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ON THE SIGNIFICANCE OF DEMAND AND INVENTORY SMOOTHING INTERVENTIONS IN SUPPLY CHAIN

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On the Significance of Demand and Inventory Smoothing Interventions in Supply Chain

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Abstract

The aim of this paper is to quantify the benefit of demand and inventory smoothing in contrasting the extreme volatility and impetuous alteration of the market produced by the current economic recession. To do so we model a traditional supply chain and we test five settings of order smoothing under two shocks in the market demand, and we measure the effect in term of internal process benefits. Results highlight how a higher level of smoothing can generally improve the operational performance of the supply chain.

Keywords: Bullwhip effect, Inventory management, Order up to, Economic recession.

JEL Code: C0, C1

1. Introduction

The current economic recession places the production-distribution system at the antipode to the Taylor-Ford system: extreme volatility and need for profound reengineering in search of robust solutions. The global crisis is generating impetuous changes in market demand in several sectors all over the world. This context exposes the supply chain to tremendous shocks, among whose consequence is included one of the most destructive symptoms affecting distributions systems: the bullwhip effect (Lee et al. 1997). It refers to the tendency of the variability of order rates to increase as they pass through the echelons of a supply chain toward producers and raw material suppliers (Disney and Lambrecht 2008). As a result, the variance of orders increases as demand moves up the chain, causing significant costs in the system (Holweg et al. 2005).

As reported by Dooley et al. (2010), the impact of the bullwhip effect on the manufacturing sector has been particularly acute. Between 2007 and 2008, consumer demand for manufactured products decreased on average of 3.2 percent (Dooley et al. 2010). In particular sectors, the decrease was more dramatic. Some retailers and many wholesalers over-responded to the decrease in demand by aggressively cutting demand while losing control of their inventory. Some wholesalers and many retailers acted to buffer themselves from demand variability by inventory and order smoothing, purposefully acting to stabilise inventory and order levels. The authors conclude that smoothing of demand and inventory is demonstrated as an alternative response to the extreme volatility of the market demand generated by the current economic recession.

From a practical perspective smoothing demand and inventory simply happens when we get customers to buy little and often to flatten ordering process. However, from inventory management view point, smoothing of demand and inventory corresponds to adopting a peculiar set of rules and procedures in the inventory control system, commonly known as smoothing replenishment policies. They are (S, R) policies in which the entire deficit between the S level and the available inventory is not recovered in a review period. For each review period R, the quantity O is generated to recover only a fraction of the gap between the target on-hand inventory and the current level of on-hand inventory, and a fraction of the gap between the target pipeline inventory and the current level of pipeline inventory. The amount of the gaps to recover is regulated by decision parameters known as proportional controller. This class of OUT has come to researchers and practitioners' attention for its noticeable bullwhip dampening properties (Towill 1982, Mason-Jones et al. 1997, Disney and Towill 2003, Disney et al. 2004, Boute et al. 2007, Chen and Disney 2007, Strozzi et al. 2007, Chen and Lee 2009, Zhou et al. in 2010), as it can limit the tiers' over-reaction/under-reaction for changes in demand (Cannella et al. in press).

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The aim of this article is to quantify the advocated benefit of demand and inventory smoothing under the extreme volatility and the impetuous alterations of the market produced by the current economic recession. To perform the study and reproduce the current features of the market demand we adopt Towill et al's (2007) shock perspective: a useful methodological approach to studying the bullwhip problem. Using a mathematical modelling, the bullwhip shock lens aims at inferring on the performance of supply chains for an unexpected and intense change in market demand. It could be reasonably considered a stress test to determine the resilience of a given supply chain structure. More specifically, in our work we simulate a traditional supply chain and we test five settings of demand and inventory smoothing under two shocks in market demand. The adopted measurement system assesses the operational performance or "internal process benefits" in term of bullwhip reduction, inventory stability and operational responsiveness. The results confirm the empirical study of Dooley et al. (2010) and highlight how a higher level of smoothing can generally improve the operational performance of the supply chain.

