Supply chain focus dependent supplier selection problem
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A B S T R A C T
Increasing globalization, diversity of the product range, and increasing customer awareness are making the market(s) highly competitive thereby forcing different supply chains to adapt to different stimuli on a continuous basis. It is also well recognized that overall supply chain focus should be given an overriding priority over the individual goals of the players, if one were to improve overall supply chain surplus. Among all the possible order winners, 'cost' and 'responsiveness' seem to be the most significant metrics based on which majority of the supply chains compete with each other. Supplier selection problem is one of the crucial problems that need to be addressed in configuring a supply chain that could have far reaching ramifications on the total supply chain costs and order winnability. Our model, that considers inventory costs and the supply chain 'cycle time' reduction costs, would aid a supply chain manager to make informed decisions with regard to supplier selection problem at any stage, dependent upon the priorities attached to supplier selection costs and cycle time. Inventory related costs and responsiveness related costs are the two primary cost elements that are considered in this model. We are also making use of a novel dimensionless quantity called the 'coefficient of inverse responsiveness' that not only facilitates the introduction of responsiveness related costs into the model but also improves the scalability and simplifies the analysis and interpretation of the results. Based on the strategic model developed, we offer some very interesting managerial insights with respect to the effect of cost efficient operations and/or location and cost of volume related flexibility at a stage on alternate suppliers, which in turn affects the overall supply chain performance.

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1. Introduction

"Purchased products and services account for more than 60% of the average company's total costs. For steel companies, it may go up to 75%; it is 90% in petrochemical industry, etc. Bringing down procurement costs can have a dramatic effect on the bottom line—a 5% cut can translate into a 30% jump in profits" (Degraeve and Rooffhoof, 2001). As the emphasis shifts from vertical integration to horizontal interconnectivity in today's competitive markets, supplier selection turns out to be one of the key issues that affect the product's competitiveness.

The reduction of the manufacturing depth leads to an increase of the proportion of the purchased parts and consequently increases the dependency on suppliers (Maron and Brückner, 1998). Kagnicioglu (2006) opines that supplier selection is a critical activity of purchasing management in a supply chain due to the key role of supplier's performance on cost, quality, delivery and service in achieving the objectives of a supply chain.

An efficient supplier management that begins with the identification of potential suppliers is of central importance for successful supply chain management (Lasch and Janker, 2005). Also, proper supplier selection significantly reduces the purchasing costs and improves corporate competitiveness (Ghodsypour and O'Brien, 2001).

Lin (2009) opines that supplier selection for reducing supplier base is an important goal in supply chain management (SCM).

Majority of the supplier selection literature focuses upon the selection of relevant performance metrics, supplier rating for a chosen set of performance metrics and optimization models. In today's competitive markets, it is a known fact that it is the respective supply chains that are competing and not the individual business entities. Lack of supply chain focus, planning horizon, inclusion of subjective performance metrics, multiple goals vs. unitary goal, consideration of interrelationships among the performance metrics chosen for supplier evaluation are some of the key issues that distinguish our model from the models presented in existing literature. Under this category the emphasis is primarily on delineating different performance metrics for supplier selection not the supplier evaluation itself.

The number of performance metrics that one could consider to aid in supplier selection is not only large but also depends on the context (strategic, operational, etc.), type of the product, nature of the markets,
etc. Among the possible order winners cost and responsiveness turn out to be more crucial than others. In the context of our model, responsiveness is the ability of the supply chain to respond quickly to changing customer needs, preferences, options, etc., in terms of supply chain cycle time, emphasis being on volume related flexibility. Majority of the existing models are cost focused and do not address the responsiveness aspect in an explicit fashion. Also interrelationships between cost and responsiveness are not sufficiently explored. Both of these issues are addressed in our model. Another major difference is that the model works on the strategic perspective with the aim of developing managerial insights that would aid supplier selection at a particular stage in a supply chain.

We are modeling the supplier selection problem as a supply chain configuration problem in the sense that we are assuming that product design and supply chain topology are already fixed and there are competing suppliers at a stage who differ only in terms of cost and responsiveness. A typical configuration for a supply chain consists of defining components of the system, assigning values to characteristic parameters of each component and setting operation policies for governing the interrelationships among these components (Truong and Azadivar, 2005).

There are primarily four drivers of cost in a supply chain, namely, infrastructure, inventories, transportation and information (Chopra and Meindl, 2004). Since we are assuming that the necessary network topology is already in place, it obviates the necessity to include infrastructure related cost elements and transportation related aspects explicitly into our model. However, these issues are addressed in an indirect fashion in our model. For example, cost added at a stage can be considered to be a function of fixed costs associated with infrastructure such as location, buildings, machinery, etc. Even though we are developing the model assuming that all the stages are involved in manufacturing, a stage purely dealing with transportation could be easily accommodated. We are also assuming information symmetry at all the stages and leave information asymmetry related issues for future research. That leaves us with inventory as our primary cost driver. We are considering both cycle stocks (in-process inventory) and safety stocks in our model.

For a stochastic service model (Graves and Willems, 2003; Simchi-Levi and Zhao, 2005; Lee and Billington, 1993; Ettl et al., 2000), which we have adopted in our model, we assume that the increase in cost at a stage depends on the opportunities that exist for resource flexibility. We model it as a continuous function of a novel dimensionless parameter called the ‘coefficient of inverse responsiveness’ (CIR) that also enhances the scalability of the model, with the focus being to develop managerial insights with regard to supplier selection at a stage. With the introduction of CIR, research gaps in terms of addressing the interrelationship between the costs and the responsiveness and the scalability limitation are addressed. Also, lack of explicit consideration of the processing time variability is one of the key issues in the existing literature. We have included both the demand variability and the processing time variability in our model thereby mimicking the reality as closely as possible.

The rest of this manuscript is organized as follows. In Section 2 we present the relevant literature review. Section 3 deals with the development of the overall cost expression for the supply chain. Section 4 offers managerial insights in regards to the supplier selection problem in a serial supply chain. Section 5 offers an illustrative example involving the selection of a wiring harness supplier for an OEM facility. Finally, conclusions and limitations are offered in Section 6.

2. Literature review

Primarily, the literature dealing with supplier selection/management can be broadly classified into three categories.

First category deals with choosing the appropriate performance metrics that aid in supplier selection and evaluation. The number of supplier performance metrics varies from 13 to 60 in different publications (Huang and Keskar, 2007). Huang and Keskar (2007) view that cost and quality have been the most dominant factors along with on-time delivery and flexibility. Hsu et al. (2006) develop and validate a supplier selection construct and demonstrate that underlying the documented supplier selection criteria there is need to assess a supplier’s quality and service capabilities as well as its strategic and managerial alignment with the buyer. Quality, delivery, price of materials and services, responsiveness and service consistently emerge to be the important criteria for supplier selection (Kannan and Tan, 2002; Verma and Pullman, 1998). Huang and Keskar (2007) present an integration mechanism in terms of a set of comprehensive and configurable metrics arranged hierarchically that takes into account product type, supplier type and OEM/supplier integration level. The introduction of degree of alignment with the buyer is a novel feature in Hsu et al. (2006) and Huang and Keskar (2007). Under this category the emphasis is primarily on delineating different performance metrics for supplier selection not the supplier evaluation itself, which is the primary theme that we are trying to address in our research.

