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Inventory performance of some supply chain inventory policies under impulse demands

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This paper attempts to study the impact of impulsive demand disturbances on the inventory-based performance of some inventory control policies. The supply chain is modelled as a network of autonomous supply chain nodes. The customer places a constant demand except for a brief period of sudden and steep change in demand (called demand impulse). Under this setting, the behaviour of each inventory policy is analysed for inventory performance of each node. It is found that the independent decision-making by each node leads to a bullwhip effect in the supply chain whereby demand information is amplified and distorted. However, under a scenario where the retailer places a constant order irrespective of the end customer demand, the inventory variance was actually found to decrease along the supply chain. The variance of the inventory remained constant along the chain when only the actual demands are transmitted by each node. The results also showed that the inventory policy which is best for one supply chain node is generally less efficient from a supply chain perspective. Moreover, the policy which performs poorly for one node can be most efficient for the supply chain. In a way, our results also provide a case for coordinated inventory management in the supply chain where all members prepare a joint inventory management policy that is beneficial for all the supply chain nodes. The results have significant industrial implications.

Keywords: inventory control policies; inventory performance; supply chain; simulation; impulse demands

1. Introduction

Supply chains can be structurally considered as network of independent and autonomous entities which work in unison towards some common objective. Each entity or member of the supply chain can be represented as a node on the supply network. Since each node of the supply chain is an autonomous member, each node takes decisions in accordance with what it perceives is best for it. There are numerous examples in supply chain literature that demonstrate that this autonomous decision-making by each node leads to overall poor performance of the supply chain. This also results in the phenomenon of *Bullwhip Effect* whereby the demand information is delayed, distorted and amplified at each supply chain node (see Lee *et al.* 1997a, 1997b).

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From an inventory management point of view, this autonomous decision-making results in poor performance of the supply chain as demonstrated by simultaneous occurrence of poor service levels and very high inventory carrying costs. In other words, the inventory policy followed by a supply chain node affects the inventory-related performance of the supply chain to a very large extent. The impact of various inventory policies on the supply chain performance is widely studied (Atkins and Iyogun 1988, Viswanathan 1997, Nielson and Larsen 2005). However, the performance of these policies under different degrees of variability has not been studied well.

Demand impulse is a unique kind to demand disturbance where the demand pattern is deviated substantially for a very short interval of time and then it stabilises again. Hence, impulse could be considered as the smallest disturbance that can occur in a demand pattern. As this disturbance does not change the mean demand substantially, the impact of this impulse automatically stabilises over time. However, this small disturbance can have unexpected effects on the entire supply chain depending on the inventory policies followed by different supply chain nodes. More impulses can be added to the demand pattern to simulate different degrees of demand variability.

This paper attempts to study the impact of impulse demand disturbances on different supply chain inventory policies through simulation. Each member of the supply chain is modelled as an independent entity, which takes its decisions autonomously. The impact of these policies on each member of the supply chain and the entire supply chain is then studied by simulating the decision-making process at each node having some pre-defined inventory policy. The demand variance is induced by increasing the number of impulses in the demand pattern. The rest of the paper is presented as follows. The next section provides a brief review of inventory management literature to highlight the scope for our research. This is followed by the presentation of a conceptual supply chain model and its definition in context of the study. The experimental results are presented in two sections: one showing the impact of demand impulses in individual supply chain nodes and the other highlighting the overall impact of these disturbances on the supply chain. The implications of these findings on managers are discussed in the subsequent section. The last section concludes the paper by presenting the key findings of the research.

2. Literature review

The inventory policies can be broadly classified in two categories depending on the review period. The first category is the continuous review policy where the inventory position is continuously monitored and new orders are triggered by some events. The (s, Q) policy and (s, S) are two such inventory policies which are defined by two parameters. The first parameter is called the reorder point (or level) s. The second parameter is the *quantity to be ordered* (Q) for (s, Q) policy and *order upto level* (S) for (s, S) policy. In (s, Q) policy, each time the inventory falls below the reorder level, a new order of quantity Q is placed. Similarly in (s, S) the order quantity is so as to make the total inventory level to S.

The second type of inventory policy is the periodic review policy. In a periodic review policy, the inventory position is reviewed only once every T_i periods. The length of T_i is always some integral multiple of the base period. A comparison of continuous review policies and periodic review policies by Atkins and Iyogun (1988) revealed that periodic review policies have twin advantages over continuous review policies. They are simpler to compute and they also outperform the continuous review policies significantly. A periodic version of the (*s*, *S*) policy was suggested by Viswanathan (1997). In this policy, the inventory position is analysed at the end of each review period and (*s*, *S*) is applied to each item, such that each item with inventory level lower than the reorder level is included in the order. Nielson and Larsen (2005) evaluated the performance of an (*s*, *S*) policy for a multi-product supply chain where the demand of each product followed a Poisson process. They found out that (*s*, *S*) policy performs best among the considered policies.

The essential difference between continuous review policy and periodic review policy is the way in which orders are placed. The order placement process in continuous review policies is preceded by some events that require placement of new orders. In a periodic review policy, the order placement process is withheld until the review period. The decision as to whether to place the order or not is only taken at the end of the review period. Hence, this type of policy is advantageous for multiple-product supply chain where clubbing of orders can result in reduction of ordering and transportation costs. Motivated by this finding, we compare only the periodic review policies in our research.

Many inventory policies are found in literature, which cater to one form of demand or other (Brecman *et al.* 1989, Viswanathan and Piplani 2001, Giannoccaro *et al.* 2003, Xu *et al.* 2003, Aburto and Weber 2005, Disney *et al.* 2006, Schwartz *et al.* 2006). One of the desirable features of a good inventory policy is its ability to accommodate the demand uncertainty. In this direction, many researchers have modelled the supply chains under stochastic demands (Amin and Altiok 1997, Fleisch and Tellkamp 2005, Chung *et al.* 2006). Zhang (2005) considered an inventory setting in which the historical data used for demand forecasting is delayed. He demonstrated that such delays reduce the variability of order history and dampens the bullwhip effect by using order upto policies.

Hosoda and Disney (2006) analysed a three-echelon supply chain with autoregressive end consumer demand and obtained exact analytical expressions for bullwhip and net inventory variance at each echelon in the supply chain. Disney and Towill (2003) presented a discrete control theory model of a generic model of a replenishment rule. They found that bullwhip can be reduced by taking a fraction of the error in the inventory position and pipeline position rather than account for all of the errors every time an ordering decision is made. Furthermore, increasing the average age of the forecast and reducing the production lead-time reduces bullwhip. They derived an analytical expression for the variance of the inventory position and used it together with the bullwhip expression to determine a suitable ordering system design that minimises both bullwhip and inventory variance.

One of the methods of improving the supply chain performance is through coordinated inventory management. In this setting, all the supply chain members jointly decide about the inventory policies rather than each member taking its inventory decision independently. Many papers in literature demonstrate the improvements that can be achieved by using coordinated inventory management. The paper by Boute *et al.* (2006) considered the inventory management problem in a single-product two-echelon supply chain having a single retailer and a manufacturer. In a stochastic demand setting, they showed that the retailer's order decision has a direct impact on the manufacturer's production. They further observed that integrating the impact of the retailer's order decision on the manufacturer's production leads to a smooth order pattern and generates shorter and less variable (production/replenishment) lead times. The disparity between local and central planning of multiple-stage, deterministic demand inventory systems was investigated by Simpson (2006) under a broad range of environmental factors. Gavirneni (2005) showed that in the presence of information sharing, the supply chain performance can be improved by the supplier offering fluctuating prices. Sahin and Robinson (2005) mathematically modelled and developed simulation procedures to analyse the manufacturer's and vendor's control policies under five alternative integration strategies. Their experimental results showed that while information sharing reduces the system costs, the main economic benefit comes from coordinated decision-making.

Sucky (2005) studied the coordination of order and production policies between buyers and suppliers. He is of the view that cooperative order and production policy can reduce total cost significantly. He proposed some bargaining models to induce the buyer to order in quantities more favorable to the supplier. The paper by Zhang *et al.* (2006) evaluates the benefit of a strategy of sharing shipment information, where one stage in a supply chain shares shipment quantity information with its immediate downstream customers (a practice also known as advanced shipping notice). Their results indicate that in most circumstances sharing shipment information helps supply-chain members to resolve shipment quantity uncertainty effectively. Chu and Lee (2005) modelled a two-member supply chain as a Bayesian game and found out that two conditions affect the information sharing in the supply chain: the cost of revealing the information and the nature of market demand signal that the retailer receives. According to them, reducing the cost of sharing information and increasing the profit margin of either the retailer or the vendor (or reducing the cost of the vendor or retailer) facilitates information sharing.

This literature review highlights the need to study the supply chains under dynamic demands. One of the ways to study the dynamism of the system in a controlled manner is by incorporating the impulses in the actual demand. Moreover, a generic model of the supply chain needs to be developed that can reflect the autonomous decision-making process of each node. This model is discussed in the next section.

3. Conceptual model of a supply chain

The supply chain can be considered as a *system* composed of a number of *objects*. A *system* is defined to be a collection of entities, e.g., people or machines that act and interact together toward the accomplishment of some logical end (Schmidt and Taylor 1970). The selection and meaning of the system depends on the objectives of a particular study. The collection of objects that compose a system for one study might be only a subset of the overall system for another (Law and Kelton 1991). The system can again be classified as *discrete* or *continuous*. For a discrete system, the variables that define the state of the system change instantaneously at separated points in time. The "points in time", at which the state of the system changes are called *events*. On the other hand, the state variables change continuously with respect to time in a continuous system.