The paper is organised as follows. In Section 2 the mathematical formalism of the studied supply chain and of the smoothing order policy is detailed. Section 3 introduces the measures adopted to assess the model. Section 4 presents experimental design, numerical analysis and discussion. Finally, Section 5 presents conclusions.

2. Mathematical model

This section is devoted to detail the mathematical formalism regulating orders and material flow in the presented model. The supply chain is modelled under the following assumptions:

a) *K*-stage production-distribution serial system.
b) Each echelon in the system has a single successor and a single predecessor.
c) Unconstrained production-distribution capacity. No quantity limitations in production, buffering and transport are considered.
d) Single product. Aggregate production plans are assumed.
e) Non negative condition of order quantity. Products delivered cannot be returned to the supplier.
f) Backlog is allowed as a consequence of stock out. Orders not fulfilled in time are backlogged and the backlog is fulfilled as soon as on-hand inventory becomes available.
g) Unlimited raw material supply. Orders from echelon i=1 (Manufacturer) are always entirely fulfilled in time.
h) The customer demand is known only by echelon i=3 (Retailer). The remaining echelons forecast the demand by considering the incoming orders from downstream echelons. All echelons adopt the exponential smoothing rule to forecast demand.
i) The smoothing order policies strictly follow the order of events used in the Beer Game (Sterman 1989).

Table 1 reports the model notation. The mathematical formalism of the supply chain model is reported below.

Table 1. Notation.

MODEL VARIABLES AND PARAMETERS			
O_i	replenishment order	$\hat{d}_i$	customer demand forecast
W_i	work in progress	α_i	demand smoothing forecasting factor
I_i	Inventory of finished materials	λ_i	production-distribution lead time
B_i	backlog of orders	ε_i	safety stock factor
C_i	units/orders finally delivered	β_i	proportional controller
d	customer demand	p	generic echelon's position in the serial system
STATISTICS			
σ_d^2	variance of the market demand	μ_d	steady state market demand
σ_O^2	variance of the order quantity	μ_I	steady state value of the inventory level
σ_I^2	variance of the inventory	ϑ_{PCB}	proportional controller bullwhip angle
μ_O	steady state value of the order rate	ϑ_{PCII}	proportional controller inventory instability angle
INDICES			
i	echelon in the serial system	K	total number of echelons

Equations (1)-(3) define the state variables of the model (work in progress, inventory and backlog). The relation regulating the work in progress variable is such that, for each echelon i, the products sent from supplier Ci-1 immediately become work in progress (Eq. (1)).

$$W_i(t) = W_i(t-1) + C_{i-1}(t) - C_{i-1}(t-\lambda_i)\ , \tag{1}$$

The inventory is decreased by the quantity C_i (items sent to the downstream echelon) and increased by the quantity C_{i-1} sent by the supplier at time (t-λ_i) (Eq. (2)).

$$I_i(t) = I_i(t-1) + C_{i-1}(t-\lambda_i) - C_i(t)\,, \tag{2}$$

Eq. (3) describes the backlog ($B_i(t)$) as the sum of unfulfilled orders (orders from the subsequent echelon minus delivered items).

$$B_i(t) = B_i(t-1) + O_{i+1}(t) - C_i(t)\ , \tag{3}$$

Eq. (4) defines the item delivery from one echelon to its successor.

$$C_i(t) = \min\{O_{i+1}(t) + B_i(t-1); I_i(t-1) + C_{i-1}(t-\lambda_i)\}\ , \tag{4}$$

Eq. (5) models the non negativity condition of inventory, as it is explained in the following. If $C_i(t) = O_{i+1}(t) + B_i(t-1)$, then the quantity delivered is exactly equal to what was ordered from the adjacent echelon plus the backlogged quantity, which is non-negative (see eq. (6) below). Consequently, $I_i(t-1) + C_{i-1}(t-\lambda_i) \geq O_{i+1}(t) + B_i(t-1) \geq 0$. If $C_i(t) = I_i(t-1) + C_{i-1}(t-\lambda_i)$, then the quantity that can be delivered is the total amount of items in the inventory at time t (sum of inventory at time t plus items sent by the precedent node one lead time before). Therefore, $I_i(t-1) = 0$.

