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System dynamics modelling for supply-chain management: A case study on a supermarket chain in the UK

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Abstract

This paper presents a system dynamics (SD) approach for the analysis of the demand amplification problem, also known as the bullwhip effect, which has been studied fairly extensively in the literature. The construction of an SD model is reported using a part of a supermarket chain system in the UK as an example. Based on the model, the causes of the dynamic behaviour of the system and the sources of amplification from the downstream to the upstream of the chain are investigated. The impact of information delays, demand forecasting and information sharing on the performance of the multi-echelon supply chain is analysed. Some implementation issues are also addressed based on the simulation analysis.

Keywords: system dynamics; demand amplification; bullwhip effect; simulation; control theory

Introduction

Concepts and strategies for the successful management of a supply chain system have been offered in the literature as the concept has gained popularity (Lummus and Vokurka, 1999; Simchi-Levi, Kaminsky and Simchi-Levi, 2000; Stevens, 1989). According to Stevens (1989) a supply chain is a system whose constituent parts include material suppliers, production facilities, distribution services, and customers linked together via the feed-forward flow of materials and the feedback flow of information.

One common phenomenon exhibited by most supply-chain systems is the demand amplification or bullwhip effect, which has been studied fairly extensively in the literature (Forrester, 1961; Lee, Padmanabhan and Whang, 1997a, 1997b; Simchi-Levi et al., 2000; Sterman, 1989). This paper aims to investigate further the demand amplification phenomenon using the SD approach based on a part of a supermarket chain system in the UK.

The company at the downstream end of the supply chain investigated in this paper is a large grocery retailer in the United Kingdom, with multi-billion-pound revenues, hundreds of thousands of employees, and several hundreds of stores across the UK, Ireland, France, Eastern Europe, and Asia. It has a double-figure share of the supermarket sector in the UK. As a leading grocery retailer, the company is focused on customer service and loyalty, and committed to working with its suppliers to meet consumer demands better, faster, and at lower costs. One supplier of the company's napkin product is a global fast-moving consumer goods company, with multi-billion-pound turnover globally. Over the past years the retailer company has been collaborating with its suppliers, in better predicting and meeting consumer demands and thus reducing shortages, overstocks, and waste, and ensuring the performance and resilience of its supply systems. The model used in this research is based on Silén's (1998) model built in iThink (High Performance Systems Inc., 1997). The product concerned is a leading napkin product, which holds two-thirds of the market. However, due to promotion policies commonly adopted by the manufacturing company, the supply-chain system often experiences the demand amplification problem, which has a serious impact on the performance of both the retailer and the supplier. Therefore the supply chain has the objective to maintain the inventory at a desired level in spite of fluctuation in demands taking into account various kinds of information and physical delays, and the dynamics of the system.

Literature review

The demand amplification or the bullwhip effect was initially known as the 'Forrester Effect' (Forrester, 1961). According to Forrester (1961), medium-period demand amplification was an SD phenomenon that could be tackled by reducing or even eliminating delays and the proper design of feedback loops. Sterman (1989) examines and reports evidence of the bullwhip effect through an experiment with the 'beer distribution game' to convince senior executives of the effect of system structure on system behaviour. A formal definition of the bullwhip effect is given by Lee, Padmanabhan and Whang (1997a) as follows:

> The bullwhip effect or whiplash effect refers to the phenomenon where orders to the supplier tend to have larger variance than sales to the buyer (i.e., demand distortion), and the distortion propagates upstream in an amplified form (i.e. variance amplification) (p. 546).

The demand amplification effect has been well described in the literature over many years; however, it is only recently that the full extent of the problem has been recognised (Towill, 1996b), which has stimulated the interest of a number of researchers.

Bourland, Powell and Pike (1996) provided an analytical study on how timely demand information can alter the behaviour of a two-level supply chain composed of a supplier that supplies a single product to a customer. It is concluded that with more accurate demand information, the supplier could reduce inventories and improve the reliability of its deliveries to its customer, which in turn could enable its customer to reduce its inventories, so the whole supply chain can benefit from the timely demand information. Gavirneni (2001) examined the value of information sharing for managing echelon inventories in a simple production distribution environment in which one supplier was producing a single product and supplying it to many identical retailers.