For the purpose of simulating the supply chain, it can be modelled as a discrete system composed of many objects. Some objects flow through the supply chain while some others remain in it and modify the flowing objects. We have defined the flowing objects as *entities* and the non-flowing objects as the *resources*. Some resources also serve as *decision points*. In other words, they determine the course of some other action. According to Wadhwa and Rao (2003), the points where the decision flow and information flows meet are the decision points and the points where the material flow and resource flows meet are the action points. The result of an action is the transformation of the material. This view was very effective in analysing the manufacturing systems where transformation of the material always takes place. But supply chain system includes both manufacturing and non-manufacturing nodes. Moreover, no transformation of the material takes place in the non-manufacturing nodes.

We extend this framework to include both manufacturing and non-manufacturing nodes. For this purpose, an action is defined as a sequence of events that intentionally changes the state of the system. Since an action is always intentional, it includes only the intentional events. Now a decision can be defined as something that determines *what*, *when*, *where*, *who* and *how* of an action. Therefore, a decision always precedes an action. In our extended framework (shown in Figure 1), the decision points are treated as the points where all the other entity flows meet. The decision point makes a decision about which action to initiate. Completion of an action may also lead to some other decision or action. This decision may either lead to some other action or some other decision also. Depending on the material flow, there can be four types of actions:

(1) *Material In*: Material storage.
(2) *Material Out*: Material release from a store.
(3) *Material In Material Out*: Material transformation, similar to the action point described by Wadhwa and Rao 2003.
(4) *No Material Flow*: All other types of actions.

Using this model, any system can be modelled as a chain of action and decision points. For the purpose of experimentation, the supply chain was modelled as a sequence of action and decision points. Each supply chain node was treated as a decision point which is connected to other such nodes by some relationship. In our model, only two kinds of

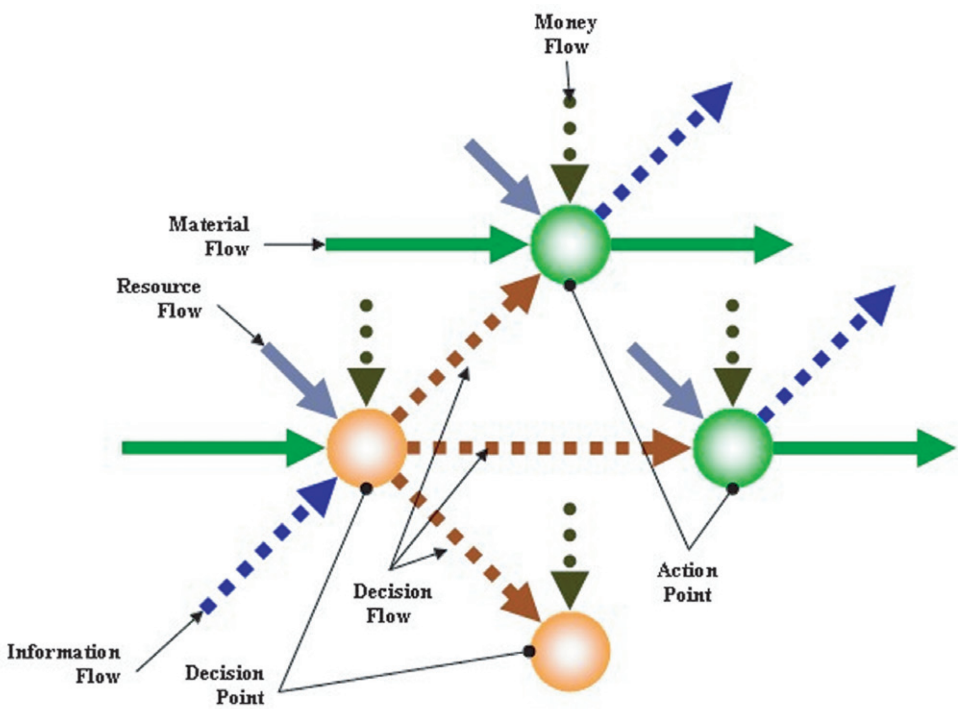

Figure 1. Multiple-entity flow perspective.

relationships: buyer and seller were sufficient to define the entire supply chain. Whenever a demand arrives to the node, the node selects the specific action depending on its inventory policy. For instance, the total inventory is identified and quantity to be supplied is determined. If total inventory is more than the demand, the total demand is fulfilled, otherwise, some backorders are created. The inventory position is then updated, and the inventory policy is used to determine whether to place an order or not. The order generated by this node is treated as demand for the seller of this node. Similarly, when the ordered goods are received at a node, backorders, if any, are fulfilled and the inventory position is updated. When the material supplied by this node is received by the buyer, it has to make a decision to store or supply the material (if there are backorders). This sequence of events is repeated for all the nodes in the supply chain.

4. Model definition

4.1 *Model parameters*

A linear supply chain with four nodes was considered for our experiments (see Table 1 for details). The objective was to study the impact of demand impulses on the stability of the supply chain for different inventory policies. For this purpose, the linear supply chain was first balanced with a constant demand and then demand impulses were introduced. The balancing of the demands assumed that all inventory policies were periodically monitored and the orders are placed once in each period. However, for simplicity and ease of comparing different inventory policies, the period of review was taken as one week. Each inventory policy places new orders in a review period if some conditions are satisfied. These conditions are different for each policy as explained below:

(i) *Demand flow*: As the name suggests, this policy just transfers the actual demand from one node to another with transforming it. The demand only gets delayed by the time equal to the ordering lead time.

(ii) *Order Q*: In this policy a fixed quantity of the product is ordered each period irrespective of the actual demand. Therefore, this policy does not consider the input demand at all.

(iii) *Order Upto*: In this policy, an *order-upto level* is selected first. This level indicates the maximum inventory to be kept. Whenever the actual inventory falls below this level, an order is placed so that the available inventory and the ordered quantity become equal to the *order-upto* level.

(iv) (s, Q) *policy*: This policy requires two parameters for definition. The first parameter (s) is called the reorder level. A new order is placed as soon as the

Table 1. Model parameters.

S. no.	Model parameter	Value
1.	Demand	Constant demand of 40 units per day
2.	Transportation lead time	Same lead time of 2 weeks between each node pair
3.	Ordering lead time	Same lead time of 2 weeks between node pair (lead time of 1 week for supplier who produces the product)
4.	Number of nodes	4 (retailer, wholesaler, manufacturer, supplier)
5.	Period	52 weeks

inventory falls below this level. The other parameter is the order quantity (Q). Therefore, in this policy, a fixed order quantity is ordered as soon as the actual inventory falls below the reorder level of inventory.

(v) (s, S) *policy*: This policy is similar to the (s, Q) policy with a difference of one parameter. Instead of a fixed quantity Q a variable quantity is ordered so that the sum of in-hand inventory and the ordered quantity become equal to some predefined maximum inventory level or order up to level (S). This policy is different from *Order Upto policy* in the sense that there is a predefined reorder level in this policy. In *Order Upto policy*, the order is placed each time the inventory position is changed. This is not necessary for (s, S) *policy*.

(vi) *Moving average policy*: In this policy, the quantity equal to the average demand of previous n periods is ordered. If previous periods are less than n, an order equal to the mean demand in available periods is placed. If the value of n becomes 1, this policy becomes equivalent to the demand flow policy. If the value of n is greater than the time of the simulation run (or the time span studied), this policy always takes into consideration the average of demand in all the previous periods. In our simulation study, we have considered n to be equal to span of simulation. Therefore, this policy is referred to as *Average demand* policy.

4.2 *Performance metrics*

Performance metrics were required to compare the results of the simulation experiments for different inventory policies. These performance metrics were individually calculated for each of the supply chain nodes. A brief description of each follows:

(i) *Inventory variation over time*: In the simulation, the negative inventory was considered to represent the backorders. Therefore, this single metric showed both inventory and backorders over time.

(ii) *Total inventory*: For calculating the total inventory, only the positive values of inventory were considered. Thus total inventory is the sum of all positive inventory values for the duration of simulation.

(iii) *Standard deviation of inventory*: This represents the standard deviation of inventory at each node. This metric included both the negative and positive values of the inventory.

Each of these metrics can be converted to cost terms by attaching a cost component to each metric. We have not included any cost terms because the costs of these metrics are different for each supply chain (and may also be different for each node in the supply chain as all nodes are autonomous members).

4.3 *Setting the policy parameters for each policy*

Each policy was first balanced so that all of them gave the same results for the test demand. For this purpose, other than the policy parameters, initial inventory at each node was also varied, so as to result in zero inventory in steady state condition. Only the inventory in steady state condition was considered significant because some inventory always remains during the initial time for most of the policies (primarily because of initial inventory). Another factor influencing the presence of inventory in transient conditions is the lead time involved in ordering and transportation. An order placed by buyer node takes a finite amount of time to reach the seller node. The seller node has to keep some inventory up to this time to fulfill this demand. However, in steady state condition, the inventory reduces to zero, as the supplies and demands match each other. The settings for each inventory policy and the reasons for each setting are discussed below.

