REDUCING THE IMPACT OF DEMAND PROCESS VARIABILITY WITHIN A MULTI-ECHELON SUPPLY CHAIN

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Abstract

Forrester analyzed Supply Chain and the different levels existing in it, as well as the participant companies and the role played by each of them inside the chain as a global group, and observed that small variations in end item demand caused oscillations that are amplified throughout the chain. This phenomenon, called the Bullwhip effect, has detrimental consequences on inventory levels and on all kind of inventory costs that may affect the added value of the activities throughout the logistics chain and ultimately affect the Net Present Value of all the activities in the chain. There is a set of collaborative supply chain structures which reduce these harmful consequences within the supply chain. The study presented in this paper quantifies how collaborative supply chain structures reduce the Bullwhip effect in terms of demand variability and inventory cost.

***Keywords**: Bullwhip effect, Demand amplification, Supply Chain, Systems Dynamics.*

1. Introduction

A supply chain is the set of structures and processes an organization uses to deliver an output to a customer. The output can be a physical product such as an automobile, the provision of a key resource such as skilled labor, or an intangible output such as a service or product design (Sterman, 2000). A supply chain consists of the stock and flow structures for the acquisition of the inputs to the process and the management policies governing the various flows.

Each of these processes features a number of clearly defined characteristics, which represent a wide range of topics to be investigated. Research on supply chains represents an attractive field of study, offering numerous approaches to organizational integration processes. Some of the problems regarded as most important, which focus any research project in the field of supply chains, are those related to demand variability and demand distortion throughout the Supply Chain. Forrester (1958) analyzed Supply Chain and the different levels existing in it, as well as the participant companies and the role played by each of them inside the chain as a global group, and observed that a small fluctuation in a customer’s demand was magnified as it flowed through the processes of distribution, production and supply. This effect was identified and also studied by Burbidge (1991) and it is known as the Forrester Effect. That

amplification is due -according to Forrester- to the problems derived from the existence of lead times in delivery ("non zero lead times"), and the inaccuracy of the forecasts carried out by the different members of the chain regarding the variability of the demand received.
Most of the research on demand amplification has focused on demonstrating its existence, identifying its possible causes, and developing methods to reduce it. Lee et al. (1997a) identified four main causes of amplification: wrong methods of demand forecasting, anticipation of supply shortage, batch ordering and price variation. Demand amplification occurs mostly due to finite perturbations in final demand and in lead time all along the supply chain, which is always anticipated and in interaction with other causes. By his seminal work "Industrial Dynamics, A Major Breakthrough for Decision Makers" in 1958, Jay Forrester is viewed as the pioneer of the modern-day supply chain management. His work on the demand amplification as studied via systems dynamics simulation has explored these supply chain phenomena from many viewpoints. How industry is facing this phenomenon(called Bullwhip Effect) has been broadly studied by Lee et al. (1997a), who present some considerations on the Bullwhip Effect in supply chains in details, too. Our study has also been motivated by many other production – distribution considerations about the Bullwhip Effect on the supply chain perturbations, such as those exposed by Lee et al (1997a), and especially the results of Disney (2001, 2002, 2003a, 2003b) and other researchers on this phenomenon from the Cardiff Business School.

Disney (Disney et al, 2004) remarks on the interest of using new supply chain management structures, such as EPOS (Electronic Point of Sales), VMI (Vendor Management Inventory) (based on collaborative structures among the members that make up the Supply Chain), Reduced and E-shopping, for the analysis of the Bullwhip effect.

In this paper, a Supply Chain Management model has been used parametrizable according to the different scenarios we wish to simulate. So the VMI and EPOS collaborative structures have been the scenarios used in this study. After the simulation of both scenarios, the results have been compared with those obtained from the simulation of a Traditional Supply Chain (Campuzano et al., 2006) in section 5 of this paper, in order to analyze the effect of using these collaborative strategies in the reduction of the Bullwhip effect and inventory cost.

The behaviour of the scenarios under study is analyzed by means of a simulation model based on the principles of the system dynamics methodology. The simulation model proposed by Campuzano (2006) provides an experimental tool, which can be used to evaluate alternative long term decisions such as replenishment orders, capacity planning policies, or even inter-organizational strategies ("what-if" analysis), since this methodology allows to study the interdependencies among all the modelled echelons.

2. Measuring the bullwhip effect

An integrated supply chain includes the purchasing of raw materials, the manufacturing with assembly or sometimes also disassembly, and the distribution and repackaging of the produced goods sent to the final customers. Various operating stages in the logistic chain (echelons of the chain) can be represented by a simple model of some material-transformations or location-transformations processing cells (and arcs). Every processing echelon adds value and some costs are acquired due to the logistic activity.