Second category in supplier selection/management literature deals with supplier rating/evaluation methods for a given set of performance metrics (Lasch and Janker, 2005; Timmermann, 1986; Weber et al., 1991). Lasch and Janker (2005) designed a supplier rating system that uses principal component analysis to create a classification and ranking of the potential suppliers by means of ellipsoidal clusters. Huang and Keskar (2007) is a useful reference for literature review for supplier selection using Analytical Hierarchy Process (AHP), Multi Attribute Utility Theory (MAUT) and outranking methodologies. A thorough description of supplier rating methods with respect to their popularity and other features can be found in Lasch and Janker (2005). Reader can also refer to AHP models (Barbarosoglu and Yazgac, 1997; Nydick and Hill, 1992) that deal with supplier selection problems. In this category the primary emphasis is on supplier rating for a given set of performance metrics using different quantitative approaches. Importance attached to the interrelationships between different performance metrics and how those interrelationships affect the competitiveness of an organization is one of the key differences between this line of research and the model presented in this research paper.

In the third category, supplier selection problem is treated as a part of an optimization problem. To account for many conflicting and vague objectives and constraints in making supplier selection decisions, Kagniocioglu (2006) proposes a fuzzy multi-objective model, where both the objectives and some of the constraints are fuzzy. Morlacchi (1997) developed a model that combines the use of fuzzy set theory with AHP and implements it to evaluate small suppliers in engineering and machine sectors. Kumar et al. (2004) used fuzzy goal programming to deal with the effect of information uncertainty in supplier section problems. Application of different weights to the chosen set performance metrics to aid in supplier selection is another established procedure. Reader can refer to linear weighting models (Cooper, 1977; Mazurak et al., 1985) for more information. Use of fuzzy variables and linear weighting models bring an element of subjectivity into the model, which is always not desirable. Also, emphasis on too many factors might sometimes dilute the significance of important performance metrics, which could be the order winners for the product in context.

Ghodsypour and O’Brien (1997) used an integrated AHP model with mixed integer programming to reduce the number of suppliers. Integrating AHP model into the optimization architecture is the distinguishing feature of this model. Ghodsypour and O’Brien (2001)
developed a mixed integer non-linear programming (NLP) approach for supplier selection to minimize the total cost of logistics, including net price, storage, ordering costs and transportation. This approach facilitates the inclusion of non-linear objective function and/or constraints into the model, when compared to other optimization models mentioned previously. Use of goal programming for supplier selection is the distinguishing feature of Karpak et al. (1999). To systematically analyze the tradeoffs between conflicting factors in supplier selection, Weber and Current (1993) used multi-objective linear programming. For a detailed list of optimization methodologies used in supplier selection literature, one can refer to Huang and Keskar (2007). Cebi and Bayraktar (2003) propose a model, wherein supplier selection problem has been structured as an integrated lexicographic goal programming (LGP) and AHP that includes both quantitative and qualitative factors. The novel application of a genetic algorithm by Truong and Azadivar (2005) in combination with mixed integer programming to determine simultaneously the values of quantitative as well as policy variables that aid in making strategic decisions regarding facility locations, stacking locations, supplier selection, production policies, production capacities and transportation modes is an interesting paper distinguishing it from the other optimization models. Talluri and Baker (2002) propose a multi-phase mathematical programming approach for supply chain design. Even though the element of subjectivity is not a primary concern in these models dilution of the focus on key order winners could still be a problem.

The following examples motivated us in choosing the responsiveness as one of the key performance metrics in addition to the traditional cost component. A close examination of the following real-world supply chains and their objectives reveals that the responsiveness is one of the key performance metrics that not only serves as an important order winner but also has a significant effect on overall costs. Nazzal et al. (2006) present a case study for Agere Systems’ wafer fabrication facility, wherein, they use simulation, design of experiments, and statistical analysis to construct operating characteristic (OC) curves to relate cycle time to production volume capabilities for the subsequent economic analysis. Agere Systems, one of the leading companies in the microelectronics, is trying to increase its market share and profits with the primary goal being able to quantify the economic impact of reducing lead times. This case study brings out the importance of cost and responsiveness as the primary order winners in today’s highly competitive markets. Another interesting motivating example is the Revlon’s supply chain addressed in Davis et al. (2005). Revlon’s supply chain includes more than 5000 active finished good Stock Keeping Units (SKUs) with life-cycles that last less than three years, sales in more than 100 countries, seven manufacturing facilities and approximately 450 suppliers located around the world. To meet its aggressive inventory reduction targets and achieving high customer service levels, Revlon realized that it would be possible only by reducing the manufacturing and supplier lead times and the associated variability. This example also emphasizes cost and responsiveness as the primary levers that help in achieving the supply chain goals. There are similar examples from other industries. For example, automobile industry is no longer focusing upon manufacturing mass volumes, instead focusing more upon flexibility to respond to change because of the shrinking model life-cycles with the goal of lowering the capital investment required for changeover or introduction of a new product (Pelagagge, 1997).

Vickery et al. (1999) emphasize the importance of supplier responsiveness to changing buying needs particularly in an environment characterized by short product life-cycles and downward pressure on product lead times. Yang and Geunes (2007) emphasize that longer lead times in addition to reducing the customer responsiveness, increase demand forecast error, since forecast error generally increases as the forecast horizon increases. Also, longer lead times expose the supply chain to more in-process inventories, design changes, degradation, accidents, changes in demand patterns, etc. (Felgate et al., 2007), which in turn increase the supply chain costs.

The above-mentioned examples served as a motivation to choose cost and responsiveness as the key order winners even though supplier selection problem was not their primary focus. Since we are addressing the issue of supplier selection as a supply chain configuration problem in our model a brief literature review of supply chain configuration models will be in order.

Huang et al. (2007) dealt with optimizing the configuration of a set of platform products and the associated supply chain consisting of one manufacturer and multiple suppliers using a three move dynamic game theoretic approach. They describe the integrated configuration of platform products and supply chain (ICPPSC) game as a dynamic multi-stage non-cooperative configuration game. In this game, the manufacturer is treated as the leader and suppliers as followers. The decision variables to be optimized are mainly concerned with product and supply chain configuration, including supplier selection and selection of module options. As with Hsu et al. (2006), our research is more suitable for selecting strategically important suppliers that aid in realizing the supply chain strategy related goals than suppliers of commodities, wherein supplier selection is likely to focus on short-term price/cost tradeoffs. Graves and Willems (2003) address the problem of how to configure the supply chain for a new product for which the product’s design has already been decided and the topology for the supply chain network has been set to determine suppliers, parts, processes and transportation modes at each stage. Cakravastia et al. (2002) present a mathematical approach for design of the supply chain configuration at two stages, operational and supply chain levels.

Now, let us examine the relevant literature specifically in relation to the strategic mathematical model we adopted. The relevant literature review is largely adapted from Vanteddu et al. (2007). Gallego and Zipkin (1999) develop and analyze several heuristic methods to study the problem of stock positioning in serial production-transportation systems and offer a number of interesting insights into the nature of the optimal solution. Stochastic service model as advocated by Graves and Willems (2003) addresses the issue of strategic placement of safety stocks across a multi-echelon supply chain in the presence of demand uncertainty. The primary purpose of their model is to develop a multi-echelon model and the relevant optimization algorithm that is specifically designed for optimizing the placement of safety stocks in real-world supply chains. Unlike Graves and Willems (2003), where inventory is the only lever to counter demand variability, our model has two levers, namely, inventory and responsiveness (cycle time) at each stage.