(i) *Demand flow*: The test demand was a constant demand of 40 units per week. To fulfill the current obligations, each node has to keep a minimum of 40 units. Due to finite lead times (both ordering and transportation), the quantity ordered by a node is received only after some finite amount of time. We have assumed the ordering and transportation lead times to be 2 weeks each. Therefore, each node has to keep an initial inventory equal to four weeks of demand. As a result, an initial inventory of 160 units was allocated to each node. Total lead time of the supplier was 3 weeks; initial inventory of 120 was allocated to it.
(ii) *Order Q*: In this policy, orders are placed even when there is no demand. Therefore, inventory builds up for each node, until the actual demand is received. As a result, all nodes only need to keep an inventory equal to the value of demand per week (40 units).
(iii) *Order Upto*: No inventory build-up occurs in this policy in the initial time periods. As a result, an initial inventory has to be allocated so that each node is able to suffice the demands until they receive their corresponding ordered quantities from their sellers. This initial inventory for each node was kept the same as that for demand flow policy.
(iv) (s, Q) *policy*: The initial inventories for each node were the same as those for demand flow policy. A reorder point (s) of 160 and order quantity (Q) of 40 was set for this policy.
(v) (s, S) *policy*: Initial inventories were kept the same as the demand flow policy. Both reorder point (s) and reorder level (S) were set to be 160 units.
(vi) *Average demand policy*: The initial inventories were kept the same as those for demand flow policies.

These setting resulted in zero inventories for each of the policies under steady state conditions. The inventories for demand flow policy are shown in Figure 2 as an illustration.

4.4 *Demand impulses*

We considered the demand impulses as demand fluctuations that occur instantly but do not change the mean demand. These fluctuations last for a very short time, but their after-effects remain in the supply chain for a comparatively longer time period. As shown in Figure 3 an impulse can be defined along two primary variables: *amplitude* and *length*. For the experimentation purposes, amplitude is taken equal to the mean demand i.e. 40 and length of the impulse is taken as 2 weeks. The number of simultaneous impulses was varied from 1 to 6 to induce different degrees of variability in the supply chain. The impact of this variability on the performance of each supply chain node and on the entire chain was then evaluated based on the performance metrics recorded for each inventory policy. The subsequent sections discuss the results of these experiments.

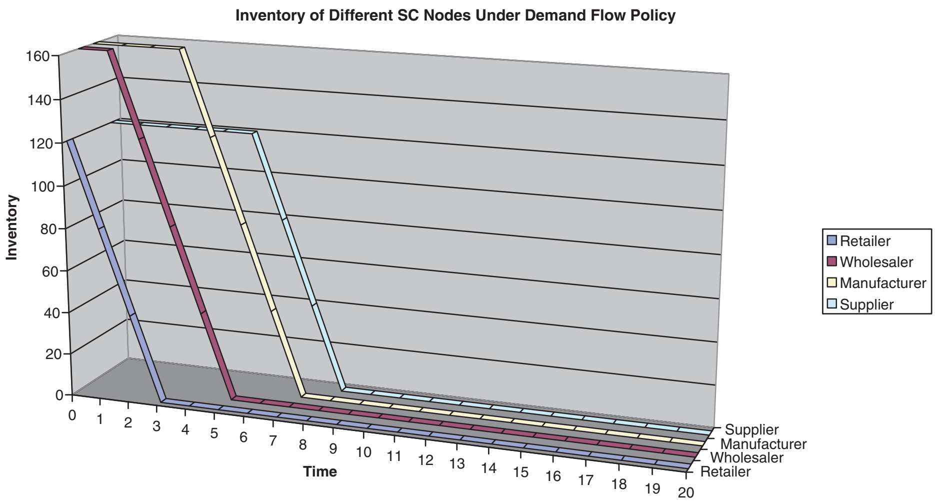

Figure 2. Inventory of supply chain nodes under demand flow policy.

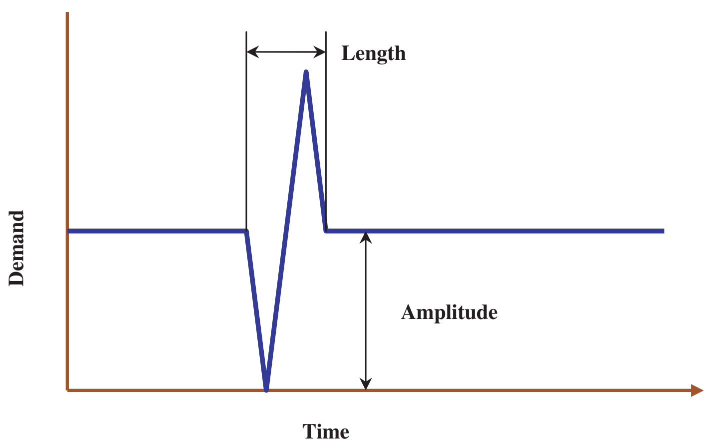

Figure 3. Impulse demand.

5. Impact of demand impulses on the performance of SC nodes

Four supply chain nodes were considered in the study. The impact of demand impulses on each node is described separately for each node in this section. For each node, the impact of demand impulses on different performance metrics under different inventory policies is discussed.

5.1 *Impact on retailer*

The inventory of the retailer for the six-impulse demand case was plotted for different inventory policies (see Figure 4). The variations in retailer's inventory can be viewed along

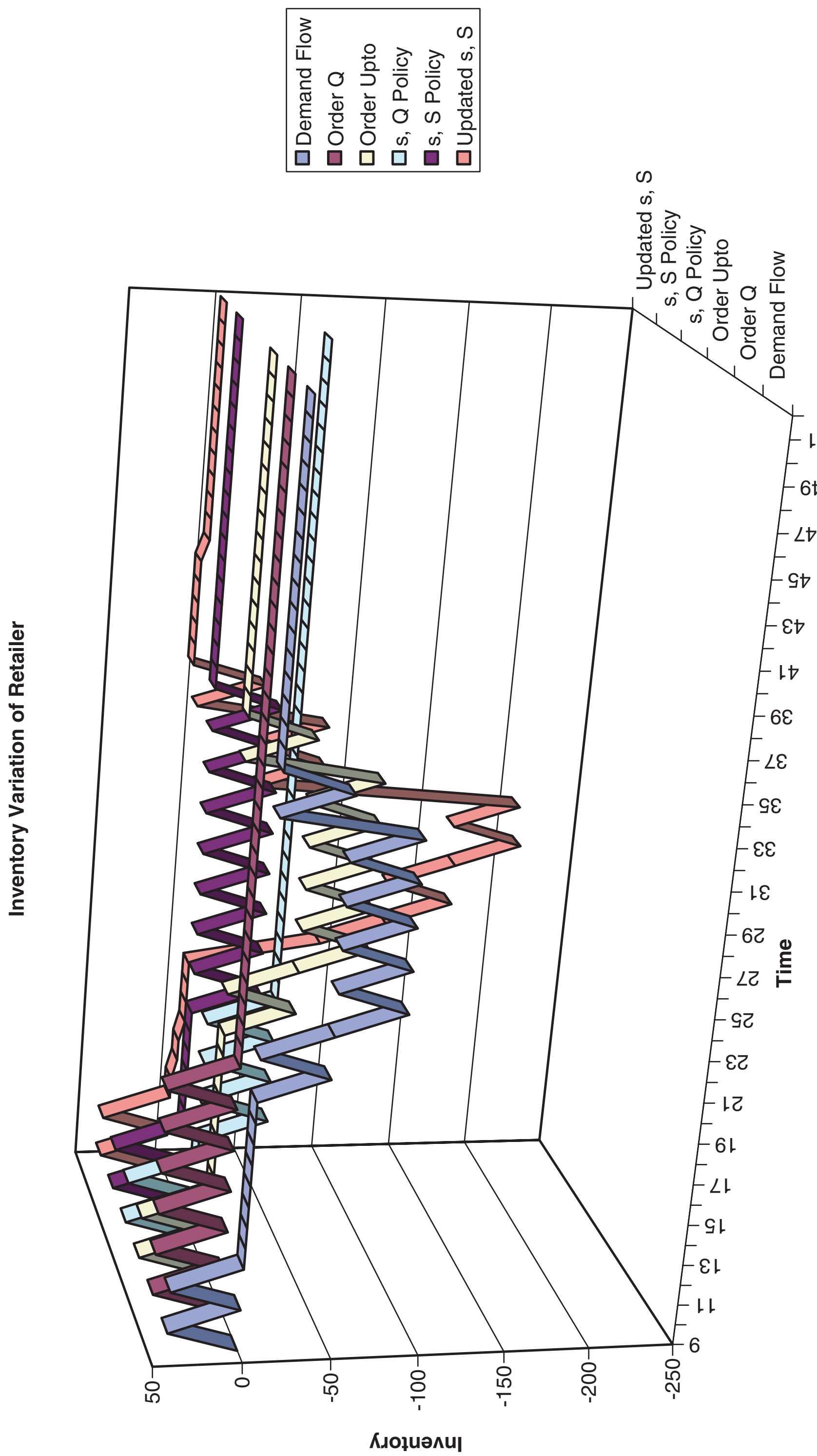

Figure 4. Inventory variation of retailer over time (for six-disturbance demand). (All figures available in colour online).

