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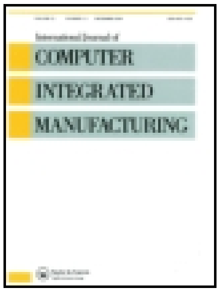

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Current economic downturn and supply chain: the significance of demand and inventory smoothing

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Current economic downturn and supply chain: the significance of demand and inventory smoothing

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The aim of this article is to analyse and quantify the effects of demand and inventory smoothing into supply-chain performance, facing the extreme volatility and impetuous alteration of the market produced by the current economic recession. To do so, we model a traditional serial three-stage supply chain and we test five settings of order smoothing under two shocks in the market demand, and we measure effects in terms of internal process benefits and customer service level of all supply chain partners. Results show that the implementation of this inventory strategy should be based on reward schemes; in fact a higher level of smoothing can generally improve the performance of the upstream stages. On the contrary, this approach cannot be always beneficial for the retailer as the decrease in service level can outweigh the decrease in bullwhip.

Keywords: bullwhip effect; inventory management; order up to; economic recession; incentives

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 re-engineering in search of robust solutions. The global crisis is generating impetuous changes in the 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 towards 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 an average of 3.2% (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 viewpoint, 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. The *S* level is dynamically computed every period *R* as the sum of the forecast on the customer demand, plus a target inventory on hand, plus a target pipeline inventory (Cannella et al. 2011). The order quantity 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 (Cannella and Ciancimino 2010). The amount of the gaps to recover is regulated by the decision parameters known as proportional controller. This class of order-up-to (OUT) policy has come to researchers and practitioners' attention for its noticeable bullwhip dampening properties (Towill 1982; Mason-Jones et al. 1997; Disney and Towill

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2002, 2003; Disney et al. 2004; Boute et al. 2007; Chen and Disney 2007; Strozzi et al. 2007; Chen and Lee 2009; Zhou et al. 2010), as it can limit the tiers' overreaction/underreaction for changes in the demand (Cannella et al. 2011). Essentially, a smoothing replenishment policy is able to solve the detrimental consequence of the adoption of the classical OUT, as it is well recognised that this policy may lead to the bullwhip effect (Disney and Towill 2003a; Wei et al. 2013). In fact, it has been shown that the classical OUT policies will always produce a bullwhip effect (Dejonckheere et al. 2003). In contrast, smoothing replenishment rules do not only increase the flexibility for decision-making, but also allow managers to balance the target of inventory costs and production fluctuations (Wei et al. 2013).

However, most of the studies report the effect of the smoothing replenishment rules only in terms of demand amplification and inventory instability, which are measured by the two quantitative metrics: order rate variance ratio (ORVrR) (Chen et al. 2000) and inventory variance ratio (IVrR) (Disney and Towill 2002). On the contrary, according to Cagnazzo et al. (2010), performance metrics should not only assess internal processes efficiency but also their effectiveness in terms of the impact on the customers (Cannella et al. 2013). Nevertheless, there are studies that analyse the impact of the smoothing replenishment rule not only in terms of the bullwhip effect, but also in terms of customer service level (see, e.g. Dejonckheere et al. 2003; Disney et al. 2007; Disney and Lambrecht 2008). These studies showed how dampening order variability may have negative impact on customer service as exaggerate smoothing of order rate could impede to fulfil the marketplace demand in time (Cannella and Ciancimino 2010).

Moreover, to the best of our knowledge there are no quantities studies showing how the smoothing replenishment can impact on the service customer level of the upstream partners of a supply chain. Nevertheless, in the presence of structured contracts between partners, if the retailer receives its order after the due date, the supplier might be subjected to a penalty (Eliman and Dodin 2013). In fact, the cost of late-delivered and cancelled orders, owing to stock-out, is commonly observed in practice, and needs to be considered in the cost model (Miranda and Garrido 2009; Lu et al. 2012). For instance, in the consumer goods industry, 70% of the retailers measure the service levels of their suppliers (Sieke et al. 2012). On the contrary, there is limited research on measuring and monitoring on-time delivery under uncertainty and dynamic input and system conditions, within broader supply chain environments (Nakandala et al. 2013). Thus, the assessment of the internal as well as the external customer service level in a supply chain is relevant.

Finally, the majority of the literature addressing the bullwhip effect usually assumes special demand models, e.g. an autoregressive (AR) (1) process and independently and identically distributed (Wei et al. 2013). On the contrary, to understand how this inventory strategy works under the current marketplace conditions, it can be appropriated to adopt a different input demand that emulate the dynamic behaviour of the market in the 'era of turbulence' (Christopher and Holweg 2011).