Towill's (1996b) research confirmed the findings of Forrester (1961) and other pioneer researchers that the collapsing of all cycle times within a supply chain would enhance business competitiveness to the advantage of all players in the chain.

Based on Forrester's (1961) research, Lee et al. (1997a, 1997b) further analysed the information distortion and demand variability amplification along a supply chain from retailers to distributors. The following are the four sources of uncertainty identified which lead to the 'bullwhip effect': demand signal processing, rationing game, order batching, and price variations. Lee et al. (1997a) mathematically proved that the demand variation was amplified when orders were passed from a downstream retailer to an upstream supplier and demonstrated that information sharing reduces the supplier's demand variance. However, they did not investigate the impact of the bullwhip effect on the performance of the supply chain.

Chen, Drezner, Ryan and Simchi-Levi (2000a) quantified the bullwhip effect for a simple, two-stage supply chain consisting of a single retailer and a single manufacturer. In their model, the retailer used a moving-average technique for demand forecast, and a simple order-up-to inventory policy for replenishment. Under certain assumptions, they demonstrated that the observation frequency used in the moving average and the lead time between the retailer and the manufacturer have significant impact on the bullwhip effect. Chen, Ryan and Simchi-Levi (2000b) compared an exponential-smoothing forecasting model and a moving-average model. They demonstrated that reduction in ordering lead time, and using longer-period information in forecasting could decrease the bullwhip effect. These two papers evaluated the bullwhip effect by comparing alternative demand processes and forecasting techniques for a simple supply-chain structure. However, they did not investigate the bullwhip effect in a supply chain with more than two echelons, which is more pertinent to the real situation.

Simchi-Levi et al. (2000) presented a good discussion of the bullwhip effect with some analytic results based on a case study on the supply chain of the world's largest pasta producer, Barilla SpA. It is concluded that 'centralising demand information can significantly reduce, but will not eliminate, the bullwhip effect' (Simchi-Levi et al., 2000, p. 91). Several methods for coping with the bullwhip effect have also been analysed, which include reducing uncertainty and variability, lead-time reduction, and strategic partnerships.

McCullen and Towill (2001) investigated the bullwhip effect of a three-echelon global supply chain consisting of overseas warehouses, a central UK finished-goods warehouse, and a UK factory. They observed the following phenomenon exhibited by the supply chain system: 'Storage and obsolescent costs are both high. At the same time, marketing often exacerbates these out-of-phase effects through their excessive reliance on sales promotions and end-of-period sales bonuses' (McCullen and Towill, 2001, p. 24). Four material-flow principles including the selection of appropriate control systems, cycle time-compression, information transparency, and echelon elimination are proposed to reduce the bullwhip effect.

The literature review shows that variability in demand increases as one moves upstream in the supply chain, which causes significant operational inefficiencies. The bullwhip effect has been studied extensively and various methods to reduce its impact have been explored. However, the effectiveness of various methods on reducing the bullwhip effect of a multi-echelon supply-chain system has not been fully investigated. This paper aims to shed some light on this issue based on some practical promotion scenarios of the supply-chain system using a SD approach.

SD model

In the SD model of the company's supply-chain system, the following are the most important factors to be included: major rates of flow, principal information delays and physical delays, and sources of amplification.

Principal information delays and physical delays were included in the model because these delays play an important part in the dynamic behaviour of supply chain systems and are critical causes of instability. The major physical delays of the supply-chain model are as follows: 1) store's delivery delay; 2) distribution centre's delivery delay; 3) supplier's production delay; 4) import transportation delay; and 5) raw-material delivery delay.