Eq. (5) models the exponential smoothing demand forecast rule, where the value of α reflects the weight given to the most recent observation $d(t\text{-}1)$.

$$\hat{d}_K(t) = \alpha O_{i+1}(t-1) + (1-\alpha)\hat{d}(t-1)\ , \tag{5}$$

Eq. (6) models assumption d), the non negativity condition of order quantity.

$$O_i(t) \geq 0\ , \tag{6}$$

Eq. (7) defines that the order received in echelon K is equal to the customer demand

$$O_{k+i}(t) = d_k(t)\ , \tag{7}$$

In order to model the infinite raw material availability assumption, orders from echelon i=1 are always entirely fulfilled (Equation (8)), as in Beamon and Chen (2001):

$$C_{i-1}(t) = O_1(t);\ \ i = 1\,, \tag{9}$$

The replenishment order (Eq. (10)) is equal to the sum of the exponential demand forecast, plus the smoothed Inventory difference between Target Inventory TI_i and Inventory level I_i, plus the smoothed difference between Target Work in Progress TW_i and current orders placed but not yet received W_i (Cannella and Ciancimino 2009). This typology of order policy is also known as APVIOBPCS, acronym of Automatic Pipeline Variable Inventory and Order Based Production Control System (Dejonckheere et al. 2003)

$$O_i(t) = \hat{d}_i(t) + \beta\left(TI_i(t) - I_i(t) + TW_i(t) - W_i(t)\right), \tag{10}$$

Target Inventory TI_i (11) is the product of the forecast of the orders from the subsequent echelon and the local safety stock factor ε_i.

$$TI_i(t) = \hat{d}_i(t)\varepsilon_i\ , \tag{11}$$

Target Work in Progress TW_i (Eq. (12)) is the product of the forecast of the order from the subsequent echelon and the local Lead Time λ_i.

$$TW_i(t) = \hat{d}_i(t)\lambda_i\ , \tag{12}$$

3. Performance metrics

The supply chain performance is measured via a set of metrics, whose reduction reflects improved cost effectiveness of members' operations as followings: (I) the Order Rate Variance Ratio proposed by Chen et al. (2000), (II) the Inventory Variance Ratio, proposed by Disney and Towill (2003), (III) Average Inventory and Zero Replenishment (Cannella and Ciancimino, 2009).

3.1 Order Rate Variance Ratio (ORVrR)

This metric (Eq. (13)) was proposed by Chen et al. (2000) and it is so far the most common bullwhip-related measure in the literature (Disney and Lambrecht, 2008). It compares the variance of the order rate σ_O^2 with the variance of market demand σ_d^2, each of which is divided by their respective mean value μ (coefficient of variation). Therefore, Order Rate Variance Ratio is a quantification of the instability of orders in the network (Cannella and Ciancimino 2009):

$$Order\ Rate\ Variance\ Ratio_i = \frac{\sigma_{O_i}^2 / \mu_{O_i}}{\sigma_d^2 / \mu_d}, \qquad (13)$$

3.2 Inventory Variance Ratio (IVrR)

This metric was proposed by Disney and Towill (2002) to measure net stock instability, as it quantifies the fluctuations in actual inventory σ_I^2 against the fluctuations in demand σ_d^2 (Eq. (14)). An increased inventory variance results in higher holding and backlog costs, and increasing average inventory costs per period (Disney and Lambrecht, 2008).

$$Inventory\ Variance\ Ratio_i = \frac{\sigma_{I_i}^2 / \mu_{I_i}}{\sigma_d^2 / \mu_d}, \qquad (14)$$