Following are some of the prominent inventory models that make use of the concepts of stochastic service model and/or installation policy, which we used in our model. By assuming an installation, continuous-time base stock policy for supply chains with tree network structures, another interesting paper that is based on the stochastic service model concept is Simchi-Levi and Zhao (2005), wherein, they derive recursive equations for the back order delay (because of stock out) at all stages in the supply chain and based on those recursive equations, dependencies of the back order delays across different stages of the network are characterized and useful insights with respect to the safety stock positioning are developed in various supply chain topologies. In addition, Simchi-Levi and Zhao (2005) present a good summary of the literature for installation policies that are used in various network topologies: multi-stage serial systems (Simpson, 1958; Hansmann, 1959; Lee and Zipkin, 1992) and distribution systems
centers (Axsäter, 1993; Graves, 1985; Lee and Moinzadeh, 1987a, b). For
capacitated models using a modified base stock policy, the reader can refer to
thorough comparison of installation and echelon stock policies for multi-level
inventory control, the reader is referred to Axsäter and Rosling (1993).
They primarily consider
serial and assembly systems and prove that for \((Q, r)\) rules echelon
stock policies are, in general, superior to installation stock policies.

Advocating the necessity of models that include both cost
and responsiveness, which are the primary order winners in our
strategic model, Moon and Choi (1998) suggest extending the lead
time reduction concept to other inventory models to justify
the investment to reduce the lead times. Choi (1994) used an expediting
cost function to reduce the variance of supplier's lead times. As
opposed to network design models that focus on the tradeoff
between the fixed costs of locating facilities and variable
transportation costs between facilities and customers, Sourirajan et al. (2007)
present a model for single product distribution network
design problem with lead times and service level requirements,
which enables them to capture the tradeoff between lead times and
inventory risk pooling benefits. The objective is to locate distribution
centers (DCs) in the network such that the sum of the location and
inventory (pipeline and safety stocks) costs is minimized.

One very interesting \((Q, r)\) model with stochastic lead times that
could serve as a building block in supply chain management is
proposed by Bookbinder and Cakanyildirim (1999) as opposed to
constant lead time assumption in many other studies. The
dimensionless quantity \(CIR\) proposed in our model is similar in spirit to
the "expediting factor" for the lead time proposed by them. Ryu and
Lee (2003) consider dual sourcing models with stochastic lead times in
which lead times are reduced at a cost that can be viewed as an
investment. They make use of the concept of "expediting factors"
proposed by Bookbinder and Cakanyildirim (1999) in their model. They
analyze \((Q, r)\) models with and without lead time reduction and
compare the expected total cost per unit time for the two models.

Even though, we did not consider the product mix flexibility
related issues in our model, the reader can refer to Upton (1997) for
exploring the relationship between process range flexibility and
structure, infrastructure and managerial policy at the plant level.
We assume information symmetry at all the stages in our model.
The effect of information sharing for time series structure of the
demand on safety stocks is addressed in Gaur et al. (2005). Even
though we did not address environmental issues, reader can refer to
Wolff and Seuring (2010) who analyze whether environmental
issues form a supplier selection criteria of companies when sourcing
third party logistics (3PL) services.

3. Model development

At any stage in supply chain primarily there are two types of
inventory elements namely cycle inventory (in-process inventory) and
safety inventory. The quantity of cycle inventory depends on
the average demand per period and the average cycle (processing)
time and is given by the multiplied product of those two quantities.
Among inventory cost elements, safety stock, which is maintained
to account for the internal and external variability in a supply chain,
is vital in the sense that it directly affects customer satisfaction and
safety stock costs also constitute a significant portion of the cost of
goods at a stage. We are considering both cycle stocks (in-process
inventory) and safety stocks in our model. Responsiveness related
costs are the costs incurred on account of the volume related
flexibility at any stage in a supply chain, the inclusion which into
the model is made possible by the inclusion of a new parameter
called coefficient of inverse responsiveness \((CIR)\). The inclusion of
\(CIR\) also facilitates the explanation of the interrelationship between
inventory costs and the responsiveness related costs.

At any stage in a supply chain,

\[ \text{Total cost} = \text{Safety stock costs} + \text{Cycle stock costs} + \text{Responsiveness related costs} \]

This section is devoted to developing total cost expression,
make up of safety stock costs, cycle stock costs and responsiveness
related costs, for a serial supply chain.

3.1. Expression for safety stock costs

The content in Sections 3.1 and 3.2 is largely adopted from
Vantiedu et al. (2007). We follow the building block model (Graves
and Willems, 2003) with installation base stock policies and a
common underlying review period for all stages. A typical base
stock policy works as follows. When the inventory position (i.e., on
hand plus on order minus back orders) at stage \(i\) falls below some
specified base stock level \(B_i\), the stage places a replenishment order
thereby keeping the inventory position constant. Simchi-Levi and
Zhao (2005) attribute the popularity of base stock policy to the fact
that it is simple, easily implementable, and because this policy has
been proven to be optimal or close to optimal in many cases. For
example, in serial supply chains with zero setup costs and without
capacity constraints, because the installation base stock policy is
equivalent to an echelon base stock policy under certain initial
conditions (Axsäter and Rosling, 1993), it is indeed optimal in these
cases (Clark and Scarf, 1960). In serial systems, even modified base
stock policy with capacity constraints is still close to optimal (Speck
and van der Wal, 1991; Van Houtum et al., 1996).

In an installation policy, each facility only needs the inputs from the
immediate upstream \((US)\) and downstream \((DS)\) facilities and
makes ordering decisions based on its local order and inventory
status (Simchi-Levi and Zhao, 2005) as opposed to an echelon base-
stock policy, which is a centralized control scheme that allows for a
central decision maker to coordinate and control the actions at all
stages in the SC (Graves and Willems, 2003).

Even though our model assumes all the stages to be manufac-
turing stages, without loss of generality, a stage could be modeled
as a distribution center \((DC)\) as well. A pure transportation function
can also be modeled with the building block concept, wherein the
transport time is the lead time with pipeline inventories.

Orders are placed at discrete time intervals and each stage is
considered as a building block (Graves, 1988) that generates a
stochastic lead time. A building block is typically a processor plus a
stock keeping facility (Simchi-Levi and Zhao, 2005). Depending on
the scope and granularity of the analysis being performed, the stage
could represent anything from a single step in manufacturing or
distribution process to a collection of such steps to an entire
assembly and test operation (Graves and Willems, 2003). Demand
is assumed to be stationary and uncorrelated across different time
periods with no capacity constraints.

Our model is designed as a decentralized supply chain (Graves
and Willems, 2003; Lee and Billington, 1993) to mimic the reality
more closely with each stage following a local base-stock policy.
Buttressing the same view, Lee and Billington (1993) state that
organizational barriers and restricted information flows between
stages may result in complete centralized control of material flow in
a supply chain to be not feasible or desirable.

