.31, \quad \mu_2^* = 15.35, \quad \mu_3^* = 6.45, \quad \mu_4^* = 18.94, \quad \mu_5^* = 6.30, \quad \mu_6^* = 4.63$

Step 4

Now at first let us consider stage 1. Out of all six service providers for stage 1,we select two service providers $\boldsymbol{L}_{16}$ (i.e. $\boldsymbol{j} = 6$) and $\boldsymbol{L}_{11}$ (i.e. $\boldsymbol{j} = 1$) such that the optimal processing lead time $\mu_1^* = 13.31$ days is immediately above of the value of $\mu_{16} = 12$ days and is immediately below of the value of $\mu_{11} = 14$ days. In similar manner, two logistic service providers are found out in each of the other stages except stage six because optimum lead time $\mu_6^* (= 4.63)$ is less than all candidates processing lead times. Therefore, for stage six, only one logistics service provider L_{65} is selected, since $\mu_{65} (= 5)$ is closest to μ_6^*. Pairs of optimal logistic service providers have been shown in **Table 3.**

Table 3
Pairs of optimal logistic service providers

Stage	1	2	3	4	5	6
Optimum Logistic Service Provider pairs	L_{11} L_{16}	L_{25} L_{26}	L_{35} L_{31}	L_{43} L_{44}	L_{55} L_{51}	L_{65}

Now from Table 3, It is evident that for each of the first five stages, there is a pair of optimum logistics service providers. Hence, there are 2^5 i.e. 32 alternative ways in which logistics service provider mix for the entire supply chain can be designed. Table 4 displays these 32 alternatives along with their status regarding the constraints and the total processing cost of supply chain for only those alternatives which satisfy the constraints of the model.

Table 4
Logistics Service Provider Mix

Sl. No.	Logistic Service Provider Mix						Status regarding constraints	Total processing cost of supply chain
1	L11	L26	L31	L44	L55	L65	Not Satisfied	-
2	L11	L26	L31	L44	L51	L65	Not Satisfied	-
3	L11	L26	L31	L43	L55	L65	Not Satisfied	-
4	L11	L26	L31	L43	L51	L65	Not Satisfied	-
5	L11	L26	L35	L44	L55	L65	Not Satisfied	-
6	L11	L26	L35	L44	L51	L65	Not Satisfied	-
7	L11	L26	L35	L43	L55	L65	Not Satisfied	-
8	L11	L26	L35	L43	L51	L65	Satisfied	Rs. 60,225
9	L11	L25	L31	L44	L55	L65	Not Satisfied	-
10	L11	L25	L31	L44	L51	L65	Not Satisfied	-
11	L11	L25	L31	L43	L55	L65	Not Satisfied	-
12	L11	L25	L31	L43	L51	L65	Not Satisfied	-
13	L11	L25	L35	L44	L55	L65	Satisfied	Rs. 60,180
14	L11	L25	L35	L44	L51	L65	Satisfied	Rs. 60,250
15	L11	L25	L35	L43	L55	L65	Satisfied	Rs. 60,280
16	L11	L25	L35	L43	L51	L65	Satisfied	Rs. 60,350
17	L16	L26	L31	L44	L55	L65	Not Satisfied	-
18	L16	L26	L31	L44	L51	L65	Not Satisfied	-
19	L16	L26	L31	L43	L55	L65	Not Satisfied	-
20	L16	L26	L31	L43	L51	L65	Not Satisfied	-
21	L16	L26	L35	L44	L55	L65	Satisfied	Rs. 60,220
22	L16	L26	L35	L44	L51	L65	Satisfied	Rs. 60,290
23	L16	L26	L35	L43	L55	L65	Satisfied	Rs. 60,320
24	L16	L26	L35	L43	L51	L65	Satisfied	Rs. 60,390
25	L16	L25	L31	L44	L55	L65	Not Satisfied	-
26	L16	L25	L31	L44	L51	L65	Not Satisfied	-
27	L16	L25	L31	L43	L55	L65	Not Satisfied	-
28	L16	L25	L31	L43	L51	L65	Satisfied	Rs. 60,310
29	L16	L25	L35	L44	L55	L65	Satisfied	Rs. 60,345
30	L16	L25	L35	L44	L51	L65	Satisfied	Rs. 60,415
31	L16	L25	L35	L43	L55	L65	Satisfied	Rs. 60,445
32	L17	L25	L35	L43	L51	L65	Satisfied	Rs. 60,515

Table 4.shows that the mix having serial no. 13 qualifies as the optimum mix, since for that mix, the total processing cost of supply chain is minimum, being equal to Rs. 60,180. So the optimum solution to our example is given below in Table 5.