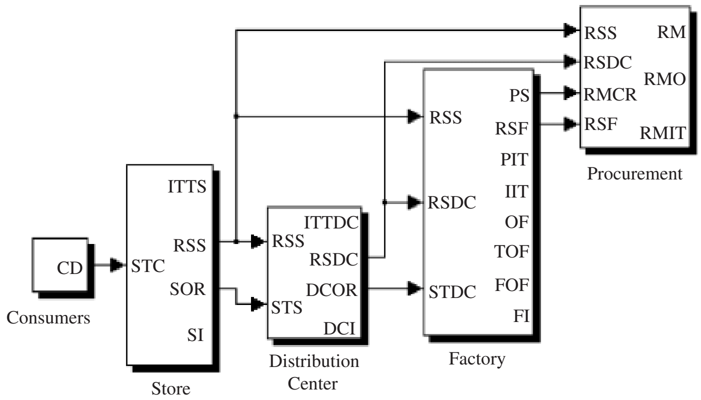
Sources of amplification should also be incorporated and identified for its importance in the dynamic behaviour of the whole system. According to Forrester (1961), the first of these amplifications arises from the necessity for filling supply pipelines with goods to satisfy the demand of its immediate customer. The second amplification arises from the desire to maintain an inventory that is proportional to its perceived demands at different parts of the echelon. Because of these two key sources, amplifications are transferred unavoidably from one end of the supply chain—the consumer—to the other end of the chain—raw-material supplier. This research is focused on the main channel of material flow from raw-materials supplier to consumers, and on the principal stream of information flow in the form of orders moving from consumer to raw-material supplier.

SD model of the supply chain

Figure 1 is the high-level diagram of the SD model for the company's supply chain system built in MATLAB/SIMULINK (Mathworks Inc., 1996). It shows how information of consumer demands is passed from downstream consumers to upstream raw material suppliers. The high-level diagram of Fig. 1 shows that the supply chain is composed of five subsystems: the end consumers, the retailer's store, the retailer's distribution centre, the manufacturer's factory, and its procurement system. Each subsystem can be examined closely using low-level diagrams and equations that actually govern the dynamic behaviour of the system.

Take for example the raw-material ordering subsystem. The subsystem is composed of one sixth-order physical delay, one integrator, four information delays, one first-order exponential smoothing block, six switches, and several mathematical function blocks as shown in Fig. 2.

Raw material purchasing is a complicated task in rapidly changing operating conditions. This subsystem is at the upstream end of the whole supply chain. There is normally a lead time from material ordering to its actual arrival at the manufacturer. In this model, it is assumed that the manufacturer's order of raw materials can always be met. In other words, the source of raw materials has unlimited capacity. However, with more accurate information available, it can be extended to situations where the supply of raw materials is limited. In Silén's (1998) model, it is assumed that production rate is fixed and as a result the raw material consumption rate is fixed at the rate of 1000 units/day. This inflexibility cannot meet the requirement of changing demands. When demands increase or decrease, inventory will build up or the company will have to import from another country at much higher costs. However, this is improved by introducing flexible production and raw material ordering mechanisms in the model developed in this paper. In constructing the decision of raw material ordering, the first task is to identify the principal sources



Note:		
	CD—consumer demand	STC—sold to consumers
	ITTS—in transit to store	RSS—requisition smoothed at store
	SOR—store order rate	DCOR—distribution centre order rate
	STS—shipped to store	ITTDC—in transit to distribution centre
	SI—store inventory	DCI—distribution centre inventory
	PS—production schedule	STDC—shipped to distribution centre
	PIT—product in transit	RSF—requisition smoothed at factory
	IIT—import in transit	FI—factory inventory
	OF—over flow	TOF—to over flow
	FOF—from over flow	RMCR—raw material consumption rate
	RM—raw material (inventory)	RMO—raw material ordered
	RMIT—raw material in transit	RSDC—requisition smoothed at distribution centre

Fig. 1. Overview of the supermarket chain model.

of information on which the rate of ordering is to depend. First, orders are necessary for the correction of differences between actual and ideal inventories. Also, it is necessary to recognise the demands of pipeline filling. It is necessary that the order should have the effect of correcting the discrepancy of inventory and pipeline raw materials due to various delays.

The SD equations for the raw material ordering subsystem are shown as follows:

$$RMIT(t) = RMIT(t - \Delta t) + \int (RMO(t) - RMA(t))dt \tag{1}$$

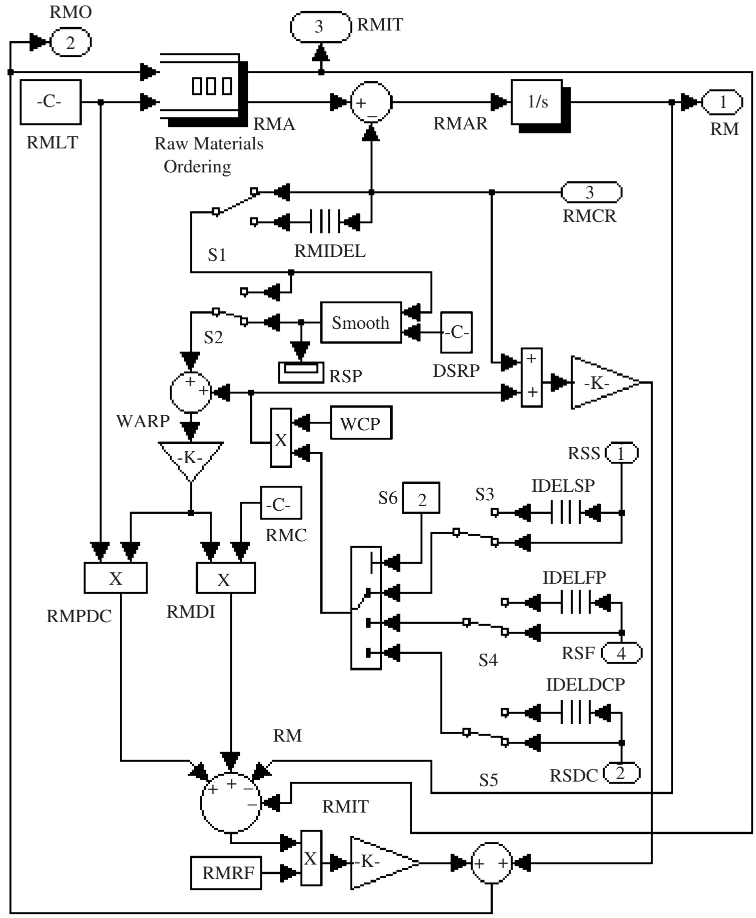
$RMIT$ = raw material in transit (units)
RMO = raw material ordered (units/hour)
RMA = raw material arrived (units/hour)

$$RSP(t) = Smooth\,(RMCR(t),\, DSRP) \tag{2}$$

RSP = requisition smoothed at procurement (units/hour)
$RMCR$ = raw material consumption rate (units/hour)
$DSRP$ = delay in smoothing requisitions at procurement, the exponential smoothing time constant (hours)

$$WARP(t) = [RSP(t) + WCP * RSS(t)]/(1 + WCP) \tag{3}$$

$WARP$ = weighted average requisition at procurement (units/hour)
WCP = weighting constant at procurement (dimensionless ratio)
RSS = requisition smoothed at store (units/hour)



Note: RMLT—raw material lead time
RM—raw material (inventory)
RMO—raw material ordered
RMC—raw material cover
RMIT—raw material in transit
RMRF—raw material reorder fraction
RMA—raw material arrived
RMAR—raw material accumulation rate
RMIDEL—raw material information delay
RMDI—raw material desired inventory
RMCR—raw material consumption rate
WCP—weighting constant at procurement
RMPDC—raw material pipeline desired ccontents
WARP—weighted average requisition at procurement
DSRP—delay in smoothing requisition at procurement
IDELSP—information delay from store to procurement
IDELFP—information delay from factory to procurement
IDELDCP—information delay from distribution centre to procurement

Fig. 2. Block diagram of the raw materials ordering subsystem.

$$RMDI(t) = RMC * WARP(t) \tag{4}$$

$RMDI$ = raw material desired inventory (units)
RMC = raw material cover (hours)

$$RMPDC(t) = RMLT * WARP(t) \tag{5}$$

$RMPDC$ = raw material pipeline desired content (units)
$RMLT$ = raw material lead time (hours)

$$\begin{aligned} RMO(t) =& [RMCR(t) + WCP * RSS(t)]/(1 + WCP) + \\ & (RMDI(t) - RM(t) + RMPDC(t) - RMIT(t)) * RMRF * (dt/24) \end{aligned} \tag{6}$$

RMO = raw material ordered (units/hour)
$RMCR$ = raw material consumption rate (units/hour)
WCP = weighting constant at procurement (dimensionless ratio)
$RMDI$ = raw material desired inventory (units)
RSS = requisition smoothed at store (units/hour)
RM = raw material inventory (units)
$RMIT$ = raw material in transit (units)
$RMRF$ = raw material reorder fraction (dimensionless ratio)

$$RMA(t) = DELAY6(RMO(t), RMLT) \tag{7}$$

RMA = raw material arrived (units/hour)
$RMLT$ = raw material lead time (hours)
$DELAY6$ = specifies 6th-order-delay equations

$$RM(t) = RM(t - \Delta t) + \int (RMA(t) - RMCR(t))dt \tag{8}$$

RM = raw materials (units)
RMA = raw material arrived (units/hour)
$RMCR$ = raw material consumption rate (units/hour), this equals to the rate of production schedule