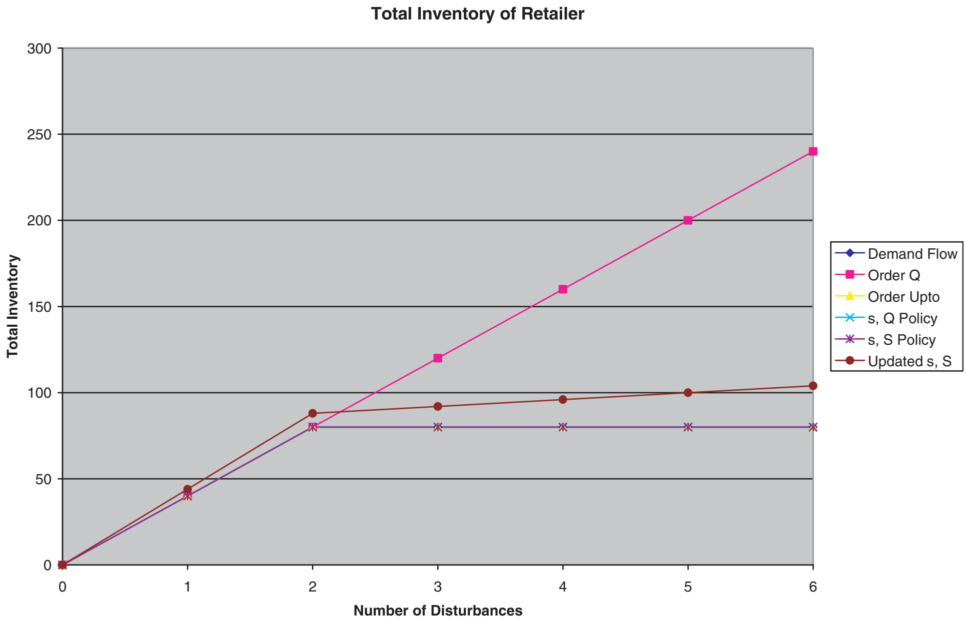

Figure 5. Total inventory of the retailer.

two distinct categories. The first type of variation is due to the nature of demand. In the impulse demand, inventory builds up during periods of no demand. This can be seen for each policy in the initial periods where inventory build-up is clearly visible. The second category of variation is visible when after a brief period of stability a large number of backorders occur for all the policies. This is attributable to finite lead times between the retailer and wholesaler. The retailer doesn't order anything during the periods of zero demand. Consequently, it doesn't receive any quantity at some point of time in future (resulting in backorders in those periods). However, the actual demand again becomes (non-zero) constant after the periods of impulse. As a result, the retailer will lack the required quantity when it needs them in future.

The impact of *number of demand* disturbances on retailer under different inventory policies is shown in Figure 5. The inventory of retailer stabilises for all policies except *Order Q* policy and *Average demand* policy. *Order Q* policy does not take into account the actual inventory levels and demands, therefore, it tends to build up inventory even though there is no demand. The picture will become clear when we discuss the retailer's backorders under this policy. The Average demand policy tends to overestimate the actual demand by averaging out the previous demands. This behaviour also induces variability in the system due to this overestimation (repercussions of this behaviour become clear for higher nodes in the supply chain as discussed later).

The standard deviation of inventory measures the variability of inventory levels for the entire span of simulation (more specifically, the span of steady state in the simulation). As shown in Figure 6, the effects are similar to those for total inventory. The maximum change in variability occurs when there is only one impulse. The effect reduces for subsequent impulses. In fact, for all policies other than *Order Q* and *Average demand*, the effect of increase in variability becomes zero after two disturbances. The standard deviation continually increases for both *Order Q* policy and *Average demand* policy but the

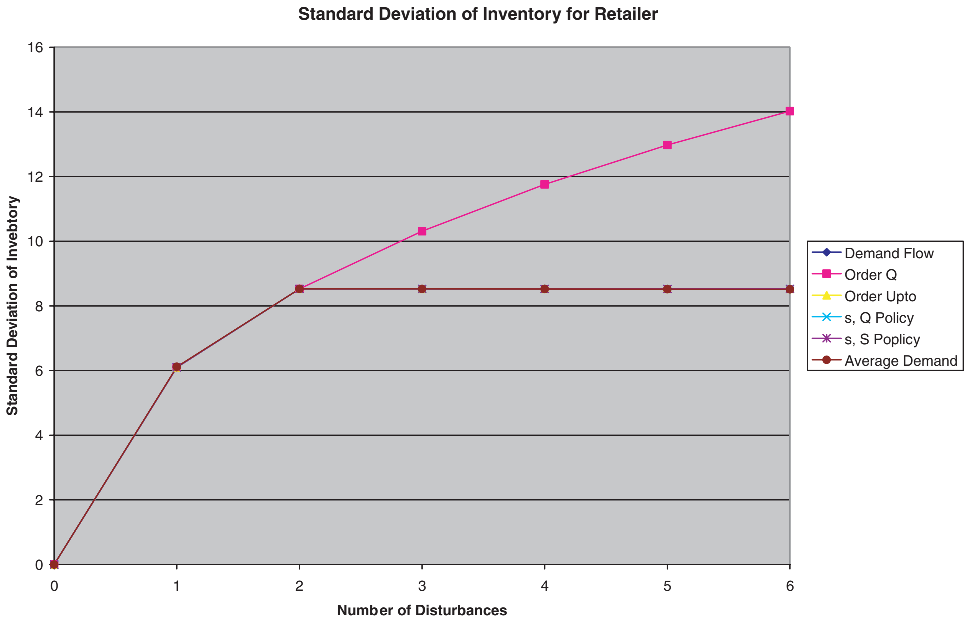

Figure 6. Standard deviation of inventory for the retailer.

increase is more pronounced for *Order Q* policy. The increase in standard deviation for *Average demand* policy after two impulses is negligible.

5.2 *Impact on wholesaler*

The demand received by the wholesaler is dependent on the orders placed by the retailer. The orders placed depend on the inventory policy used by the retailer. Therefore, the demand of the wholesaler is also dependent on the inventory policy of the retailer. Hence, the demand received by the wholesaler is different for each inventory policy. For instance, under *Order Q* policy, the wholesaler receives a constant demand of 40 units irrespective of the actual customer demand. As discussed below, the demand patterns also affect the inventory levels of the wholesaler.

This inventory pattern of the wholesaler for each inventory policy is shown in Figure 7. It needs to be highlighted that for the *Order Q* policy, the inventory remains zero throughout the simulation period. This is due to the fact that no demand disturbances were transferred to the wholesaler and as a result, the balance of the supply chain from this point onwards is not disturbed. *Demand flow* and *Order Upto* policies behave identically. Both of them show the periods of inventory build-up and backorders. The reasons for these observations are the same as those for the retailer. For the (s, Q) policy, initially only inventory build-up occurs and subsequently the inventory reduces to zero. For the same policy, the retailer does not place any fluctuated demand even when it has so many backorders. As a result, the wholesaler receives a constant demand of 40 units.

Total inventory stabilises for all policies except *Average demand* (see Figure 8). The inventory of the wholesaler under *Average demand* policy continuously increases due

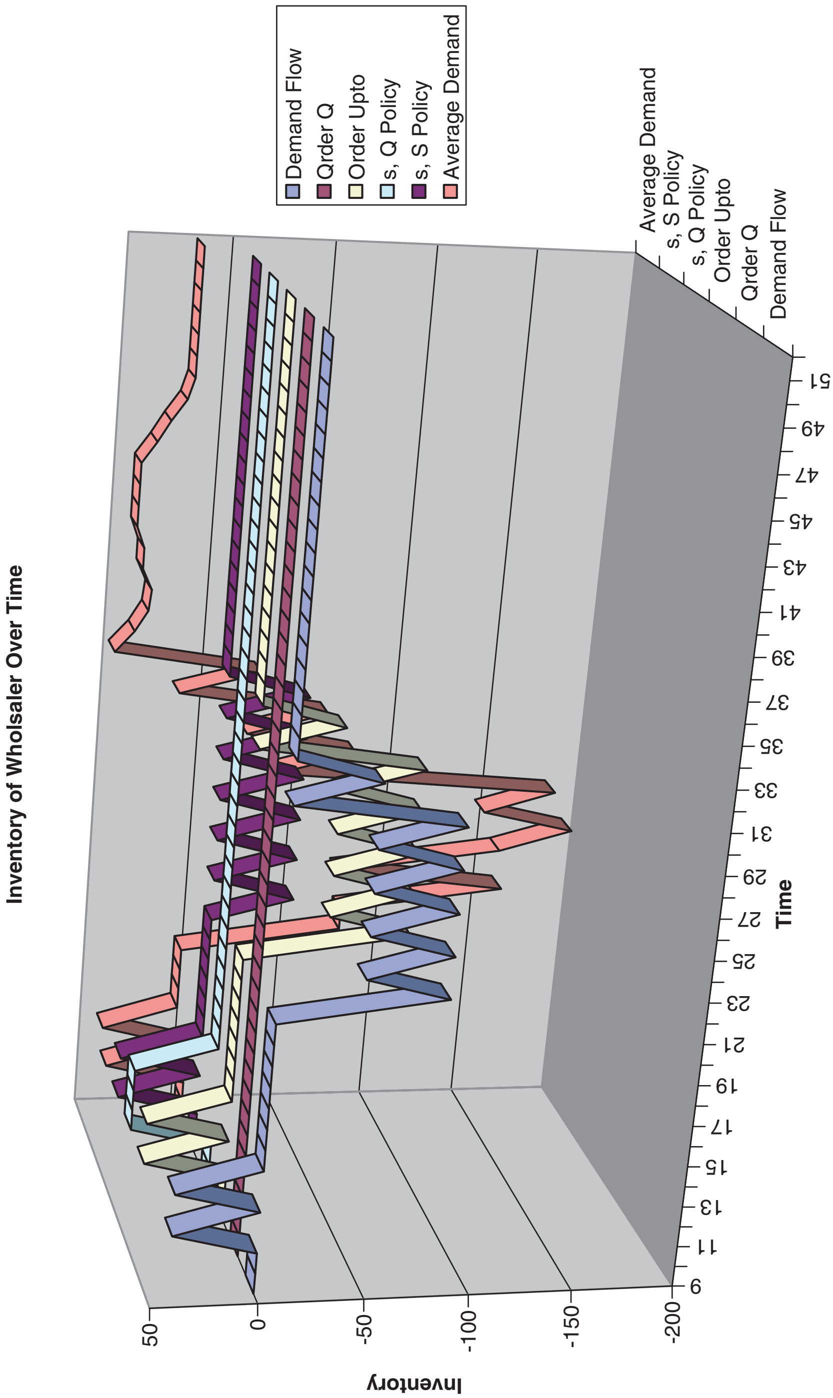

Figure 7. Inventory of wholesaler over time (for six-disturbance demand).