Table 5
The results

Stage	1	2	3	4	5	6	-
Optimum Logistic Service Provider	L_{11}	L_{25}	L_{35}	L_{44}	L_{55}	L_{65}	-
Corresponding Processing Lead Time (days)	14	14	6	19	7	5	65 (Optimum end-to-end delivery lead time)
Optimum Cost of processing (Rs.)	14,180	5,175	1200	31,240	3,885	4,500	60,180 (Optimum *TC* of supply chain)

7. Sensitivity Analysis

Using numerical example mentioned under section 6, sensitivity analyses have been done graphically to study the effect of under or overestimation of various parameters like 'time tolerance', 'lead time variance', and 'customer waiting time' on the total cost of supply chain.

These analyses have been carried out by increasing or decreasing the percentages of model parameters (from -20% to +20%), taking one at a time and keeping the others at their original values. From Fig. 3, it is observed that an increment in *T* is having a declining effect on *TC* and vice versa. Moreover, the percentage change in *T* may not alternate decision of choosing the optimal logistic service provider mix because it has little effects on the percentage change in *TC*.

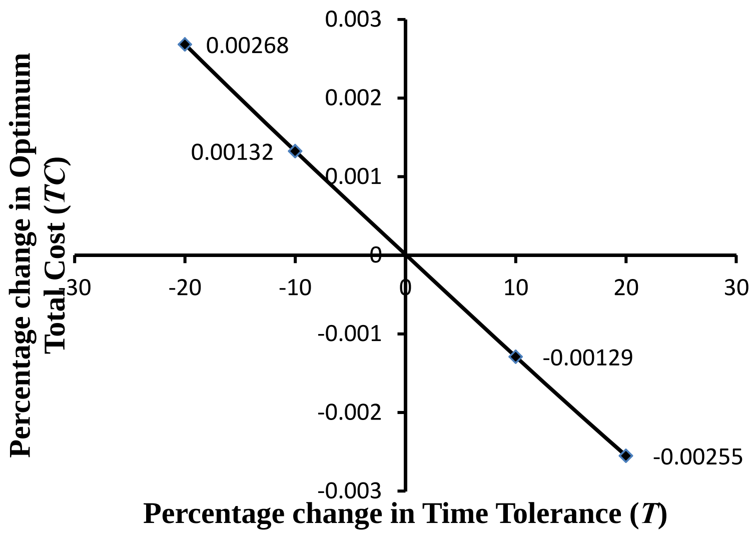

Fig. 3. Total Cost (*TC*) versus Time tolerance (*T*)

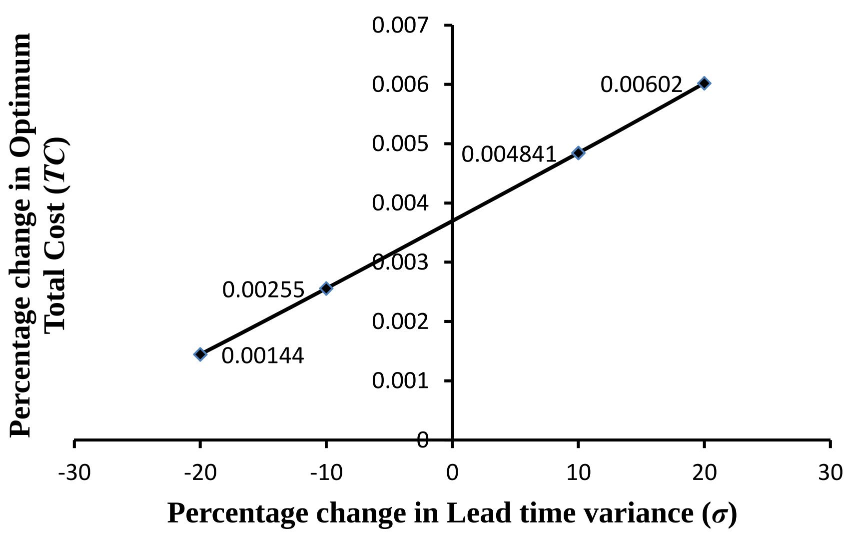

Fig. 4. Total Cost (*TC*) versus Lead time variability (σ)