3.3 Average Inventory

Average inventory (Eq. (15)) is the mean of a tier's Inventory values over the interval *T*. The metric is commonly used in production-distribution system analysis in order to provide concise information on inventory investment, see e.g. holding cost modelled as linearly dependent from stock levels in Cachon and Fisher (2000), Disney and Grubbström (2004), Chen and Disney (2007) and Reichhart et al. (2008).

$$AI_{m,i} = \frac{1}{T}\sum_{t=0}^{T} I_i(t) \qquad (15)$$

3.4 Bullwhip Slope

As reported by Cannella and Ciancimino (2009), Dejonckheere et al. presented in 2004 a study on the dynamic behaviour of multi-echelon replenishment rules in a four-tier supply chain. They adopted the Order Rate Variance Ratio to assess different bullwhip solution approaches. In order to compare several supply chain configurations, they plotted the obtained values using the echelon position as independent variable. They observed the interpolated curve and inferred qualitatively on the linear or geometric nature of the trend. The authors state that a geometric increase of the Order Rate Variance Ratio interpolating curve is representative of strong bullwhip propagation, more intense than in a linear trend. Dejonckheere et al.'s (2004) curve is a smart representation of bullwhip propagation in a multi-echelon system and serves to concisely compare different supply chain configurations (Ciancimino et al. in press). To extend Dejonckheere et al.'s (2004) inferring technique to a general case, a statistical analysis of the curve could be performed for both Order Rate Variance Ratio and Inventory Variance Ratio.

We assume a linear propagation of bullwhip. This allows us to use slopes for the comparison of different boundary conditions generated by the various proportional controller settings. By defining ϑ_{ORVrR} as the angle of inclination of the linear regression of Order Rate Variance Ratio in Dejonckheere et al.'s curve, p_i as the position of i^{th} echelon, Bullwhip Slope is formalised in eq. (16).

$$Bullwhip\ Slope = tg\,\vartheta_{ORVrR} = \frac{K\sum_{i=1}^{K} p_i ORVrR_i - \sum_{i=1}^{K} p_i \sum_{i=1}^{K} ORVrR_i}{K\sum_{i=1}^{K} p_i^2 - (\sum_{i=1}^{K} p_i)^2} \qquad (16)$$

3.5 Zero-Replenishment

For (*S*, *R*) order policies, the Zero-Replenishment Phenomenon is defined as the event in which, in a review period *R*, a tier does not place any order (Cannella and Ciancimino 2008, Ciancimino and Cannella 2009). An order pattern characterised by a significant number of Zero-Replenishment Phenomena is known in literature as sporadic, intermittent or lumpy (Croston 1972, Schulz 1987, Chatfield and Hayya 2007). In a given time horizon, if the demand is a positive and stationary signal and the parameters of the inventory replenishment rule remain unaltered, the occurrence of the Zero-Replenishment Phenomenon could be indicative of an erroneous excessive dimensioning of previous orders. The Zero-Replenishment metric (Eq. (18)) is the total amount of the Zero-Replenishment Phenomenon occurrences in the observation period T. The metric is used to measure timely and pondered reactivity and scalability of tier's operations.

$$ZR_{m,i} = \sum_{t=0}^{T} x_i(t) \tag{17}$$

$$x_i(t) = \begin{cases} 1 & O_{m,i}(t) = 0 \\ 0 & O_{m,i}(t) \neq 0 \end{cases} \tag{18}$$

4. Experimental design, numerical results and discussion

To set the numerical values for the experiments, we sought for values employed in the related literature. The lead time and demand smoothing forecasting factor, the initial values of the state variables and safety stock factor refer to the setting of Sterman's traditional supply chain model (Sterman, 1989).