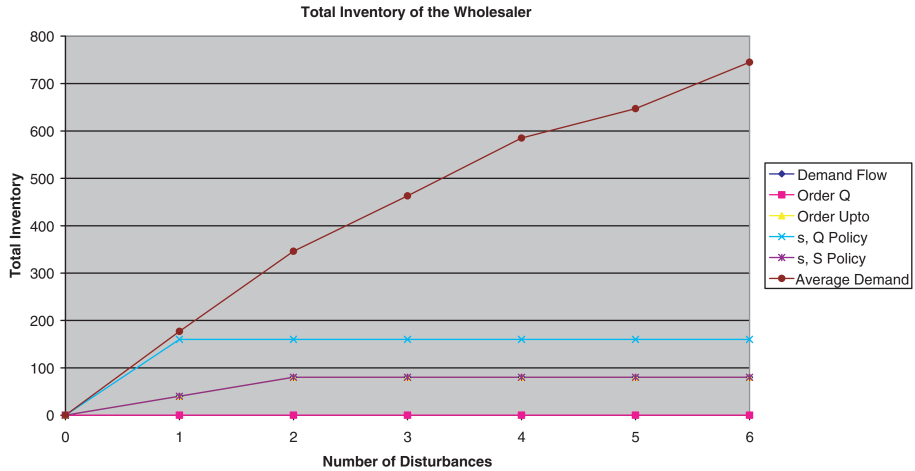

Figure 8. Total inventory of the wholesaler.

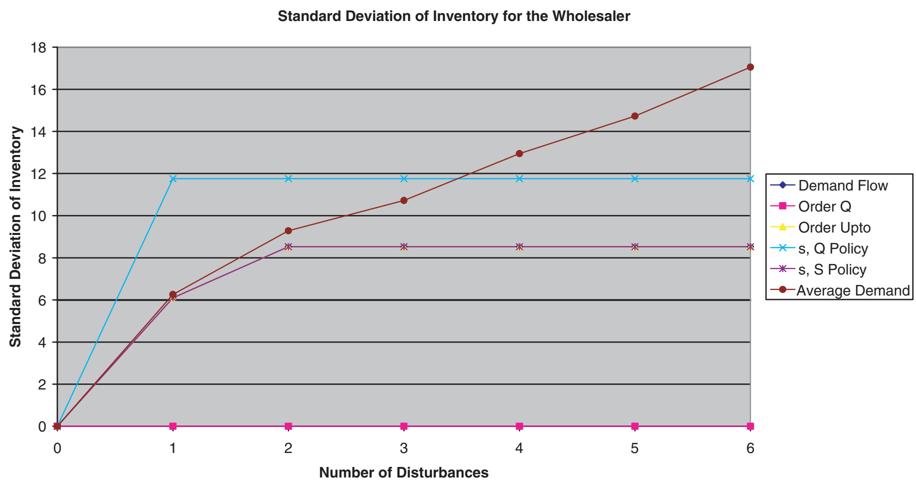

Figure 9. Standard deviation of inventory for the wholesaler.

to the demand variability induced by the retailer and this variability being magnified by the wholesaler. The *Order Q* policy, which showed the worst results for the retailer, shows the best result for the wholesaler. As discussed above, this is due to the fact that the retailer does not transfer any demand variability further up in the supply chain. Among the other policies, the (s, Q) policy stabilises most quickly as the variability due to demand impulses is not transferred to it. But these are not as efficient as the other policies that stabilise late but lead to lower total inventory of the wholesaler. The variation of standard deviation of inventory under different inventory policies was similar to that of total inventory as shown in Figure 9.

5.3 *Impact on manufacturer*

Inventory variation of manufacturer over time is shown in Figure 10. All the policies behave similar to their behaviour for the wholesaler. A finite lead time effect is clearly visible in the initial periods where each corresponding peak or valley on the manufacturer's inventory graph is delayed by the corresponding peak or valley on the wholesaler's inventory graph by a time equal to the information lead between wholesaler and retailer. The total inventory of the retailer and standard deviation of inventory are shown in Figures 11 and 12, respectively. They show a trend similar to that for the wholesaler except for the time delays.

5.4 *Impact on supplier*

Figure 13 shows the variation of inventory for the supplier over time. It can be seen that *Average demand* policy leads to very high inventories and backorders. The two specific disturbance regions, one of inventory build-up and the other of backorders, are not distinctly visible for the supplier. These two regions overlap each other for the supplier. As a result, both inventory build-up and backorders occur in alternate periods. Of course, the two disturbance regions are distinct with (*s*, *S*) policy. The variation of total inventory and the standard deviation of inventory are shown in Figure 14 and Figure 15, respectively. No abnormal trend can be observed from these figures.

6. Impact on the entire supply chain

The impact of demand disturbance on the entire supply chain could be viewed along two separate lines: the impact of demand disturbance on the collective performance metrics and the impact on the performance metrics along the supply chain. For the former case, the collective measure of each performance metric was calculated by the taking the sum of the individual metrics for each supply chain node. For instance, the total inventory in the supply chain was found by adding the total inventories at all four nodes. For comparing the performance along the supply chain, the worst-case demand of six impulses was considered for comparison.

6.1 *Collective impact on the supply chain*

The inventory in the supply chain over time for a six-impulse demand under different inventory policies is shown in Figure 16. The variation of inventory is somewhat similar to that obtained for individual nodes. There are two distinct disturbance regions for most of the policies: one of inventory build-up and the other of backorders. For all the policies other than *Average demand* policy, the supply chain inventory stabilised after some time. The *Average demand* policy, on the other hand, shows some residual inventory even up to the end of simulation span.

The total inventory in the supply chain shows some abnormal but important results (see Figure 17). The *Order Q* policy showed maximum inventory levels for the retailer. However, when the entire supply chain is considered, this policy leads to minimum inventory in the system. The retailer absorbs all the demand disturbances and hence all subsequent nodes always get a constant and stable demand. The next best policy in terms

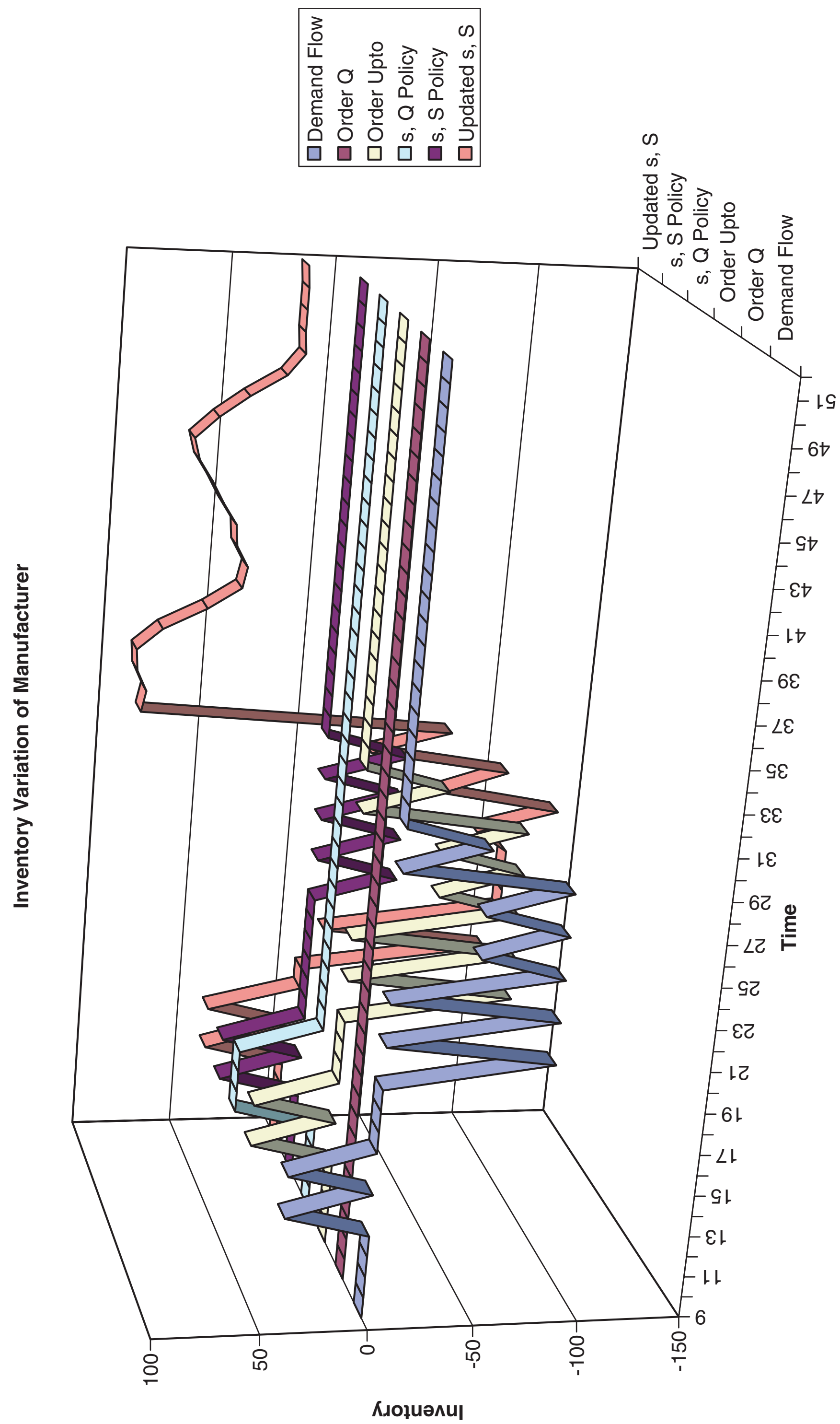

Figure 10. Inventory of manufacturer over time (for six-disturbance demand).