Some strategies like price variations or the promotion effect in a supply chain are used to stimulate end customers demand, offering products at reduced prices. Assuming an elastic demand, this creates temporary increases in demand rates where customers take advantage of this opportunity and forward buy or "stock up". However, this has serious impacts on the dynamics of the supply chain and added value, especially when a certain security level of supply is prescribed.

High Inventory levels are insurance against the problem of stockout in each echelon of the logistic chain. Inventories are limited by the physical capacity of each echelon and by the transportation resources of input and output flows.

Ordering goods (input flow) in distribution centres can be studied as a multi-period dynamic problem. The demand (output flow) during each period has to be considered as a stochastic variable. The distribution of this variable is often described with a certain probability function, which is here normal.

This variation of flows of items or finished goods in supply chains influence transportation costs, inventory cost and definitively costs of activities in logistic networks.

As we mentioned above, the Bullwhip Effect creates a distortion on the replenishment orders which propagates amplified upstream the supply chain. As distortion creates additional costs, the indicators or measures of bullwhip effect are supposed to be in correlation with costs or added value.

Our study was based on the production and inventory control results, especially on the variability trade-off study presented by Dejonckheere et al. (2003), a control theoretic approach to measuring and avoiding the bullwhip effect, presented by these authors, and the study of the impact of information enrichment on the bullwhip effect in supply chains - a control engineering perspective by Dejonckheere et al. (2004), where some measures have been introduced.

The amplification upstream the supply chain can be measured through the variance of demand along the supply chain. The variance of a set of data is defined as the square of the standard deviation and is thus given by s^2 for the estimation of population variance σ^2.
Lee et al.(1997b) suggested the changes of variance in demand σ^2 upstream as the measure of bullwhip effect. It is a good measure only when the units of flow are not changing along the chain, which is not the case in many logistics cases. In recent literature by Chen et al. (2000), it is suggested that to avoid this problem bullwhip effect should be measured by changing the ratio of σ^2/μ upstream of supply chain, but again it does not help to avoid the effect of changing the unit measure. Chen et al. (2000) suggested that its measure could be the ratio of these parameters between input and output flows at each activity cell in a supply chain, when only one stage is considered, or the ratio of these parameters between final demand and first stage of manufacturing when the whole supply chain is to be evaluated (Equation 1)

$$Bullwhip = \frac{\sigma_O^2 / \mu_O}{\sigma_D^2 / \mu_D} = \frac{\sigma_O^2}{\sigma_D^2} \qquad (1)$$

O: Orders
D: Demand

On the other hand, Disney and Towill (2003b) propose that the last measure of the variance ratio can easily be applied to quantify fluctuations in net inventory as shown in Equation 2.

$$NSAmp = \frac{\sigma^2_{NS} / \mu_{NS}}{\sigma^2_D / \mu_D} \qquad (2)$$

NS: Net Stock
D: Demand

3. Methodological approach

Systems Dynamics methodology is a modeling and simulation technique designed for studying problems associated, among others, with logistics, manufacturing management process, organizations or socioeconomics. The aims of systems dynamics are to examine the interaction of various functions (physical processes, information flows and management policies) within a system in order to obtain a better understanding, improve the interaction of components and to integrate them into a meaningful whole, design adequate mechanisms and decision rules. Therefore, the purpose of our model would not be to predict what the total supply chain profit level would be each week for the years to come, but to reveal under what conditions the total profit would be higher, if and when it would be negative, if and how it can be controlled (Sterman 2000).

The structure of a system in Systems Dynamics methodology is represented by causal loop diagrams. Causal loop diagrams consist of variables connected by arrows denoting the causal influences among the variables. These variables are related by causal links, shown by arrows. Each causal links is assigned a polarity, either positive (+) or negative (-) to indicate how the dependent variable changes when the independent variable changes. Identifying reinforcing and balancing loops is very useful as may represent important dynamic behaviours of the system. The way to find out the polarity of a loop is to trace the effect of a small change in one of the variables as it propagates around the loop. If the feedback effect reinforces the original change, it is a positive loop; if it opposes the original change, it is a negative loop

The structure of a dynamic system model contains the stock (state of the system) and flow (rate) variables. Stocks are accumulations and can only be changed via flows. Mathematically a stock can be seen as an accumulation or integration of flows over time - with outflows subtracting from the stock. Stocks typically have a certain value at each moment of time – (i.e. inventories). Flow variables (or "rate") changes a stock over time (i.e., order rate). Usually we can clearly distinguish inflows (adding to the stock) and outflows (subtracting from the stock). Flows typically are measured over a certain interval of time.