The numerical experiments are performed under the following settings:

- The serial system is composed by three echelons (K=4), i.e. Retailer (i=3), Wholesaler (i=2), and Manufacturer (i=1)
- The initial values of the state variables are: $[W_i(0), I_i(0), B_i(0)]=[\lambda_i d(0), \varepsilon_i d(0), 0]\ \forall i$.
- The lead time levels is $\lambda_i = 2\ \forall i$.
- The safety stock factor is $\varepsilon_i = 3\ \forall i$.
- The demand smoothing forecasting factor varies over the values $\alpha_i = [0.17, 0.33, 0.67]\ \forall i$.
- The proportional controller are $[\beta_1, \beta_2, \beta_3, \beta_4, \beta_5]= [1, 0.8, 0.6, 0.4, 0.2]\ \forall i$.
- Numerical experiments are performed for a time length T=52
- The solutions for the initial-value problem are approximated through Vensim PLE. The Euler-Cauchy method with order of accuracy $\Delta t = 0.25$ is adopted.
- The assumed demand *d(t)* is a multi step-function demand shock. This demand patterns reproduces two sudden changes from one state to another, according to the "shock lens" perspective (Towill et al.'s 2007) for the analysis of production-inventory systems. The demand is initialised at 8 units per time unit, until there is a negative pulse at t=5, decreasing the demand value up to 4 units per time unit, until there is a positive pulse at t=21, increasing the demand value up to 8.

In the following the numerical experiment output is presented. The Order Rate Variance Ratio is plotted according to Dejonckheere et al.'s notation (Figure 1). In italic the Bullwhip Slope values for each set are reported.

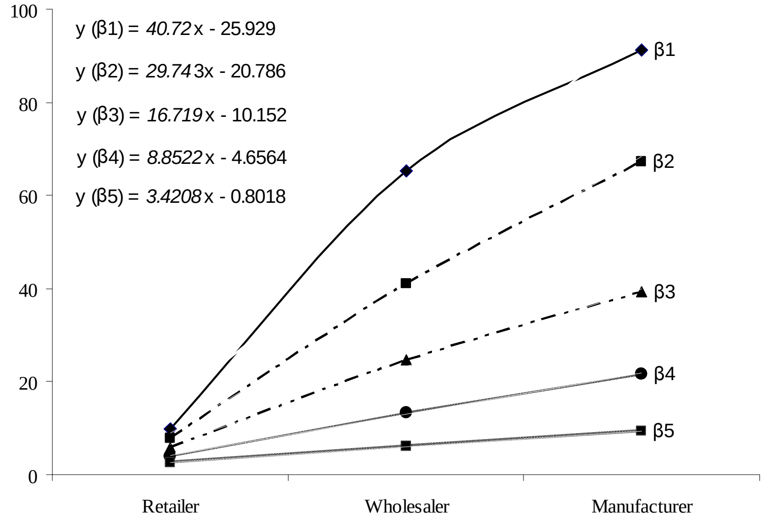

Figure 1. Order Rate Variance Ratio and Bullwhip Slope

The Inventory Variance Ratio and the Average Inventory are reported in Table 2.

Table 2. Inventory Variance Ratio and Average Inventory.

	INVENTORY VARIANCE RATIO			**AVERAGE INVENTORY**		
	Retailer	Wholesaler	Manufacturer	Retailer	Wholesaler	Manufacturer
B_1	10.60	76.14	44.20	22.3	53.0	65.1
B_2	8.08	47.92	31.92	21.3	39.3	53.9
B_3	6.73	23.80	23.58	20.6	29.7	42.3
B_4	6.82	10.29	15.36	20.4	23.4	33.7
B_5	7.91	8.30	8.96	20.3	21.5	28.4

Zero replenishment is reported in Figure 2.

