STRATEGIC SUPPLY CHAIN MODELING – A SUPPLY CHAIN PERSPECTIVE OF COST EFFICIENCY AND RESPONSIVENESS

by

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DEDICATION

I dedicate my PhD dissertation to my parents for their love, affection and the constant encouragement, which made me realize insurmountable goals at different stages in my life.

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CHAPTER 1

SUPPLY CHAIN FOCUS DEPENDANT SAFETY STOCK PLACEMENT

Abstract:

Increasing globalization, growing product range diversity, and rising consumer awareness are making the market(s) highly competitive, forcing supply chains to constantly adapt to different stimuli. The growing competition between supply chains (besides players within) is also warranting a priority for overall supply chain performance over the goals of individual players. It is now well established in the literature that among the many order-winners, both overall supply chain cost as well as responsiveness (i.e., supply chain lead-time) are the most significant determinants of supply chain competitiveness. The literature, however, mostly focuses on supply chain cost minimization with rather simplistic treatment of responsiveness. By introducing the concept of 'coefficient of inverse responsiveness' (CIR), we facilitate efficient introduction of responsiveness related costs into the scheme of supply chain performance evaluation and/or optimization. Thus, our model aids supply chain managers in achieving better strategic fit between the individual business unit strategies and the overall supply chain requirements in terms of cost efficiency and responsiveness. In particular, it aids in strategic placement of safety stocks at different stages in the supply chain. Our model also offers managerial insights that help improve our intuitions for supply chain dynamics. The model is more suited for strategic SC alignment, for example when dealing with product changeovers or introduction of new product, rather than for operational control.

Keywords: Supply chain strategy, business strategy, safety stock costs, cost of responsiveness, supply chain cycle time, and coefficient of inverse responsiveness.

1. Introduction

In today's dynamic global market environment, it has become necessary for organizations to focus upon all the relevant performance metrics. Hill (1993) advocates close attention to functional perspectives, customer's views, and actual orders while determining order-winners and qualifiers. Among the possible order winners, supply chain (SC) cost and responsiveness turn out to be more crucial than others. Responsiveness here is the ability of the supply chain to respond quickly to changing customer needs, preferences, and options through improved supply chain cycle time (i.e., velocity), and not the higher service levels achievable through increased distribution of channel inventory. The optimal supply chain strikes the right balance between supply chain cost efficiency and responsiveness, depending on the nature of product(s) supplied by it.

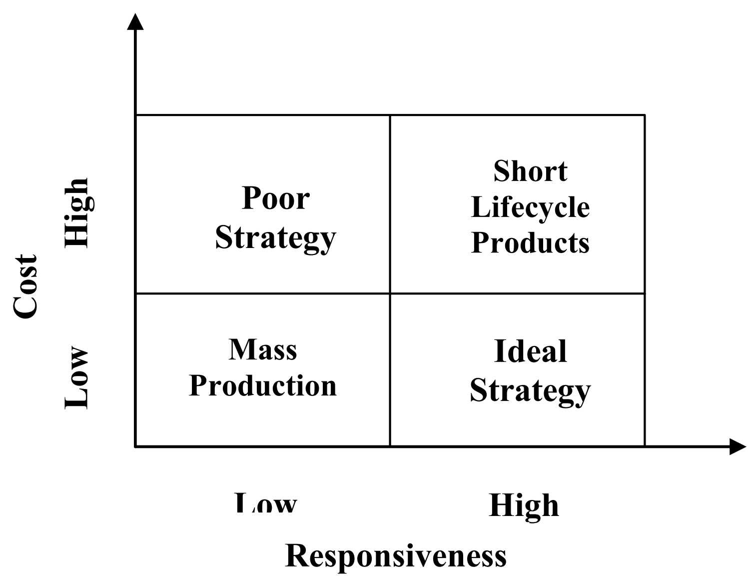


Fig 1: Supply chain responsiveness vs. cost (Source: Vanteddu *et al.,* 2006)

Fig.1 divides the cost-responsiveness spectrum of the SC into four basic quadrants, and provides some indications of their appropriateness. In reality, the treatment will not be that distinct, and depending on the type of products and markets targeted by the SC, the focus could be anywhere on the spectrum. In this context, Fisher (1997) emphasizes the importance of considering the nature of product demand before devising the respective supply chains. More precisely, one needs to account for both the nature of the product as well as uncertainty from both demand and supply in designing the SC (Chopra and Meindl 2004). Similar comments have been echoed in industry literature. Nazzal et al (2006) present a case study for Agere Systems, wherein they use structured simulation and statistical analysis to construct operating characteristic curves to relate SC cycle time to production volume capabilities of a wafer fabrication facility. In particular, the goal was to increase its market share and profits by reducing lead times in the highly competitive and capital intensive semi-conductor manufacturing industry. Another example is Revlon, a personal care products company, whose supply chain is addressed in Davis et al (2005). Its supply chain includes more than 5,000 active finished good SKUs with product life-cycles spanning less than three years, sales in over 100 countries, seven manufacturing facilities, and approximately 450 global suppliers. To meet its aggressive inventory reduction targets and achieving high customer service levels, Revlon is emphasizing reduction of manufacturing and supplier lead times and the associated variability. Even in industries with relatively long product life-cycles, such as the automobile industry, we are seeing increased emphasis on SC responsiveness for matching supply and demand, handling model changeovers, and introduction of new product, all with the goal of lowering capital investment and improving profitability (Pelagagge 1997). Advising against too much emphasis on lowest labor costs, Cannon (2006) opines that companies that can respond with the greatest flexibility will have a clear competitive advantage. Highlighting the importance of lead-time reduction, Cannon (2006) narrates the following example. A large global telecom company was getting a lot of pressure from its customers to reduce lead time from 6 weeks to 6 days for their high-end network switches with more than 5,000 different configurations consisting of over 2,000 different parts from 150 suppliers around the globe. Stated otherwise, the company needed to be more responsive! .Also, Yang and Geunes (2007) emphasize that longer lead times, in addition to reducing customer responsiveness, increase demand forecast error, since forecast error generally increases as the forecast horizon increases. In addition, 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. In summary, striking the right balance between supply chain cost efficiency and responsiveness is critical, which can be neglected at one's own peril. On the contrary, existing literature overly focuses on just one order-winner, cost efficiency.

The other important problem with existing literature is that the typical focus is not on offering practical insights that can be used by SC managers in a real-world context. One SC situation is different from the other; hence, case study models can't be replicated without major modifications. Any model's prescriptions that do not take into account the SC ramifications in the present day globalized context will only be resulting in short-term gains. It is of essence to realize that a SC would gain optimally by subordinating individual player interests to the SC interests. As Ken Cottril (1997) puts it, supply chain's economic value is best enhanced when the realization occurs that true competition is between SCs, wherein performance is measured using overall chain metrics. Thus, it is important for a SC to align the activities from the strategic level through the managerial to the operational level to be cost effective (Simchi-Levi *et al.*, 2000). Though vertical integration seems to address the aforementioned issues for SC management, it may prove to be a risky option in the presence of highly specialized manufacturers and service providers. For example, Michael Dell, in his interview with J. Magretta (Magretta 1998), believes that if his company were vertically rather than virtually integrated, it would need 5 times as many employees and would suffer from a "drag effect".

Model based decision support systems are a necessity in today's highly competitive markets. Model based systems are necessary to anticipate and act upon supply/demand uncertainties, changes in the design of the SC network, changes in transportation mode etc, so that manufacturing managers are able to compare alternative opportunities in terms of cost and service impact (Lee & Billington 1993). There are primarily four drivers influencing the performance of the SC, namely, infrastructure, inventories, transportation, and information (Chopra and Meindl 2004). Given that 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. These issues, however, 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 and transportation to the immediate downstream stage. 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. Thus, we are primarily considering the inventory cost driver in our model.

Among inventory cost elements, safety stock, maintained to account for the internal and external variability in the supply chain, is vital in the sense that it directly affects customer satisfaction and constitutes a significant portion of the cost of goods sold (COGS). Explaining the necessity of inventories in a supply chain, Lee & Billington (1993) opine that inventories are used to protect the supply chain from different sources of uncertainties that exist along a supply chain such as demand uncertainty (volume and mix), process uncertainty (yield, machine down time, transportation reliability), and supply uncertainty (part quality, delivery reliability) etc.

In summary, in terms of supply chain strategy, one can choose to compete purely on price (for a commodity product) or product velocity (fashion industry, for example) or choose a third path, a niche strategy, a hybrid of the other two (Cherukuri et al 1995). Our research primarily focuses upon the third strategy, where in there are opportunities to be exploited with respect to both the order winners.

The rest of this manuscript is organized as follows: Section 2 discusses relevant literature; Section 3 deals with development of the overall cost expression for the supply chain, that accounts to SC responsiveness; Section 4 describes how one can use the model for achieving the strategic fit; Section 5 offers managerial insights for strategic safety stock placement in a serial supply chain; Finally, Section 6 offers conclusions and limitations that should be addressed in future research.

2. Literature Review

Clark (1958) introduces the concept of echelons for systems consisting of stock at any given installation plus stock in transit to or on hand at a lower installation. Assuming centralized control for a series system with a periodic review inventory control policy that excludes setup costs, Clark and Scarf (1960) were able to show that an order-up-to policy is optimal for each node. 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. One of the key insights offered is that downstream lead-times have a greater impact on system performance than upstream ones. The tradeoff between the flexibility of a manufacturing system with respect to both rate change and mix and investment in inventory is addressed in Graves (1988), wherein the author considers demand uncertainty, a stationary demand process, and lot for lot scheduling. In this model, aggregate production output is determined by a production control rule that attempts to smooth the aggregate output and is parameterized by a planned lead time, a decision variable in the model. Flexibility is modeled as the ratio of a measure of slack available to demand variability. Our research focuses upon the opportunities at a stage for resource flexibility to reduce the lead-time and the relevant costs. In Graves (1988), safety stocks are planned to account for only a portion of the variability and assumes that other measures are also available to counter variability.

Stochastic service model as advocated by Graves and Willems (2003) addresses the issue of strategic placement of safety stocks across a multi-echelon SC in the presence of demand uncertainty. As with Graves and Willems (2003), the primary emphasis of our research is to provide decision support for SC design, rather than SC operation, and the intent is not to find inventory control policies as is the case with much of the multi-echelon inventory literature. Another common feature is that the local decisions (decentralized control as opposed to central control) are made at each stage based on local information. It is worth noting at this point, as buttressed by Graves and Willems (2003), that a SC subjected to decentralized control is not equivalent to SC being locally optimized. In an optimization context, the model attempts to find the optimal parameter values, under the assumption of decentralized control, that minimize the total SC cost. The primary purpose of their model is to develop a multi-echelon model and the relevant optimization algorithm is specifically designed for optimizing the placement of safety stocks in a real world SC. Unlike Graves and Willems (2003), where inventory is the only lever to counter demand and supply variability, our model has two levers, namely, echelon inventory and responsiveness (cycle time) at each stage.

The supply chain configuration problem, a special case of supply chain design problem, consists of the set of decisions that are made after the network design that act to configure each stage in the network by taking into account certain relevant parameters (Graves and Willems 2003). They argue that the central question is to determine what suppliers, parts, processes, transportation modes (called options) to select at each stage in the supply chain. Our model is similar in spirit to the optimization model proposed by Graves and Willems (2003). The primary similarity is that both the models balance the increase in COGS (Cost of goods sold) against the decrease in inventory related cost, though both models differ significantly with regard to the methodology adopted and serve different end purposes. Graves and Willems (2003) have used their model for a Bulldozer network to optimize the total costs, where in costs are added in a discrete way for each option. For example, an operation can be done in a standard way or expedited way (company investing in process investments) with different lead times and costs, or standard procurement vs. consignment (0 lead time), consignment being costlier.

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 and model it as a continuous function of a novel dimensionless parameter called the 'coefficient of inverse responsiveness (CIR)', with the focus of: a) developing managerial insights with regard to strategic safety stock placement in a serial supply chain and b) achieving strategic fit between the supply chain strategy and the individual business strategies for a given set of parameter values.

Graves and Willems (2000) is another interesting paper that has some relevance to our research. In this, they develop what is called a 'guaranteed service model' and also present an optimization algorithm based on dynamic programming for the placement of safety stock for supply chains that can be modeled as spanning trees under certain assumptions. Key assumptions such as modeling the supply chain as a network, each stage operates with a periodic review policy, stationary demand (bounded incase of Graves & Willems 2000) etc are common to both stochastic service (Graves and Willems 2003) and guaranteed service models. They also describe the successful application of the model at Eastman Kodak to reduce finished goods inventory, target cycle time reduction, and to determine component inventories. The authors also mention that Kodak's flow teams have used the model to determine the cost effectiveness of lead time reduction efforts in manufacturing.

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 w.r.t the safety stock positioning are developed in various supply chain topologies. The two other papers that use stochastic service approach that are relevant to our research are Lee and Billington (1993), Ettl et al. (2000). We share the ample production capacity assumption with Simchi-Levi and Zhao (2005) and Graves and Willems (2003). For capacitated models using a modified base stock policy, the reader can refer to Glasserman and Tayur (1995, 96) and Kapuscinski and Tayur (1999). Simchi-Levi and Zhao (2005) enhances the work of Gallego and Zipkin (1999) and provide stronger results. They also point out through their computational study of the Bulldozer supply chain problem (Graves and Willems 2003) the perils of ignoring lead time uncertainties, which is accounted for in our model. The key difference is that, to achieve a specific service level, the only lever available for them is to increase the safety stock costs at a stage whereas our model has an additional lever in the form of exploring the responsiveness related options, so that over all cost is lower. In addition, Simchi-Levi and Zhao (2005) present a nice summary of the literature for installation policies that are used in various network topologies.

- Multi stage serial systems (Simpson 1958, Hanssmann 1959, Lee & Zipkin 1992)
- Distribution Systems (Axsäter 1993, Graves 1985, Lee & Moinzadeh 1987 a, b)

Given the size and complexity of supply chains such as those found in computer, electronics and auto industries, a common problem for asset managers is not knowing how to quantify the trade-off between service levels and the investment in inventory required to support those service levels (Ettl *et al.* 2000). This problem is compounded by the response related performance measures. As with Ettl et al (2000) model, our model is intended to be a strategic model not caring much about the operational details.

Ettl et al (2000), who have developed a supply network model that takes as input the bill of materials, required customer service levels, nominal leadtimes, demand and cost data etc, generates the base stock level, stocking location for a part etc at each stage. Modeling the dynamics at each stage in the network as an inventory queue, both performance evaluation and optimization can be performed for a supply chain with service level constraints. They have formulated a constrained nonlinear optimization problem that minimizes the total average dollar value of the inventory subject to meeting the service level requirements. Making use of analytically obtained gradient estimates, optimization was carried out using the conjugate gradient method.

Eppen & Martin (1988) present a very nice critique of the standard procedure using standard (Q,r) model for setting safety stocks in the presence of stochastic lead time and demand. In (Q,r) model, Q units are ordered whenever the inventory position reaches r units. Providing numeric examples, they demonstrate that this standard procedure, that assumes known parameters for demand and the lead time distributions, can produce reorder points and safety stock levels that are inconsistent with the desired probability of stocking out. They argue that it is not appropriate to assume that lead time is normal based on central limit theorem justification. When the above mentioned parameters are unknown, they present a procedure for determining reorder points that uses the output from a forecasting system such as exponential smoothing method and a discrete probability distribution for the lead time that can be developed from historical data under certain assumptions. When parameters are unknown, our research model could be extended by following the procedure suggested by the authors.

Chopra et al (2004) build on the work of Eppen & Martin (1988) but the focus is on the flaws in the managerial prescriptions implied by the normal approximation. In particular they infer the following by using the exact demand during the lead time instead of the normal approximation: 1) For cycle service levels above 50% but below a threshold, reducing lead time variability increases the reorder point and safety stock and 2) For cycle service levels above 50% but below a threshold, reducing lead time variability increases the reorder point and safety stock, whereas reducing the lead time decreases the reorder point and safety stock. Our research addresses the issue of reducing lead time variability indirectly as a result of reducing the lead time because of the flexibility options available at a stage.

Another interesting paper that studies the effect of lead-time uncertainty is by Song (1994) in which the focus is upon the effect of stochastically larger lead times and lead time variability on the long run average cost for a basic continuous time single item inventory model. They show that a stochastically larger lead time results in a higher optimal base stock level but may not necessarily lead to a higher optimal average cost. On the other hand, a more variable lead time always leads to a higher optimal average cost. A more variable lead time requires a higher optimal base stock level if and only if the unit penalty (holding) cost rate is high (low).

For a 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. Yang and Geunes (2007) study a problem in which a supplier wishes to determine the best positioning of a product with respect to order lead time and price, wherein the demand is lead-time sensitive. They consider a continuous review inventory replenishment system, where the difference between the procurement lead time and promised sales order lead time influences both cycle stock and safety stock costs, and procurement costs may increase as a result of investment in production lead time reduction. Their results indicate that, for a broad range of practical settings, such systems employ a pure make-to-stock policy or a policy that sets sales lead time equal to the procurement lead time at optimality.

Lin et al (2000) developed an asset management tool that integrates graphical process modeling, analytical performance optimization, simulation, activity based costing and enterprise data connectivity to enable IBM in 1994 to reengineer it's global supply chain to achieve quick responsiveness to customers with minimal inventory. The primary focus is upon optimization of multi echelon supply network with base stock control. The model emphasizes operational details for a specific application as opposed to our model which has a strategic focus.

Advocating the necessity of models that include both cost and responsiveness, Moon and Choi (1998) suggest extending the lead time reduction concept to different 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.

In their extensive literature review of strategic production distribution models, Vidal and Goetschalckx (1997) conclude that among others, the main drawback of the existing models is the fact that most uncertainties (exchange rates, supplier's reliability, lead times, stochastic demand, stochastic customer service level, stochastic facility fixed costs, political environment etc) are not considered in the formulations. We hope that, our model that considers both demand and lead time variability could be further extended in future to consider other types of uncertainties to closely mimic the reality.

As opposed to network design models that focus on the trade off 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 DCs in the network such that the sum of the location and inventory (pipeline and safety stocks) is minimized. Our CIR concept is similar in spirit to the replenishment lead time calculation at a DC (Sourirajan et al 2007), which depends upon the volume of flow through the DC.

For their model, replenishment lead time (L) at a DC is assumed to be of the form $L = p/Z + q + r/(C - Z)$, where Z is the total mean demand assigned to the DC, C: Max demand volume that can be handled by DC, q: Constant DC replenishment time per unit, p: Load makeup time parameter, and r: Congestion time parameter. For a given C value, increasing the mean demand increases the contribution of the third term (congestion component) to the L, which is similar to our concept that if CIR increases, generally it means that there is less scope for flexibility. The model is solved by developing a Lagrangian heuristic near optimality with reasonable computational requirements. A scenario analysis shows that the properties of the supply network as embodied in the number of DCs located and the utilization of the DCs depend on the priorities given to various metrics.

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. This paper introduces a term called ‘expediting factor’ for the lead time, which is similar in spirit to the dimension less quantity proposed in our model CIR. 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.

Another interesting research in the context of lead time management in supply chains is by Ray (2001), who in his model considers speed and cost as important competitive priorities and focuses upon the investment requirements for lead time reduction specifically for MTS and MTO firms. Considering process improving investments and amortization schemes in reducing supplier lead time, they show that such investments in lead time reduction can, after accounting for all the associated costs and benefits, result in substantial reduction of inventory costs for an MTS firm. For MTO firms, by assuming the unit operating cost to be a decreasing cost function of the demand rate, their analytical model for delivery lead time management trades off the costs of investment against the resultant benefits. They show that ignoring: a) the dependence of market price on the lead time offered and economies of scale, when they exist and b) the inherent preference of customers for price or lead time can lead to potentially large profit losses.

Even though, we did not consider 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).

3. Model Development

The section mostly develops total cost expression, made up of safety stock costs and responsiveness related costs, for a serial supply chain.

3.1 Expression for Safety Stock Costs

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 there by 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 Wall 1991, van Houtum et al 1996).

In an installation policy, each facility only needs the inputs from the immediate U/S and D/S facilities and makes ordering decisions based on it's 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 manufacturing stages, without loss of generality, a stage could be modeled as a 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. 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 non overlapping intervals and there are 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 & 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 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 serial 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 can’t 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 consider backorder penalty cost, which could be easily included. The horizon is finite, all data are stationary and the objective is to evaluate the performance and optimize depending upon the supply chain focus on the cost–responsiveness spectrum. Information is centralized but control is decentralized.