Stock and flow diagrams (Forrester diagrams) represent the model structure and the interrelationships among the variables. Stock and flow diagrams have a mathematical meaning. Stocks accumulate or integrate their flows; the net flow into the stock is the rate of change of the stock. In our case, the graphical simulation program used to support the analysis and study of the model created was Vensim by Ventana Systems.

4. Problem and model construction

For this work we have used the model created to study the demand management process along a Traditional Supply Chain (Campuzano et al 2006*)*. Several of its variables have been modified in order to simulate the scenarios corresponding to the VMI and EPOS structures The main characteristics of this model are summarized in the following points:

- A four stage supply chain system (multi-echelon supply chain) consisting of identical agents was considered, where each agent orders products only to its upper stage. These stages are: Customer, Retailer, Wholesaler and Manufacturer.
- An agent ships goods immediately upon receiving the order if there is sufficient amount of on-hand inventory.
- Orders may be partially fulfilled (every order to be delivered includes current demand and backlogged orders, if any), and unfulfilled orders are backlogged.
- Shipped goods arrive with a transit lead-time and they are also delayed because of information lead time.
- Last stage (manufacturer) receives raw materials from an infinite source and manufactures finished goods under capacity constraints.

A short description of each structure follows.

4.1 Traditional Supply Chain.

A traditional supply chain may be characterized by four ''serially linked'' echelons in a supply chain. Each echelon only receives information on local stock levels and sales. Each echelon then places an order onto its supplier based on local stock, sales and previous ''orders placed but not yet received'' (Sterman, 1989).

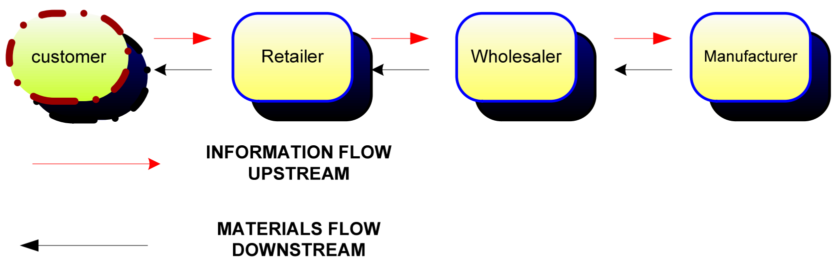

Figure 1: The traditional 4 –stage supply chain. Source (Campuzano (2006))

The first step for developing the model was to create the causal loops which integrate the key factors of the system (variables) and set the relations between each pair of them. It is expected that the differences between bullwhip indicators are the highest in the case of the traditional supply chain.
The variables used to create the Traditional Supply Chain causal diagram have been selected taking as reference the APIOBPCS model (Automatic Pipeline, Inventory and Order-Based Production Control System) (Jhon et al, 1994), and are set out below:

a) Final customer demand and demand from one level towards the level situated immediately upstream.

b) Firm orders (for Retailer, Wholesaler and Manufacturer). Firm orders will consist of the demand sent by the level immediately downstream of the one that is being considered and of the backlogs of the concerned chain echelon.
In other words, if subindex "i" corresponds to the chain level we're considering, D_{i-1} to the demand of the level immediately downstream, and Ppi to the backlogs of the relevant level, the firm orders will be:
Firm orders i= D_{i-1}+Ppi
c) Backlogged orders (for Retailer, Wholesaler and Manufacturer)
d) The on-hand inventory (for Retailer, Wholesaler and Manufacturer): this is the inventory that can be in the warehouse, and the on hand amount of it can never be negative. This amount is important because it allows to determine if the demand from a certain customer can be satisfied directly from the warehouse.
e) Demand Forecasting (for Retailer, Wholesaler and Manufacturer). The forecast has been made using exponential smoothing forecasting.
f) Inventory Position (for Retailer, Wholesaler and Manufacturer):
The inventory position is defined by the following relation:
Inventory position= Inventory on hand + orders placed but not yet received (or on-order products) – backlogged orders. (Silver et al , 1998)
g)Replenishment orders (both for Retailer and Wholesaler)
h) Orders to the Manufacturer (Manufacturer level)
Both replenishment and manufacturing orders to be made according to the inventory policy chosen to manage the demand. Regardless of the policy followed, the variables Demand Forecasting, Inventory Position and Supply or Manufacturing lead times will be taken into account to trigger these orders.
The ordering policy we have chosen for our analysis is a generalized Order-Up-To policy (Silver et al. 1998). In any order-up-to policy, ordering decisions are as follows:

$$O_t = S_t - inventoryposition \quad (3)$$

The order quantity is equal to S_t, reduced for inventory state as:

Inventory position= Inventory on hand-backlogged orders+orders placed but not yet received.