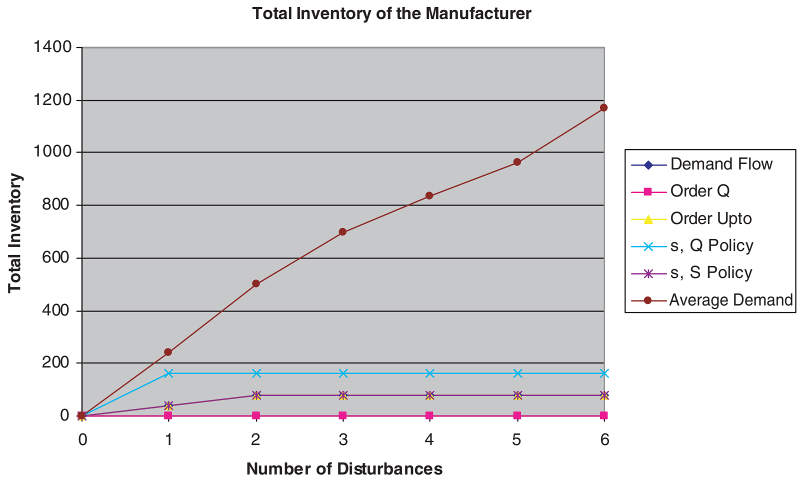

Figure 11. Total inventory of the manufacturer.

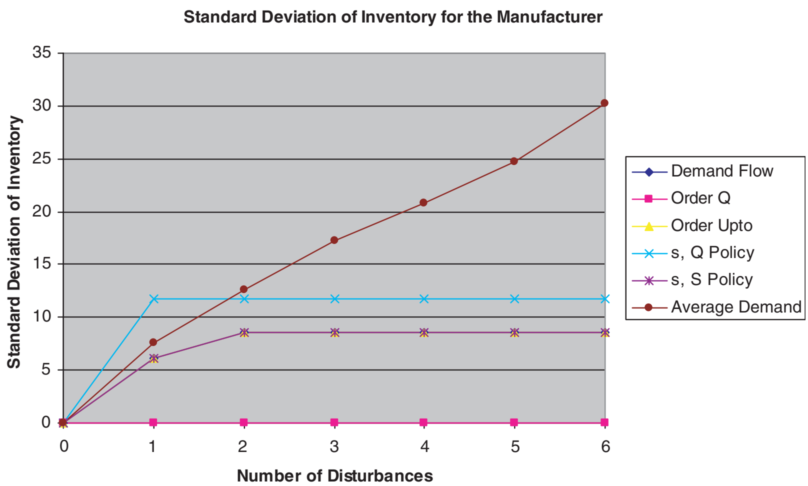

Figure 12. Standard deviation of inventory for the manufacturer.

of total inventory is the (s, S) policy. The total inventory in *Average demand* policy always shows an increasing trend.

6.2 *Impact along the supply chain*

The impact of demand disturbance is different for each supply chain node even for the same inventory policy. For analysing the impact of demand disturbance along the supply chain, the performance metrics obtained by using the six-impulses demand were compared for each inventory policy. Figure 18 shows the total inventory along the supply chain. Although the total inventory was maximum for retailer under *Order Q* policy, it was zero

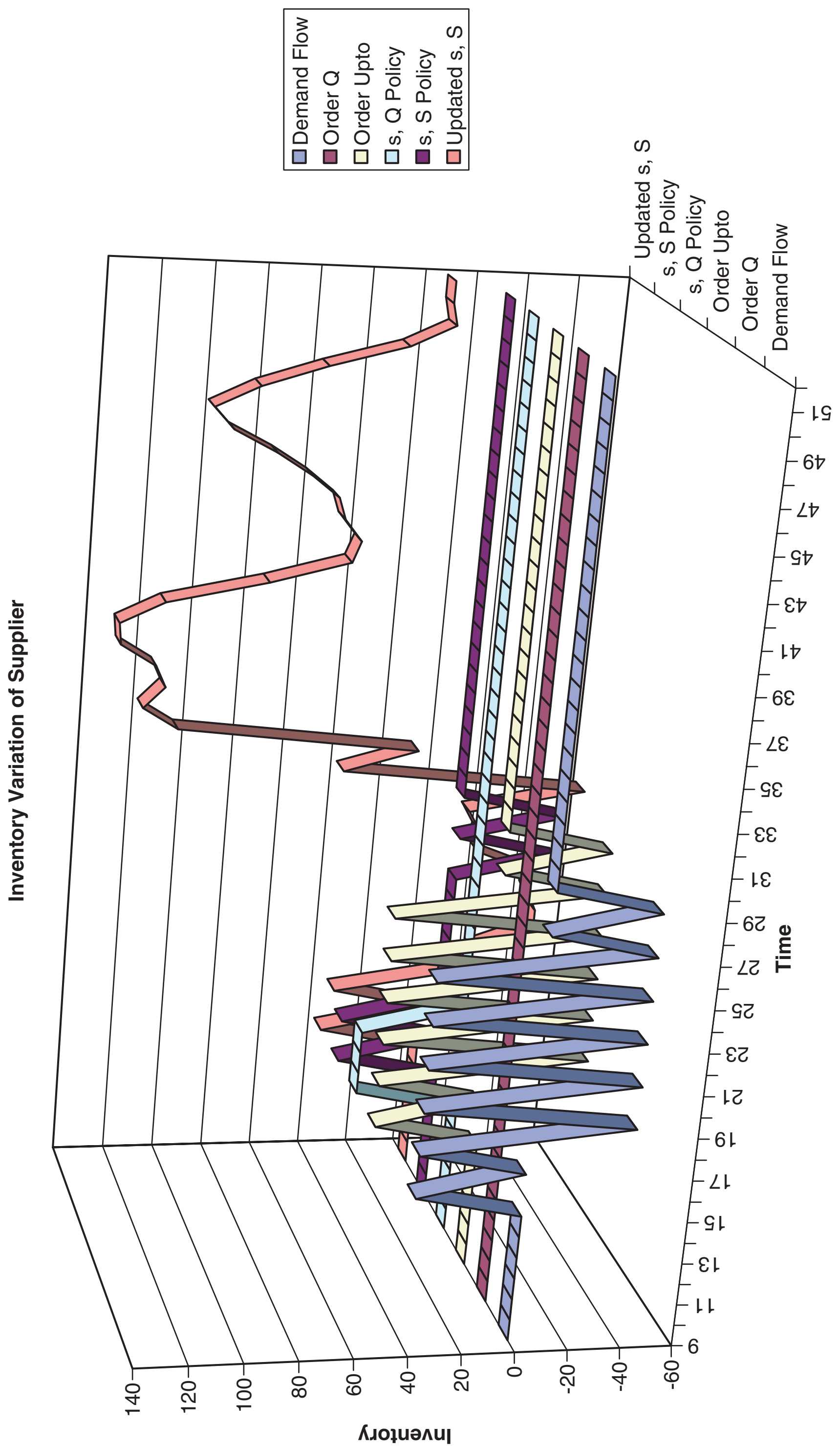

Figure 13. Inventory of the supplier over time (for six-disturbance demand).

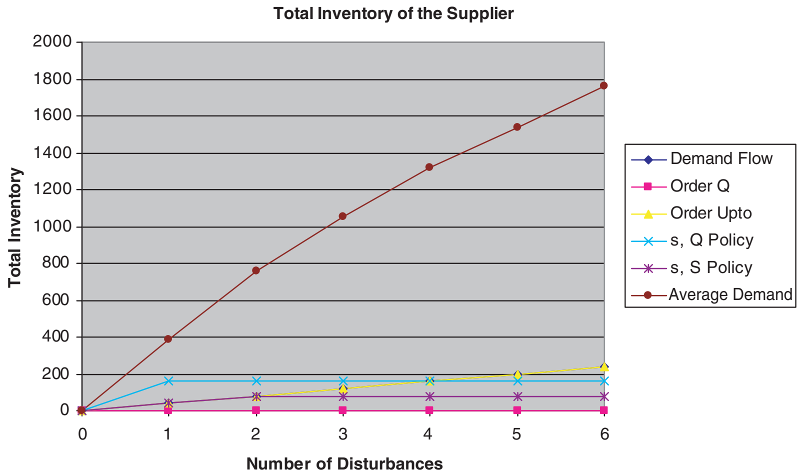

Figure 14. Total inventory of the retailer.