The primary distinction between centralized and decentralized
supply chain is put in the following succinct form by Lee and
Billington (1993) "Centralized control means that decisions on how
much and when to produce are made centrally, based on material
and demand status of the entire system. Decentralized control, on
the other hand, refers to cases where each individual unit in the
supply chain makes decisions based on local information".
Assuming each building block operates independently using a simple installation policy, one can first characterize various building blocks such as serial, assembly, distribution, etc. and then identify the links among these building blocks (Simchi-Levi and Zhao, 2005). We have chosen a series system for the simplicity of analysis and primarily to develop certain insights that are insensitive to the specific supply chain topology. Also, other networks such as assembly system can be reduced to an equivalent series system (Rosling, 1989). Most of the features are similar to the features of a series system presented in Gallego and Zipkin (1999) with some modifications.

There are several stages or stocking points arranged in series. The first stage receives supplies from an external source. Demand occurs only at the last stage. Demands that cannot be filled are immediately backlogged. There is one product, or more precisely, one per stage. To move units to a stage from its predecessor, the goods must pass through a supply system representing production or warehousing activities. There is an inventory holding cost at each stage and our model does not represent production or warehousing activities. There is an inventory holding cost at each stage and our model does not represent production or warehousing activities. There is an inventory holding cost at each stage and our model does not represent production or warehousing activities.

As in Gallego and Zipkin (1999), the number of the stages follows the flow of goods; stage one is the first and at the last stage demand occurs. The external source, which supplies stage one has ample stock and it responds immediately to orders.

We have assumed that the service level targets required at each of the players are exogenous, i.e., dictated by the immediate D/S player or the final customer. Following Graves and Willems (2003) and Ettl et al. (2000) with a modification that takes into account the fact that there is only one player at the preceding stage (see for example, Eppen and Martin, 1988; Feller, 1960).

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We have adopted the procedure for calculating this delay due to the stock out at the preceding stage as presented in Graves and Willems (2003). If $\Delta_i$ is the random delay at the preceding stage $i$, then the replenishment cycle time at stage $j$ equals

$$E[T_j] = \tau_j + \Delta_i$$

Assuming that the demand is $N(\mu, \sigma^2)$, where $\mu$ is the mean demand during one time period and $\sigma^2$ is the demand variance during one time period, to satisfy average demand $\mu$, given the average replenishment cycle time from (2), ‘average cycle stock’ is given by

$$\mu + (1 - \Phi(k_i))L_i$$

Assuming the independence of processing times at a stage and between the stages, we realize that

$$\sigma^2_{W_j} = \sigma^2_1(1 - \Phi(k_i))$$

$$\sigma^2_{W_j} = \sigma^2_1 + \sigma^2_2(1 - \Phi(k_i))$$

Now, we introduce another parameter $\gamma_j$ termed as the ‘coefficient of inverse responsiveness’ at stage $j$ defined as the ratio of the average demand to the rate of production (throughput) $p_j$.

$$\gamma_j = \mu / p_j$$

Assuming that there is enough capacity at all the stages to satisfy a given demand, $\gamma_j \leq 1$ at all the times. When $\gamma_j = 1$, expected replenishment cycle time is given by (2). We also assume that there is some upper bound above which rate of production cannot be increased further. CIR at a stage is similar to the “expediting factor” proposed by Bookbinder and Cakanyildirim (1999). They define the “expediting factor” $\tau$ as the constant of proportionality between random variables $T$ (the expedited lead time) and $T$ (ordinary lead time).

For expedited orders ($\tau < 1$) shorter than average lead time can be obtained at a cost. Similarly, longer mean lead time results in a rebate for the customer when $\tau > 1$. By considering a model with three decision variables $(Q, r, \tau)$, they show that the expected cost per unit time is jointly convex in the decision variables and obtain the global best solution.

Keeping the average cycle stock constant (given in (4)), from Little’s law, at expedited rates of production, it is $< 1$, replenishment cycle time mean and variability for player $j$, when operating at a CIR level $\gamma_j$ will be equivalent to

$$E[T_j] = (L_j + (1 - \Phi(k_i))L_i)\gamma_j$$

$$\sigma^2_{W_j} = \sigma^2_1 + \sigma^2_2(1 - \Phi(k_i))\gamma_j$$

As $\gamma_j$ decreases, average replenishment cycle time for player $j$ decreases, which means player $j$ is becoming more responsive.

Because of this inverse relationship between $\gamma_j$ and responsiveness at stage $j$, $\gamma_j$ is termed as ‘coefficient of inverse responsiveness’ at stage $j$.

In light of Eqs. (9) and (10), we assume that demand during replenishment period $W_j$ for stage $j$, is normally distributed as follows:

$$\mu_W = \mu E[T_j]$$

$$\sigma^2_W = \sqrt{\sigma^2_1 E[T_j] + (\sigma^2_2 \mu)^2}$$

The above equation considers both the demand variability and the replenishment cycle time variability. Replenishment cycle time
variability is made up of two components

1. Processing time variability at stage $j$.
2. Portion of processing time variability at stage $i$ that is transferred to stage $j$.

We assume that base stock at stage $j$ is given by $B_j = \mu E[r_j] + k_j T_{r,j}$, where $k_j$ is the safety factor to achieve the service level target $\Phi(k_j)$ for that stage.

After accounting for the average demand over the replenishment period, expected on hand inventory is given by

$$E[I_j] = k_j \sigma_w$$

(12)

By augmenting the above expression with the following term, which is the expected number of Back orders (Graves and Willems, 2003; Ettl et al., 2000)

$$E[BO] = \sigma_w \int_{z=k_j}^{\infty} (z-k_j) \phi(z) dz$$

(13)

we realize the following expression for the expected safety stock at stage $j$.

$$E[SS_j] = \sigma_w (k_j + \int_{z=k_j}^{\infty} (z-k_j) \phi(z) dz)$$

(14)

At stage $j$, let $C_j$ be the nominal cumulative cost of the product realized when $c_1=1$, and let $h_j$ be the holding cost rate per period. Per unit holding cost of safety stock at stage $j$ per period equals $C_j h_j$.

Total safety stock holding cost at stage $j$ per period is given by

$$C_j^{SSC} = C_j h_j E[SS_j]$$

(15)

Total safety stock holding cost for the supply chain per period is given by

$$C^{SSC} = \sum_{j=1}^{n} C_j^{SSC}$$

(16)

### 3.2. Responsiveness related costs at stage $j$:

When players (1,...,n) operate with their respective CIRs being $(c_1,...,c_n)$, stage $j$ incurs two types of responsiveness related costs.

#### 3.2.1. Direct responsiveness related costs

The difference in nominal cumulative costs of the product at stages $j$ and $i$ (i.e., $C_j - C_i$) will increase by a value, which is assumed to be a function of $(1 - c_j)$. This is the cost that the stage $j$ will pay for operating at a higher processing speed that lowers the average replenishment cycle time at stage $j$.

The increase in cost is typically due to increase in investment in the so-called 5M resources (i.e., manpower, machine, methods, material and measurement). We are addressing the issue of cycle time reduction due to the opportunities for flexibility available at a stage which can be harnessed at a cost. This should not be confused with cycle time reductions due to better operational efficiencies such as efficient removal of wastes from the processes such as down time, setup time, etc. Flexibility related costs will increase/decrease depending on how flexible these 5M resources are at a stage.

Direct response related costs at stage $j$ per period are given by

$$DRC_j = (1-c_j)(C_j - C_i) \mu$$

(17)

Even though we do not advocate any specific function type for modeling $f(1 - c_j)$, cost of volume flexibility function (COF), we strongly recommend that it be derived from the historical data.