Where O_t is the ordering decision made at the end of period t, S_t is the order-up-to level used in period t and the inventory position equals net stock plus on order (orders placed but not yet received), and net stock equals inventory on hand minus backlog. The order-up-to level is updated every period according to:

$$S_t = \hat{D}_t^{\,L} + k\hat{\sigma}_t^{\,L} \quad (4)$$

Where S_t is equal to the estimate mean of demand $\hat{D}_t^{L}$ over L periods ($\hat{D}_t^{L} = \hat{D}_t \cdot L$) increased for prescribed fill rate with buffer stocks, $\sigma^L{}_t$ is an estimation of the standard deviation over L periods, and k is the fill rate factor (safety factor) which depends on demand distribution (here it is supposed to be normally distributed).

i)Lead Time (both for Wholesaler and Manufacturer) j*) On-order products (for Retailer, Wholesaler and Manufacturer)* Made up of the inventory that has been served and will not be on hand until the stipulated lead time has elapsed and the inventory that will be on hand at the warehouse after completion of the manufacturing process.

k*)Manufacturing capacity (Manufacturer level):* To be expressed as the number of units that can be made in a period.

l) Manufacturing (Manufacturer level)

m) Manufacturing lead time (Manufacturer level)

n) Fill rates (for Retailer, Wholesaler and Manufacturer). Fill rates will be defined as *the quotient between the number of units shipped to the costumers on time and the total number of units demanded by them.*

o) Inventory costs (holding and order costs) (for Retailer, Wholesaler and Manufacturer) and stockout costs (generated when an order is not served on time)

Obviously, these variables will be modified depending on the scenario that is being modelled. In the cases of VMI and EPOS collaborative structures, new variables will be added, that are presented in sections 4.2 and 4.3.

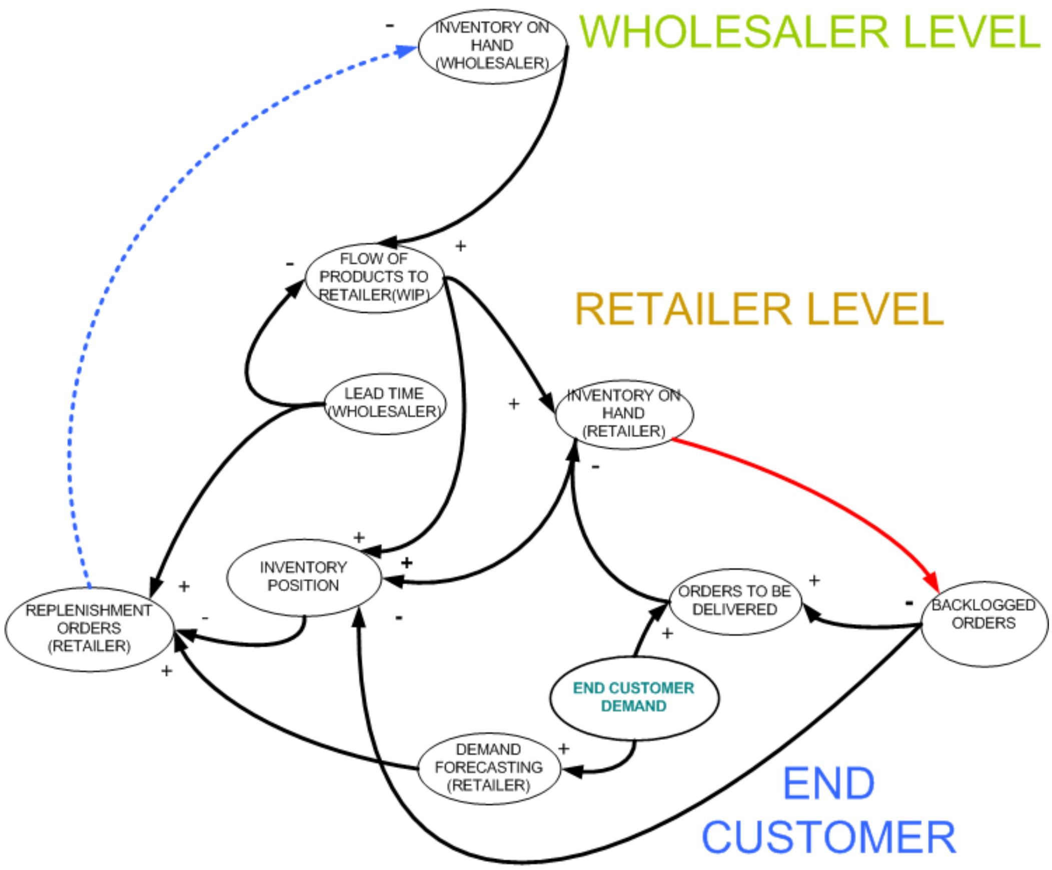

Figure 2: The causal loop of a Traditional Supply Chain. Source (Campuzano (2006))

Figure 2 presents a piece of the structure for a multi-echelon supply chain system in its corresponding causal loop diagram. The arrows represent the relations among variables. The direction of the influence lines shows the direction of the effect. Signs ‘‘+’’ or ‘‘–’’ at the upper end of the influence lines indicate the type of effect. When a sign is ‘”+’’, the variables change in the same direction, otherwise these change in the opposite one.