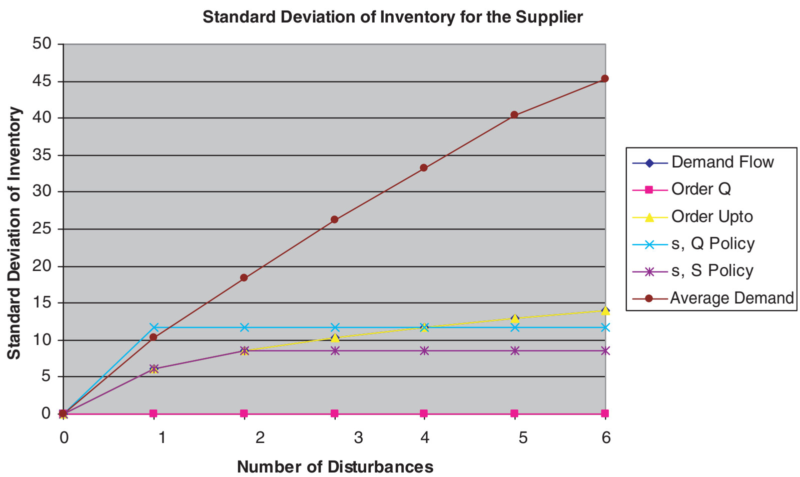

Figure 15. Standard deviation of inventory for the supplier.

for all other subsequent nodes, thus leading to minimum total inventory. The inventory at each node remains the same for the (s, S) policy. For *Order Q* and *Demand flow* policies, the inventory is the same for all the nodes except the retailer. The retailer maintains maximum inventory under these policies. In the (s, Q) policy, the retailer doesn't place enough orders to fulfill its own backorders. As a result, inventory builds up at other subsequent nodes. The *Average demand* policy monotonously increases the inventory along the supply chain.

The variation of standard deviation of inventory along the supply chain is shown in Figure 19. Standard deviation of inventory remains the same along the supply chain for *Demand flow* policy. This inventory policy only transfers the actual demand. The disturbances in inventory occur only due to finite lead times. As compared to other

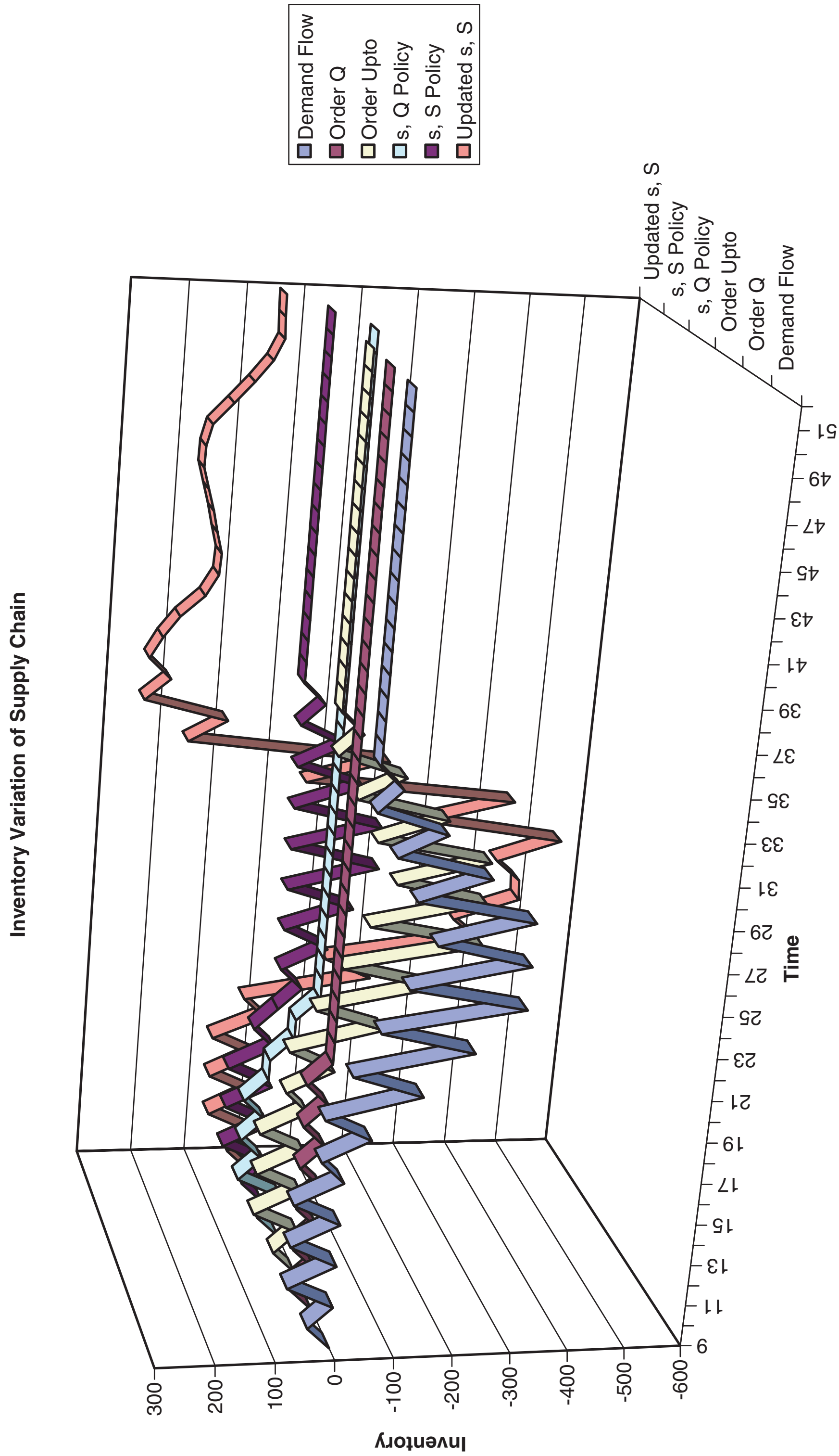

Figure 16. Inventory in the supply chain over time.

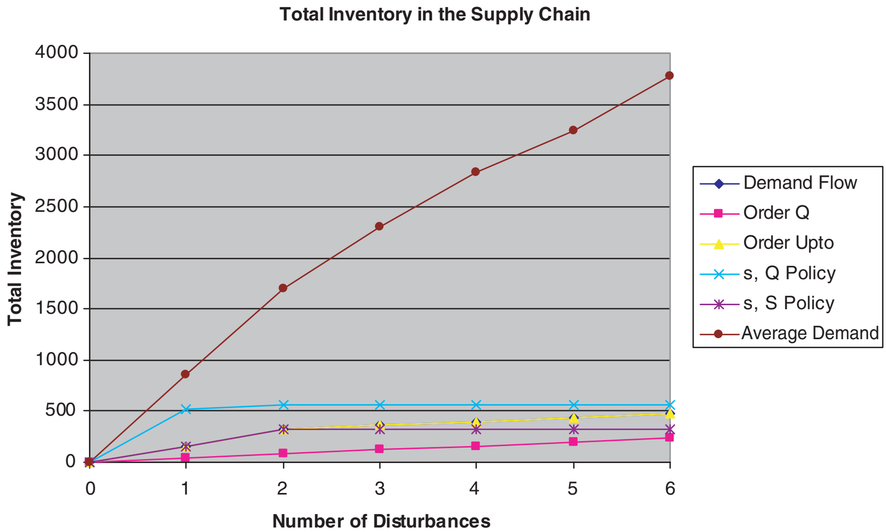

Figure 17. Total inventory in the supply chain.

policies, the standard deviation of inventory for retailer is maximum with this policy. But when the entire supply chain is considered, this policy is better than most other policies. The *Order Q* policy shows reduction in standard deviation of inventory along the supply chain. Although, standard deviation of inventory is quite high for the retailer, it is zero for all other supply chain nodes. This is because the retailer does not transfer any demand fluctuations higher up in the chain by always sending a constant demand to the wholesaler. Standard deviation of inventory increases for all other policies. However, the increase is more pronounced in the case of *Average demand* policy. The increase in standard deviation is restricted up to manufacturer by using the (s, S) or (s, Q) policies. However, out of these two policies (s, S) policy performs better in terms of standard deviation of inventory.

7. Research implications

This demand variability is present in all supply chains but their impact on whole supply chain was not studied well. As a result, making suitable ordering decisions becomes difficult for the managers. Our results show the effects of demand disturbances on the performance of each member of the supply chain. In our experimental study, the impulsive demand fluctuations were used to induce controllable variability in the supply chain. This induced variability affected each supply chain node differently, based on the inventory policy used by that node. Our studies revealed the impact of each inventory policy on the supply chain under different degrees of demand disturbance.