Constant
$RMLT$ = 30 (days) = 720 (hours)
RMC = 30 (days) = 720 (hours)
$DSRP$ = 360 (hours)
WCP = 5 (could be adjusted for better performance)

Initial conditions
$RMIT$ = 3000 (units)
RM = 30000 (units)
RSP = 1000 (units/day) = 1000/24 (units/hour)

In order to make the system less sensitive to outside disturbances, smoothed data is used to improve system stability. There are two basic smoothing methods — moving average and exponential smoothing (Forrester, 1961). The exponential smoothing method is used in the SD model for raw material ordering, which gives the largest weight to the most recent value and attaches progressively less significance to older information. The first-order exponential smoothing function $RSP(t)$ in equation (2) can also be expressed in the following equation:

$$RSP(t) = RSP(t - \Delta t) + \int (RMCR(t) - RSP(t - \Delta t))dt/DSRP \tag{9}$$

This is a first-order exponential delay. It states that the newly calculated level of average sales RSP at present time $RSP(t)$ is given by the previous value of $RSP(t - \Delta t)$, corrected by a fraction of the difference between the rate of raw material consumption at last time interval $RMCR(t)$ and the previously computed average $RSP(t - \Delta t)$. $DSRP$ gives the fraction of the difference that is to be corrected each hour.

Figure 2 also shows that the switch *S1* controls whether delayed information is used or not, and the switch *S2* controls whether smoothed information or raw data is used as input for the controller. Depending upon the status of the switch *S6*, different sources of information from downstream can be selected to reflect the structural changes of information flow. For example, equation (3) is based on the assumption that information of requisition smoothed at store (*RSS*) is available to the raw material ordering subsystem. It can be adapted to other scenarios by changing the status of the switch *S6*. Equation (3) also shows that weighted average is used to filter out noisy demand while keeping the real trend in demand changes.

Equation (6) shows that the ordering policy *RMO* is designed to meet the demand that is represented by a weighted average of raw material consumption rate (*RMCR*) and requisition smoothed at its downstream customer, e.g. *RSS*. *RMO* is also designed to correct the discrepancy between its desired inventory (*RMDI*) and actual inventory (*RM*), and the discrepancy between raw material desired pipeline contents (*RMPDC*) and the actual raw material in transit (*RMIT*). The fraction *RMRF* represents the speed at which the manufacturer is attempting to close any gap between desired and actual raw material inventories. It is determined by the rate at which the manufacturer, on average, acts on raw material inventory and pipeline-deficit situations.

Performance indicators

The purpose of performance evaluation is to assist management in evaluating supply-chain performance, identifying weak areas, and developing improvement solutions. The following are the performance indicators identified by Van der Vorst, Beulens and Van Beek (2000), Powell, Schwaninger and Trimble (2001), Harland (1995), and Simchi-Levi et al. (2000): holding costs, processing costs related to all logistical processes in a supply chain, costs of product write-offs and necessary price reductions, stock-out frequency, delivery reliability, and cycle time. If the decision-maker has more than one objective, for example to minimise both stock-outs and holding costs, then some sort of weighting scheme must be introduced to balance the two objectives.

Inventory cost and penalty cost

An efficient organisation maintains as small an inventory as possible. However, there can be severe penalties for failure to keep enough goods on hand, ranging from delayed profits to loss of customers. In some situations, inappropriate policies can result in order-of-magnitude swings in inventories and orders (Metters, 1997). Therefore, an effective organisation maintains an inventory that is only as large as necessary to meet the vagaries of demand.

Set-up cost

Generally, when products are manufactured in lots, there is a cost associated with starting a new lot, which is called a set-up cost. To reduce set-up costs, a small number of production lots are preferred, with each one having more items to meet demands. However, having a number of large production lots generally increases inventory costs.