As in Gallego and Zipkin (1999), the numbering 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.

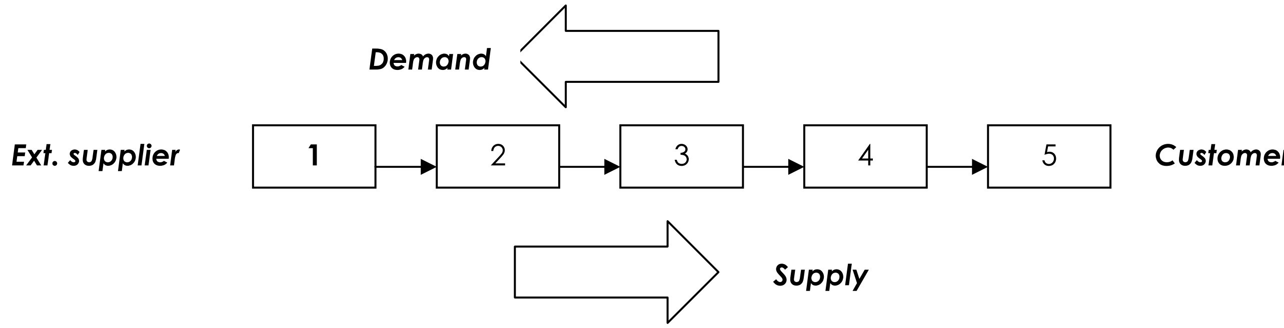


Fig 2: Schematic description of a serial supply chain

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) treatment of stochastic service model in supply chains, let $\Phi(k_1),....,\Phi(k_n)$ be the service levels for corresponding safety factors $k_1,...,k_n$ where $\Phi(k_i)$ represents the cumulative distribution function for a standard normal variable. k_j is the multiplying factor for the variability term for stage j ,which along with the average in process inventory would give the expected base stock to achieve a given service level. Let the processing time at stage j be a random variable τ_j with mean L_j and variance σ_j^2.

The stochastic service model (Graves and Willems 2003, Simchi-Levi and Zhao 2005, Lee and Billington 1993, Ettl et al. 2000) assumes delivery or service time between stages to vary based on the material availability at that stage and each stage in the supply chain maintains a base stock sufficient to meet it's service level target (Graves and Willems 2003). If Δ_i is the random delay at the preceding stage i, then the replenishment cycle time at stage j equals

$$\gamma_j = \tau_j + \Delta_i \qquad (1)$$

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) and Ettl et al. (2000) with a modification that takes into account the fact that there is only one player at the preceding stage. Thus, we are assuming that the expected value of this delay is simply equivalent to the probability of stock out at the preceding stage π_i times it's average processing time.

Therefore, expected replenishment cycle time at stage j is given by

$$E\left[\gamma_j\right] = L_j + \pi_i L_i \qquad (2)$$

where,

$$\pi_i = 1 - \Phi(k_i) \qquad (3)$$

Assuming that the demand is $N\left(\mu,\sigma^2\right)$, to satisfy average demand μ, given the average replenishment cycle time from (2), 'average cycle stock' is given by

$$\mu * \left(L_j + \left(1 - \Phi(k_i)\right) L_i\right). \qquad (4)$$

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

$$\sigma_{\Delta_i}^2 = \sigma_i^2 (1 - \Phi(k_i)) \qquad (5)$$

$$\sigma_{\gamma_j}^2 = \sigma_j^2 + \sigma_i^2 (1 - \Phi(k_i)) \qquad (6)$$

When the demands are uncorrelated between time periods, then the mean and variance of the demand during replenishment period for stage j denoted by the continuous random variable W_J are obtained as follows by slightly modifying the equations to account for the portion of the lead time variability transferred from the preceding stage (see for example, Eppen and Martin 1988 and Feller 1960)

$$\mu_{W_j} = \mu E[\gamma_j]$$
$$\sigma^2_{W_j} = \sigma^2 E[\gamma_j] + \sigma^2_{\gamma_j}\mu^2 \qquad (7)$$

Now, we introduce another parameter 'c_j' termed as the 'coefficient of inverse responsiveness (CIR)', defined as the ratio of the average demand to the rate of production (throughput) p_j:

$$c_j = \mu \; / \; p_j \qquad (8)$$

Assuming that there is enough capacity at all the stages to satisfy a given demand, $c_j \leq 1$ at all the times. When c_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" τ as the constant of proportionality between random variables $\tilde{T}$ (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, τ), 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 (c_j <1), average replenishment cycle time for player j, when operating at a CIR level c_j will be equivalent to

$$E\left[\gamma_j\right] = (L_j + (1 - \Phi(k_i))L_i)c_j \qquad (9)$$

$$\sigma^2_{\gamma_j} = (\sigma_j^2 + \sigma_i^2(1 - \Phi(k_i)))c_j \qquad (10)$$

As c_j decreases, average replenishment cycle time for player j decreases, which means player j is becoming more responsive. Because of this inverse relationship between c_j and responsiveness at stage j, c_j is termed as 'coefficient of inverse responsiveness' at stage j.

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

$$\begin{aligned} \mu_{W_j} &= \mu E\left[\gamma_j\right] \\ \sigma_{W_j} &= \sqrt{\sigma^2 E\left[\gamma_j\right] + (\sigma_{\gamma_j}^2)\mu^2} \end{aligned} \quad . \tag{11}$$

The above equation considers both the demand variability and the replenishment cycle time variability. Replenishment cycle time variability has got two components

a) Processing time variability at stage j.

b) 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 $B_j = \mu E\left[\gamma_j\right] + k_j \sigma_{W_j}$, 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

$$E\left[I_j\right] = k_j \sigma_{W_j} \tag{12}$$

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),

$$E\left[BO\right] = \sigma_{W_j} \int_{z=k_j}^{\infty} (z - k_j)\phi(z)dz \tag{13}$$

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

$$E\left[SS_j\right] = \sigma_{W_j}\left(k_j + \int_{z=k_j}^{\infty}(z-k_j)\phi(z)dz\right) \tag{14}$$

At stage j, let C_j be the nominal cumulative cost of the product realized when c_j =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:

$$C_j^{SSC} = C_j h_j E\left[SS_j\right] \tag{15}$$

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

$$C^{SSC} = \sum_{j=1}^{n} C_j^{SSC} \tag{16}$$

3.2 Expression for Responsiveness Related Costs

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 two consecutive stages j and 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 $5M$ 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, which we will consider in the extension of this framework. 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 is given by

$$DRC_j = [f(1-c_j)](C_j - C_i)\mu \qquad (17)$$

Even though we do not advocate any specific function type for modeling $f(1-c_j)$, cost of volume flexibility function, 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 piece-wise 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 piece-wise linear crashing cost function in their model. Ben-Daya 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 etc) time $\psi(\tau)$ 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 $\psi(\tau)$ to take negative values for $\tau > 1$, 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) chose their expediting cost functions $\psi_1(\tau_1)$ and $\psi_2(\tau_2)$ to be decreasing convex functions of the expediting factors τ_1 and τ_2. They considered $\psi_1(\tau_1) = c_1(-1+1/\tau_1)$

and $\psi_2(\tau_2) = c_2(-1 + 1/\tau_2)$, where c_1 and c_2 are positive coefficients. Our cost function, for example equation (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 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:

$$IRC_j = [f(1-c_j)](C_j - C_i)h_j E\left[SS_j\right] \quad (18)$$

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

$$TRC_j = DRC_j + IRC_j \quad (19)$$

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

$$C_j^{TSC} = C_j^{SSC} + TRC_j \quad (20)$$

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

$$C^{TSC} = \sum_{j=1}^{n} C_j^{TSC} \quad (21)$$

4. Model Usability for Achieving Strategic Fit

The model can be used primarily as a building block in any kind of a supply chain network both to evaluate the performance of individual stages with respect to the key order winners cost and responsiveness and to optimize the supply chain dependent upon the supply chain focus on the cost-responsiveness spectrum. The results can be used to evaluate the gap between the individual business strategies of different stages and the supply chain strategy, so that, appropriate actions could be taken to achieve the strategic fit. Once the supply chain design is completed and the network is in its place, the model will be particularly useful for making strategic decisions with regard to the safety stock placement while considering a changeover/ or introducing to a new product.

4.1 Performance Evaluation

Total safety stock related cost (safety stock cost and the responsiveness cost) expression for all the stages (using equation 20) can be easily evaluated given the different parameter values and can obtain the costs separately for safety stock holding and cycle time reduction (if so desired by a stage) and the expected cycle times assuming that all the stages operate without any coordination with respect to the overall supply chain strategy (that is there is no central decision maker). This will allow stages to evaluate their performance with regard to the key order winners of cost and responsiveness and facilitates their comparison to the internal performance bench marks. For example, a particular stage may realize that better operations management practices that involve the reduction of waste (lean practices) that had been planned for are ineffectual. Hence, they may want to know ‘what went wrong?’, and implement appropriate corrective and preventive actions such that cost and cycle time reductions can be achieved without any major investments.

4.2 Optimization

Now assuming that, there is a central decision making mechanism, which acts to coordinate the whole supply chain, the overall safety stock related cost expression for the supply chain (equation 21) can be optimized, say for the optimal CIR values at all the stages given the constraints on target supply chain cycle time, individual stages' rates of production, service levels, inventories, cost of inventory holding etc. The optimal costs (safety stock inventory and responsiveness) can be compared with the costs obtained assuming the absence of the central decision maker (as for performance evaluation explained in sec 4.1) to initiate necessary actions.

4.3 Achieving Strategic Fit

If the overall costs at a stage are increasing as a result of optimization to achieve the strategic supply chain objectives, when compared to the costs in the absence of a central decision maker i.e. by following it’s independent business strategy, then, by devising a scheme for the sharing of the additional profits for the whole supply chain in an equitable fashion, say, through changing the contract structure, discounts or other incentives, efforts could be made to coordinate the individual business strategy with the supply chain strategy to achieve the strategic fit.

5. Managerial Insights for Strategic Safety-stock Placement

In this section, we attempt to study the safety stock placement problem primarily w.r.t the key parameters such as replenishment cycle times, replenishment cycle time variability, cost of responsiveness etc as we travel from U/S to D/S and offer some interesting insights.

5.1 Position of the Bottleneck Player

We consider a hypothetical serial supply chain with five stages to study the impact of the position on the bottleneck player on supply chain performance. The different parameters for this serial supply chain are illustrated in Table 1.

	Stage/Player				
	1	2	3	4	5
Nominal cumulative cost C_j	80	112	175	327	863
Average demand μ	100	100	100	100	100
Demand variability σ^2	400	400	400	400	400
Mean Processing time (periods) L_j	1	1	1	1	1
Processing variability ($\mu^2\ \sigma_j^2$) (in terms of number of units^2 of product)	50	50	50	50	50
CIR c_j	1	1	1	1	1
Safety coefficient k_j	1.28	1.28	1.28	1.28	1.28
Average back order coefficient	0.1	0.1	0.1	0.1	0.1
Probability of stockout π_j	0.1	0.1	0.1	0.1	0.1
Inventory holding cost h_j	0.017	0.017	0.017	0.017	0.017
Service level $\Phi(k_j)$	0.9	0.9	0.9	0.9	0.9

Table 1: Parameters of five-stage serial SC adopted for numerical analysis.

For the purpose of our discussion, we consider the player with no flexibility whatsoever with respect to it’s processing time as the bottleneck player. The effect of changing the position of the bottleneck player on the SC safety inventory costs is depicted below. We have considered three cases, wherein the processing time variability progressively increases, decreases and remains constant as we move from the most U/S stage to the most D/S stage. For increasing and decreasing cases, we have kept the total processing variability constant and progressively increased/decreased the process variability as we move from U/S to D/S in a symmetric fashion. When a particular stage is a bottleneck, CIR for that particular stage would be one and for all other stages CIR is considered to be 0.9. Response related costs are not considered in the analysis as our primary intention is to show the effect of reducing the lead time on the safety stocks as the bottleneck player moves from U/S to D/S. By considering the incremental total supply chain safety stock costs with respect to a benchmark case, wherein all the players are operating at a CIR equivalent to 0.9 and the processing variability is same at all the stages (as with EV case in the chart), one can clearly see that the incremental total supply chain safety stock costs progressively increase as the bottleneck player moves from U/S to D/S for all the three cases.

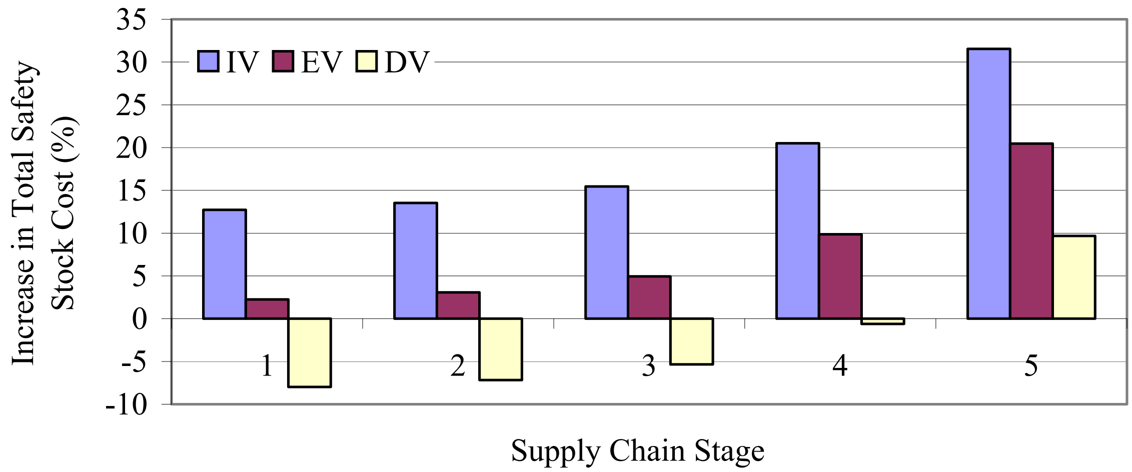


Fig 3: Incremental SC safety stock costs vs. position of bottleneck player

Key Managerial Insight #1: Safety stock cost depends on the placement of the bottleneck player in a serial supply chain and it is desirable for the bottleneck player to be located towards the U/S rather than the D/S.

5.2 Safety Stock Costs vs. Responsiveness Costs

We illustrate the impact of CIR on the different cost curves in Figure 4, using the cost expressions developed earlier.

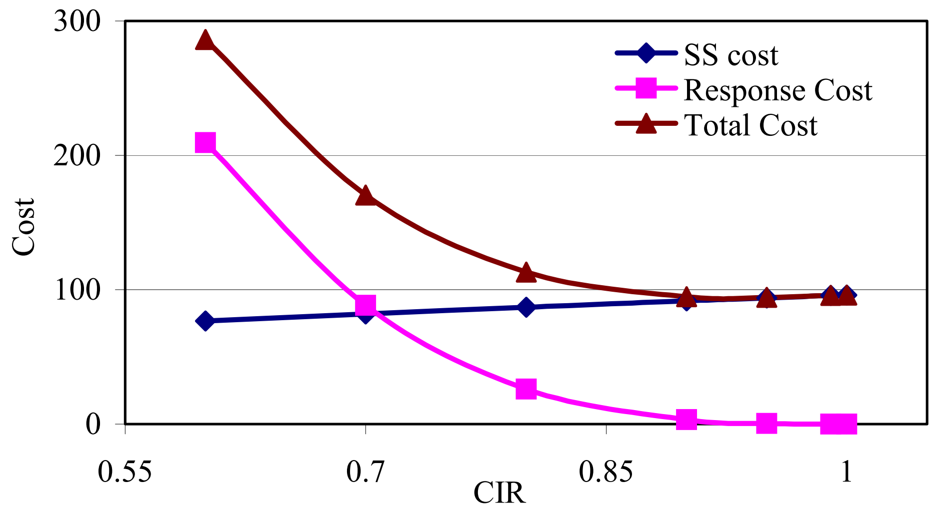


Fig 4: CIR vs. Stage Costs

We know that for any stage, safety stock related costs decrease (equation 15) and response related costs increase (equations 17 and 18) with decrease in cycle time, or in other words, with decrease in CIR. Hence, without loss of generality, we can say that the total cost function, which is a combination of safety stock and response related costs, tends to be convex, the optimum CIR shifting either towards or away from unity depending on whether responsiveness cost component or safety stock cost component is dominating. A very interesting result relevant to the nature of the total costs is by Bookbinder and Cakanyildirim (1999), wherein they show that the expected cost per unit time is jointly convex in the decision variables (Q,r,τ), τ being the expediting factor for a (Q,r) inventory system with expedited orders and random lead times.

5.3 Effect of Cycle Times and Processing Time Variability on Total Stage Cost

The following graph illustrates the effect of increasing processing time variability at a particular stage on the total cost while keeping the other parameters constant. For the sake of numerical analysis, we have considered the parameter values for stage three. PV in the chart stands for processing time variability and DV stands for demand variability.

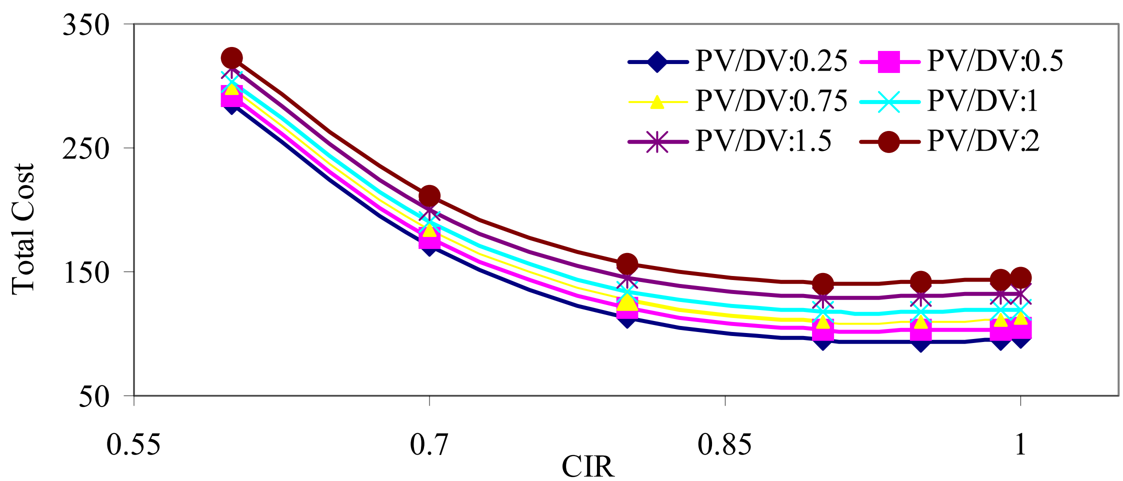


Fig 5: CIR vs. Total Stage Costs

Increasing process variability tends to increase both the safety stock related costs and responsiveness related costs at different rates primarily depending on the nominal cumulative cost C_j, cost of volume flexibility function $f(1-c_j)$, and the cost added at a stage $(C_j - C_i)$. In the presence of increasing processing time variability, therefore, optimum CIR either moves away from/ or towards unity, depending on whether safety stock cost component/or the responsiveness cost component is dominating. With increasing variability, the degree of departure of the optimum CIR value either way depends on the three factors mentioned above for a particular stage. To explain, to counter the excessive variability, a typical supply chain manager tries to reduce the cycle time (by reducing CIR), which would minimize the SS related costs. However, that action does not necessarily lead to reducing the over all costs. For example, if the cost added at a particular stage is very high then the decrease in safety stock costs by cycle time reduction might not be able to offset the increase in cycle time reduction (responsiveness) costs. In such a scenario, moving CIR counter intuitively towards unity (i.e. increasing the cycle time), which means in the direction that increases safety stock costs, could be a better measure to reduce the over all costs.

Key Managerial Insight #2: *As the processing time variability increases at a stage, optimum value of CIR moves away from unity if safety stock cost component dominates the responsiveness cost component and optimum CIR moves towards unity if the responsiveness cost component dominates the safety stock cost component.*

In Fig 5, optimum CIR is progressively moving away from unity as the PV/DV ratio increases, because we have considered the safety stock costs component to be larger than the responsiveness cost component for our numerical analysis. The trend will be reversed if the response related costs dominate the safety stock related costs.

Optimum value of CIR at a stage would primarily depend upon the cumulative cost of the product, which in turn will depend upon the position of the stage in the supply chain, cost added and the nature of cost of volume flexibility function. Using the cycle time reduction as a lever may/or may not be cost effective depending on, for example, whether a wind screen wiper is being assembled or an engine is being assembled at a stage. For the same cost of volume flexibility function, it might be a good idea to reduce the cycle time if wind screen wiper is being assembled as opposed to an engine.