4.2 EPOS Supply Chain

In the collaborative EPOS scenario, the end consumer sales are sent to all members of the supply chain. Specifically, in this strategy the end consumer sales may be used by each echelon for their own planning purposes, but each echelon still has to deliver (if possible) what was ordered by their customer (Disney et al 2004).
The main difference between the EPOS and the traditional structure when it comes to modelling them, lies in the fact that in the former one the information on sales from the retailer to the final consumer is sent to each member of the chain, which improves the demand forecasts of all them, since periods of lack of information that distort the right performance of the forecasting techniques used are eliminated.

4.3 VMI Supply Chain

The VMI scenario that we consider in this research is as follows. The Wholesaler in a two-echelon VMI relationship manages the retailer's stock. The Wholesaler receives information on the retailer's sales and stock levels. In this scenario the retailer does not place orders on the distributor, instead the Wholesaler dispatches the adequate amounts of stock to ensure that there is enough stock at the retailer with the aim of avoiding stock out periods. We use the VMI strategy for Retailer and Wholesaler echelons in the supply chain. The other two echelons in this scenario (Wholesaler and Manufacturer) were simulated in traditional scenario (no collaboration strategy among echelons).
Unlike the previous modelled chains, a collaborative process between the two chain levels has been simulated, between Retailer and Wholesaler in this case. The replenishment policy used by the wholesaler in this structure to meet the retailer's demand is the Order -Up -to level (S,s). When using this inventory control policy, the replenishment orders are carried out with the intention of taking the inventory position to an S level whenever this reaches or is below the order point s. It has been called so because when an inventory level reaches a previously defined amount, the replenishment or manufacturing order is released. Besides, two variables are introduced: maximun and minimum inventory allowed in the retailer's warehouse, in order to ensure that this latter delivers an appropriate service to the customer avoiding stockout periods.

5. Numerical Investigation

In this section we demonstrate the application of the developed methodology by means of a numerical example and we discuss some interesting insights gained.
The potential of this model allows to visualize the interdependencies among the different members of the modelled chain; that is to say, i.e. the impact that backlogged orders of a level have on the adjacent levels, which may cause an increase in the variability of inventories and consequently in replenishment orders and in forecasts. The variables representing fill rates or total costs in the model reflect these disruptions along the chain.

The values of the main variables used in the scenarios simulation of the Traditional Supply Chain , EPOS and VMI structures are shown below.
The initial values for these main variables were randomly selected and are the following:

1. ***The demand pattern** follows a normal distribution*

2. ***The initial inventory** for every echelon is 100 units*
3. ***Manufacturer capacity :** 160 units/per period*
4. ***Lead time: 3 days for the wholesaler and 2 days for the manufacturer.** Lead times are supposed to be constant except in case of stockout*
5. ***The Manufacturing process takes 2 days***
6. ***Fill rate factor** for every echelon is (k=2)*

The variables modelled to analyze inventory costs in the different modelled scenarios are the following:

1. Holding Costs
2. Order Costs
3. Stockout Costs
4. Penalty costs in failure to keep the on-hand inventory levels at the retailer's store that result in stockout periods (VMI scenario only)

The inventory costs were fixed as follows:

- Holding cost : 0,5 euros unit /period
- Stockout cost: 1 Euro /per stockout
- Order cost : 0,5 euros /order
- Penalty cost (VMI only) : 500 €/per stockout period

365 periods were simulated. This observation seems to be sufficient, since the system reached a stable state.

5.1 Simulation results

The Bulwhip effect and the NSAmp measure are then detailed at wholesaler level for each simulated scenario (Figure 3). These effects are not shown at retailer level because being this the first echelon of the supply chain the difference between the modelled structures is not significant. Note in figure 3 that the EPOS and VMI scenarios obtain better results for the bullwhip effect at wholesaler level than the traditional chain. At the beginning of the simulation the bullwhip effect in the VMI structure is very strong, as a result of the requirements set to the wholesaler in terms of inventory (limits previously set by the retailer), so that replenishment orders to the manufacturer undergo strong variations until the retailer's inventory reaches the level set in the agreement. Then the Bullwhip effect and NSAmp of the VMI chain start to decrease. The EPOS chain shows better results in terms of variance of replenishment orders and net stock amplification than the Traditional and VMI ones, because of the improvement in the forecasts owed to the fact that the wholesaler gets continuous information on the sales.The modelled entrepreneurial collaboration between Wholesaler and Retailer for VMI Chain has an effect in terms of stockout cost, since this chain presents the lowest costs. Backlogged orders that exist in certain moments of the periods of this simulation cause stockout costs. These periods cause important variations in the Bullwhip effect and in NSAmp (see figure 3) that are numerically presented in Table 1 shaded and delimited by a box with broken lines, and in figure 3 surrounded by a circle with broken lines as well. Note the sharp rises that occur in the measure of the Bullwhip effect after the periods of backlogged orders. For the manufacturer level the results are similar to those shown for the wholesaler level (see figure 4).