Transportation cost

This is also an important factor contributing to a supply chain's performance. In the model developed in this research, the transportation cost was indirectly evaluated using the pipeline contents in each subsystem.

Flexibility

It is the ability to 'adapt to dynamic changes in business environments surrounding the firm's supply chain operations' (Min and Melachrinoudis, 1999). Because of difficulties in accessing more accurate data, it is hard to evaluate it as a performance indicator. However, the ability of the supply-chain system to adapt to different environments can be evaluated by analysing the system's response to different scenarios.

In this research, because of the limited information available and the scope of the research, the focus is on inventory, in transit to inventory, and lead time. These indicators can capture the most salient features of a supply chain system. Cost factors, such as inventory cost, penalty cost, and transportation cost, can be partially reflected by inventory and goods in transit to inventory. Re-order cost is ignored here. However, when more information is available, the model could readily be extended to include this factor.

Simulation analysis

Most supply-chain problems are caused by demand variations that exist in all business systems. Limited by space, this paper is focused on analysing problems caused by promotion policies commonly adopted for the napkin product. Research conducted by Silén (1998) shows that 'competition in the market is intense, and often based on sales promotions, when prices are cut in favour of bulk buying and considerable, but transient sales volume uplifts are experienced either in selected retailers, or across all sales channels'.

Common scenarios and the problems experienced

One common scenario for the supply-chain system is the temporary promotion policy implemented by the supplier, such as promotion with expected 50% uplift in sales for a week. It is assumed that sales increase evenly by 10% of the original level per day for five days until it reaches the maximum of 50% above the original level, and then sales remains at that level for a week. After that, sales gradually decline by 10% of the original level per day, until they reach the new equilibrium level, which is 10% above the original level. Before the promotion, the manufacturer needs to make such decisions as to when production should be increased and for how long. This leads to the decision on when and how much the changed raw-material order should be placed in advance of increased production or the promotion planning because of the long delay in raw-material ordering.

Other scenarios and the associated problems are as follows. What would be the level of the expensive surplus of stocks if the promotion turned out to be not as successful as planned, yet the production and material ordering had been adjusted according to the anticipated demand? What would be the stock-out level if sales policy were effective or better than anticipated? The occurrence may lead the company to over-expand production capacity. This may lead to another cycle of poor supply-chain management.

From the above scenarios it is shown that the common phenomena in the supply-chain system of the napkin product are that 'inventory demands are filled at a time that coincides with falling retail sales', which leads to 'falling retail sales and inventory liquidation combined with the reduction of in-process orders', then 'a combination of rapidly falling factory orders, a swiftly declining backlog of unfilled orders and a suddenly rising factory inventory'. All the above lead to 'the natural result' of 'curtailing production from its maximum level to 62% below normal' (Silén, 1998).

Having examined the current operations of the supply chain, the next step is to determine ways to improve management control. It is expected that with properly designed supply-chain management policies, some of the above problems can be avoided.

Controller design and simulation

'The behaviour of a simple production–distribution system is probably more affected by the practices followed in adjusting inventories and in-process orders than by any other single characteristic' (Forrester, 1961). The goal of an effective control regime in supply-chain management is to recognise demand changes quickly and to adjust the ordering policy to new equilibrium levels without lengthy delays or expensive oscillations.

Because the four most important subsystems — store, distribution centre, manufacturing, and raw material procurement are of similar characteristics, the raw-material ordering subsystem is selected for operational level analysis.

At the operational level, the ordering policy is very important to the performance of a subsystem as a part of a supply chain. A common question in the ordering policy design is that when inventories are lower than desired for the current level of business activity, how much of the difference or imbalance should be added to the orders sent to the factory in the next order. This determines how quickly any discrepancy between the desired and current level of activity can be corrected. Research shows that better performance could be achieved using advanced controllers, such as PID controllers and intelligent fuzzy logic controllers. Due to limitations of space, only a proportional controller is employed in this paper. However, interested readers can refer to Ge, Yang, Proudlove and Spring (2002) for detailed discussion of this topic.

The effect of information delay, demand forecasting, and information sharing on system performance

The following are the assumptions made for the supply-chain model in this paper.