Irrespective of the component that is being assembled, this effect will be more pronounced at D/S when compared to U/S because the cumulative cost of the product will progressively increase as we move D/S.

Key Managerial Insight #3: To reduce the safety stock costs, reducing the cycle time is a better lever at downstream stages when compared to upstream stages for a given responsiveness cost, all the other parameters being held constant.

Key Managerial Insight #4: All the other parameters being constant, for a given cycle time reduction, cost of flexibility function has to be milder for a stage with high cost addition when compared to a stage with low cost addition, to justify savings in safety stock costs.

The insight from Ryu and Lee (2003) "that in order to attain greater savings from the symmetric cost scheme for the two suppliers, the investment cost for the supplier with the more unreliable lead time should be smaller" looks similar in essence to our key managerial insight 2, albeit in a different context. One of the key insights offered that downstream lead-times have a greater impact on system performance than upstream ones (Gallego and Zipkin 1999) is also similar in spirit to our research as well.

5.4 Effect of Cost of Volume Flexibility on Total Stage Cost

Figure 6 illustrates the effect of cost of volume flexibility at a particular stage on the total cost while keeping the other parameters constant. For the sake of numerical analysis, we have one again considered the parameter values for stage three. COF in the chart stands for cost of volume flexibility function mildness/steepness, when compared to a randomly chosen increasing convex function (COF : 1).

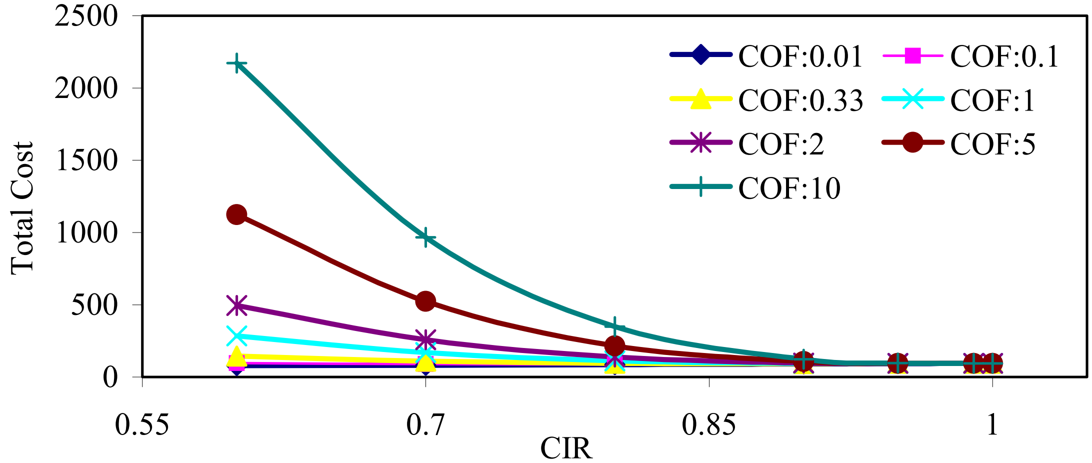


Fig 6: CIR vs. Total Stage Costs

In Fig 6, as expected, optimum CIR is progressively moving towards unity as the COF increases. As opposed to processing time variability, which affects both the safety stock cost component and the responsiveness cost components, cost of flexibility affects only the responsiveness cost component. Intuitively speaking, given that the stage is not operating at optimal CIR, increasing the cost of flexibility makes a typical supply chain manager to operate close to nominal cycle times (CIR close to one), but going back to the example given earlier, if a wind screen wiper is being assembled, particularly at a D/S stage, it is quite likely that there will be significant savings in safety stock costs by reducing the cycle time (moving the CIR away from unity), overtaking the extra cost of responsiveness because of a steeper flexibility function. The opposite will be true, for example, if an engine is being assembled at a stage.

Key Managerial Insight #5: Given that a stage is not operating at optimal CIR, as cost of volume flexibility function becomes steeper, optimum value of CIR moves towards unity if responsiveness costs segment dominates the safety stock cost segment and vice versa.

Key Managerial Insight #6: All the other parameters being constant, for the same cost addition at a stage, cost of flexibility function has to be milder at U/S than D/S for a given amount of savings in safety stock costs.

6. Conclusions

In this paper, in addition to offering several managerial insights with regard to strategic safety stock placement in a supply chain, an attempt has been made to address the problem of achieving compatibility between the supply chain strategy and the individual stage's business strategy by primarily considering safety stocks and responsiveness related costs. We introduce a new parameter called coefficient of responsiveness (CIR) to model response related costs at a stage, which also enhances the scalability of the model. The developed cost function for the 'building block' could be extended for other types of supply chain networks. By knowing the values of the parameters of the model, one can know the safety stock costs and responsiveness related costs at each stage and compare them to an ideal supply chain strategy in terms of cost and responsiveness to make informed decisions. The key managerial insights developed are generic in nature and are applicable to any supply chain irrespective of it's placement on the cost-responsiveness spectrum and topology.

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. For example, we did not factor "bullwhip effect" into our model. It would make an interesting extension to our research if bullwhip effect and other information asymmetry related issues are factored into the model. We have not incorporated order sizes into our model, because the model is supposed to be largely a strategic model. Research could be extended by incorporating this aspect into the model to see how it affects the managerial insights that we offered. Relaxing the assumptions on the stationary nature of the demand and stage base stock policy with periodic review will make the model more realistic and robust to real world situations. Introducing contracts that affect the flexibility at a stage with financial ramifications will also be a very fertile area to pursue that will make our model mimic the reality more closely. So is considering other types of network topologies particularly assembly and distribution, which we are planning on considering in the extension of this framework. It would also make more sense to consider capacity constraints at certain stages. Product mix related flexibility is also a crucial factor which is not addressed in our model. Addition of this feature would truly make the research more in tune with the reality especially in mass customization settings. Finally, we really would like to see this model used in some real world application so that insights presented in our model could be validated.

CHAPTER 2

SUPPLY CHAIN FOCUS DEPENDANT SUPPLIER SELECTION PROBLEM

Abstract:

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 a recognized fact that overall supply chain focus should be given an overriding priority over the individual goals of the players. Among all the possible order-winners, cost and responsiveness turn out to be the most significant ones 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 by a typical supply chain manager, while 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 typical supply chain manager to make informed decisions with regard to supplier selection problem at any stage dependent upon the priorities attached to costs and the supply chain cycle time. Inventory related costs and responsiveness related costs are the two primary cost elements that are considered in this model. We are also introducing a 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 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.

Keywords: Supply chain strategy, supply chain configuration, supplier selection, cost of responsiveness, supply chain cycle time, and coefficient of inverse responsiveness.

1. Introduction

As the emphasis shifts from vertical integration to horizontal interconnectivity in today's competitive markets, suitable supplier selection is 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). 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). 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. And also right suppler selection significantly reduces the purchasing costs and improves corporate competitiveness (Ghodsypour and O' Brien 2001). Huang and Keskar (2007) opine that cost and quality have been the most dominant factors along with on-time delivery and flexibility. "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's 90 % in petrochemical industry … 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 Roofhooft 2001).

Primarily, the literature dealing with supplier selection/management can be broadly classified into three categories. First category is those journal articles that deal 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). 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 it's 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.

Second category in supplier selection/management literature deals with supplier rating/evaluation methods for a given set of performance metrics. In this context, reader can refer to Lasch and Janker (2005), Timmermann (1986) and Weber et al (1991) for more information. Lasch and Janker (2005) designed a suppler rating system that uses principal component analysis to create a classification and ranking of the potential suppliers by means of ellipsoid clusters. Huang and Keskar (2007) is a useful reference for literature review for supplier selection using AHP, MAUT (multi attribute utility theory) 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).

In the third category, suppler selection problem is treated as a part of the optimization problem, typically at the strategic level. To account for many conflicting and vague objectives and constraints in making supplier selection decisions, Kagnicioglu (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. In addition, linear weighting models (Cooper 1977, Mazurak et al 1985), AHP models (Barbarosoglu and Yazgac 1997, Nydick and Hill 1992) are also quite popular to deal with supplier selection problems.Ghodsypour and O' Brien (1997) used an integrated AHP model with mixed integer programming to reduce the number of suppliers. Ghodsypour and O' Brien (2001) developed a mixed integer NLP approach for supplier selection to minimize the total cost of logistics, including net price, storage ,ordering costs and transportation. Karpak et al (1999) suggested the use of Goal programming for supplier selection. To systematically analyze the trade offs between conflicting factors in supplier selection, Weber and Current (1993) used multi objective linear programming. For a detailed list of optimization methodologies used in literature one can refer to Huang and Keskar (2007). Cebi and Bayraktar (2003) propose a model, where in supplier selection problem has been structured as an integrated lexicographic goal programming (LGP) and analytic hierarchy process (AHP) that includes both quantitative and qualitative factors. Truong and Azadivar (2005) have used a combination of mixed integer programming and a genetic algorithm to determine simultaneously the values of quantitative as well as policy variables that aids in making strategic decisions regarding facility locations, stocking locations, supplier selection, production policies, production capacities and transportation modes. Talluri and Baker (2002) propose a multi-phase mathematical programming approach for supply chain design.

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.

Now, let's look at some of the real world supply chains and what they are looking for. Nazzal et al (2006) present a case study for Agere Systems wafer fabrication facility, wherein they use simulation, design of experiments, statistical analysis etc to construct 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 increase their 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.

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.

Another interesting motivating example is the Revlon's (cosmetics, fragrance and personal care products company) supply chain addressed in Davis et al (2005).Revlon's supply chain includes more than 5,000 active finished good 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, that 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.

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 cycle with the goal of lowering the capital investment required for changeover or introduction of a new product (Pelagagge 1997).

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 . Following are some of the journal articles that deal with supply chain configuration problem.

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).

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 etc.

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, where in supplier selection is likely to focus on short term price /cost trade offs.

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.

As mentioned earlier, we have chosen supply chain cycle time as the performance metric to measure responsiveness. 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..

Now, we need to decide which cost drivers the model should include. There are primarily four drivers of the 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. But those 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 the future research. That leaves us with inventory as our primary cost driver.

Among inventory cost elements, safety stock, which is maintained to account for the internal and external variability in the 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. Explaining the necessity of inventories in a supply chain, Lee & Billington (1993) opine that the inventories are used to protect the supply chain from different sources of uncertainties that exist along a supply chain such as demand uncertainty (volume and mix) process uncertainty (yield, machine down time, transportation reliability) and supply uncertainty (part quality, delivery reliability), etc. We are considering both cycle stocks (in process inventory) and safety stocks in our model. Now, let us look at some of the relevant literature for our research that addresses both of the important order winners namely cost (associated with inventory) and responsiveness.

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 in to the nature of the optimal solution.

The tradeoff between the flexibility of a manufacturing system with respect to both rate change and mix and the investment in inventory is addressed in Graves (1988), wherein the author considers demand uncertainty, a stationary demand process and lot for lot scheduling(ignoring lot sizing). In this model, aggregate production output is determined by a production control rule that attempts to smooth the aggregate output and is parameterized by a planned lead time, which is a decision variable in the model. Flexibility is modeled as the ratio of a measure of slack available to the demand variability. Our research focuses upon the opportunities at a stage for resource flexibility to reduce the lead time and the relevant costs. In Graves (1988), safety stocks are planned to account for only a portion of the variability and assumes that other measures are available to account for the other portion of the variability.

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. 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 and 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 .

Graves & Willems (2000) is another interesting paper, wherein they develop what is called a 'guaranteed service model' and also present an optimization algorithm based on dynamic programming for the placement of safety stock for supply chains that can be modeled as spanning trees under certain assumptions. They also describe the successful application of the model at Eastman Kodak to reduce finished goods inventory, target cycle time reduction and to determine component inventories. The authors also mention that Kodak's flow teams have used the model to determine the cost effectiveness of lead time reduction efforts in manufacturing.

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 w.r.t the safety stock positioning are developed in various supply chain topologies. In addition, Simchi-Levi and Zhao (2005) present a nice summary of the literature for installation policies that are used in various network topologies.

- Multi stage serial systems (Simpson 1958, Hanssmann 1959, Lee & Zipkin 1992)
- Distribution Systems (Axsäter 1993, Graves 1985, Lee & Moinzadeh 1987 a, b)

For capacitated models using a modified base stock policy the reader can refer to Glasserman and Tayur (1995, 96) and Kapuscinski and Tayur (1999).

Ettl et al (2000), who have developed a supply network model that takes as input the bill of materials, required customer service levels, nominal leadtimes, demand and cost data etc and generates the base stock level, stockimg location for a part etc at each stage. Modeling the dynamics at each stage in the network as an inventory queue, both performance evaluation and optimization can be performed for a supply chain with service level constraints. They have formulated a constrained nonlinear optimization problem that minimizes the total average dollar value of the inventory subject to meeting the service level requirements. By making use of analytically obtained gradient estimates, optimization was carried out using the conjugate gradient method.

For a 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.

Yang and Geunes (2007) study a problem in which a supplier wishes to determine the best positioning of a product with respect to order lead time and price, wherein the demand is lead-time sensitive. They consider a continuous review inventory replenishment system ,where the difference between the procurement lead time and promised sales order lead time influences both cycle stock and safety stock costs, and procurement costs may increase as a result of investment in production lead time reduction . Their results indicate that for a broad range of practical settings, such systems employ a pure make-to-stock policy or a policy that sets sales lead time equal to the procurement lead time at optimality.

Lin et al (2000) developed an asset management tool that integrates graphical process modeling, analytical performance optimization, simulation ,activity based costing and enterprise data connectivity to enable IBM in 1994 to reengineer it's global supply chain to achieve quick responsiveness to customers with minimal inventory. The primary focus is upon optimization of multi echelon supply network with base stock control.

Advocating the necessity of models that include both cost and responsiveness, 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.

In their extensive literature review of strategic production distribution models, Vidal and Goetschalckx (1997) conclude that among others, the main drawback of the existing models is the fact that most uncertainties (exchange rates , supplier's reliability, lead times, stochastic demand, stochastic customer service level, stochastic facility fixed costs, political environment etc) are not considered in the formulations. We hope that, our model that considers both demand and lead time variability could be further extended in future to consider other types of uncertainties to closely mimic the reality.

As opposed to network design models that focus on the trade off 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 net work 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 DCs in the network such that the sum of the location and inventory (pipeline and safety stocks) 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.

Another interesting research in the context of lead time management in supply chains is by Ray (2001), who in his model considers speed and cost as important competitive priorities and focuses upon the investment requirements for lead time reduction specifically for MTS and MTO firms.

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).

The organization of the remaining part of this paper is as follows. Section 2 deals with development of the overall cost expression for the supply chain. Section 3 offers managerial insights in regards to the supplier selection problem in a serial supply chain. Section 4 offers a case study involving the selection of a wiring harness supplier for an OEM facility. Last but not the least conclusions and limitations are offered in section 5.

2.0 Model Description

Development of total cost expression for a serial supply chain:

2.1 Developing an expression for safety stock costs:

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 that is 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 there by 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 partly because this policy has been proven to be optimal or close to optimal in some special but important 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 Wall 1991, van Houtum et al 1996)

In an installation policy, each facility only needs the inputs from the immediate U/S and D/S facilities and makes ordering decisions based on it's local order and inventory status as opposed to an echelon base-stock policy, which is a centralized control scheme that monitors each stage's echelon inventory (the stage's own stock and everything downstream) and determines external orders and inter stage shipments according to a base stock policy. Even though our model assumes all the stages to be manufacturing 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 as in Graves & Willems (2003) and Lee & Billington (1993) to mimic the reality more closely with each stage following a local base-stock policy (Gallego and Zipkin 1999) .Buttressing the same view, Lee & 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 & 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 series system for the simplicity of analysis and primarily to develop certain insights that are insensitive to the specific supply chain topology. And 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 serial 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 can’t 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 (Gallego and Zipkin 1999).

There is an inventory holding cost at each stage and our model does not consider backorder penalty cost, which could be easily included. The horizon is finite, all data are stationary, information is centralized but control is decentralized.

As in Gallego and Zipkin (1999) the numbering 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.

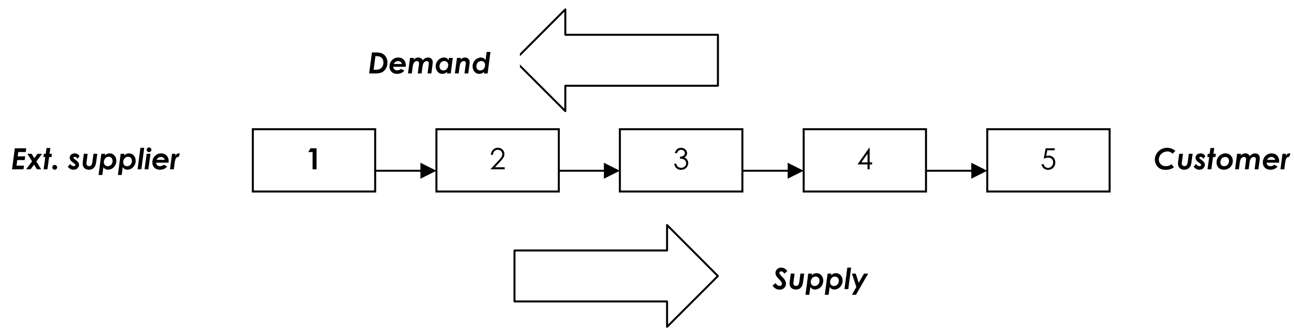


Fig 1: Schematic description of a serial supply chain

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) treatment of stochastic service model in supply chains,

Let $\Phi(k_1),....,\Phi(k_n)$ be the service levels for corresponding safety factors $k_1,...,k_n$ where $\Phi(k_i)$ represents the Cumulative distribution function for a standard normal variable.

Let the processing time at stage j be a random variable τ_j with mean L_j and variance σ_j^2.

The stochastic service model (Graves and Willems 2003, Simchi-Levi and Zhao 2005, Lee and Billington 1993, Ettl et al. 2000) assumes delivery or service time between stages to vary based on the material availability at that stage and each stage in the supply chain maintains a base stock sufficient to meet it's service level target (Graves and Willems 2003).

If Δ_i is the random delay at the preceding stage i, then the replenishment cycle time at stage j equals

$$\gamma_j = \tau_j + \Delta_i \qquad (1)$$

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) with a modification that takes into account the fact that there is only one player at the preceding stage. We are assuming that the expected value of this delay is simply equivalent to the probability of stock out at the preceding stage π_i times it's average processing time

Therefore, expected replenishment cycle time at stage j is given by

$$E\left[\gamma_j\right] = L_j + \pi_i L_i \qquad (2)$$

Where, $\pi_i = 1 - \Phi(k_i)$ (3)

Assuming that the demand is $N\left(\mu,\sigma^2\right)$, to satisfy average demand μ, given the average replenishment cycle time from (2), 'average cycle stock' is given by

$$\mu * \left(L_j + \left(1 - \Phi(k_i)\right) L_i\right) \qquad (4)$$

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

$$\sigma^2_{\Delta_i} = \sigma_i^2 (1 - \Phi(k_i)) \qquad (5)$$

$$\sigma^2_{\gamma_j} = \sigma_j^2 + \sigma_i^2 (1 - \Phi(k_i)) \qquad (6)$$

When the demands are uncorrelated between time periods, then the mean and variance of the demand during replenishment period for stage j denoted by the continuous random variable W_J are obtained as follows by slightly modifying the equations to account for the portion of the lead time variability transferred from the preceding stage (see for example, Eppen and Martin (1988) and Feller 1960)

$$\mu_{W_j} = \mu E[\gamma_j]$$
$$\sigma^2_{W_j} = \sigma^2 E[\gamma_j] + \sigma^2_{\gamma_j}\mu^2 \quad (7)$$

Now, we introduce another parameter 'c_j' termed as the 'coefficient of inverse responsiveness (CIR)' defined as the ratio of the average demand to the rate of production (throughput) p_j.

$$c_j = \mu \ / p_j \quad (8)$$

Assuming that there is enough capacity at all the stages to satisfy a given demand, $c_j \le 1$ at all the times. When c_j =1, expected replenishment cycle time is given by (2). We also assume that there is some upper bound above which rate of production can not be cranked up further.

CIR at a stage is similar to the "expediting factor" proposed by Bookbinder and Cakanyildirim (1999). They define the "expediting factor" τ as the constant of proportionality between random variables $\tilde{T}$ (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, τ), they show that the expected cost per unit time is jointly convex in the decision variables and obtain the global minimizer.