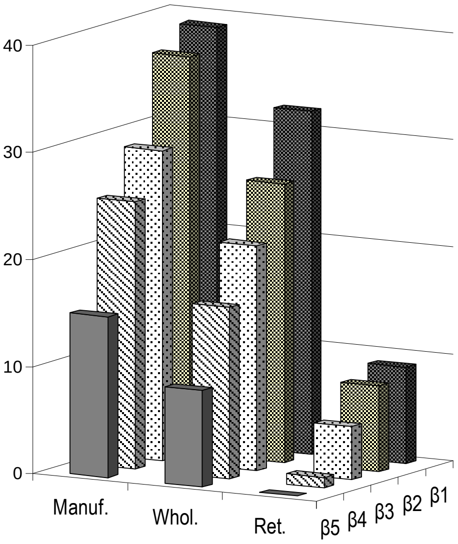

Figure 2. Zero Replenishment

The results confirm the empirical study of Dooley et al. (2010) and highlight that a higher level of smoothing can generally improve the operational performance of the supply chain. Bullwhip is not completely avoided, since a traditional supply chain has a structural tendency to demand amplification eliminated (Disney et al. 2004), but smoothing replenishment rules considerable limits the propagation of the noxious phenomenon. As shown by Dooley et al (2010) and reasserted in this simulation study, smoothing of demand and inventory is an appropriate response to the extreme volatility of the market demand under the current economic recession.

Firstly, Order Rate Variance Ratio values and Bullwhip Slope (Figure 1) values show that bullwhip magnitude is monotonically reduced for increasing order smoothing. The curves obtained by plotting the values of bullwhip magnitude over the four echelons (Figure 4) present a progressive slope reduction from the no-smoothing condition (B_1=1) to the high smoothing (B_5=0.2). "Low" level of proportional controller refers to a moderate smoothing, that is, the smoothing (*S*, *R*) tends towards or correspond to a classic (*S*, *R*). A "high" level reflects an intense smoothing of the discrepancy between actual and target levels of net stock and pipeline stock. Inventory Variance Ratio and Average Inventory (Table 2) show the same trend that Order Rate Variance Ratio: fluctuation and average levels of inventory decrease for increasing order smoothing levels. In particular, we note a considerable reduction of the Inventory instability for the Wholesaler from 76.14 to 8.30 shifting from the no smoothing condition to the high smoothing setting.

In general, we observe a monotonous decrement both in the order variability and inventory instability at each level of the supply chain for increasing order smoothing levels. From a managerial viewpoint, the advocated smoothing of demand and inventory converts in a highly beneficial reduction of holding costs for all the levels of the chain. In traditional structures, smoothing replenishment rules are able to reduce bullwhip by 40% and realise economic savings of nearly 20% (Chen and Disney 2007).

Zero-Replenishment (Figure 2) indicates a relevant sporadic order occurrence in the traditional supply chain for low smoothing levels, and a monotonic reduction for increasing values of the proportional controller. Furthermore, the value of Zero Replenishment for the design B_5 in the retailer is equal to the optimal theoretical value and indicates an high operational scalability and responsiveness.

As reported by Simchi-Levi (2009), in such a challenging and volatile environment, supply chain strategies are expected to reduce cost and cut working capital, while at the same time maintain or increase service levels and prepare for future growth. Our results underline that smoothing replenishment rules could be reasonably considered strategies to the actual world's crisis in the field of production-inventory control, thanks to the cost reduction and efficiency increase provided by pondered decision making.

5. Conclusion

The aim of this paper was to analyse the advocated benefit of the smoothing order under the extreme volatility and the impetuous alterations of the market demand produced by the current economic recession. We simulated five levels of order smoothing in a serially linked traditional supply chain and we studied the response for two shocks in demand, i.e a negative pulse and a positive pulse. A Measurement System to assess the supply chain was detailed, based on "internal process benefits" (Order Rate Variance Ratio, Inventory Variance Ratio, Bullwhip Slope, Average Inventory, and Zero Replenishment phenomenon). Results showed how a higher level of smoothing can generally improve the operational performance of the supply chain. The present work suggest that, from an operational view point, an over-reaction to the volatility of the current market demand creates instability of the inventory and unstable production schedules. The adoption of a smoothing order rule represents a possible strategy to contrast the operational inefficiencies caused by the present impetuous changes in market demand.

5. Conclusion

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