1. Expected demand in response to promotion results in expected 50% uplift in sales for a week, and then sales falls to 10% above the original level, which is 1000 units/day;
2. flexible production capacity with production level can be adjusted within the range of [0, 1.1], (Suppose the original fixed production level is 1 which can be increased by maximum 10% above the original production level);
3. capacity of raw material supply is flexible with 30 days' lead time.

Further assumptions can be made as follows.

4-A1. information from a downstream chain is only available to its immediately connected upstream part of the chain;
4-A2. information of demands at the end of the downstream customers is available at each subsystems of the chain;
5-B1. information handling and decision delay is one day;
5-B2. with the development of IT and some programmed decision-making process, information handling and decision delay is negligible;
6-C1. no information smoothing is applied;
6-C2. information smoothing with DSRS = 7 days, DSRT = 7 days, DSRM = 7 days, and DSRP = 15 days are assumed. (Note that these are the exponential smoothing time constants at the store, the distribution centre, the manufacturer, and the raw material procurement, respectively).

Based on the above assumptions, the effect of information delay, demand forecasting and information sharing on system performance can be analysed using the following scenarios: 1) Scenario 1 (A1, B1, C1); 2) Scenario 2 (A1, B2, C1); 3) Scenario 3 (A1, B1, C2); 4) Scenario 4 (A1, B2, C2); 5) Scenario 5 (A2, B1, C1); 6) Scenario 6 (A2, B2, C1); 7) Scenario 7 (A2, B1, C2); 8) Scenario 8 (A2, B2, C2). Take raw materials inventory for example. The curves in Fig. 3 shows the simulation results for different scenarios.

As shown in Fig. 3, the maximum inventory for Scenario 1 reaches 40,910 units, while its counterpart — Scenario 5, with better information sharing, has maximum inventory of only 37 960 units. The 2950 units, or 7.2% reduction in raw material inventory means considerable savings and improved financial performance. Similar reduction in inventory can also be found in Scenario 6, Scenario 7, and Scenario 8, as compared with Scenario 2, Scenario 3, and Scenario 4 respectively. With the elimination of the one-day information delay, Scenario 2 shows slight improvement in terms of response speed and overshoot over Scenario 1. The maximum inventory has been reduced from 40,910 units to 40,310 units, a 1.47% reduction. While with the introduction of better forecasting mechanism—exponential smooth and weighted average method—Scenario 3, though having a few days' lag in tracing the demand variations, has a maximum inventory of 39,670 units, a 240 units or 3.03% reduction as compared to Scenario 1. The above analysis confirms the hypothesis raised in the previous section that the information sharing is more important than the method used in forecasting and the speed of information transmission. And the improvement of information sharing among different parts of the chain and

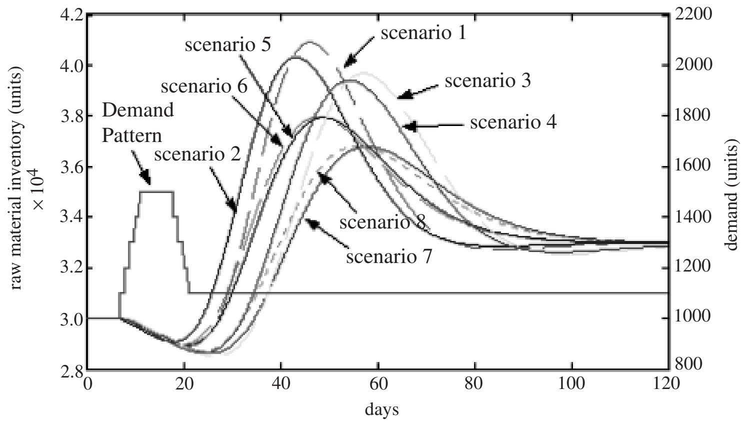


Fig. 3. Effect of information delay, demand forecasting, and information sharing on system performance (using raw materials inventory as an example).

the structural changes in information flow is the most effective means of supply-chain performance improvement.

It can be concluded from Fig. 3 that Scenario 5 to Scenario 8—with improved information flow—show considerable improvements over Scenario 1 to Scenario 4, with information available only about its immediately connected downstream customers. However, the problem associated with production planning or raw material ordering cannot be eliminated even with information about retail sales fully available to all parts of the chain.