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

$$E\left[\gamma_j\right] = (L_j + (1 - \Phi(k_i))L_i)c_j \quad (9)$$

$$\sigma^2_{\gamma_j} = (\sigma_j^2 + \sigma_i^2(1 - \Phi(k_i)))c_j \quad (10)$$

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

$$\begin{aligned} \mu_{W_j} &= \mu E\left[\gamma_j\right] \\ \sigma_{W_j} &= \sqrt{\sigma^2 E\left[\gamma_j\right] + (\sigma_{\gamma_j}^2)\mu^2} \end{aligned} \quad . \tag{11}$$

The above equation considers both the demand variability and the replenishment cycle time variability. Replenishment cycle time variability has got two components

a) Processing time variability at stage j.

b) 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 $B_j = \mu E\left[\gamma_j\right] + k_j \sigma_{W_j}$, where k_j is the safety factor to achieve the service level target $\Phi(k_j)$ for that stage.

After subtracting the average demand over the replenishment period, we get the following expression for the expected on hand inventory.

$$E\left[I_j\right] = k_j \sigma_{W_j} \tag{12}$$

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

$$E\left[BO\right] = \sigma_{W_j} \int_{z=k_j}^{\infty} (z - k_j)\phi(z)dz \tag{13}$$

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

$$E\left[SS_j\right] = \sigma_{W_j} \left(k_j + \int_{z=k_j}^{\infty} (z - k_j)\phi(z)dz \right) \tag{14}$$

At stage j, let C_j be the nominal cumulative cost (excluding inventory costs) of the product realized when c_j =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

$$C_j^{SSC} = C_j h_j E\left[SS_j\right] \quad (15)$$

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

$$C^{SSC} = \sum_{j=1}^{n} C_j^{SSC} \quad (16)$$

2.2 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.

2.2.1 Direct responsiveness related costs

The difference in nominal cumulative costs of the product at stages $j \,\&\, i$ will increase by a value, which is assumed to be a function of $(1-c_j)$. This is the cost that the stage 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 $5M$ resources. 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, which we will consider in the extension of this frame work. $5M$ resources are briefly described below. Flexibility related costs will be relatively larger/smaller depending on how flexible these resources are at a stage.

A) Manpower: Jacobelli (1997)

Hiring: Quantity of new hires, individual worker skill set, training and cycle familiarization

Indirect labor: Requirement and availability

Morale: Worker morale related issues when the work environment changes

B) Machine:

Flexibility, shop floor design, work station design, quality, reliability, dependability issues, MRO requirement frequency, availability of spares etc

C) Methods:

Uniformity and flexibility of methods, dissemination of information w.r.t change in methods, adequate training facilities, morale related issues, workforce culture related aspects in a dynamic environment etc.

Effect of manufacturing operation sheet revision that change the method of manufacture or the equipment/machinery where the operations are performed (Jacobelli 1997).

D) Material:

Availability in quantity and on time, oppurtunities for substitution, material handling costs (that can consume up to 15 to 75 % of the product cost (Allegri 1994), logistics etc

E) Measurement:

Adequacy of tools for process control, product identification and traceability, inspection and testing, calibration of the equipment etc.

Direct response related costs at stage j per period is given by

$$DRC_j = [f(1-c_j)](C_j - C_i)\mu \qquad (17)$$

Even though we do not advocate any specific function type for modeling $f(1-c_j)$, cost of volume flexibility function, we strongly recommend that it is derived from the past 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 piece-wise 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 piece-wise linear crashing cost function in their model. Ben-Daya 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 etc) time $\psi(\tau)$ 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 $\psi(\tau)$ to take negative values for $\tau>1$, 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 $\psi_1(\tau_1) and \psi_2(\tau_2)$ to be decreasing convex functions of the expediting factors $\tau_1 and \tau_2$.They considered $\psi_1(\tau_1)=c_1(-1+1/\tau_1) and \psi_2(\tau_2)=c_2(-1+1/\tau_2)$ where c_1 and c_2 are positive coefficients. Our cost function 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 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.

2.2.2 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 2.2.1. As a result, the difference in nominal cumulative costs of the product at stages $j \& i$ will increase by a value, which is a function of $(1-c_j)$. Therefore indirect responsiveness related cost at stage j is given by

$$IRC_j = f(1-c_j)(C_j - C_i)h_j E\left[SS_j\right] \quad (18)$$

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

$$TRC_j = DRC_j + IRC_j \quad (19)$$

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

$$C_j^{TSC} = C_j^{SSC} + TRC_j \quad (20)$$

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

$$C^{TSC} = \sum_{j=1}^{n} C_j^{TSC} \quad (21)$$

2.3 Cycle inventory related costs

2.3.1 Cycle inventory at stage j:

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

$$WIP_j = ((C_j + C_i)/2)h_j \mu (L_j + (1-\Phi(k_i))L_i) \quad (22)$$

2.3.2 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 at stages $j \& i$ by a value, which is a function of $(1-c_j) \& (1-c_i)$.

$$RWIP_j = [f((1-c_j),(1-c_i))]((C_j - C_h)/2)h_j \mu(L_j + (1-\Phi(k_i))L_i) \qquad (23)$$

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

$$TC_j = C_j^{SSC} + TRC_j + WIP_j + RWIP_j \qquad (24)$$

Total inventory and responsiveness related cost for the whole Supply Chain is given by

$$TC_{SC} = \sum_{j=1}^{n} C_j^{SSC} + TRC_j + WIP_j + RWIP_j \qquad (25)$$

3.0 Model related results

3.1 Supply Chain focus based Supplier Selection Problem:

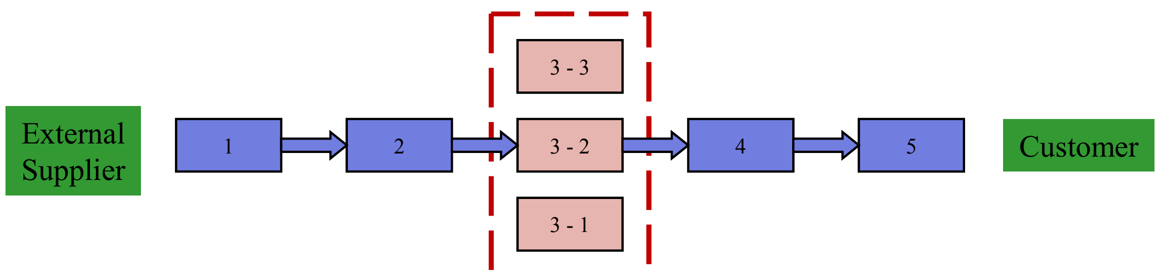


Fig 2: Schematic description of the supplier selection problem in a serial supply chain

The total cost expression developed for a stage could be used as a building block for any network and by the use of mixed integer non linear programming one could address the issue of supplier selection at a stage.

However, our focus is primarily to offer certain managerial insights with respect to the supplier selection problem at a stage by balancing the inventory costs with responsiveness related costs. The relevant insights can be used as an aid in supplier selection either for purchasing parts or to make outsourcing decisions (make/buy decisions) at a stage. As mentioned previously, we assume that the structural decisions are already made with respect to the supply chain topology and we know the values of the parameters such as lead times, inventory carrying costs, cost added at a stage, nature of the cost of flexibility function etc.We are also assuming that the competing suppliers are equivalent on other attributes say quality etc that are not considered in the model.

Our model deals with single sourcing not multiple sourcing i.e. the whole order at a stage is serviced by just one supplier. Order splitting among more than one suppliers is not permitted. Reader can refer to Burke (2005) for single versus multiple sourcing strategies under different scenarios.

And also we are assuming one buyer per stage, i.e. collaborative procurement is not allowed .Reader can refer to Savasaneril (2004) to study the effects of demand aggregation and collaborative procurement on buyer's profitability.

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. Our purpose is to develop insights with respect to determining the supplier at stage 3(choosing one among 30, 31 & 32 in fig 2) who would be the best fit as the supply chain focus moves on the cost – responsiveness spectrum.

	Stage/Player				
	1	2	3	4	5
Nominal cumulative cost C_j	106	150	240	472	1362
Mean Processing time (periods) L_j	1.00	1.00	1.00	1.00	1.00
Demand variability σ^2	400	400	400	400	400
Processing time variability $(\mu^2\ \sigma_j^2)$ (in terms of number of units^2 of product)	100	100	100	100	100
Safety coefficient k_j	1.28	1.28	1.28	1.28	1.28
Average back order coefficient	0.1	0.1	0.1	0.1	0.1
π_j	0.1	0.1	0.1	0.1	0.1
Average demand μ	100	100	100	100	100
Inventory holding cost h_j	0.017	0.017	0.017	0.017	0.017
Service level $\Phi(k_j)$	0.9	0.9	0.9	0.9	0.9

Table 1: Typical values of the parameters adopted for numerical analysis

For the sake of simplicity suppliers 30, 31 & 32 in figure 2 are denoted as suppliers 1, 2 & 3 respectively.

Player/Stage	1	2	3
Mean Processing time (periods) L_j	1	1.5	2
Processing time variability $(\mu^2\ \sigma_j^2)$	100	300	600
Inventory holding cost h_j	0.017	0.025	0.034

Table 2: Key values of the parameters for the three potential suppliers

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 equation (25).

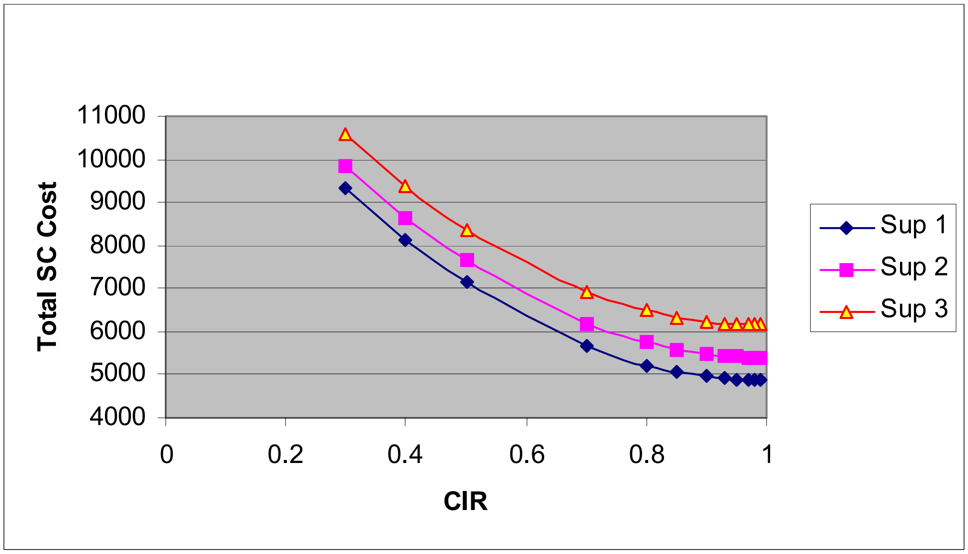


Fig 3: Supply chain focus dependant supplier selection problem -1

As CIR decreases, difference among the safety stock costs for supplier 1 vs. suppliers 2&3 diminishes due to the reduction in average processing time and the associated variability. With decreasing CIR ,differences among indirect safety stock costs 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 & 3 and will differ from supplier 1 by a fixed amount. With decreasing CIR ,differences in responsiveness related cycle stock costs will progressively increase, supplier 1 contributing the least to the total cost followed by suppliers 2 & 3 respectively. In addition, there will be a progressive increase in safety stock cots 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 & 3. It can be clearly seen from the above figure 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.

3.2 Effect of Cost efficient operations and/or location

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

Player/Stage	1	2	3
Nominal Cumulative Cost	C_3	$C_3 * 0.96$	$C_3 * 0.94$
Mean Processing time (periods) L_j	1	1.5	2
Processing time variability $(\mu^2 \ \sigma_j^2)$	100	300	600
Inventory holding cost h_j	0.017	0.025	0.034

Table 3: Key values of the parameters for the three potential suppliers

Let's consider the hypothetical case, as shown in table 3, wherein suppliers 2 & 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 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 & time study etc)
2. Better management of the machinery
3. Efficient use of materials
4. Existence & use of improved methodologies / procedures for carrying out different operations
5. Better inventory management techniques
6. Use of deterministic management techniques for optimizing the 5 M resources
7. Better quality management techniques leading to less scrap & rejections.
8. Better reliability management techniques that reduce the field complaints and improve the useful life of the machinery.

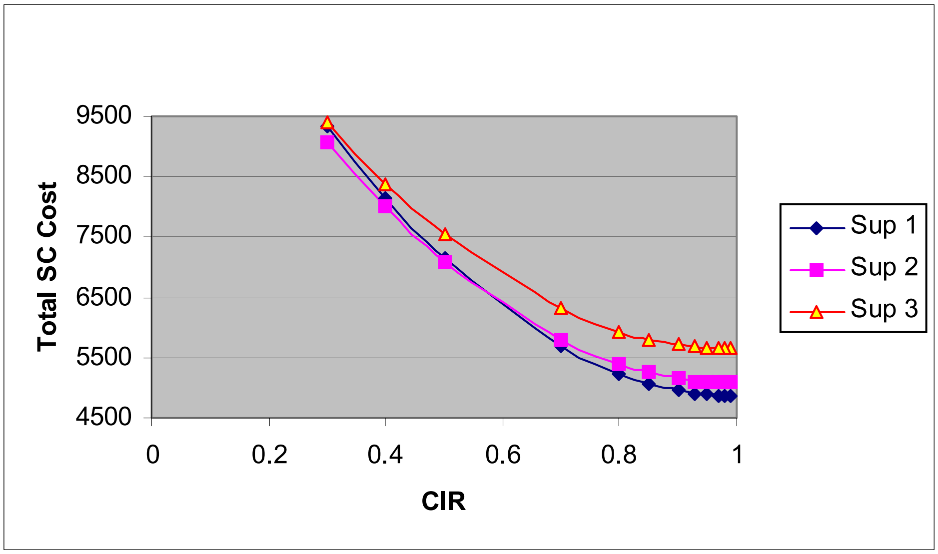


Fig 4: Supply chain focus dependant supplier selection problem –2

As CIR decreases, difference among the safety stock costs for supplier 1 vs. suppliers 2&3 diminishes at a faster pace when compared to the scenario described in 3.1 due to the reduction in average processing time and the associated variability and the lesser nominal processing cost added at suppliers 2&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 decreasing CIR for suppliers 2& 3 when compared to supplier 1. Supplier 1 costs will be maximum followed by suppliers 2 & 3 in that order. Cycle stock costs will be smaller for suppliers 2 & 3 by a fixed amount when compared to the earlier scenario described in 3.1. With decrease in CIR ,the increase in responsiveness related cycle stock costs for suppliers 2 & 3 will occur at a decreased rate (because of lower nominal processing cost) compared to the scenario discussed in 3.1. 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, over all, as the CIR decreases, total cost difference for suppliers 2&3 compared to supplier 1 progressively get reduced. This effect will be accentuated as the cost added gets smaller and smaller at suppliers 2 & 3 compared to supplier 1.

By taking into consideration the parameter values presented in table 3, we realize figure 4. 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 CIR decreases. As the supply chain becomes more responsive, the increase in costs on account of the poor process parameters for suppliers 2 & 3 will be offset by the decrease in inventory (SS + Cycle stock) costs, associated response related costs and the echelon safety stock & 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 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 CIR band within which a particular company wants to operate. But, the gap between supplier 1 and suppliers 2 & 3 in terms of total cost will progressively decrease with decreasing CIR. 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 & 3 will overtake supplier 1 at a higher CIR value than realized in Fig 4.

For example, for a supplier dealing with a commodity product such as coffee maker warming plate will operate 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 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 etcetera 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* 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 .*

3.3 Effect of low cost of flexibility (responsiveness):

Player	1	2	3
Cost of flexibility function	$(1-CIR)^2$	$\frac{(1-CIR)^2}{3}$	$\frac{(1-CIR)^2}{6}$
Mean Processing time (periods) L_j	1	1.5	2
Processing time variability $(\mu^2\ \sigma_j^2)$	100	300	600
Inventory holding cost h_j	0.017	0.025	0.034

Table 4: Key values of the parameters for the three potential suppliers

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 either held constant.

Now let's consider the hypothetical case, as shown in table 4, wherein suppliers 2 & 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/firing

5) Flexible machinery

6) Flexible workforce

7) Flexible work procedures

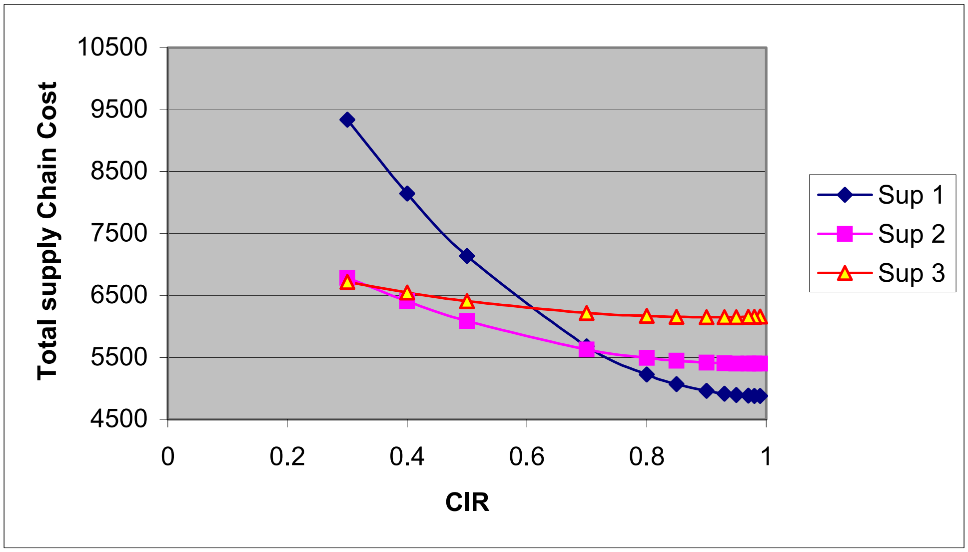


Fig 5: Supply chain focus dependant supplier selection problem -3

As CIR decreases, difference among the safety stock costs for supplier 1 vs. suppliers 2&3 diminishes due to the reduction in average processing time and the associated variability as with scenario presented in 3.1. Differences among indirect safety stock costs also decrease when compared to the scenario discussed in 3.1. Direct response cost contribution difference will become progressively larger with decreasing CIR for suppliers 2& 3 when compared to supplier 1. Supplier 1 costs will be maximum followed by suppliers 2 & 3 in that order. Cycle stock costs for suppliers 2 & 3 compared to supplier 1 will differ by a fixed amount as in 3.1, supplier1 costs being the minimum followed by suppliers 2 & 3 in that order. With decrease in CIR ,the increase in responsiveness related cycle stock costs for suppliers 2 & 3 will occur at a decreased rate (because of lower cost of flexibility) compared to the scenario discussed in 3.1. In addition there will be a reduction in responsiveness related cycle stock costs at stage 4 for suppliers 2 & 3 compared to the case in 3.1 on account of lower cost of flexibility .Over all, as the CIR decreases, total cost difference for suppliers 2&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&3 compared to supplier 1.

By taking into consideration, the above-mentioned modifications in the cost of flexibility function for suppliers 2 & 3, we realize the figure 5. We can observe that as the supply chain becomes more responsive, both supplier 2 & supplier 3 overtake supplier 1 in terms of least total cost and supplier 3 overtakes even supplier 2 as CIR decreases further.

As the supply chain becomes more responsive, the increase in costs on account of the poor process parameters for suppliers 2 & 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 3.1. 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 CIR, the difference in the costs for suppliers 2 & 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 CIR band within which a particular company wants to operate. In a typical context, the gap between supplier 1 and suppliers 2 & 3 in terms of total cost will progressively decrease with decreasing CIR.

Revisiting the example mentioned in the earlier section for a supplier dealing with a commodity product such as 'coffee maker warming plate' will operate 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 etcetera 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* .

4.0 Case Study

A Wiring harness is designed to wire the vehicle and 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.

OEM facility located in Detroit is considered for this case study. Identities of the OEM facility and the potential supplier information are not revealed for confidentiality reasons. A local supplier located in Flint, MI and a supplier from Hermosillo, Mexico are considered as potential suppliers for wiring harnesses. Information for the key parameters is provided in table 5.