For example, for a specific average demand, from the past data one could fit a regression model between $(1 - c_j)$ and the incremental cost at a stage. Moon and Choi (1998) advocate the use of a piecewise linear crashing cost function that is widely used in project management in which the duration of some activities can be reduced by assigning more resources to the activities. They have used a piecewise linear crashing cost function in their model. Bendaya and Raouf (1994) could be a useful reference to consider using other types of crashing cost functions.

Bookbinder and Cakanyildirim (1999) assume the expediting cost per unit (because of technological investments or hiring extra workers) time $\psi(t)$ to be a decreasing convex function of the expediting factor with $\psi(1) = 0$ (additional cost when CIR = 1 is zero in our model as well). As opposed to our model, they allow $\psi(t)$ to take negative values for $t > 1$, meaning that for longer lead times they assume that the manufacturer gives the buyer some rebate per unit time.

Proceeding from the research of Bookbinder and Cakanyildirim (1999), Ryu and Lee (2003) choose their expediting cost functions $\psi_1(t_1)$ and $\psi_2(t_2)$ to be decreasing convex functions of the expediting factors $t_1$ and $t_2$. They considered $\psi_1(t_1) = c_1 (1 - 1/4 t_1)$ and $\psi_2(t_2) = c_2 (1 - 1/4 t_2)$, where $c_1$ and $c_2$ are positive coefficients. Our cost function, for example Eq. (17) looks similar in spirit to the above cost functions.

Yang and Geunes (2007) expect the cost of reducing procurement time, because of supplier’s investment in production processes or technologies, to increase at a non-decreasing rate in the amount of lead time reduction and therefore employ a convex function for lead time reduction. They consider a piecewise linear, convex and decreasing form (as the production lead time increases) for the unit procurement cost function but note that their analysis of this function applies to general piecewise linear functions and convexity is therefore not required although they expect this function to be convex in practical context. We, for our numerical analysis consider a simple increasing convex function although the results would not be different for any non-decreasing function.

#### 3.2.2. Indirect responsiveness related costs

In addition to the above mentioned ‘Direct responsiveness related costs’, the stage will experience an increase in safety stock costs, when it operates at $c_j$ for the reasons mentioned in Section 3.2.1. As a result, the difference in nominal cumulative costs of the product at stages $j$ and $i$ will increase by a value, which is a function of $(1 - c_j)$. Therefore, indirect responsiveness related cost at stage $j$ is given by

$$IRC_j = \sum_{j=1}^{n} C_j^{SSC}$$

(18)

Therefore, total responsiveness related cost at stage $j$ is given by

$$TRC_j = DRC_j + IRC_j$$

(19)

Hence, total safety stock costs in the presence of increase in costs at stage $j$ that account for increase in the responsiveness per period is given by

$$C_j^{SSC} = C_j^{SSC} + TRC_j$$

(20)

Hence, total safety stock related cost for the whole supply chain per period is given by

$$C^{SSC} = \sum_{j=1}^{n} C_j^{SSC}$$

(21)

### 3.3. Cycle inventory related costs

#### 3.3.1. Cycle inventory at stage $j$

Average cycle stock cost at stage $j$ per period is given by

$$WIP_j = (C_j + C_i) \mu (L_j + (1 - \Phi(k_i)) L_i)$$

(22)
3.3.2. Responsiveness related cycle inventory costs at stage j:
When players (1, ..., n) operate with their respective CIRs being \((c_1, ..., c_n)\), stage j incurs response related cycle stock costs.
Response related cycle stock cost at stage j is assumed to increase the difference of average cycle stock value per unit at stages i and j, that is \(((C_i + C_j)/2) - ((C_i - C_j)/2) = (C_j - C_i)/2\), by a value, which is a function of \((1 - c_j)\) and \((1 - c_i)\).

\[ RWIP_j = \left[ f((1 - c_j),(1 - c_i))\right] (C_j - C_i)/2 \]  

(23)

Therefore total inventory and responsiveness related cost at stage j per period is given by

\[ TC_j = C_j^{SSC} + TRC_j + WIP_j + RWIP_j \]  

(24)

Total inventory and responsiveness related cost for the whole supply chain per period is given by

\[ TC_{SC} = \sum_{j=1}^{n} TC_j \]  

(25)

4. Model related results

In this section, we attempt to study the supplier selection problem by considering alternate suppliers with different values of key parameters such as replenishment cycle times, replenishment cycle time variability, cost of holding inventory, cost of responsiveness, etc. Typical values of the parameters adopted for stages 1 through 5 are presented in Table 1. Our purpose is to develop insights with respect to determining the supplier at stage 3 (choosing one among 31, 32 and 33) who would be the best fit as the supply chain focus moves on the cost–responsiveness spectrum.

For the sake of simplicity suppliers 31, 32 and 33 are referred to as suppliers 1, 2 and 3, respectively.

Based on the values of the parameters as shown in Table 2, all the other things being equal, the total supply chain cost increases progressively as we move from supplier 1 to supplier 3. The CIR is changed from 1 to 0.3 in a discrete manner for all the five players at the same time and total supply chain cost is calculated using Eq. (25).

As CIR decreases, difference among the safety stock costs for supplier 1 vs. suppliers 2 and 3 diminishes due to the reduction in average processing time and the associated variability. With decrease in CIR, differences among indirect safety stock costs

<table>
<thead>
<tr>
<th>Supplier</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean processing time (periods) (L_j)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Processing time variability ((\mu^2 \sigma_f^2)) ((\text{in terms of number of units}^2 \text{ of product}))</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Inventory holding cost (h_j)</td>
<td>0.017</td>
<td>0.025</td>
<td>0.034</td>
</tr>
<tr>
<td>Safety coefficient (k_j)</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
</tr>
<tr>
<td>Average back order coefficient (\pi_j)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Average demand (\mu_j)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Service level (\Phi(k_j))</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 1: Key values of the parameters for the three potential suppliers.
may increase or decrease depending on how steep or flat the cost of flexibility function is and the values of other parameters. Direct response cost contribution, even though changes with \( CIR \) will be the same for all the three suppliers. Cycle stock costs will be progressively larger for suppliers 2 and 3 and will differ from supplier 1 by a fixed amount. With decrease in \( CIR \), differences in responsiveness related cycle stock costs will progressively increase, supplier 1 contributing the least to the total cost followed by suppliers 2 and 3, respectively. In addition, there will be a progressive increase in safety stock costs and cycle stock costs at the immediate D/S stage as we move from supplier 1 to supplier 3 because of the process delay and the associated variability that is transmitted. Typically the contribution of safety stock costs is much smaller than cycle stock costs in an industrial setting. Based on the above explanation, we can say that in ordinary situations, supplier 1 is more likely to be the least cost supplier over the practical range of \( CIR \) values followed by suppliers 2 and 3, respectively. It can be clearly seen from Fig. 1 that supplier 3 is consistently a poor performer with respect to the total cost criterion for any degree of responsiveness required of the supply chain followed by supplier 2 and supplier 1 in that order. So, in this context, all the other parameters being equal, supplier 1 will be the best choice irrespective of the targeted supply chain cycle time.

4.2. Effect of cost efficient operations and/or location

In this section we attempt to address the effect of nominal processing cost added at a stage for all the potential suppliers.

Let us consider the hypothetical case, as shown in Table 3, wherein suppliers 2 and 3 are progressively cheaper compared to supplier 1. In other words, nominal cumulative cost added at stage 3 is 4% or 6% lesser than supplier 1 for suppliers 2 or 3, respectively, by virtue of their reduced cost addition. Other parameters are unchanged from the case considered earlier.