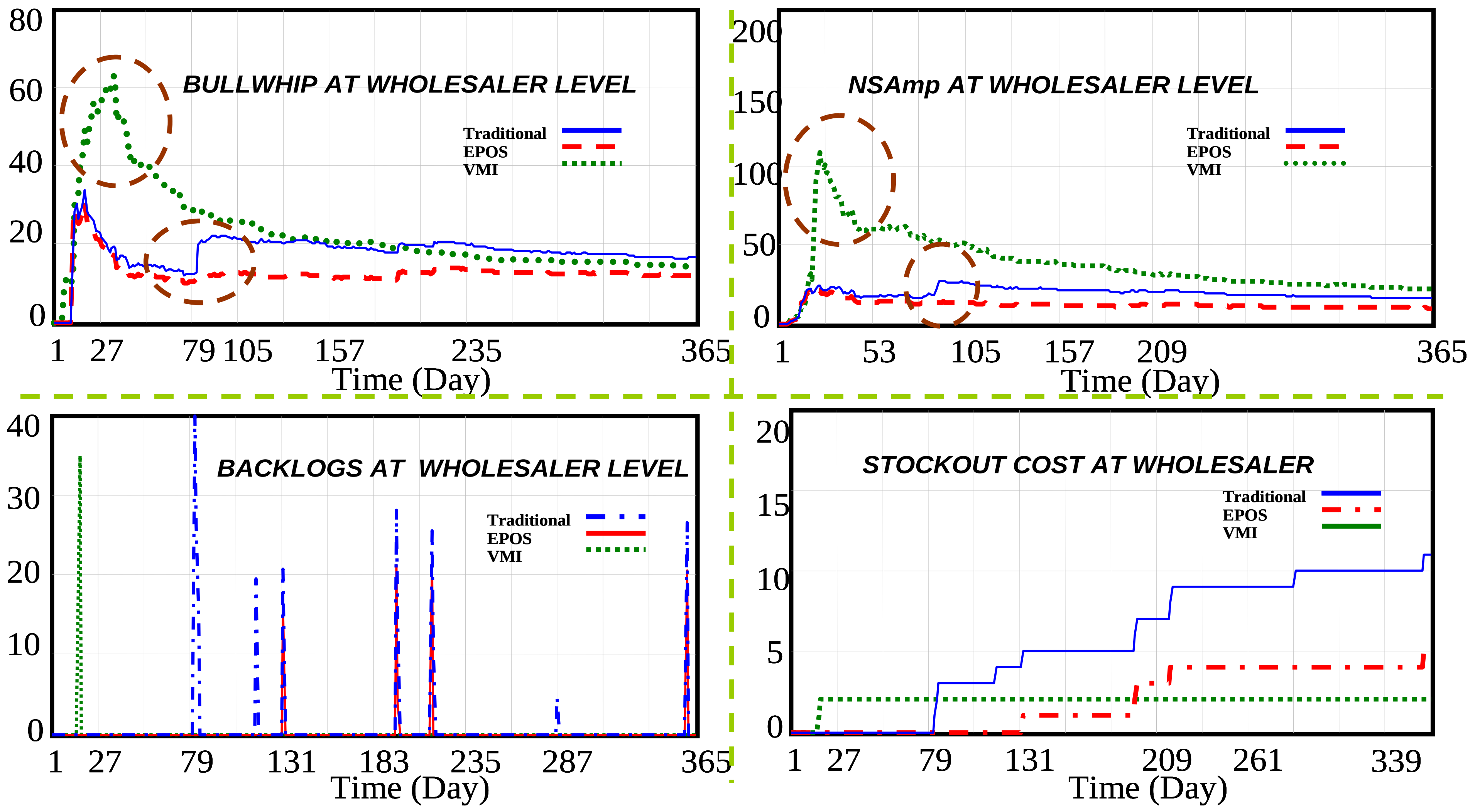

Figure 3 Variations in the Bullwhip effect and NSAmp caused by Stockout. Traditional, VMI and EPOS chain