	Local Supplier		Mexico Supplier	
	Local Facility	Local Transport	Mexico Facility	Mexico Transport
Cost ($) / Unit	256	4	243	12
Mean Processing time(Days) L_j	1	0.25	3	11
Processing time SD (Days) σ_j	0.25	0.1	1	2
Inventory carrying cost per year % h_j	24	24	24	24
Mean Demand per day μ	800	800	800	800
Demand SD per day σ	150	150	150	150
Safety Coefficient k_j	1.28	1.28	1.28	1.28
Average back order coefficient π_j	0.1	0.1	0.1	0.1
$\Phi(k_j)$ Service Level	0.9	0.9	0.9	0.9

Table 5: Key parameter values for the local vs. Mexico suppliers.

As can be clearly seen from the table, when compared to the local supplier, Mexican 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 Mexico supplier as reflected in the cost per unit.. In this case study 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.

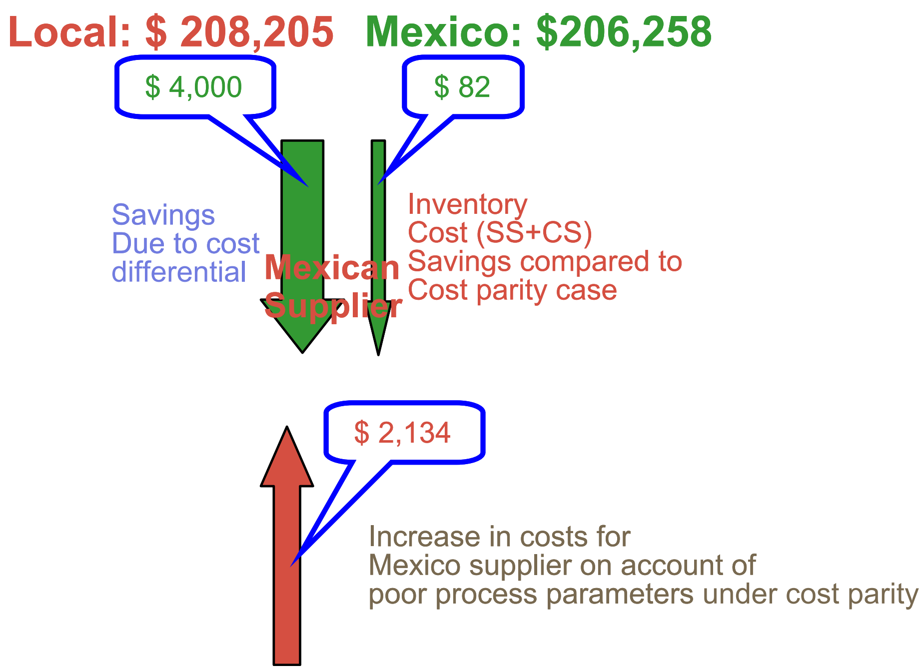


Fig 6: Effect of cheaper manufacturing cost on the Mexico supplier

There is an increase in cost to the tune of $ 2,134 for the Mexico 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 $ 4,000 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 Mexican 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 Mexico 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 Mexican supplier, savings due to direct cost differential are able to clearly offset the disadvantage due to poor process parameters that may not be case in complex supply chains, wherein the echelon inventory cost savings also play a key role. In this case total cost for the Mexican supplier per day turns out to be lower than the local supplier making him the ideal choice.

Now an extension is offered to the above case, wherein the responsiveness option is considered for the Mexican supplier. Transport parameters considered in table 5 for the Mexico supplier are for less than truck transportation (LTL), which tends to be a little cheaper but slower as well. The responsive option considered is truck load option (TL), which tends to be costlier but more responsive. The key parameters are presented in the following table.

					Responsive Mexico	
	Local Facility	Local Transport	Mexico Facility	Mexico Transport	Mexico Facility	Mexico Transport
Cost ($) / Unit	256	4	243	12	243	14
Mean Processing time(Days) L_j	1	0.25	3	11	3	8
Processing time SD (Days) σ_j	0.25	0.1	1	2	1	1
Inventory carrying cost per year % h_j	24	24	24	24	24	24
Mean Demand per day μ	800	800	800	800	800	800
Demand SD per day σ	150	150	150	150	150	150
Safety Coefficient k_j	1.28	1.28	1.28	1.28	1.28	1.28
Average back order coefficient π_j	0.1	0.1	0.1	0.1	0.1	0.1
$\Phi(k_j)$ Service Level	0.9	0.9	0.9	0.9	0.9	0.9

Table 6: Key parameter values for the local vs. Mexico suppliers

When compared to the LTL option TL option (Mexico (R)) 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.

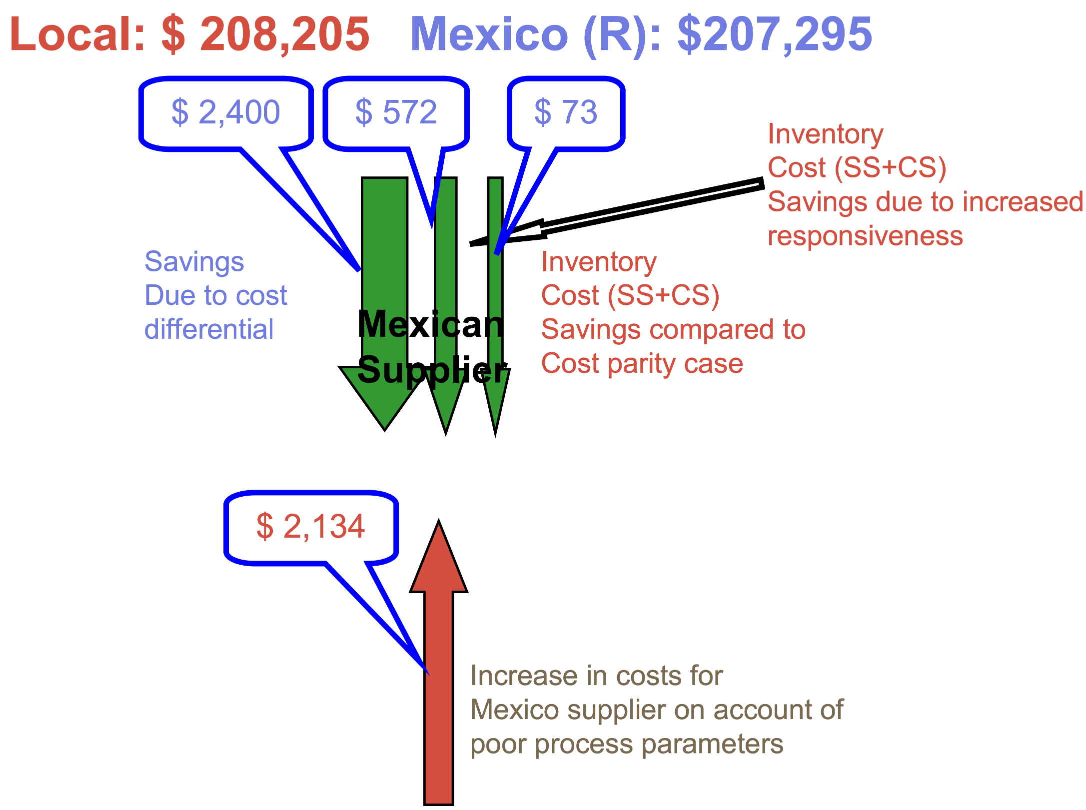


Fig 7: Effect of cheaper manufacturing cost on the Mexico (R) supplier

There is an increase in cost to the tune of $ 2,134 for the responsive Mexico supplier (Mexico(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 Mexico LTL option. But this cost is being counterbalanced by an amount of $ 2,400 per day on account of the direct cost differential between both the suppliers. This amount is less by $1,600 when compared to the Mexico LTL 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 Mexican supplier . This is smaller than LTL case because of increase in transportation cost under parameter parity. But, there is an additional cost savings of \$ 572 when compared to the LTL case in inventory costs on account of improved parameters (reduced mean and variability of transportation) for TL option. For TL option responsiveness cost component is increasing at a faster rate than the savings in inventory costs. Because of this, TL option is costlier compared to LTL option. Over all, Mexico (R) is still cheaper than local supplier. As with the earlier case, as the SC 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 Mexico supplier.

5.0 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 primarily 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 in to the model, which allows us to monitor the supply chain performance with respect to these two critical order-winners. We introduce a new parameter called coefficient of 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 other types of supply chain networks 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 a purchasing decision. 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.

We did not factor Bullwhip effect into our model. It would make an interesting extension to our research if bullwhip effect and other information asymmetry related issues are factored into 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 truly make the research more in tune with the reality.

Finally, we really would like to see this model used in some real world application so that insights presented in our model could be validated.

CHAPTER 3

SUPPLY CHAIN FOCUS DEPENDANT TREATMENT OF THE SENSITIVITY OF THE POINT OF PRODUCT DIFFERENTIATION

Abstract:

Customer preferences for variety in the product(s) with improved customer service and lower prices are forcing the supply chains to overhaul the current practices from design to operational level. Postponement or delayed differentiation of the products is one such strategy, which is becoming increasingly popular especially in mass customization settings. Postponement strategy is found to be cost effective especially in reducing the inventory costs and improve different aspects of product delivery thereby increasing the customer satisfaction. It is also an accepted notion that the point of product differentiation should be as close to the customer as possible to take advantage of better forecasts. Life cycles are shrinking not only for individual products but for product families as well. In this context, supply chain responsiveness becomes one of the crucial factors to succeed in the present day competitive markets. Determining the point of differentiation is one of the crucial problems that need to be addressed by a supply chain manager, while 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 determining the point of differentiation dependent upon the priorities attached to costs and the supply chain cycle time. Inventory related costs and responsiveness related costs are the two primary cost elements that are considered in this model. We are also introducing a 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 insights with respect to the location of point of differentiation in a supply chain.

Keywords: Supply chain strategy, supply chain configuration, point of differentiation, postponement, supply chain cycle time, and coefficient of inverse responsiveness.

1.0 Introduction

Postponement of product differentiation in a mass customization setting is gaining popularity particularly in terms of inventory cost reduction and better operations management.

Mass customization has been described as providing ‘numerous customer chosen variations on every order with little lead time or cost penalty (Ahlstrom and Westbrook 1999). As the product variety increases, obtaining accurate demand forecasts for each item becomes more difficult, and the level of inventories that must be carried to meet demand increases (Timucin 2000). Mass customization provides the good qualities of hand-crafted products (unique designs and customized service) and it also reflects the most important gain from mass production – low operating cost (Graman and Magazine 2006). The implied challenge for manufacturers is how to deal with the high demand uncertainty, resulting from the provision of many variants, whilst ensuring low operational costs are maintained, as well as short, reliable lead-times (Skipworth and Harrison 2006). “Point of differentiation refers to the node in the supply chain where an item is given its distinct features that differentiate it from other members of the product or component family. Delaying the point of differentiation is known as postponement” (Timucin 2000). Skipworth and Harrison (2006) opine that form postponement reduces the risks associated with make to stock (MTS) and improves responsiveness compared with engineered to order (ETO) or make to order (MTO) while enabling a high level of customization.

As the complexity of supply chains' becomes greater by the day, the advantages of using generic products with late customization through the channel can't be emphasized more. A point of differentiation is where the number of SKUs increasers, because a material, component, subassembly, or product is split into separate items (Lee and Tang 1998). This may occur because components with different technical specifications are created, multiple end products with diverse functionalities are created, a product is packaged in different ways, or the exact same item is stored in different geographical locations (Lee and Tang 1998, Van Hoek 2001). Davila and Wouters (2007) analyze the data from a disk drive manufacturer and their results indicate that higher levels of postponement are associated with better service, lower inventory and lower cost particularly in terms of better on-time delivery and lower variable costs. For example Oracle/ Cap Gemini Ernst & Young survey found that by implementing successful postponement initiatives the sector leaders have reduced overall inventory costs by as much as 40 percent (Matthews and Syed 2004).

It has been clearly demonstrated in the literature that introducing a common component that replaces a number of unique components reduces the overall level of safety stock required to meet service level requirements (Hillier 2000).Empirical evidence suggests that firms that match their supply chain structure to the type of product variety they offer, outperform firms that do not make use of such opportunities (Randall and Ulrich 2001). In this context, the location of the point of differentiation in a supply chain would play a vital role in enhancing the competitiveness. Davila and Wouters (2007) suggest postponing the configuration of a product to customer's specifications as late as possible in the supply chain. For reducing the costs and risks of product variety, the concept of postponing the configuration of the product has received considerable attention (e.g. Lee1996, Lee and Tang 1998.Aviv and Federgruen 2001, Yang and Burns 2003). Given opportunities for postponement we investigate the issue of the location of the point of differentiation as a supply chain configuration problem.

Hewlett Packard PC example (Lee and Billington 1995) and HP's laser printer example (Feitzinger and Lee 1997) that indicate benefits of postponement are well noted in literature. Xilinx redesigned its integrated circuits so that a generic device could be customized within a certain range of parameters rather than determining all product characteristics during fabrication (Brown *et al*. 2000). Imation used a contract manufacturer in Asia to produce its CDs, shipped them in bulk to Kansas in the USA and packaged for retail customers into several different pack sizes with different types of labels. A small number of SKUs was differentiated into many different products (Andel 2002). Inspite of the benefits that these examples present, they also show that additional efforts are often required such as product redesign, modification of the configuration process, or redesign of the supply chain (Davila and Wouters 2007). With cost and supply chain cycle time as the two key order winners ,we investigate the issue of whether it is advantageous to postpone the point of differentiation(POD) until the last stage in a supply chain or if there are advantages to shifting the POD upstream.

In spite of the benefits of postponement, it can't be said that it will always lead to overall reduction in costs. Even though postponement decreases operational costs, since the common component has to meet the most stringent performance requirements across the group of products in which it is used, that is likely to increase costs because of excess capability of shared components (Davila and Wouters 2007).

Skipworth and Harrison (2006) studied the application of form postponement at a manufacturer of industrial electric motors and showed that though the form postponement improved responsiveness of manufacturing it involves the removal of components and often time-consuming invasive modifications, which suggests that the Customer Order Decoupling Point (CODP) would be better located further up stream in the manufacturing process. Downstream from CODP production is order driven and upstream it is forecast driven (Hoekstra and Romme 1992, Browne *et al* 1996). We primarily investigate the sensitivity of the location of POD in light of different process parameters with respect to the supply chain emphasis on the cost –responsiveness spectrum.

Skipworth and Harrison (2004) also addressed the issue of implementation of form postponement in a manufacturer of specialist high-voltage cabling equipment. They found that provision of a planning system capable of supporting form postponement was the greatest challenge due to the lack of which form postponement was abandoned.

Prior results utilizing single-period models indicate that even if the common component is more expensive than the components it replaces, there are many circumstances under which it is still worthwhile to employ it (Hillier 2000). By using a very general multiple- period model with the objective of minimizing production, holding, and shortage costs, Hillier (2000) indicate that using expensive common components may not be worthwhile for multiple period models. For a single period model ,our investigation proceeds on similar lines primarily taking into account inventory and responsiveness related costs and we have come up with certain counter intuitive results in regards to the location of the POD.

The decision on whether to employ component commonality is usually made at the design stage (Eynan and Rosenblatt 1996). We primarily analyze, given the opportunities for postponement whether or not it is advantageous to postpone the POD and if the decision to postpone is made, which stage would be ideal as a POD, such that strategic supply chain goals are met. As with Eynan and Rosenblatt (1996), our emphasis will be on cost savings due mainly to the reduction in inventory levels resulting from the 'risk pooling' effect. We specifically investigate the issue of the trade off between the cost savings from 'risk pooling' effect and the additional costs because of the typically expensive common components, different inventory parameters etcetera at different stages in a supply chain, which have a key bearing on the location of POD, whilst addressing the supply chain's priorities with respect to the key order winners namely cost and supply chain responsiveness. In case of competitive markets with demand uncertainty, Anand and Girotra (2007) demonstrate that purely strategic considerations not previously identified in the literature play a pivotal role in determining the value of delayed differentiation. They show that in the face of either entry threats or competition, these strategic effects can significantly diminish the value of delayed differentiation. Under plausible conditions, they also show that, these effects dominate the traditional risk-pooling benefits associated with delayed differentiation, in which case early differentiation is the dominant strategy for firms, even under cost parity with delayed differentiation.

The number of performance metrics that one could consider to study the problem of the effectiveness of postponement 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.

Now, let's look at some of the real world supply chains and what they are looking for. Nazzal et al (2006) present a case study for Agere Systems, wherein they use structured simulation and statistical analysis to construct operating characteristic curves to relate SC cycle time to production volume capabilities of a wafer fabrication facility. In particular, the goal was to increase its market share and profits by reducing lead times in the highly competitive and capital intensive semi-conductor manufacturing industry. Another example is Revlon, a personal care products company, whose supply chain is addressed in Davis et al (2005). Its supply chain includes more than 5,000 active finished good SKUs with product life-cycles spanning less than three years, sales in over 100 countries, seven manufacturing facilities, and approximately 450 global suppliers. To meet its aggressive inventory reduction targets and achieving high customer service levels, Revlon is emphasizing reduction of manufacturing and supplier lead times and the associated variability. Even in industries with relatively long product life-cycles, such as the automobile industry, we are seeing increased emphasis on SC responsiveness for matching supply and demand, handling model changeovers, and introduction of new product, all with the goal of lowering capital investment and improving profitability (Pelagagge 1997). Advising against too much emphasis on lowest labor costs, Cannon (2006) opines that companies that can respond with the greatest flexibility will have a clear competitive advantage. Also, Yang and Geunes (2007) emphasize that longer lead times, in addition to reducing customer responsiveness, increase demand forecast error, since forecast error generally increases as the forecast horizon increases. In addition, 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. In summary, striking the right balance between supply chain cost efficiency and responsiveness is critical, which can be neglected at one's own peril. On the contrary, existing literature overly focuses on just one order-winner, cost efficiency.

We are modeling the sensitivity of the POD 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 players at a stage who differ only in terms of cost and responsiveness. Following are some of the journal articles that deal with supply chain configuration problem.

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).

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.

Now, we need to decide which cost drivers the model should include. There are primarily four drivers influencing the performance of the SC, namely, infrastructure, inventories, transportation, and information (Chopra and Meindl 2004). Given that 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. These issues, however, 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 and transportation to the immediate downstream stage. 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. Thus, we are primarily considering the inventory cost driver in our model.

Among inventory cost elements, safety stock, maintained to account for the internal and external variability in the supply chain, is vital in the sense that it directly affects customer satisfaction and constitutes a significant portion of the cost of goods sold (COGS). Explaining the necessity of inventories in a supply chain, Lee & Billington (1993) opine that inventories are used to protect the supply chain from different sources of uncertainties that exist along a supply chain such as demand uncertainty (volume and mix), process uncertainty (yield, machine down time, transportation reliability), and supply uncertainty (part quality, delivery reliability) etc. We are considering both cycle stocks (in process inventory) and safety stocks in our model.

Now, let us look at some of the relevant literature for our research that addresses both of the important order winners namely cost (associated with inventory) and responsiveness.

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 in to the nature of the optimal solution.

The tradeoff between the flexibility of a manufacturing system with respect to both rate change and mix and the investment in inventory is addressed in Graves (1988), wherein the author considers demand uncertainty, a stationary demand process and lot for lot scheduling(ignoring lot sizing). In this model, aggregate production output is determined by a production control rule that attempts to smooth the aggregate output and is parameterized by a planned lead time, which is a decision variable in the model. Flexibility is modeled as the ratio of a measure of slack available to the demand variability. Our research focuses upon the opportunities at a stage for resource flexibility to reduce the lead time and the relevant costs. In Graves (1988), safety stocks are planned to account for only a portion of the variability and assumes that other measures are available to account for the other portion of the variability.

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. 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 and 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 the location of POD .

Graves & Willems (2000) is another interesting paper, wherein they develop what is called a 'guaranteed service model' and also present an optimization algorithm based on dynamic programming for the placement of safety stock for supply chains that can be modeled as spanning trees under certain assumptions. They also describe the successful application of the model at Eastman Kodak to reduce finished goods inventory, target cycle time reduction and to determine component inventories. The authors also mention that Kodak's flow teams have used the model to determine the cost effectiveness of lead time reduction efforts in manufacturing.

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 w.r.t the safety stock positioning are developed in various supply chain topologies. In addition, Simchi-Levi and Zhao (2005) present a nice summary of the literature for installation policies that are used in various network topologies.

- Multi stage serial systems (Simpson 1958, Hanssmann 1959, Lee & Zipkin 1992)
- Distribution Systems (Axsäter 1993, Graves 1985, Lee & Moinzadeh 1987 a, b)

For capacitated models using a modified base stock policy the reader can refer to Glasserman and Tayur (1995, 96) and Kapuscinski and Tayur (1999).