Nominal processing cost added at a supplier stage could be less primarily for two reasons:

(a) Location related costs: depending on the location where the supplier is located, processing costs could be lower primarily due to cheap labor, material, etc. (outsourcing from Mexico, China, India, etc.)

(b) Effective operations management: among the potential suppliers some are operationally more efficient than others.

To explain (b), the increase in the efficiency for a particular supplier at a particular stage can be due to any of the following possible factors:

1. Better management of the human resources (use of work study and time study).
2. Better management of the machinery.
3. Efficient use of materials.
4. Existence and use of improved methodologies/procedures for carrying out different operations.
5. Better inventory management techniques.
6. Use of deterministic management techniques for optimizing the 5M resources.
7. Better quality management techniques leading to less scrap and rejections.
8. Better reliability management techniques that reduce the customer complaints and improve the useful life of the machinery.

As \( CIR \) decreases, difference among the safety stock costs for supplier 1 vs. suppliers 2 and 3 diminishes at a faster pace when compared to the scenario described in Section 4.1 due to the reduction in average processing time and the associated variability and the lesser nominal processing cost added at suppliers 2 and 3. Differences among indirect safety stock costs also decrease when compared to the earlier case. Direct response cost contribution difference will become progressively larger with decrease in \( CIR \) for suppliers 2 and 3, when compared to supplier 1. Supplier 1 costs will be maximum followed by suppliers 2 and 3 in that order. Cycle stock costs will be smaller for suppliers 2 and 3 by a fixed amount when compared to the earlier scenario described in Section 4.1 due to the reduction in responsiveness related cycle stock costs for suppliers 2 and 3 will occur at a decreased rate (because of lower nominal processing cost) compared to the scenario discussed in Section 4.1. In addition, there will be savings in echelon safety stock costs and cycle stock costs downstream from stage 3 on account of lower cost structures for suppliers 2 and 3 compared to supplier 1. Typically, cost added at a stage is many times when compared to the cycle stock costs, which in turn is significantly larger than the safety stock costs. As a result, overall, as the \( CIR \) decreases, total cost difference for suppliers 2 and 3 compared to supplier 1 progressively gets reduced. This effect will be accentuated as the cost added gets smaller and smaller at suppliers 2 and 3 compared to supplier 1.

\[
\text{As } CIR \text{ decreases, difference among the safety stock costs for } \text{supplier 1 vs. suppliers 2 and 3 diminishes at a faster pace when compared to the scenario described in Section 4.1 due to the reduction in average processing time and the associated variability and the lesser nominal processing cost added at suppliers 2 and 3. Differences among indirect safety stock costs also decrease when compared to the earlier case. Direct response cost contribution difference will become progressively larger with decrease in } CIR \text{ for suppliers 2 and 3, when compared to supplier 1. Supplier 1 costs will be maximum followed by suppliers 2 and 3 in that order. Cycle stock costs will be smaller for suppliers 2 and 3 by a fixed amount when compared to the earlier scenario described in Section 4.1 due to the reduction in responsiveness related cycle stock costs for suppliers 2 and 3 will occur at a decreased rate (because of lower nominal processing cost) compared to the scenario discussed in Section 4.1. In addition, there will be savings in echelon safety stock costs and cycle stock costs downstream from stage 3 on account of lower cost structures for suppliers 2 and 3 compared to supplier 1. Typically, cost added at a stage is many times when compared to the cycle stock costs, which in turn is significantly larger than the safety stock costs. As a result, overall, as the } CIR \text{ decreases, total cost difference for suppliers 2 and 3 compared to supplier 1 progressively gets reduced. This effect will be accentuated as the cost added gets smaller and smaller at suppliers 2 and 3 compared to supplier 1.}
\]

\[
\text{As } CIR \text{ decreases, difference among the safety stock costs for } \text{supplier 1 vs. suppliers 2 and 3 diminishes at a faster pace when compared to the scenario described in Section 4.1 due to the reduction in average processing time and the associated variability and the lesser nominal processing cost added at suppliers 2 and 3. Differences among indirect safety stock costs also decrease when compared to the earlier case. Direct response cost contribution difference will become progressively larger with decrease in } CIR \text{ for suppliers 2 and 3, when compared to supplier 1. Supplier 1 costs will be maximum followed by suppliers 2 and 3 in that order. Cycle stock costs will be smaller for suppliers 2 and 3 by a fixed amount when compared to the earlier scenario described in Section 4.1 due to the reduction in responsiveness related cycle stock costs for suppliers 2 and 3 will occur at a decreased rate (because of lower nominal processing cost) compared to the scenario discussed in Section 4.1. In addition, there will be savings in echelon safety stock costs and cycle stock costs downstream from stage 3 on account of lower cost structures for suppliers 2 and 3 compared to supplier 1. Typically, cost added at a stage is many times when compared to the cycle stock costs, which in turn is significantly larger than the safety stock costs. As a result, overall, as the } CIR \text{ decreases, total cost difference for suppliers 2 and 3 compared to supplier 1 progressively gets reduced. This effect will be accentuated as the cost added gets smaller and smaller at suppliers 2 and 3 compared to supplier 1.}
\]

\[
\text{As } CIR \text{ decreases, difference among the safety stock costs for } \text{supplier 1 vs. suppliers 2 and 3 diminishes at a faster pace when compared to the scenario described in Section 4.1 due to the reduction in average processing time and the associated variability and the lesser nominal processing cost added at suppliers 2 and 3. Differences among indirect safety stock costs also decrease when compared to the earlier case. Direct response cost contribution difference will become progressively larger with decrease in } CIR \text{ for suppliers 2 and 3, when compared to supplier 1. Supplier 1 costs will be maximum followed by suppliers 2 and 3 in that order. Cycle stock costs will be smaller for suppliers 2 and 3 by a fixed amount when compared to the earlier scenario described in Section 4.1 due to the reduction in responsiveness related cycle stock costs for suppliers 2 and 3 will occur at a decreased rate (because of lower nominal processing cost) compared to the scenario discussed in Section 4.1. In addition, there will be savings in echelon safety stock costs and cycle stock costs downstream from stage 3 on account of lower cost structures for suppliers 2 and 3 compared to supplier 1. Typically, cost added at a stage is many times when compared to the cycle stock costs, which in turn is significantly larger than the safety stock costs. As a result, overall, as the } CIR \text{ decreases, total cost difference for suppliers 2 and 3 compared to supplier 1 progressively gets reduced. This effect will be accentuated as the cost added gets smaller and smaller at suppliers 2 and 3 compared to supplier 1.}
\]
By taking into consideration the parameter values presented in Table 3, we realize Fig. 2. We can observe that, as the supply chain becomes more responsive, supplier 2 overtakes supplier 1 in terms of least total cost and even supplier 3 tends to reach the level of supplier 1 as \( C\text{IR} \) decreases. As the supply chain becomes more responsive, the increase in costs on account of the poor process parameters for suppliers 2 and 3 will be offset by the decrease in inventory (safety stock and cycle stock) costs, associated response related costs and the echelon safety stock and cycle stock costs due to better location and/or operational efficiencies resulting in lower total costs. This reduction in total costs is happening at a faster rate for supplier 2 than for supplier 3 because of the proximity of the process parameters chosen and the amount of reduction in the nominal cumulative processing cost relative to supplier 1. It is not necessary that suppliers with adverse parameters will always overtake supplier 1 in the \( C\text{IR} \) band within which a particular company wants to operate. But, the gap between supplier 1 and suppliers 2 and 3 in terms of total cost will progressively decrease with decrease in \( C\text{IR} \). Also, if we take into account the nominal processing cost added at a stage into the model along with inventory and responsiveness costs, suppliers 2 and 3 will overtake supplier 1 at a higher \( C\text{IR} \) value than realized in Fig. 2.