Table 1: Example of Stockout periods at wholesaler level that cause strong variations in the Bullwhip effect

	BULLWHIP			BACKLOGS (units)			STOCKOUT COST (€)		
Time (Day)	TRADITIONAL	EPOS	VMI	TRADITIONAL	EPOS	VMI	TRADITIONAL	EPOS	VMI
11	0	0	9,401421547	0	0	0	0	0	0
12	18,24206352	25,21645737	12,07368088	0	0	0	0	0	0
13	28,13849068	27,4438076	29,79172516	0	0	0	0	0	0
14	30,32672501	28,73581314	31,35440445	0	0	0	0	0	0
15	26,37573051	24,97788048	32,72219849	0	0	0	0	0	0
16	27,3589859	25,62117577	39,34178925	0	0	10,93181992	0	0	0
17	29,34154701	27,51931572	41,09218979	0	0	34,87882996	0	0	1
18	31,58477974	29,66151428	44,99264145	0	0	0	0	0	2
19	33,77663803	30,70814514	48,84652328	0	0	0	0	0	2
20	28,13183022	25,68495369	45,85219193	0	0	0	0	0	2
21	27,37767601	24,94528961	48,70548248	0	0	0	0	0	2
22	26,54804993	24,26916122	52,04801178	0	0	0	0	0	2
23	26,50686646	24,08742714	53,34993362	0	0	0	0	0	2
..	………	……….	……	…	…	…..	…	….	….
80	12,40871334	10,32421017	28,54396439	0	0	0	0	0	2
81	12,41743183	10,36775303	28,34231567	0	0	0	0	0	2
82	12,50933552	11,13770676	28,78705025	39,82827759	0	0	0	0	2
83	19,63022232	10,976367	27,72580719	26,14720917	0	0	1	0	2
84	20,65755844	11,20983982	27,9746666	14,84303665	0	0	2	0	2
85	21,02940941	11,49358463	28,45935249	0	0	0	3	0	2
86	20,57542801	11,30225754	27,3553791	0	0	0	3	0	2
87	20,61560059	11,37910366	26,97792244	0	0	0	3	0	2

The EPOS chain still offers better results for the Bullwhip effect than the traditional and VMI ones. In this latter, the results obtained for the two previous measures allow to establish that the lack of connection between wholesaler and manufacturer causes errors in the forecasts of the latter which are to the detriment of the stockout costs and cause a high variability of the net inventory.

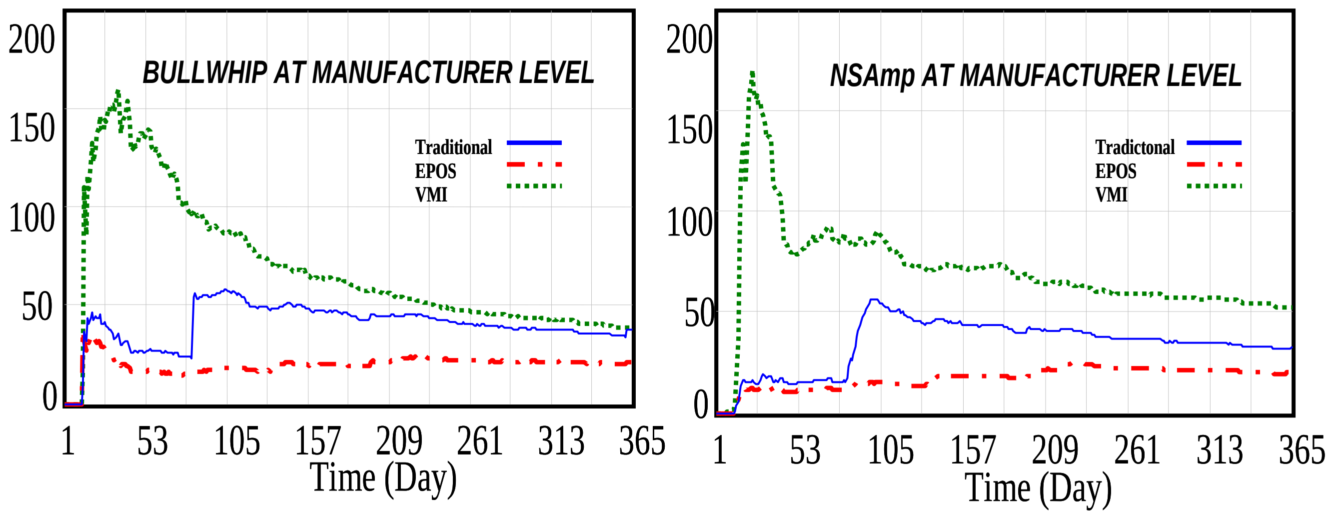

Figure 4 Bullwhip Effect at Manufacturer level

The VMI chain produced the worst results in terms of holding costs, again because of the requirements set to the wholesaler with regard to inventory levels. Of course, if stockout costs are considered to be the most detrimental (since they can entail, among other consequences, a loss of customers), the VMI chain is in this study the most suitable for demand management. Figure 5 shows the holding costs produced by the simulations carried out for wholesaler and manufacturer levels. Note that as the Bullwhip effect increases upstream the chain (figures 3 and 4) the holding costs also increase in a similar proportion, when the system reacts sending replenishment orders to eliminate the existing backlogged orders which cause those variations.