Ettl et al (2000), who have developed a supply network model that takes as input the bill of materials, required customer service levels, nominal leadtimes, demand and cost data etc and generates the base stock level, stockimg location for a part etc at each stage. Modeling the dynamics at each stage in the network as an inventory queue, both performance evaluation and optimization can be performed for a supply chain with service level constraints. They have formulated a constrained nonlinear optimization problem that minimizes the total average dollar value of the inventory subject to meeting the service level requirements. By making use of analytically obtained gradient estimates, optimization was carried out using the conjugate gradient method.

For a 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.

Yang and Geunes (2007) study a problem in which a supplier wishes to determine the best positioning of a product with respect to order lead time and price, wherein the demand is lead-time sensitive. They consider a continuous review inventory replenishment system ,where the difference between the procurement lead time and promised sales order lead time influences both cycle stock and safety stock costs, and procurement costs may increase as a result of investment in production lead time reduction . Their results indicate that for a broad range of practical settings, such systems employ a pure make-to-stock policy or a policy that sets sales lead time equal to the procurement lead time at optimality.

Lin et al (2000) developed an asset management tool that integrates graphical process modeling, analytical performance optimization, simulation ,activity based costing and enterprise data connectivity to enable IBM in 1994 to reengineer it's global supply chain to achieve quick responsiveness to customers with minimal inventory. The primary focus is upon optimization of multi echelon supply network with base stock control.

Advocating the necessity of models that include both cost and responsiveness, 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.

In their extensive literature review of strategic production distribution models, Vidal and Goetschalckx (1997) conclude that among others, the main drawback of the existing models is the fact that most uncertainties (exchange rates , supplier's reliability, lead times, stochastic demand, stochastic customer service level, stochastic facility fixed costs, political environment etc) are not considered in the formulations. We hope that, our model that considers both demand and lead time variability could be further extended in future to consider other types of uncertainties to closely mimic the reality.

As opposed to network design models that focus on the trade off 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 net work 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 DCs in the network such that the sum of the location and inventory (pipeline and safety stocks) 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.

Another interesting research in the context of lead time management in supply chains is by Ray (2001), who in his model considers speed and cost as important competitive priorities and focuses upon the investment requirements for lead time reduction specifically for MTS and MTO firms.

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).

The organization of the remaining part of this paper is as follows. Section 2 deals with development of the overall cost expression for the supply chain. In Section 3, we apply the overall cost expression developed in section 2 in a postponement setting and offer analysis and managerial insights in regards to the location of the POD in a serial supply chain. In section 4 a case study is presented that investigates the issue of the location of POD. Last but not the least, conclusions and limitations are offered in section 5.

2.0 Model Description

Development of total cost expression for a serial supply chain:

2.1 Developing an expression for safety stock costs:

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 that is 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 there by 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 partly because this policy has been proven to be optimal or close to optimal in some special but important 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 Wall 1991, van Houtum et al 1996)

In an installation policy, each facility only needs the inputs from the immediate U/S and D/S facilities and makes ordering decisions based on it's local order and inventory status as opposed to an echelon base-stock policy, which is a centralized control scheme that monitors each stage's echelon inventory (the stage's own stock and everything downstream) and determines external orders and inter stage shipments according to a base stock policy. Even though our model assumes all the stages to be manufacturing stages, without loss of generality, a stage could be modeled as a 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 as in Graves & Willems (2003) and Lee & Billington (1993) to mimic the reality more closely with each stage following a local base-stock policy (Gallego and Zipkin 1999) . Buttressing the same view, Lee & 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 & 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 series system for the simplicity of analysis and primarily to develop certain insights that are insensitive to the specific supply chain topology. And 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 serial 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 can't 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 (Gallego and Zipkin 1999).

There is an inventory holding cost at each stage and our model does not consider backorder penalty cost, which could be easily included. The horizon is finite, all data are stationary, information is centralized but control is decentralized.

As in Gallego and Zipkin (1999) the numbering 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.

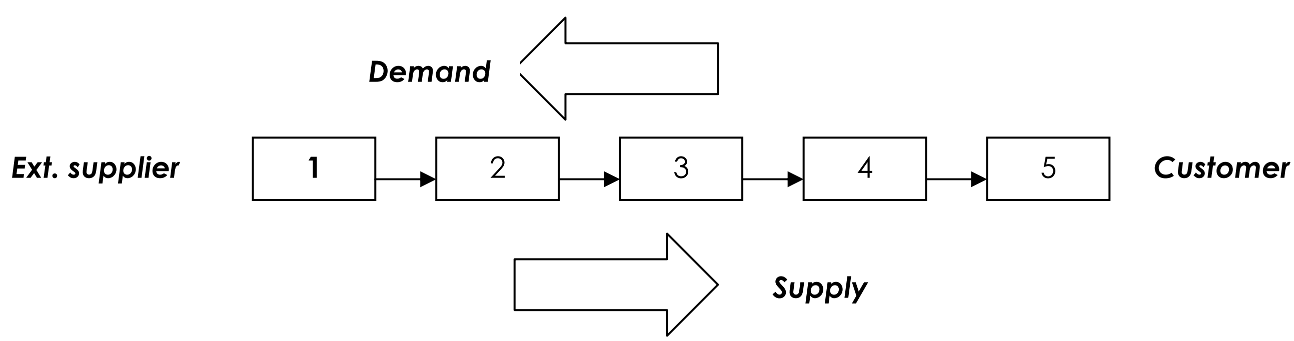


Fig 1: Schematic description of a serial supply chain

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) treatment of stochastic service model in supply chains, Let $\Phi(k_1),....,\Phi(k_n)$ be the service levels for corresponding safety factors $k_1,...,k_n$ where $\Phi(k_i)$ represents the Cumulative distribution function for a standard normal variable.

Let the processing time at stage j be a random variable τ_j with mean L_j and variance σ_j^2.

The stochastic service model (Graves and Willems 2003, Simchi-Levi and Zhao 2005, Lee and Billington 1993, Ettl et al. 2000) assumes delivery or service time between stages to vary based on the material availability at that stage and each stage in the supply chain maintains a base stock sufficient to meet it's service level target (Graves and Willems 2003).

If Δ_i is the random delay at the preceding stage i, then the replenishment cycle time at stage j equals

$$\gamma_j = \tau_j + \Delta_i \tag{1}$$

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) with a modification that takes into account the fact that there is only one player at the preceding stage. We are assuming that the expected value of this delay is simply equivalent to the probability of stock out at the preceding stage π_i times it's average processing time

Therefore, expected replenishment cycle time at stage j is given by

$$E\left[\gamma_j\right] = L_j + \pi_i L_i \quad (2)$$

Where, $\pi_i = 1 - \Phi(k_i)$ (3)

Assuming that the demand is $N\left(\mu,\sigma^2\right)$, to satisfy average demand μ, given the average replenishment cycle time from (2), 'average cycle stock' is given by

$$\mu * \left(L_j + \left(1 - \Phi(k_i)\right) L_i\right) \quad (4)$$

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

$$\sigma_{\Delta_i}^2 = \sigma_i^2 (1 - \Phi(k_i)) \quad (5)$$

$$\sigma_{\gamma_j}^2 = \sigma_j^2 + \sigma_i^2 (1 - \Phi(k_i)) \quad (6)$$

When the demands are uncorrelated between time periods, then the mean and variance of the demand during replenishment period for stage j denoted by the continuous random variable W_J are obtained as follows by slightly modifying the equations to account for the portion of the lead time variability transferred from the preceding stage (see for example, Eppen and Martin (1988) and Feller 1960)

$$\begin{aligned} \mu_{W_j} &= \mu E[\gamma_j] \\ \sigma_{W_j}^2 &= \sigma^2 E[\gamma_j] + \sigma_{\gamma_j}^2 \mu^2 \end{aligned} \quad (7)$$

Now, we introduce another parameter 'c_j' termed as the 'coefficient of inverse responsiveness (CIR)' defined as the ratio of the average demand to the rate of production (throughput) p_j.

$$c_j = \mu \; / \; p_j \quad (8)$$

Assuming that there is enough capacity at all the stages to satisfy a given demand, $c_j \le 1$ at all the times. When c_j =1, expected replenishment cycle time is given by (2). We also assume that there is some upper bound above which rate of production can not be cranked up further.

CIR at a stage is similar to the "expediting factor" proposed by Bookbinder and Cakanyildirim (1999). They define the "expediting factor" τ as the constant of proportionality between random variables $\tilde{T}$ (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, τ), they show that the expected cost per unit time is jointly convex in the decision variables and obtain the global minimizer.

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

$$E\left[\gamma_j\right] = (L_j + (1-\Phi(k_i))L_i)c_j \qquad (9)$$

$$\sigma_{\gamma_j}^2 = (\sigma_j^2 + \sigma_i^2(1-\Phi(k_i)))c_j \qquad (10)$$

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

$$\begin{aligned} \mu_{W_j} &= \mu E\left[\gamma_j\right] \\ \sigma_{W_j} &= \sqrt{\sigma^2 E\left[\gamma_j\right] + (\sigma_{\gamma_j}^2)\mu^2} \end{aligned} \qquad (11)$$

The above equation considers both the demand variability and the replenishment cycle time variability. Replenishment cycle time variability has got two components

a) Processing time variability at stage j.

b) 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

$B_j = \mu E\left[\gamma_j\right] + k_j \sigma_{W_j}$, where k_j is the safety factor to achieve the service level target $\Phi(k_j)$ for that stage.

After subtracting the average demand over the replenishment period, we get the following expression for the expected on hand inventory.

$$E\left[I_j\right] = k_j \sigma_{W_j} \qquad (12)$$

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

$$E\left[BO\right] = \sigma_{W_j} \int_{z=k_j}^{\infty} (z - k_j)\phi(z)dz \qquad (13)$$

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

$$E\left[SS_j\right] = \sigma_{W_j} \left(k_j + \int_{z=k_j}^{\infty} (z - k_j)\phi(z)dz \right) \qquad (14)$$

At stage j, let C_j be the nominal cumulative cost (excluding inventory costs) of the product realized when c_j =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

$$C_j^{SSC} = C_j h_j E\left[SS_j\right] \qquad (15)$$

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

$$C^{SSC} = \sum_{j=1}^{n} C_j^{\ SSC} \qquad (16)$$

2.2 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.

2.2.1 Direct responsiveness related costs

The difference in nominal cumulative costs of the product at stages $j \& i$ will increase by a value, which is assumed to be a function of $(1-c_j)$. This is the cost that the stage 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 $5M$ resources. 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. $5M$ resources are briefly described below. Flexibility related costs will be relatively larger/smaller depending on how flexible these resources are at a stage.

A) Manpower: Jacobelli (1997)

Hiring: Quantity of new hires, individual worker skill set, training and cycle familiarization

Indirect labor: Requirement and availability

Morale: Worker morale related issues when the work environment changes

B) Machine:

Flexibility, shop floor design, work station design, quality, reliability, dependability issues, MRO requirement frequency, availability of spares etc

C) Methods:

Uniformity and flexibility of methods, dissemination of information w.r.t change in methods, adequate training facilities, morale related issues, workforce culture related aspects in a dynamic environment etc.

Effect of manufacturing operation sheet revision that change the method of manufacture or the equipment/machinery where the operations are performed (Jacobelli 1997).

D) Material:

Availability in quantity and on time, oppurtunities for substitution, material handling costs (that can consume up to 15 to 75 % of the product cost (Allegri 1994), logistics etc

E) Measurement:

Adequacy of tools for process control, product identification and traceability, inspection and testing, calibration of the equipment etc.

Direct response related costs at stage j per period is given by

$$DRC_j = [f(1-c_j)](C_j - C_i)\mu \qquad (17)$$

Even though we do not advocate any specific function type for modeling $f(1-c_j)$, cost of volume flexibility function, we strongly recommend that it is derived from the past 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 piece-wise 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 piece-wise linear crashing cost function in their model. Ben-Daya 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 etc) time $\psi(\tau)$ 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 $\psi(\tau)$ to take negative values for $\tau > 1$, 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 $\psi_1(\tau_1) and \psi_2(\tau_2)$ to be decreasing convex functions of the expediting factors $\tau_1 and \tau_2$.They considered $\psi_1(\tau_1) = c_1(-1+1/\tau_1) and \psi_2(\tau_2) = c_2(-1+1/\tau_2)$ where c_1 and c_2 are positive coefficients. Our cost function 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 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.

2.2.2 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 2.2.1. As a result, the difference in nominal cumulative costs of the product at stages $j \& i$ will increase by a value, which is a function of $(1-c_j)$. Therefore indirect responsiveness related cost at stage j is given by

$$IRC_j = [f(1-c_j)](C_j - C_i)h_j E\left[SS_j\right] \quad (18)$$

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

$$TRC_j = DRC_j + IRC_j \quad (19)$$

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

$$C_j^{TSC} = C_j^{SSC} + TRC_j \quad (20)$$

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

$$C^{TSC} = \sum_{j=1}^{n} C_j^{TSC} \quad (21)$$

2.3 Cycle inventory related costs

2.3.1 Cycle inventory at stage j:

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

$$WIP_j = ((C_j + C_i)/2)h_j \mu(L_j + (1-\Phi(k_i))L_i) \quad (22)$$

2.3.2 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 Costs at stage j is assumed to increase the difference of average cycle stock value at stages $j \& i$ by a value, which is a function of $(1-c_j) \& (1-c_i)$.

$$RWIP_j = [f((1-c_j),(1-c_i))]((C_j - C_h)/2)h_j\mu(L_j + (1-\Phi(k_i))L_i) \qquad (23)$$

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

$$TC_j = C_j^{SSC} + TRC_j + WIP_j + RWIP_j \qquad (24)$$

Total inventory and responsiveness related cost for the whole Supply Chain is given by

$$TC_{SC} = \sum_{j=1}^{n} C_j^{SSC} + TRC_j + WIP_j + RWIP_j \qquad (25)$$

3.0 Model related results

3.1 Supply Chain focus based location of the POD problem:

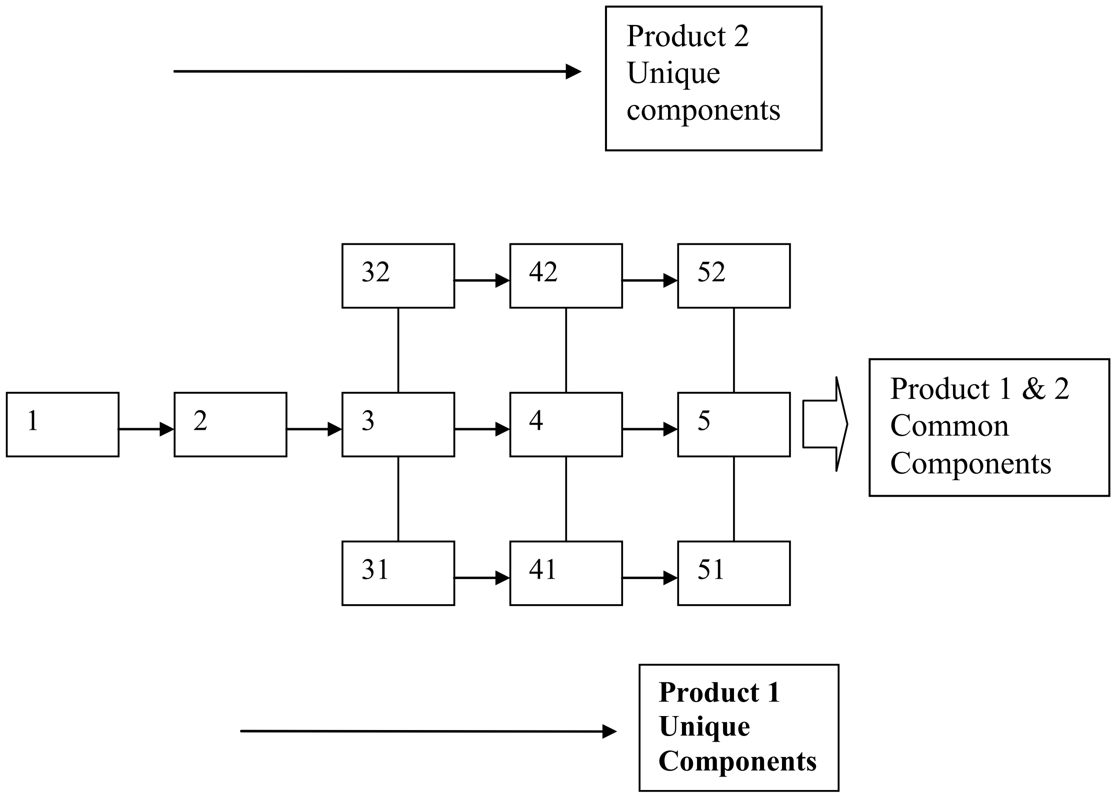


Fig 2: Schematic description of the location of the POD in a serial supply chain

The importance of product differentiation in a mass customization setting is well documented in the current literature. It is also an established fact that the use of modular design, component commonality, common machinery and processes allow the postponement of the product differentiation towards the customer, which not only increases the agility of the system but also results in significant savings in terms of reduced setup & changeover times, reduced lead-times, reduced inventory costs etc. In this section, we focus on the optimal location of the POD as the supply chain focus moves on the Cost –Responsiveness spectrum. Let us consider a hypothetical supply chain as shown above that delivers two different types of products 1 & 2. Let us also assume that there are opportunities to produce both the products by using common components at all the stages, that is, following the path 1-2-3-4-5. In this case, the common component at stage 5 will be differentiated into two different products after stage 5. Other wise,. we can choose to locate the POD either at stage 5,4 or 3. For example if POD is stage 4 product 1 will follow the path 1-2-3-41-51 and product 2 will follow the path 1-2-3-42-52. We consider inventory & response related costs using the expressions developed earlier in section 2 for determining how the least cost POD is affected as the SC focus moves on the Cost –responsiveness spectrum.

We assume all the stages follow MTS policy before and after the POD for the sake of simplicity. We assume that the demands are independent, identical and Normal for both the products. Form postponement is commonly regarded as an approach to mass customization (Skipworth and Harrison 2006), which we assume for our model. Form postponement entails the delay of activities, such as labeling,packaging,assembly, or manufacturing , in order to move the point of product differentiation downstream in the supply chain (i.e., keeping products to their generic form as long as possible) (Davila and Wouters 2007). This increases the flexibility to cope with market uncertainties (Lee1996).Also, at any point of time, we are not considering multiple points of differentiation. We also assume that standardization is the approach adopted for postponement. Standardization and modular design enable a firm to configure a large number of different end products from a limited set of standard components ,typically by combining a limited number of core modules with an array of modules that provide different levels of functionality (Ulrich 1995, Lee and Tang 1997).A major benefit of postponement in the supply chain relates to inventory reduction and service improvement, because holding inventory of a non specific product requires less safety stocks compared to holding inventory of several specific products (Aviv and Federgruen 2001).

In this context, we primarily investigate the issue of the location of the POD, particularly whether it is advantageous to locate it towards the end of the supply chain as typically advocated in the existing literature. We specifically investigate how operational parameters such as cost added at a stage, inventory costs, average processing time and processing variability etc affect the location of POD in light of the supply chain focus on the key order winners of cost and responsiveness.

The total cost expression developed for a stage could be used as a building block for any network and by the use of mixed integer non linear programming one could address the issue of location of POD at a stage.

However, our focus primarily is to offer certain managerial insights with respect to the location of the optimal POD by balancing the inventory costs with responsiveness related costs. The relevant insights can be used as an aid in the location of POD in a mass customization setting. As mentioned previously, we assume that the structural decisions are already made with respect to the supply chain topology and we know the values of the parameters such as lead times, inventory carrying costs, cost added at a stage, nature of the cost of flexibility function etc.We are also assuming that the different stages are equivalent on other attributes say quality etc that are not considered in the model.