Fig. 4 shows that increment in σ is consistently having an incremental effect on *TC*. It is also observed that the percentage change in σ has an effect on the decision of choosing logistic service provider mix. For example, 20% increment in σ increases *TC* by Rs. 362, which may influence the decision of choosing logistic service provider mix i.e. the optimal logistic service provider mix (L11, L25, L35, L44, L55, L65) with *TC*Rs. 60,180 may be replaced by new service provider mix (L17, L25, L35, L43, L51, L65) with *TC* Rs. 60,515 due to increase in σ. The difference in *TC* is Rs. 335 which is approximately nearer to Rs. 362. There is also a possibility of unbounded solution of our problem if the incremental percentage change in σ is greater than the time tolerance *T* of the model.

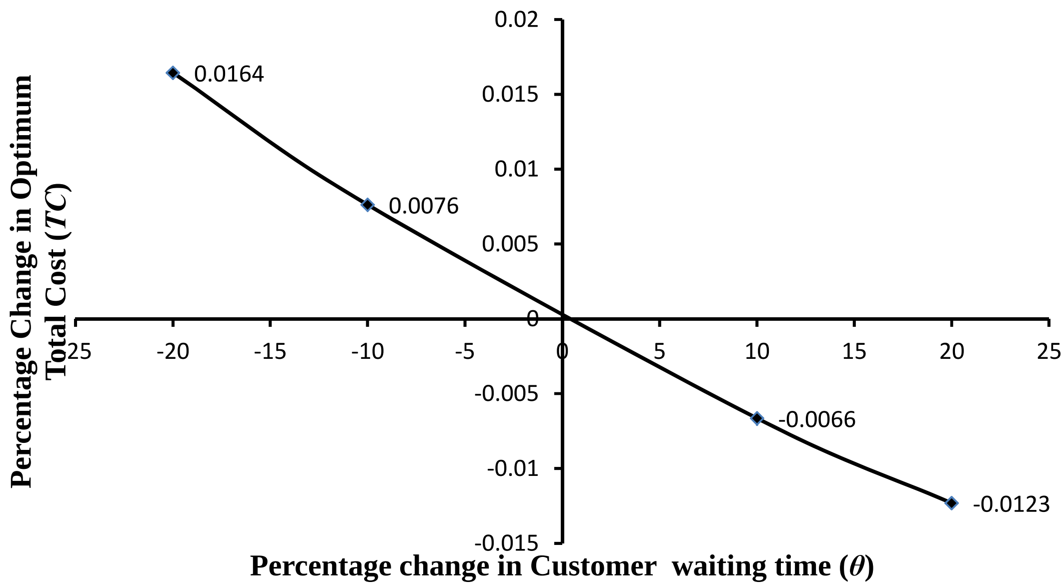

Fig. 5. Total Cost (*TC*) versus Customer waiting time (θ)

Fig. 5 implies the inverse relationship between θ and *TC*. However, the percentage change inθ has a huge effect on *TC*. For example, if the percentage of decrement in θ is increased from 10% to 20%, then it is observed that the increment in optimal TC increases two times approximately i.e. if θ is decreased by 20% instead of 10%, then *TC* increases from Rs. 60,638.70 (increment being Rs. 458.80) to Rs. 61,169.90 (increment being Rs. 989.70). Thus the percentage change in$\theta$is very likely to alter the decision of choosing the optimal logistic service provider mix of the problem.

8. Conclusion

In this paper, a technique to determine the optimum mix of logistics service providers of a make-to-order supply chain has been developed. The technique provides a solution with minimum cost, which fulfills the constraints related to timely delivery. A realistic assumption that for each stage, the logistic service providers taking more time to process charges less and vice versa has been made. Further the variance of the time taken by the different service providers has been assumed to be same for each stage of supply chain. Here we also present an approach to select best service providers to enhance the end to end delivery performance of the supply chain though our discussion has been restricted to the processing lead time and its associated cost of service without considering the other issues like demand variability, inventory level, etc. Future research needs to focus attention on the application of this optimization model in the other logistics process metric. One may develop a model by assuming differences in lead time variances as well as differences in mean processing lead time for different service providers at each stage. Further the model can be extended by considering inventories at different stages of supply chain. One may also incorporate time of transportation along with the processing time.

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