For example, for a supplier dealing with a commodity product such as coffee maker warming plate will operate close to a \( C\text{IR} \) value of 1 to minimize the total costs. In such a case it will take relatively more effort for suppliers 2 and 3 on account of cheaper costs to overtake the disadvantage due to poor process parameters when compared to a supplier of a short life cycle products such as mother boards, hard drives, etc. competing on the responsiveness end of the spectrum.

**Managerial insight 1:** As the Supply chain becomes more responsive, suppliers with poor process parameters (high processing time, high processing time variability, high inventory holding rate etc) but operationally efficient and/or cost efficient location wise are more likely to be chosen, at an appropriate value of \( C\text{IR} \) in place of suppliers with relatively better process parameters assuming that the suppliers are equivalent with respect to other parameters not considered in the model.

### 4.3. Effect of low cost of flexibility (responsiveness)

In this subsection, we attempt to address the effect of low cost of flexibility at a stage for all the potential suppliers, all the other parameters being held constant.

Now let us consider the hypothetical case, as shown in Table 4, wherein suppliers 2 and 3 are progressively cheaper with respect to the cost of flexibility compared to supplier 1.

The cheaper cost of flexibility is attainable due to any of the following possible factors:

1. Availability of redundant capacity.
2. Flexible hours of operation.
3. Availability of skilled labor at lower costs.
4. Lower costs of hiring/renting.
5. Flexible machinery.

**Table 4**

Key values of the parameters for the three potential suppliers.

<table>
<thead>
<tr>
<th>Supplier</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of flexibility function</td>
<td>((1 - C\text{IR}^2))</td>
<td>((1 - C\text{IR}^2)/3)</td>
<td>((1 - C\text{IR}^2)/6)</td>
</tr>
<tr>
<td>Mean processing time (periods)</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Processing time variability ((\mu^2\sigma^2))</td>
<td>100</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>Inventory holding cost (h_j)</td>
<td>0.017</td>
<td>0.025</td>
<td>0.034</td>
</tr>
</tbody>
</table>

As \( C\text{IR} \) decreases, difference among the safety stock costs for supplier 1 vs. suppliers 2 and 3 diminishes due to the reduction in average processing time and the associated variability as with scenario presented in Section 4.1. Differences among indirect safety stock costs also decrease when compared to the scenario discussed in Section 4.1. Direct response cost contribution difference will become progressively larger with decreasing \( C\text{IR} \) for suppliers 2 and 3, when compared to supplier 1. Supplier 1 costs will be maximum followed by suppliers 2 and 3 in that order. Cycle stock costs for suppliers 2 and 3 compared to supplier 1 will differ by a fixed amount as in Section 4.1, supplier 1 costs being the minimum followed by suppliers 2 and 3 in that order. With decrease in \( C\text{IR} \), the increase in responsiveness related cycle stock costs for suppliers 2 and 3 will occur at a decreased rate (because of lower cost of flexibility) compared to the scenario discussed in Section 4.1. In addition, there will be a reduction in responsiveness related cycle stock costs at stage 4 for suppliers 2 and 3 compared to the case in Section 4.1 on account of lower cost of flexibility. Overall, as the \( C\text{IR} \) decreases, total cost difference for suppliers 2 and 3 compared to supplier 1 progressively gets reduced. This effect will be accentuated as the cost of flexibility becomes smaller and smaller at suppliers 2 and 3 compared to supplier 1.

By taking into consideration, the above-mentioned modifications (Table 4) in the cost of flexibility function for suppliers 2 and 3, we realize Fig. 3. We can observe that as the supply chain becomes more responsive, both suppliers 2 and 3 overtake supplier 1 in terms of least total cost and supplier 3 overtakes even supplier 2 as \( C\text{IR} \) decreases further.

As the supply chain becomes more responsive, the increase in costs on account of the poor process parameters for suppliers 2 and 3 will be offset to some extent by the decrease in the associated response related costs (on account of low cost of flexibility) compared to the scenario presented in Section 4.1. This is happening at a faster rate for supplier 2 than supplier 3 because of the proximity of the process parameters chosen to that of supplier 1. Eventually, at an appropriate value of \( C\text{IR} \), the difference in the costs for suppliers 2 and 3 is also offset by the reduction in the response related costs for supplier 3, at which point supplier 3 emerges as the least cost supplier.

It is not necessary that suppliers with adverse parameters will always overtake supplier 1 in the \( C\text{IR} \) band within which a particular company wants to operate. In a typical context, the gap between supplier 1 and suppliers 2 and 3 in terms of total cost will progressively decrease with decrease in \( C\text{IR} \).

Revisiting the example mentioned in the earlier section for a supplier dealing with a commodity product such as ‘coffee maker...
warming plate’, who operates close to a CIR value of 1 to minimize the total costs. In such a case, it will take relatively more effort for suppliers 2 and 3 in spite of cheaper costs of flexibility to overtake the disadvantage due to poor process parameters when compared to a supplier of a short life cycle products such as mother boards, hard drives, etc. competing on the responsiveness end of the spectrum.

Managerial insight 2: As the Supply chain becomes more responsive, suppliers with poor process parameters (high processing time, high processing time variability, high inventory holding rate etc) but having lower costs of flexibility (responsiveness) are more likely to be chosen, at an appropriate value of CIR in place of suppliers with relatively better process parameters assuming that the suppliers are equivalent with respect to other parameters not considered in the model.

5. Illustrative example

A wiring harness is designed to wire the vehicle and is one of the crucial purchased products for an automobile. It is a string of cables that transmit information signals to different points in an automobile. Each wiring harness includes built-in fuses, relays for fans, pumps, auxiliary power and more. Harness has bundle identifiers for easy identification and installation to production sensors at the OEM facility.

In this section we develop a representative example of an OEM facility located in Detroit, a local supplier located in Flint, MI (labeled as local) and a remote supplier located in Southern states or across the border in Mexico (labeled as Remote), both being considered as potential suppliers for wiring harnesses. Information for the key parameters is provided in Table 5. The primary purpose of this example is to aid a practitioner to make use of the model and to show the interplay of inventory and responsiveness cost elements in a typical real-world context.

As can be clearly seen from the table, when compared to the local supplier, remote supplier has poor processing parameters particularly in terms of mean processing time and processing time variability. But the manufacturing costs are cheaper by around 2% for the remote supplier as reflected in the cost per unit. In this example, each supplier stage has got two sub stages namely facility and transport. The analysis of the data using the model developed in earlier sections can be summarized as follows.