	Stage/Player				
	1	2	3	4	5
Nominal cumulative cost C_j	106	150	240	472	1362
Mean Processing time (periods) L_j	1.00	1.00	1.00	1.00	1.00
Demand variability σ^2	400	400	400	400	400
Processing variability $(\mu^2\ \sigma_j^2)$ (in terms of number of units^2 of product)	100	100	100	100	100
Safety coefficient k_j	1.28	1.28	1.28	1.28	1.28
Average back order coefficient	0.1	0.1	0.1	0.1	0.1
π_j	0.1	0.1	0.1	0.1	0.1
Average demand μ	100	100	100	100	100
Inventory holding cost h_j	0.017	0.017	0.017	0.017	0.017
Service level $\Phi(k_j)$	0.9	0.9	0.9	0.9	0.9

Table 1: Typical values of the parameters adopted (Common components)

	Stage/Player					
	31	32	41	42	51	52
Nominal cumulative cost C_j	240	240	472	472	1362	1362
Mean Processing time (periods) L_j	1.00	1.00	1.00	1.00	1.00	1.00
Demand variability σ^2	200	200	200	200	200	200
Processing time variability $(\mu^2\ \sigma_j^2)$ (in terms of number of units^2 of product)	25	25	25	25	25	25
Safety coefficient k_j	1.28	1.28	1.28	1.28	1.28	1.28
Average back order coefficient	0.1	0.1	0.1	0.1	0.1	0.1
π_j	0.1	0.1	0.1	0.1	0.1	0.1
Average demand μ	50	50	50	50	50	50
Inventory holding cost h_j	0.017	0.017	0.017	0.017	0.017	0.017
Service level $\Phi(k_j)$	0.9	0.9	0.9	0.9	0.9	0.9

Table 2: Typical values of the parameters adopted (Unique Components)

For our numerical analysis, we have considered the parameter values as shown in tables 1 & 2. Our primary focus is to analyze the cost advantages in terms of reduction in safety stock costs due to the risk pooling effect by the use of common components. To isolate the advantages of reduction in safety stocks, we have either not changed the values of the parameters for the stages manufacturing unique components for different points of differentiation or neutralized the effect of some parameters. For example, cost incurred at a stage, say stage 3, for producing a common component is considered equivalent to the cost incurred for producing unique components at stages 31 and 32. We are going to relax this assumption in section 3.2 and study the effect of costly common components, which is usually the case, on the location of the POD.

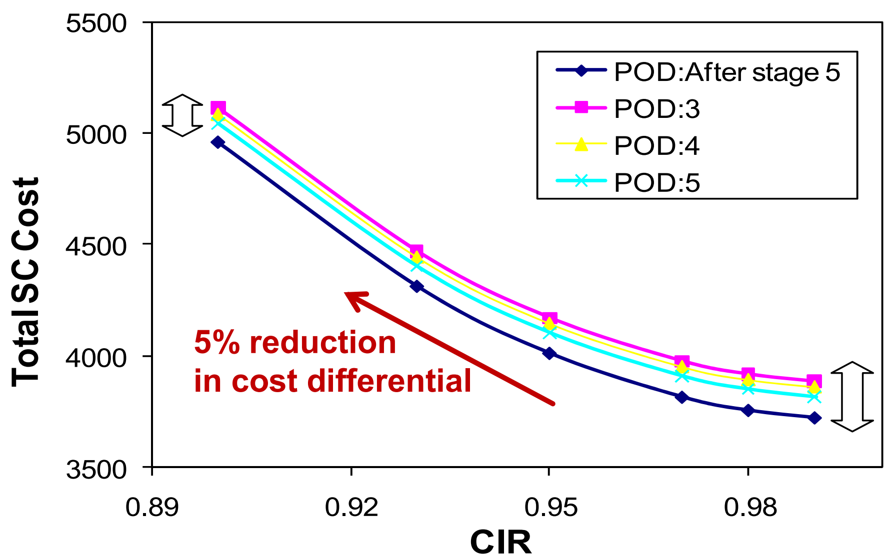


Fig 3: Sensitivity of POD

In light of the values of the parameters chosen ,it is not surprising that POD after stage 5 (POD A5) is the least cost option followed by POD 5,POD 4 and POD 3 respectively, because of the risk pooling effect. As POD moves from stage 5 to 3, risk pooling effect diminishes progressively compared to POD A5. But, the most important feature of fig 3 is that the cost difference between POD A5 and POD 3, considered for the sake of better contrast, they being the cheapest and the costliest options, is progressively decreasing as the SC focus shifts from cost to responsiveness. As the

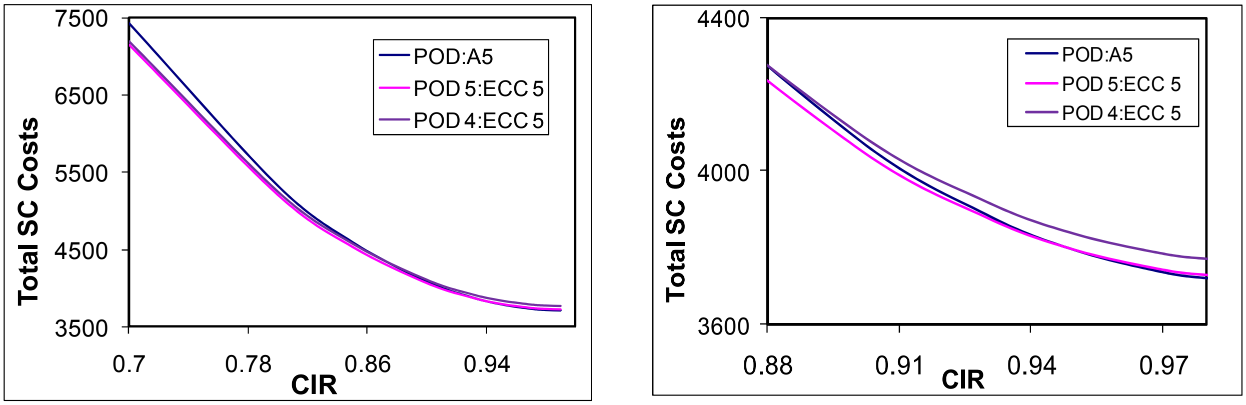
CIR moves from 0.99 to 0.9, the cost difference between POD A5 and POD 3 has shrunk by around 5% and the difference will shrink by 36 % for a CIR value of 0.3. As we have considered only safety stock related benefits of the postponement for our analysis, the coefficient of σ^2 in the safety stock cost expression and the responsiveness related safety stock cost expression gets progressively reduced along with CIR there by diminishing the benefit of risk pooling ,which might make postponement option unattractive .This analysis shows that as the emphasis moves to SC responsiveness as the order winner as opposed to cost as the order winner ,the advantage of postponement due to risk pooling progressively decreases ,which is counter intuitive . For such products, in the presence of other advantages for the stages that produce unique products, postponement may turn out to be an unattractive option. This typically holds for a potential POD stage unless responsiveness related safety costs increase (because of a steep 'cost of flexibility function' etc) is higher than the decrease in safety stock costs for unit reduction in processing time. In such a case there will be a reverse trend witnessed as opposed to the one in Fig 3.

Consider the following example on the lines of (Hillier 2000 example). Coffee makers are sold in U.S and Europe. Coffee makers in U.S use a power supply of 120V and Europe use a power supply of 220V. If the coffee maker sells very well in US but very poorly in Europe, there will be a shortage of 120V power supplies and a surplus of 220V power supplies. If the firm had used universal power supplies shortage in one market could be met by the surplus in the other market, which allows the firm to maintain smaller inventory levels of the common component. Coffee maker is a commodity product, hence cost will be the usually order winner, because of which it will be worth while for the manufacturer to operate within a very close band close to a CIR value of 1 there by reaping the benefits postponement. In the same context, for example, if the manufacturer is dealing with a printer or scanner wherein SC responsiveness plays a key role, because of frequently changing models, technology etcetera the manufacturer will operate at CIR values away from 1.In such a case, postponement will not be that effective because of the reduced processing times and the associated variability as long as the associated responsiveness costs are not too high.

Key Managerial insight 1: *Least cost POD stage will become less sensitive to the placement in the supply chain as the SC focus shifts from cost to responsiveness if the decrease in safety stock cost differential between the potential POD stages dominates the corresponding increase in responsiveness cost differential ,otherwise, vice versa will hold.*

3.2 Effect of the cost differential between common and unique components:

Hillier (2000) notes that if the common component is no more expensive than the one it replaces it is always worth while to use it. Though this is confirmed by Figure 3, we have seen that postponement loses its appeal as the SC focus shifts to responsiveness end of the spectrum under certain conditions. In the single period models, it was not unusual for commonality to be worthwhile, even if the common component was 10, 20, or even 30% more expensive than the component it replaces (Hillier 2000). In our analysis, on the lines of Eynan and Rosenblatt (1996) and Hillier (2000) we relax the assumption that the cost of each of the replaced component is equal to the cost of the replacing common component. When compared to the assumption that the common (replacing) component cost was equal to those it replaces (see Baker 1985, Gerchak *et al* 1988), the assumption that common component is costlier than the unique components is more realistic because a more 'general purpose' component typically costs more. The case wherein the common component is cheaper than the unique components that it replaces is untenable /does not make a strong case because, 'regardless of any other potential commonality advantages, one may always replace any component by a cheaper one resulting in a reduction of the total cost' (Eynan and Rosenblatt 1996). In such a case, it is always advantageous to use commonality (Eynan and Rosenblatt 1996). In addition to design/and manufacturing costs that make general purpose common components more expensive, cheap labor & material cost at unique component facilities, extensive modification costs of common components further downstream , poor quality of common components etcetera are some of the other reasons. For example, Skipworth and Harrison (2006) in their case study of the application of form postponement at a manufacturer of industrial electric motors mention that half of the motors manufactured under form postponement (FPp) required invasive modifications, such as magnet pole changes that involve a motor strip-down that required up to three working days to complete. The excessive costs that result because of the use of common components may also be due to poor quality. For example, Benton and Krajewski (1990) using the DCI (Degree of Commonality Index) and TCCI (Total Constant Commonality Index) found that 'commonality dampens the effect of lead time uncertainty but amplifies the effects of poor vendor quality'.



Figures 4(a, b): Effect of the cost differential on POD – ECC 5

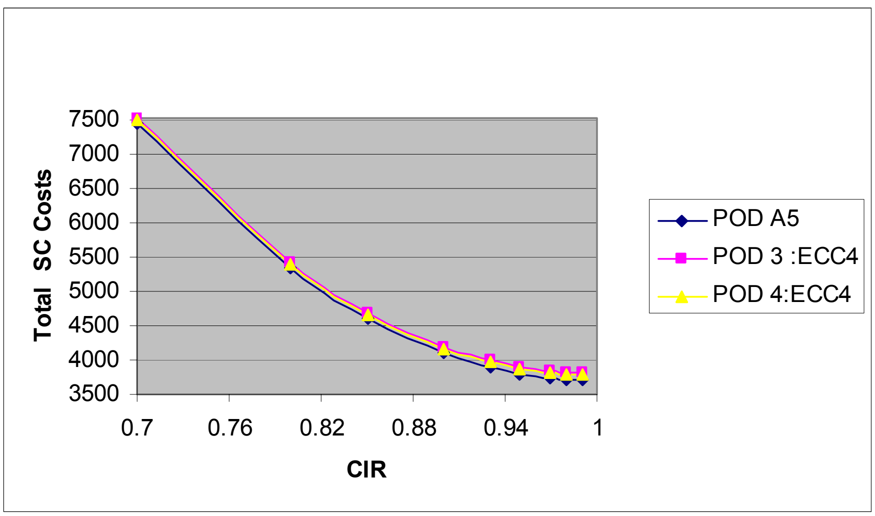


Fig 5: Effect of the cost differential on POD – ECC 4

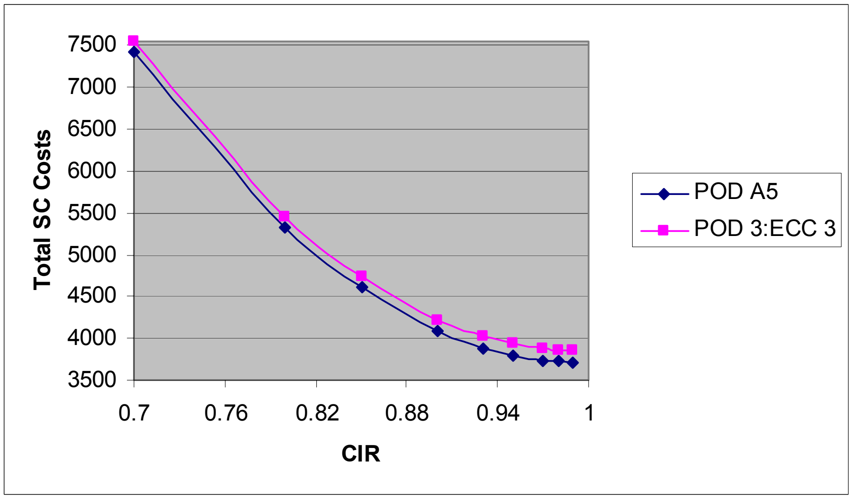


Fig 6: Effect of the cost differential on POD – ECC 3

For our numerical analysis, we have considered nominal processing cost added at stages (31, 32), (41, 42) and (51, 52) that produce unique components to be 10% less than the respective common component costs at stages 3, 4 and 5 respectively. Common components are considered to be expensive one stage at a time. Figure 4 considers expensive common components only at stage 5 (ECC5), Figure 5 considers expensive common components only at stage 4 (ECC 4) and Figure 6 considers expensive common components only at stage 3 (ECC 3). Rest of the values of the parameters remain the same as in tables 1 and 2. It is clear from figure 4 that even though POD A5 is the least cost option in the beginning, POD 5 overtakes POD A5 in terms of least total cost at a CIR value of 0.95 and even POD 4 overtakes POD A5 at a CIR value close to 0.88. The shrinkage of the advantage of the postponement as was evident from Figure 3 is accentuated by the reduction in safety stock costs, direct responsiveness costs, cycle stock costs and responsiveness related cycle stock costs for POD 4 & POD 5 on account of lower unique component costs at stage 5, because both 'cost added' and 'cumulative cost' at stages 51 and 52 are reduced. Even if the responsiveness related safety stock costs are increasing that cost component will be typically dominated by the much larger reductions in other cost components mentioned above. POD 4 is overtaking POD A5 slightly at a lower CIR value because it had to contend with additional safety stock costs on account of product differentiation occurring at stage 4. Because of the cost differential between the common and unique components, below the CIR value of 0.95 it is no longer advantageous to postpone the products until after stage 5 ,but it is cost effective to differentiate at stage 5, that is, optimal POD is moving upstream counter intuitively Therefore as the SC focus shifts to responsiveness optimal POD (starting with POD A5 as optimal, which is the case when CIR =1) becomes sensitive to the price differential at a particular stage and will move U/S at an appropriate value of CIR , when the risk pooling advantage is offset due to the reduction in processing time and associated variability with decreasing CIR (as is clear from figure 3) and the reduction in direct & indirect safety stock costs, direct responsiveness costs, cycle stock costs and responsiveness related cycle stock costs on account of the cheaper unique components.

If common component cost is cheaper at D/S close to the customer then it is always advantageous to use commonality and it is advantageous to postpone POD as farther D/S as possible. Revisiting the coffee maker example, where you are primarily competing on cost that is CIR close to 1, it might be a good idea to postpone i.e. POD is relatively insensitive to the cost of the expensive common component (universal power supply) for a range of prices depending on the context, because risk pooling advantages typically dominate the additional costs due to expensive common components. On the other hand, if you are supplying printers /or scanners or any high tech good, where in supply chain responsiveness is one of the key competitive factors, cost advantage of the unique components will have to just overtake the reduced risk pooling benefits, to shift the POD upstream thereby making POD more sensitive to expensive common components . As Hillier (2000) argued, additional costs (purchase/ or production costs) for the common component are incurred by the each and every common component produced / or purchased, while the holding cost savings are earned only for the several fewer units held in safety stock. . Cost differential is not explicitly addressed in our model, because we considered only it's indirect effect on inventory and responsiveness costs. The direct inclusion of the cost differential will further accelerate the process, that is in the numerical analysis that we performed POD 5 will become optimal at a value of CIR above 0.95

In figure 5, Common component at stage 4 is considered to expensive (by 10%) compared to unique components (ECC 4). Rest of the parameters remain the same from tables 1 & 2.Here POD A5 is the optimal POD for the whole range of CIRs considered. Here when POD is at stage 4, the additional advantage in terms of cheaper unique components is unable to offset the risk pooling advantages when compared to POD A5, even though cost differential between POD A5 and POD 4 is reduced significantly compared to figure 3 .POD 3 fares much worse compared to POD 4 because of the lack of risk pooling even at stage 3.

In figure 6, Common component at stage 3 is considered to be expensive (by 10%) compared to unique components (ECC 3). Rest of the parameters remain the same from tables 1 & 2.Here POD A5 is the optimal POD for the whole range of CIRs considered. Here when POD is at stage 3, the additional advantage in terms of cheaper unique components is unable to offset the risk pooling advantages when compared to POD A5, even though cost differential between POD A5 and POD 3 is reduced significantly compared to Figure 3.

In both the above cases, POD A5 continues to be optimal, when compared to the case in figure 4 (ECC 5) because

a) For the same amount of decrease in the cost of unique component (we considered 10% decrease in all the three cases) the effect is much more at D/S stage PODs, because of the relatively larger nominal cost added, which is typically true for products for which postponement is suitable. Even if cost parity is assumed on that account, U/S stages as a POD will be relatively less favored for the following reason

b) As the POD moves U/S, the advantages of the risk pooling effect gets progressively reduced. The only exception is when the effect of reduced cumulative costs at an U/S stage on the safety and cycle stock costs from that stage onwards(until the customer) in conjunction with the reduction in inventory and responsiveness costs at the stage itself(on account of cheaper unique components) overtakes the risk pooling benefits.

Hence, for the same percentage of cost differential, in typical circumstances, POD location at D/S stages would be advantageous compared to U/S stages.

3.3 Effect of efficient inventory parameters:

In this section we are going to look at the effect of inventory parameters at different stages on the optimal location of POD. The presence of better inventory parameters at the common component stages will always bolster the case of postponement, given that the other parameters are equivalent .Here, we particularly investigate the issue of unique component stages with better inventory parameters. The following values of the inventory parameters are adopted for the respective unique component stages compared to the values presented in table 2.

Unique component stages	31 & 32	41 & 42	51 & 52
Avg Processing time	0.98	0.98	0.98
Processing time variability	6% less	6% less	6% less
h	0.015	0.015	0.015

Table 3: Inventory parameters adopted for unique component stages

The modified inventory parameters are adopted one stage at a time as we did in the earlier analysis. Remaining parameters were adopted as they were. Here again the risk pooling benefit is in terms of only safety stock cost savings.