It was found that the inventory policies that are most efficient for one particular node are not necessarily efficient for the entire supply chain. A particular case is that of *Order Q* policy which had the worst performance for the retailer. However, from the supply chain perspective this simple inventory policy had many advantages over other complex inventory policies. First of all, this policy leads to best performance of all nodes other

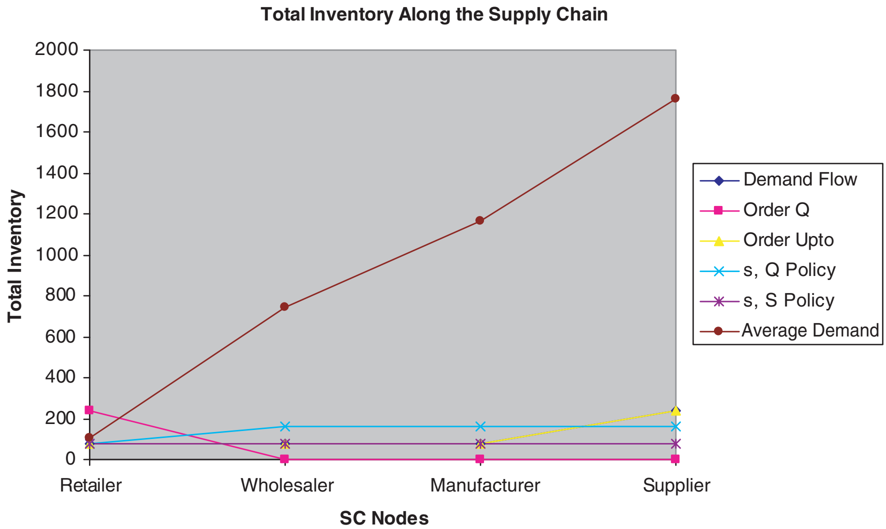

Figure 18. Total inventory along the supply chain (for six-impulse demand).

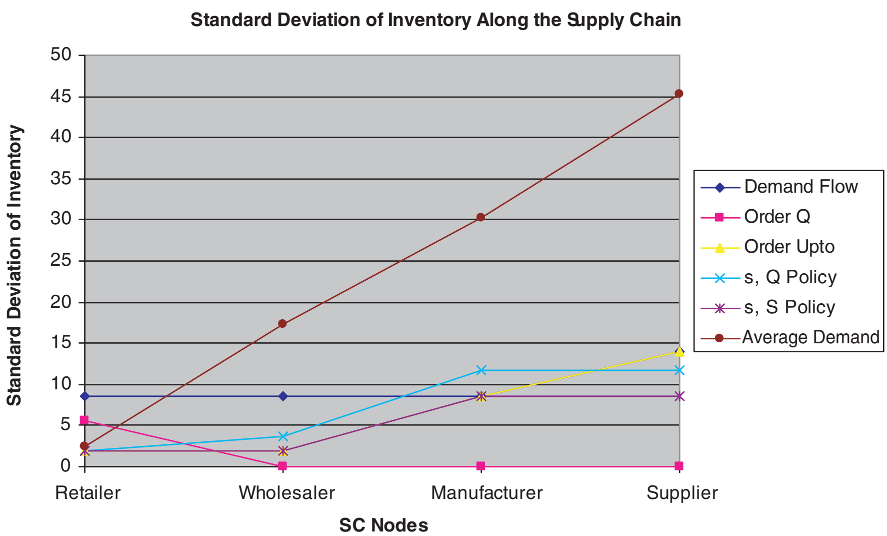

Figure 19. Standard deviation of inventory along the supply chain (for six-impulse demand).

than retailer. Second, this is the only policy where the variance of inventory reduces along the supply chain. This is because all the demand variability is absorbed by the retailer. This observation has tremendous repercussions for the supply chain managers. This provides a justification for having mutual trust and understanding among the supply chain members. By coordinated inventory management, the demand disturbances could be restricted only up to the retailer and a joint inventory policy arrived at. The overall performance of the supply chain can therefore be improved by this joint inventory policy.

To perform efficiently, the supply chain nodes need not apply complicated tools or share accurate demand information to all the members of the supply chain. By sharing only the partial information about the mean demands and ordering as per the average demand, improves the overall performance of the supply chain significantly. It dampens the demand variability of higher level nodes. From the retailer's perspective, the fluctuations in demand may cancel out each other and may not lead to very poor performance. Additionally, the retailer can keep some level of safety inventory to take care of eccentric demand fluctuations. This may lead to additional cost at the retailer's end. Under these conditions the other supply chain nodes should apply some mechanism by which they can induce the retailer to their requirements. Some form of quantity discounts or profit-sharing mechanism may be effective to motivate the retailer to absorb demand variability up to itself.

Another important observation is regarding the policies that take out the average demand for calculating the order quantity. It was observed that these policies (*Average demand* policy) perform worst in stochastic demand situations. Under this policy, each member in the supply chain tries to play safe and keeps the inventory to some current inventory level based on the demand perceived by that node. Additionally, some safety stock may be kept to accommodate unexpected demand fluctuations. These two factors distort the actual demand and the corresponding node, and in turn, send this distorted demand to the higher node. Under this setting, it is imperative that actual demand information is available to each node. But if all the supply chain nodes work independently, the information sharing may not be fruitful. However, this policy can perform better than other policies when the demand follows a particular trend.

In addition, an observation that needs to be highlighted is regarding the demand flow policy. Under this policy, the demand is transferred from one node to another without being distorted. This policy does not lead to demand amplification or increase in demand variability. This could be considered as a special case of full information sharing. The results from this policy show that it has just one weakness: it delays the demand information in accordance with the order lead times. This weakness can be partially eliminated by using Information and Communication Technology (ICT) whereby demand information could be transferred over the internet. The transportation lead times can be reduced by using efficient logistics. However, it needs to be pointed out that transportation lead time cannot be brought down to zero. This policy also calls for mutual faith and understanding among all the supply chain members.

In general, the inventory policy could be considered as a function of inventory, demand, ordering and transportation lead times.

$$O_{ij} = f(I_{ij}, D_i, OLT_i, TLT_i)$$

$$\text{where} \quad i = \text{Supply chain node}$$

$$j = \text{Time period}$$

If a linear relationship can be assumed, the order quantity can be defined as given below.

$$O_{ij} = a_1 I_{ij} + a_2 D_i + a_3 OLT_i + a_4 TLT_i + b_i + e_{ij}$$

Here, b_i is equal to some integer constant and e_{ij} is the error induced by the system. The demand of the supply chain in jth period is itself equal to the order placed by the lower

Table 2. Mathematical representation of inventory policies.

S. no.	Inventory policy	Mathematical representation
1.	*Order Q*	$O_{ij} = b_i$
2.	Demand flow	$O_{ij} = D_{ij}$
3.	Order Upto	$O_{ij} = I_{ij} + b_i + e_{ij}$
4.	(*s*, *Q*) policy	$O_{ij} = I_{ij} + b_i + c_i$
5.	(*s*, *S*) policy	$O_{ij} = I_{ij} + b_i + c_i + e_{ij}$
6.	Average demand	$O_{ij} = a_1 I_{ij} + a_2 D_{ij} + b_{ij} + c_{ij} + d_i + e_{ij}$

level node in the $(j - OLT_{i-1})$ period. Similarly, the order placed by *i*th node in *j*th period becomes the demand for $i+1$th node in $(j + OLT_{i}.)$ period.

$$D_{ij} = O_{(i-1)(j-OLT_{i-1})}$$

All the variables in the order quantity can induce variability in the supply chain. A mathematical representation of some inventory policies is given in Table 2. The *Order Q* policy places a fixed quantity order irrespective of the actual demand. Therefore, only a constant is used to define this policy. The *Order Upto* policy places a variable order depending on the current inventory level and some constant *Order-upto Quantity*. Therefore, a constant and an error term are introduced in it. Both (*s*, *S*) and (*s*, *Q*) policies require two constants for their definition. The first constant is reorder level for both policies while the second constant is order quantity for (*s*, *Q*) policy and order upto level for (*s*, *S*) policy. The average demand policy considers the previous demand pattern also. Moreover, the order-upto level and reorder level are decided based on previous demand therefore they are also added as a variable term. An additional maximum order level can also be added to show the capacity constraints.

Comparison of this mathematical model of inventory policies with their performance in dynamic demand scenarios reveals that as the number of parameters included in the inventory policy increases, their performance tends to degrade. However, this observation cannot be blindly applied in a supply chain. The performance of inventory policies shown in our results is only for impulsive demand fluctuations. In such a scenario, the mean demand remains more or less unaffected. However, if the mean demand changes, the results may differ. Therefore, a good inventory policy should also include some fraction of demand variability to some extent. This allows them to identify and adopt to actual demand changes. The amount of variability to be included depends on the nature of the product and its demand pattern. For the products having a stable demand, the minor fluctuations need not be taken into consideration. For other kinds of products, a small part of variation may be included to allow the other supply chain nodes to prepare for any significant increase or decrease in demand.

8. Conclusions

This paper attempted to study the impact of impulsive demand fluctuations on different inventory policies used in the supply chain. The supply chain was modelled as a network of independent and autonomous supply chain nodes. This generic framework was used to replicate the behaviour of a four-node single-product linear supply chain. A comparison of different inventory policies revealed that simpler inventory policies are better prepared to dampen or even reduce the impulsive demand fluctuations. In particular, ordering a fixed order quantity rather than the quantity determined by inventory position or demand history was found to be more efficient under impulsive demand fluctuations. Another important finding was that the inventory policy that was most beneficial for one node resulted in overall poor performance of the supply chain. Moreover, the inventory policies that take previous demand information tend to magnify and distort the actual demand variations. For instance, the *Average demand* policy was found to perform poorly under impulse demand fluctuations. The findings from this research are significant for the supply chains facing stable but fluctuating demand. We have shown that, under this demand pattern, the best policy is not to transmit these fluctuations along the supply chain. This is possible by ordering a fixed order quantity in each period. Although this leads to somewhat poor performance of the retailer, it proves to be most effective for all other supply chain nodes. These findings also provide an additional motivation for coordinated inventory management in the supply chain by demonstrating that the inventory policies that are best for one supply chain node are more often than not poor from the supply chain perspective.

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