As shown in Fig. 4 there is an increase in cost to the tune of $2134 for the remote supplier per day, when compared to the local supplier on account of poorer process parameters under cost parity. But this cost is being counterbalanced by an amount of $4000 per day on account of direct cost differential and, there is an inventory cost saving in terms of safety stocks and cycle stocks accounting for $82 per day, when compared to the cost parity case, on account of lower cost per unit for the facility for the remote supplier. Inventory cost savings are much smaller in magnitude in this case because just one stage (consisting of two sub stages) is considered. When you take into consideration complex supply chains with a large number of nodes there will be savings in safety stock costs and cycle stock costs even at the downstream stages on account of the lower manufacturing costs for the ‘Remote’ supplier. In such a case, inventory savings will become significant and may even be comparable to savings due to direct cost differential. Even though in this case, for the remote supplier, savings due to direct cost differential are able to clearly offset the disadvantage due to poor process parameters that may not be the case in complex supply chains, wherein the echelon inventory cost savings also play a key role. In this case, total cost for the remote supplier per day turns out to be lower than the local supplier thereby making him the ideal choice. Of course, it should be noted that it is not necessary for the remote supplier to be cost effective all the time in the band of responsiveness within which the supply chain wants to compete.

Now an extension is offered to the above example, wherein the responsiveness option is considered for the remote supplier. Transport parameters considered in Table 5 for the remote supplier are for less than truck transportation (LTL), which tends to be a little cheaper but slower as well. The responsive option

![Figure 4](image-url)

**Fig. 4.** Effect of cheaper manufacturing cost on the Remote supplier.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Key parameter values for the local vs. Remote suppliers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local supplier</td>
<td>Remote supplier</td>
</tr>
<tr>
<td>Local facility</td>
<td>Local transport</td>
</tr>
<tr>
<td>Cost ($/unit)</td>
<td>256</td>
</tr>
<tr>
<td>Mean processing time (days) ( t_i )</td>
<td>1</td>
</tr>
<tr>
<td>Processing time SD (days) ( \sigma_i )</td>
<td>0.25</td>
</tr>
<tr>
<td>Inventory carrying cost per year (%) ( h_j )</td>
<td>24</td>
</tr>
<tr>
<td>Mean demand per day ( \mu )</td>
<td>800</td>
</tr>
<tr>
<td>Demand SD per day ( \sigma )</td>
<td>150</td>
</tr>
<tr>
<td>Safety coefficient ( k_j )</td>
<td>1.28</td>
</tr>
<tr>
<td>Average back order coeff &amp; ( r_j )</td>
<td>0.9</td>
</tr>
<tr>
<td>( \Phi(k_j) ) Service level</td>
<td>0.9</td>
</tr>
</tbody>
</table>
considered is truck load option (TL), which tends to be costlier but more responsive. The key parameter values are presented in Table 6. One could consider rail transportation in lieu of LTL transportation depending on the context.

When compared to the LTL (Remote) option, TL option (labeled Remote (R): R in parenthesis stands for ‘responsive’) is costlier by $2 per unit but more responsive on account of lower mean processing time and processing time variability. The analysis of the data using the model developed in earlier sections can be summarized as follows.

As shown in Fig. 5 there is an increase in cost to the tune of $2134 for the responsive remote supplier (Remote (R)) per day, when compared to the local supplier on account of poorer process parameters under cost parity and by considering the same parameters as in ‘Remote’ option. But this cost is being counterbalanced by an amount of $2400 per day on account of the direct cost differential between both the suppliers. This amount is less by $1600 when compared to the ‘Remote’ option, because there is an increase of $2 per unit for the TL transport option. There is an inventory cost saving in terms of safety stocks and cycle stocks accounting for $73 per day, when compared to the cost parity case on account of lower cost per unit for the facility for the ‘Remote (R)’ supplier. This is smaller than ‘Remote’ case because of increase in transportation cost under parameter parity. But, there is an additional cost savings of $572 when compared to the ‘Remote’ case in inventory costs on account of improved parameters (reduced mean and variability of transportation) for ‘Remote (R)’ option. For ‘Remote (R)’ option, responsiveness cost component is increasing at a faster rate than the savings in inventory costs. Because of this, ‘Remote (R)’ option is costlier compared to ‘Remote’ option. Overall, ‘Remote (R)’ is still cheaper than local supplier. As with the earlier case, as the supply chain complexity increases, there will be additional savings in safety stock costs and cycle stock costs at the downstream stages on account of lower manufacturing costs for the ‘Remote’ supplier.

### Table 6

<table>
<thead>
<tr>
<th></th>
<th>Local facility</th>
<th>Local transport</th>
<th>Remote facility</th>
<th>Remote transport</th>
<th>Remote (R) facility</th>
<th>Remote (R) transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($)/unit</td>
<td>256</td>
<td>4</td>
<td>243</td>
<td>12</td>
<td>243</td>
<td>14</td>
</tr>
<tr>
<td>Mean processing time (days) $l_i$</td>
<td>1</td>
<td>0.25</td>
<td>3</td>
<td>11</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Processing time SD (days) $\sigma_i$</td>
<td>0.25</td>
<td>0.1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Inventory carrying cost per year % $h_j$</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mean demand per day $\mu$</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Demand SD per day $\sigma_j$</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>$b_j$, safety coefficient</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
<td>1.28</td>
</tr>
<tr>
<td>Average back order coeff and $s_j$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$F(b_j)$ service level</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Local: $208,205$</th>
<th>Remote (R): $207,295$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings due to cost differential</td>
<td>$2,400$</td>
<td>$572$</td>
</tr>
<tr>
<td>Savings compared to Cost parity case</td>
<td>$73$</td>
<td>$2,134$</td>
</tr>
</tbody>
</table>

**Fig. 5.** Effect of cheaper manufacturing cost on the Remote (R) supplier.

### 6. Conclusions

In present day competitive markets with shorter product life-cycles there is a need to reduce the costs and the supply chain cycle time. In this paper, primarily we offer certain managerial insights with regard to supplier selection problem in a supply chain by considering inventory costs and responsiveness related costs assuming that the structural decisions are already made with respect to the supply chain network. The most important aspect of this paper is that in addition to the traditional cost criterion, we have incorporated supply chain responsiveness related parameters into the model, which allows us to monitor the supply chain performance with respect to these two critical order winners. We make use of a
new parameter called coefficient of inverse responsiveness (CIR) to model response related costs at a stage, which also enhances the scalability of the model. In an optimization context, the developed cost function for the 'building block' could be extended for any type of supply chain network to aid in supplier selection.

So as to make the model more tractable we had to make certain simplifying assumptions and following are some of the limitations related to those assumptions. We did not consider order splitting in our model, which is a common phenomenon in many purchasing decisions. We plan on considering this aspect in our future research. We also did not consider buyer collaboration, which is not uncommon while making purchasing decisions. It would an interesting extension, if this aspect is included. We did not take into account any qualitative factors such as quality, suppliers' reputation, staying power/financial stability, cultural match, etc. in our model. An integrated framework that takes into account some of these factors would add more value to the model.

A useful extension of the model is to account for non-stationary demands and to consider products with seasonal demands. Another limitation is that volume discounts and quantity discounts typically offered by suppliers are not taken into account in our model. Introducing contracts that take into account such discounts with financial ramifications will also be a very fertile area to pursue, which will make our model mimic the reality more closely. So as to make our research realistic, it would make more sense to consider capacity constraints at certain stages. Product mix related flexibility is crucial which is not addressed in our model. Addition of this feature would add more value to the model. Finally, we would like to see how the model can be used in more real-world settings where insights presented in our model could be further validated.

References