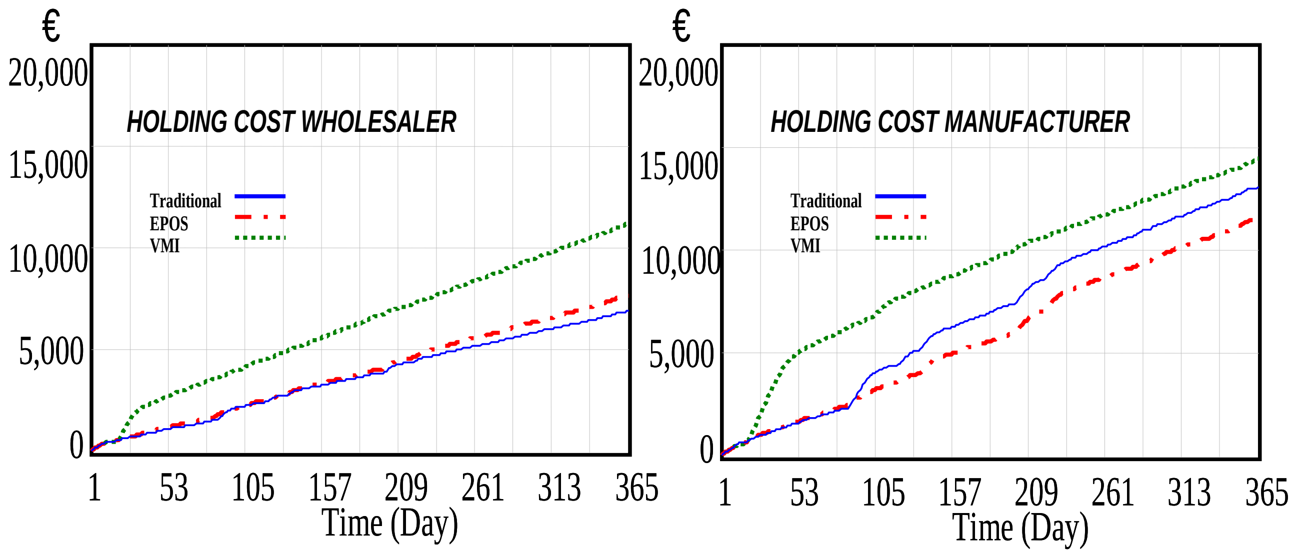

Figure 5. Holding costs at Wholesaler and Manufacturer level for Traditional, VMI and EPOS structures

6. Conclusions

After the results obtained from the simulations in the three proposed scenarios, we can conclude that collaborative structures improve the Bullwhip effect and reduce the total costs of the supply chain in which these structures applied. The EPOS chain has proved to be more efficient than the VMI and the traditional ones in reducing the Bullwhip effect and in holding costs. In the VMI chain such costs can vary according to the maximum and minimun inventories previously set and to the chosen replenishment order; this could be the subject of future studies.

The reduction of the Bullwhip effect, thanks to the improvement of the forecasts by using collaborative strategies, gives an idea of the importance of these latter to avoid other problems in the management of the demand variability, such as price fluctuations, batch ordering or the rationing of final products in certain periods promoted by providers with a view to stimulate the demand.

The point of this model is that it offers the possibility of generating different scenarios, thanks to the joint modification of several parameters (variables), so that the researcher can decide which case is better suited to the proposed objectives, i.e., the attempt to reduce the Bullwhip effect at a specific level of the chain by using in it a different replenishment order, or more efficient forecast techniques, or the impact that the modification of several characteristic parameters specific of each level of the chain (such as lead time or manufacturing capacity) has on inventory costs and fill rates.

The developed model can be useful at the tactical level in an organization or company, as a help in potential Inter-organizational Supply Chain management decision making (Gujar et al. (2007)).

Holweg and Bicheno (2002) have shown how useful simulation may be to develop management models given the difficulties that some companies find to think “beyond factory gates”. The simulation model brings a better understanding of the effects that operational decision-making may have for an enterprise and its associates in the Supply Chain where the business process is performed.

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