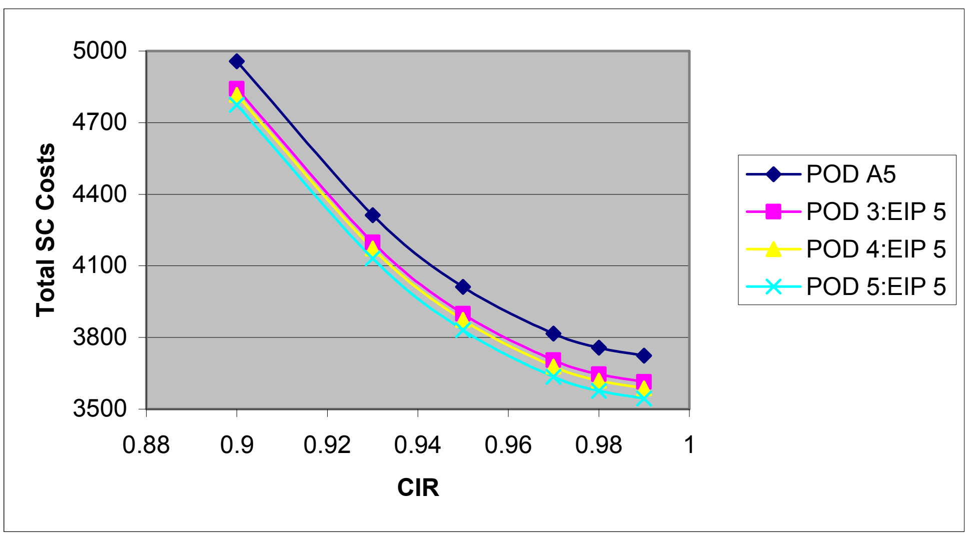


Fig 7: Effect of efficient inventory parameters on POD – EIP 5

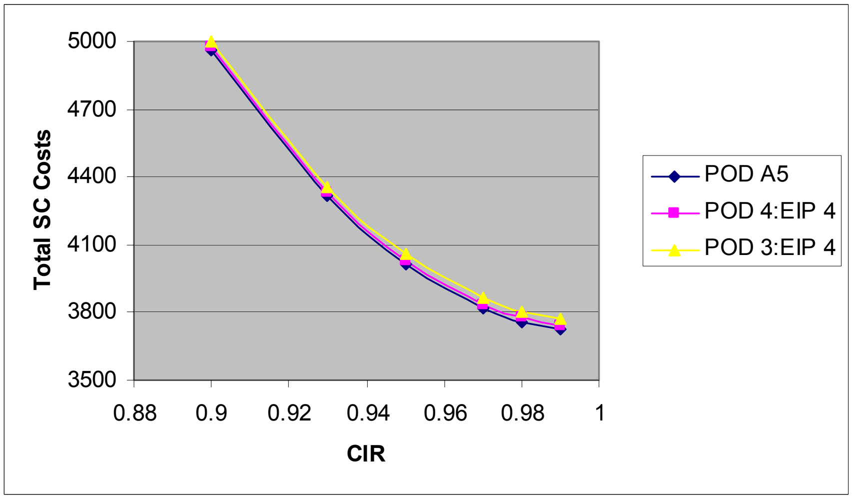


Fig 8: Effect of efficient inventory parameters on POD – EIP 4

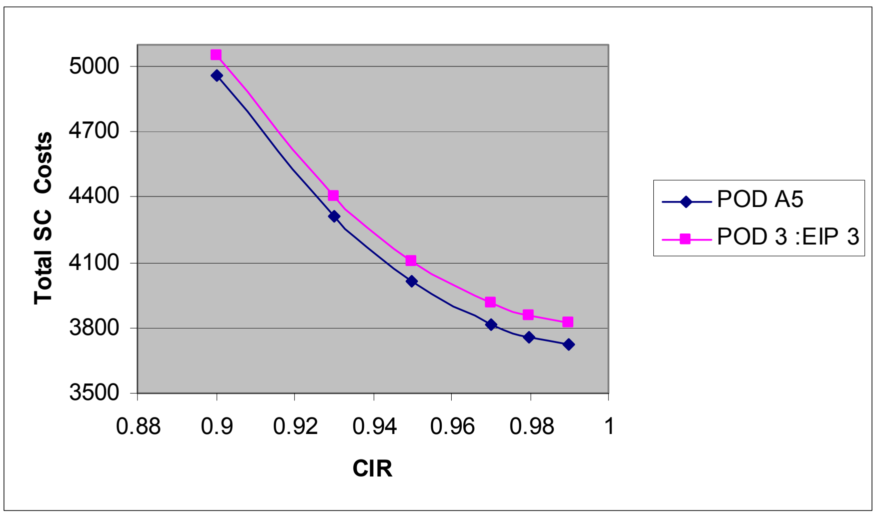


Fig 9: Effect of efficient inventory parameters on POD – EIP 3

In figure 7, when efficient inventory parameters are adopted at stages 51 and 52 it is denoted by EIP 5 etc. From figure 7 it is clear that POD A5 is lagging all the three PODs at stages 3, 4 & 5 respectively. POD 5 is the least cost POD over the entire range of CIR followed by 4 and 3 respectively. When stage 5 is POD, the effect of reduced average processing time, processing time variability and the inventory holding cost at stages 51 & 52 reduces the direct and indirect (responsiveness related) safety stock costs and cycle stock costs compared to the case presented in figure 3 and the reduction is more than the corresponding risk pooling benefit at any CIR value. The reduction also overtakes additional safety stock costs, when POD moves to stages 4 and 3. As the SC focus shifts to responsiveness this trend will become much stronger owing to the fixed reduction in cycle stock costs and the rapidly decreasing(depends on the nature of cost of volume flexibility function) responsiveness related cycle stock costs and also the accentuated reduction in safety stock costs.

POD 3 and 4 are costlier than POD 5 because of the additional safety stock costs at those stages. Once again this analysis proves that the presence of unique component manufacturing stages with efficient inventory parameters waters down the benefits of postponement and counter intuitively moves the least cost POD upstream.

When the holding costs are not unusually high and the order interval is fairly short (e.g., month or less), it appears that using a more expensive common component is essentially never worthwhile (Hillier 2000). Our result that as the responsiveness increases, which means order interval decreases, and if there are advantages in terms of efficient inventory parameters at unique component manufacturing stages, least cost POD moves towards U/S stages is similar in spirit to the above statement.

For example, Black & Decker after assessing it's total cost of ownership of it's operations jettisoned its plans for postponement, which involved shifting costs that had been carried by suppliers over to the manufacturer, for a net increase in supply chain expense (Hoffman 2006).

In figure 8, unique component stages 41 and 42 are considered to have efficient inventory parameters (EIP 4). Rest of the parameters remain the same from tables 1 &

2.Here POD A5 is the optimal POD for the whole range of CIR s considered. Here when POD is at stage 4, the additional advantage in terms of better inventory parameters is unable to offset the risk pooling advantages when compared to POD A5, even though cost differential between POD A5 and POD 4 is reduced significantly compared to figure 3 .POD 3 fares much worse compared to POD 4 because of the lack of risk pooling even at stage 3.

In figure 9, unique component stages 31 and 32 are considered to have efficient inventory parameters (EIP 3)). Rest of the parameters remain the same from tables 1 & 2.Here POD A5 is the optimal POD for the whole range of CIR s considered. Here when POD is at stage 3, the additional advantage in terms of cheaper inventory parameters is unable to offset the risk pooling advantages when compared to POD A5, even though cost differential between POD A5 and POD 3 is reduced significantly compared to figure 3.

In both the above cases, POD A5 continues to be optimal, when compared to the case in figure 7 because

a) We considered the same set of inventory parameters as shown in table 3 for the unique component facilities at stages 3,4 and 5.This results in a safety stock and cycle inventory cost reduction ,which increases depending on how D/S a particular POD is, because of the larger cumulative cost. Responsiveness related costs depend on the nominal cost added at a stage but tend to be typically larger for D/S stages for products being considered for postponement, as in our analysis, which further increases the cost differential in favor of D/S stages. The only advantage for a U/S stage as a POD is the transfer of reduced process delay and the corresponding variability to the immediate

D/S stage, which in turn will reduce the safety & cycle stock costs at that stage. But this advantage will be typically much less compared to the cost advantages of a D/S stage as a POD.

b) As we move POD upstream, the advantages of risk pooling effect gets progressively reduced because of increasing safety stock costs for unique components at those stages.

Hence, for the same set of efficient inventory parameters, in typical circumstances, POD location at D/S stages would be advantageous compared to U/S stages.

Based on the discussion in 3.2 and 3.3, we can state the following managerial insights

Key managerial insight 2: *As the SC becomes more responsive, least cost POD is more likely to move to that U/S stage (which includes not resorting to postponement at all, when U/S stage is 1), where from, the effect of cheaper unique components, better inventory parameters etcetera offsets not only the risk pooling benefits but also overtakes the other potential POD stages in terms of least total cost.*

Key managerial insight 3: *In a typical postponement scenario*, *for a given quantum of advantage in terms of cost, inventory parameters etcetera at unique component manufacturing stages compared to the respective common component manufacturing stages, keeping all the other parameters constant, least cost POD will be biased towards downstream stages compared to upstream stages.*

4.0 Case Study

We revisit the example of Mexico supplier for wiring harness that was addressed in chapter 2. Mexico supplier with LTL option (chapter2, table 5) manufactures a common wiring harness that is differentiated into two different SKUs, one a luxury version and other basic version at the OEM facility. Total cost of $ 206,258 per day is incurred with common harness option. There is also flexibility at the Mexican facility to produce these two versions by making separate allocations in terms of manpower, machines etc ,that is differentiation of SKUs is possible at the supplier facility itself. The values of the parameters when differentiation is performed at the supplier facility are given below. The goal is to investigate whether postponement is advantageous in terms of the total cost.

			Different Harnesses			
	Common Harness		Luxury Model		Basic Model	
	Mexico Facility	Mexico Transport	Mexico Facility	Mexico Transport	Mexico Facility	Mexico Transport
Cost ($) / Unit	243	12	272	17	203	16
Mean Processing time(Days) L_j	3	11	3	11	3	11
Processing time SD (Days) σ_j	1	2	1	2	1	2
Inventory carrying cost per year % h_j	24	24	24	24	24	24
Mean Demand per day μ	800	800	200	200	600	600
Demand SD per day σ	150	150	54	54	140	140
Safety Coefficient k_j	1.28	1.28	1.28	1.28	1.28	1.28
Average back order coefficient π_j	0.1	0.1	0.1	0.1	0.1	0.1
Service Level $\Phi(k_j)$	0.9	0.9	0.9	0.9	0.9	0.9

Table 4: Key parameter values for postponement vs. differentiation options

For postponement option, that is by using a common harness, which will be differentiated at the OEM facility, parameter values are same as presented in chapter2, table 5.Risk pooling advantage due to postponement in terms of safety stock cost savings, because of pooled demand standard deviation is the only benefit considered.

Under differentiation, luxury model costs more and basic model costs less compared to the postponement option with a common harness. Average price of a harness produced under differentiation option is approximately 7% cheaper than the one produced under postponement option. Unique harnesses tend to cost cheaper because of less complexity in operations particularly for the basic version that result in reduced quality related costs and allows for the use of relatively less skilled workforce. The analysis of the data using the cost model developed results in the following.

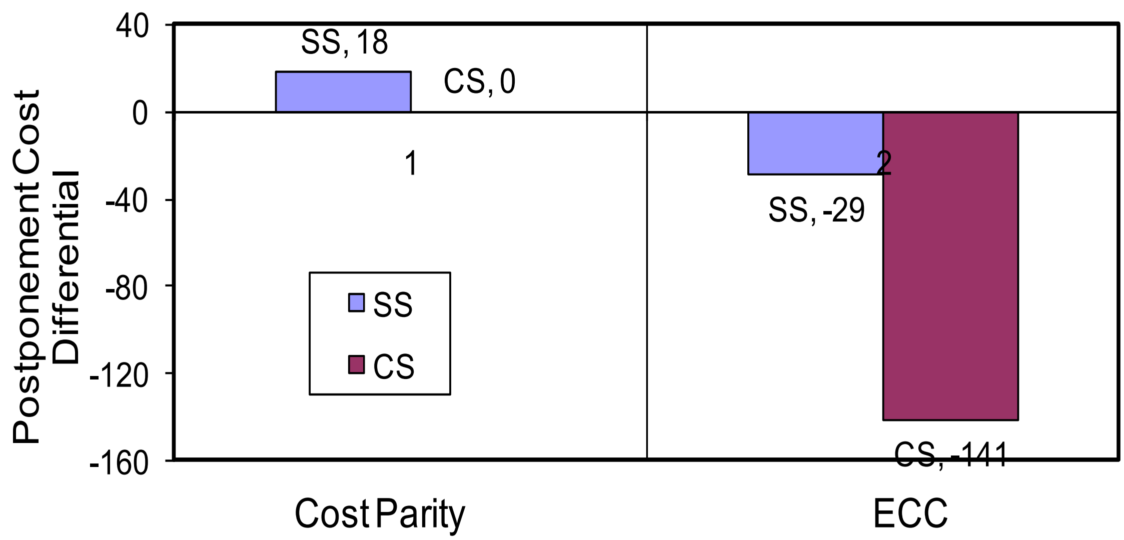


Fig 10: Postponement vs. Differentiation: Inventory cost differential

The safety stock cost advantage for postponement under cost parity with differentiation option due to risk pooling is $18 per day. But under differentiation, average cost of the wiring harness is lower than under postponement (shown as ECC, which stands for expensive common component). This results in safety stock cost advantage of $29 per day and cycle stock cost advantage of $141 per day for the differentiation option. In addition, savings due to direct cost differential are $14,800 per day for differentiation option. The total costs for differentiation option turn out to be $191,288 per day that clearly overtakes the total cost with postponement of $206,258 per day.

Inventory cost savings with differentiation are much smaller in magnitude in this case compared to direct cost differential, 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 cost structure for the differentiation option. 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, savings due to direct cost differential are able to clearly offset the disadvantage due to disaggregation of the inventories that may not be case in complex supply chains, wherein the echelon inventory cost savings also play a key role.

5.0 Conclusions

In present day competitive, globalized 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 the optimal location of the POD problem in a supply chain by considering inventory costs and the responsiveness related costs assuming that the structural decisions are already made with respect to the supply chain network, that is, we develop the problem as a supply chain configuration problem. The most important aspect of this paper is that in addition to the traditional cost criterion, we have incorporated supply chain responsiveness related parameters in to the model, which allows us to monitor the supply chain performance with respect to these two critical order-winners. We introduce a new parameter called coefficient of 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 other types of supply chain networks to aid in locating the optimal point of differentiation. We also offer some interesting counter intuitive managerial insights in regards to the placement of the optimal POD. As opposed to the general belief, we establish that the location of the POD at upstream stages/ or not resorting to postponement at all may be the best strategy under certain circumstances as the SC focus shifts towards responsiveness.

We have considered only inventory related benefits with postponement but other aspects such as short and reliable delivery lead times, reduced repair and maintenance costs, design and development costs etcetera are not addressed explicitly. Addition of these features will affect the POD location and will make the model more realistic. Organizational readiness, process type, operations scheduling etc are some of the factors, which play an important role in the successful implementation of the postponement strategy, the addition of which will enhance the applicability of the model.

Consideration of market structures and associated competition among different supply chains would be a new direction to extend the work presented here. Extent of information penetration and the degree of information symmetry are important issues in supply chain management that affect the sensitivity of the location of the POD, and their explicit consideration is also a potential area for possible extension of this research.

A useful extension of the model is to account for non stationary demands and to consider products with seasonal demands. Also it would be more in tune with the reality to consider capacity constraints at certain stages.

Finally, we really would like to see this model used in some real world application so that insights presented in our model could be validated.

CHAPTER 4

Conclusions and Future Research Directions

In the first part of the dissertation (safety stock placement problem), in addition to offering several managerial insights with regard to strategic safety stock placement in a supply chain, an attempt has been made to address the problem of achieving compatibility between the supply chain strategy and the individual stage's business strategy by primarily considering safety stocks and responsiveness related costs. We have introduced 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. The developed cost function for the 'building block' could be extended for other types of supply chain networks. By knowing the values of the parameters of the model, one can know the safety stock costs and responsiveness related costs at each stage and compare them to an ideal supply chain strategy in terms of cost and responsiveness to make informed decisions. The key managerial insights developed are generic in nature and are applicable to any supply chain irrespective of it's placement on the cost-responsiveness spectrum and topology.

So as to make the model more tractable, certain simplifying assumptions were required. For example, "bullwhip effect" was not factored into the model. It would make an interesting extension to this research if bullwhip effect and other information asymmetry related issues are factored into the model. This research has not incorporated order sizes into the model, because the model is supposed to be largely a strategic model. Research could be extended by incorporating this aspect into the model and to see how it affects the managerial insights that are offered. Relaxing the assumptions on the stationary nature of the demand and stage base stock policy with periodic review will make the model more realistic and robust to real world situations. Introducing contracts that affect the flexibility at a stage with financial ramifications will also be a very fertile area to pursue that will make the proposed model mimic the reality more closely. So is considering other types of network topologies particularly assembly and distribution, which we are planning on considering in the extension of this framework. It would also make more sense to consider capacity constraints at certain stages. Product mix related flexibility is also a crucial factor which is not addressed in our model. Addition of this feature would truly make the research more in tune with the reality, especially, in mass customization settings.

In the second part of the dissertation (supplier selection problem), key contribution is in the form of managerial insights that are offered with regard to supplier selection problem in a supply chain by primarily considering inventory costs and responsiveness related costs assuming that the structural decisions are already made with respect to the supply chain network. In an optimization context, the developed cost function for the ‘building block’ could be extended for other types of supply chain networks to aid in supplier selection.

Some of the future research directions in the context of the second part are as follows. Consideration of order splitting, which is a common phenomenon in many a purchasing decision, will enhance the value and applicability of this research. So is the consideration of buyer collaboration, which is not uncommon while making purchasing decisions. It would be an interesting extension, if this aspect is included. The work presented in this dissertation did not take into account any qualitative factors such as quality, suppliers' reputation, staying power/financial stability, cultural match etc, the consideration of which in the context of an integrated framework would add more value to the model. Another limitation is that volume discounts and quantity discounts typically offered by suppliers are not taken into account in the current model. Introducing contracts that take into account such discounts with financial ramifications will also be a very fertile area to pursue, which will make the model mimic the reality more closely.

In the third part of the dissertation (sensitivity of point of differentiation, POD), key contribution is in the form of certain managerial insights with regard to the optimal location of the POD problem in a supply chain by considering inventory costs and the responsiveness related costs assuming that the structural decisions are already made with respect to the supply chain network, that is, we develop the problem as a supply chain configuration problem. In an optimization context, the developed cost function for the 'building block' could be once again extended for other types of supply chain networks to aid in locating the optimal point of differentiation. The developed cost model also offers some interesting counter intuitive managerial insights in regards to the placement of the optimal POD. As opposed to the general belief, it is established through this research that the location of the POD at upstream stages / or not resorting to postponement at all may be the best strategy under certain circumstances as the supply chain focus shifts towards responsiveness.

The developed model considers only inventory related benefits with postponement but other aspects such as short and reliable delivery lead times, reduced repair and maintenance costs, design and development costs etcetera are not addressed explicitly. Addition of these features will affect the POD location and will make the model more realistic. Organizational readiness, process type, operations scheduling etc are some of the factors, which play an important role in the successful implementation of the postponement strategy, the addition of which will enhance the applicability of the model.

Consideration of market structures and associated competition among different supply chains would be a new direction to extend the work presented here. Extent of information penetration and the degree of information symmetry are important issues in supply chain management that affect the sensitivity of the location of the POD, and their explicit consideration is also a potential area for possible extension of this research.

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ABSTRACT

STRATEGIC SUPPLY CHAIN MODELING – A SUPPLY CHAIN PERSPECTIVE OF COST EFFICIENCY AND RESPONSIVNESS

by

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Increasing globalization, growing product range diversity, and rising consumer awareness are making the market(s) highly competitive, forcing supply chains to constantly adapt to different stimuli. It is now well established in the literature that among the many order-winners, both overall supply chain cost as well as responsiveness (i.e., supply chain lead-time) are the most significant determinants of supply chain competitiveness. The literature, however, mostly focuses on supply chain cost minimization with rather simplistic treatment of responsiveness. By focusing upon these two important order winners in a supply chain configuration context, that is assuming that the structural decisions with respect to the supply chain topology are already made, we address three important problems namely a) safety stock placement at different stages b) supplier selection at a stage and c) the sensitivity of point of differentiation in a mass customization setting. In the first part of our research, by introducing the concept of 'coefficient of inverse responsiveness' (CIR), we facilitate efficient introduction of responsiveness related costs into the scheme of supply chain performance evaluation and/or optimization. In particular, it aids in strategic placement of safety stocks at different stages in the supply chain. Our model also offers managerial insights that help improve our intuitions for supply chain dynamics. In the second part of our research, we address the supplier selection problem, while configuring a supply chain. By extending the model developed in the first part of our research by considering cycle stock inventory costs, we offer some very interesting 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. In the last segment of our research, we address the issue of sensitivity of point of differentiation in a mass customization setting. Determining the point of differentiation is one of the crucial problems that need to be addressed by a supply chain manager, while configuring a supply chain. Based on the strategic model developed, we offer some very interesting insights with respect to the location of optimal point of differentiation in a supply chain.

Keywords: Supply chain strategy, business strategy, safety stock costs, cost of responsiveness, supply chain cycle time, coefficient of inverse responsiveness, supply chain configuration, supplier selection, point of differentiation and postponement

AUTOBIOGRAPHICAL STATEMENT

Gangaraju Vanteddu has obtained his Ph.D in Industrial Engineering from the Department of Industrial & Manufacturing Engineering at Wayne State University, Detroit, USA. He received his M.Tech degree (with honors) in Quality, Reliability and Operations Research from Indian Statistical Institute, Calcutta, India and B.Tech degree (with distinction) in Civil Engineering from Sri Venkateswara University College of Enginneering, Tirupati, India .His additional professional qualifications include CSCP certification from APICS, CQE & CRE certifications from ASQ. His technical articles have been published /or accepted for publication in *International journal of Flexible Manufacturing System*s, *Int. J. Logistics Systems and Management and International Journal of Modeling and Simulation.* He has also made a number of technical presentations at DSI, INFORMS and ASQ Conferences. His research interests include Supply Chain management, Applied Statistics, Quality and Operation Research. He has rich experience teaching a variety of subjects and won many awards for his teaching at Wayne State University. He has rich managerial and consulting experience in the areas of Operations Management, Quality and Applied Statistics by serving as an employee of public and private sector organizations in India. He is also a student member of DSI, INFORMS, IIE, APICS and ASQ. His hobbies include reading, table tennis, and taking long walks.