It is also shown from Fig. 3 that Scenario 7 and Scenario 8, with the introduction of a better forecasting mechanism, i.e. exponential smoothing, show considerable improvement over Scenario 5 and Scenario 6 respectively; and Scenario 3 and Scenario 4, with a better forecasting mechanism, also show similar improvement over Scenario 1 and Scenario 2 respectively.

By comparing the performances of Scenario 2, Scenario 4, Scenario 6, and Scenario 8 with those of Scenario 1, Scenario 3, Scenario 5, and Scenario 7, it can be concluded that the information delay reduction can also contribute to the chain performance improvement, but this is not as effective as the introduction of a better forecasting method or the structural changes in information flow.

Implementation issues

If problems caused by promotion cannot be solved or are difficult to solve by the restrictions set on production capacity, other options may be considered such as reducing the number and size of promotions. Silén's (1998, p. 88) research shows that this 'is supported by the supermarket's customer service and loyalty based marketing strategy and by the manufacturer's strategy of brand loyalty through R&D and product performance superiority—in both strategies are made to make consumers less sensitive to price and promotions'.

Simulation analysis also reveals that information sharing is more important than the methods used in forecasting and the speed of information transmission. The improvement of information sharing among different parts of the chain and the structural changes in information flow are the most effective way to improve chain performance. This finding can be used as a guidance for performance improvement in situations where there is little knowledge about whether investment should be made in research on the order policy design, in information technology based on the existing structure of information flow, or in improving the structure of information flow and its relations with its customers and suppliers and sharing more information about their demands and their ordering policies. This may be difficult for some parts of the chain, due to the unwillingness to reveal confidential data. However, the problem might be solved if the potential benefit by sharing necessary information with other parts of the chain can be evaluated.

Moreover, it needs to be recognised that supply-chain management is a much broader concept. The research conducted in this paper can only explain some problems of a supply chain. Take for example the design of a raw-material ordering policy. The control curves generated by the controller can assist managers in placing orders in a dynamic environment. However, before the implementation of the control policy, further testing is needed to evaluate its feasibility based on the real situation.

Also, the simulation should not be considered to exclude other options, which might produce better results in connection with other factors that are not or could not be included in the model. For example, the simulation reveals that the system may benefit from a more flexible manufacturing capacity and shorter lead time. However, managers with years of experience might think that the most efficient solution to the problem caused by promotion lies in the source of the problem itself. By considering other functions within each part of the supply chain, such as sales and marketing, and by evaluating the suggestions proposed by the experienced managers in different fields, the whole supply chain might be better off if the promotion can be reduced. For a supply chain to be successful, not only should each part of the chain think about the benefit for itself, but also all parts should consider themselves as an integral part of an interconnected and integrated supply chain.

Conclusion

The supply chain system, by virtue of its policies, structure, physical delays, and information delays, tends to amplify retail sales changes to which the system is sensitive. Any tendency of amplification is because of its internal inclination toward oscillation. An increased demand rate from the downstream chain requires a corresponding increase in the placing of orders in the upper-stream chain, if inventory is to be maintained. In addition, the higher level of demand requires more orders in transit in the supply pipeline. An increase in demand at downstream in the chain usually creates a desire to carry a higher level of inventory upstream. In this paper, the SD approach and control theory have been employed for the modelling and analysis of a supermarket chain system in the UK.

Research (Ge, 2002) shows that physical delay reduction is a very effective way in improving supply-chain performance. Shorter delay leads to shorter overall lead time, resulting in lower costs (less inventory and less goods in transit) and better responsiveness. However, when the order processing and physical transportation time cannot be reduced further, the performance of a supply chain depends largely on the structure of the information flow and the ordering policies.

One main objective of this research is to investigate the impact of various information delays, demand forecasting and information sharing on the performance of the supply chain, so that insight can be gained and improvement can be made in the design of control policies. The information smoothing combined with the averaged weighting method employed in this paper for demand forecasting based on the trend from the rolling historic data has been proven effective. The simulation study shows that although the forecast normally generates a time lag, it is more stable because of its ability in filtering out high-frequency noises, which is especially essential in an environment with random demands. The simulation analysis also reveals that information sharing is more important than the methods used in forecasting and the speed of information transmission. It is also found that the improvement of information sharing among different parts of the chain and the structural changes in information flow are the most effective means for supply-chain performance improvement.

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