Motivated by these observations, the aim of this article is to quantify the advocated impact of demand and inventory smoothing in terms of bullwhip effect, inventory level and customer service level of each stage of the supply chain, under the extreme volatility and the impetuous alterations of the market produced by the current economic recession. To reproduce the current features of the market demand we adopt a modified version of the framework proposed by Towill et al.'s (2007) to analyse the bullwhip effect. They identified three 'observer's perspectives' to analyse the bullwhip effect: variance lens, shock lens and filter lens. Basically, this framework suggests the typology of endogenous input that can be adopted in a bullwhip analysis in order to study different characteristics of the chain. In particular, the shock lens aims at inferring on the performance of supply chains for an unexpected and intense change in the market demand. This latter approach can be viewed as a 'crash test' or a 'stress test': studying the system performance under an intense and violent solicitation test in order to determine the resilience of a given supply chain structure (Ciancimino et al. 2012). Usually, this approach is build by implementing a 'positive shock' in the market demand. In our study, in order to emulate the current market condition, we extend this approach by including a 'negative' shock in the demand patterns. In order to isolate the effect of the smoothing replenishment rule of the supply chain performance, for the aforementioned market condition, we simulate a classical traditional supply chain without information sharing and we test five settings of demand and inventory smoothing. The adopted measurement system assesses the operational performance or 'internal process benefits' in terms of bullwhip reduction, inventory stability and operational responsiveness and in terms of customer service level (Cannella et al. 2013).

The article is organised as follows. Section 2 presents a review of related literature. In Section 3, the mathematical formalism of the studied supply chain and of the smoothing order policy is detailed. Section 4 introduces the measures adopted to assess the model. Section 5 presents experimental design, numerical analysis and discussion. Section 6 presents the findings. Finally, Section 7 presents conclusions and a future research discussion.

2. Backgrounds

Demand amplification (or 'bullwhip' as it is now called) is not a new phenomenon, since evidence of its existence has been recorded at least as far back as the start of the twentieth century and is well known to economists (Geary et al. 2006). The bullwhip effect is said to occur whenever the variance of orders in a supply chain is greater than the variance of sales, and in fact, amplifies with increasing depth into the chain (Jain et al. 2009). It causes a small perturbation in orders at a downstream stage to have a large effect on the variation of an order or production rate at an upstream stage (Shin et al. 2010).

Bullwhip is the cause of a range of unnecessary costs in supply chain such as excessive inventory investments throughout the supply chain to cope with the increased demand variability; reduced customer service due to the inertia of the production/distribution system; lost revenues due to shortages; reduced productivity of capital investment; increased investment in capacity, inefficient use of transport capacity; and increased missed production schedules (Holweg et al. 2005; Chen and Disney 2007). Examples of industries include telecommunications manufacturing, computer components manufacturing, grocery, retail, automotive industry, electronics industry, furniture industry, food, apparel, and so on. (Bhattacharya and Bandyopadhyay 2011).

Currently, the most economic downturn has no doubt created a lot of bullwhips around the world (Lee 2010). In order to dampen or avoid the bullwhip effect, several countermeasures can be undertaken. Among those are (1) redesigning the physical process, (2) redesigning the information patterns and (3) redesigning the decision process (Van Ackere et al. 1993; Dejonckheere et al. 2004). The first approach could be realised through two of the bullwhip reduction principles: ‘time compression’ and ‘echelon elimination’ (Geary et al. 2006). A successful business case is represented by the well-known ‘Dell Model’ (Disney and Lambrecht 2008). The second approach could be realised through information sharing. It can be considered one of the most important strategies to avoid the bullwhip effect (Cannella and Ciancimino 2010; Lee 2010). It is the key enabler of members’ coordination and collaboration. By the centralisation of demand information, that is, providing each stage of the supply chain with complete information on customer demand, the bullwhip effect can be diminished (Kumar et al. 2006). More specifically, it has been shown how supply chain collaboration and coordination mechanism are effective strategies in reducing a variety of supply chain costs (Miranda et al. 2009; Yuan et al. 2010; Arora et al. 2010; Chan and Prakash 2012) and improving fill rate (Chan and Chan 2006; Chan and Chan 2009). Essentially, supply chain collaboration plays a crucial role in improving overall performance that benefits all partners (Derrouiche et al. 2008). However, developing an information-sharing culture as an organising context is not easy (Fawcett 2011) and implementing a collaboration practices requires large investments of money, time and expertise (Davenport 1998; Cannella and Ciancimino 2010). Information technology is certainly an enabler for supply chain members to share information quickly, accurately and inexpensively (but not at zero) (Chan and Chan 2010).

On the contrary, the adoption of smoothing replenishment rule is an easy procedure that permits to realise the redesigning of the decision process in order to limit the bullwhip effect. A smoothing replenishment rule belongs to the periodic review policies. In these policies, the inventory position is reviewed only once every *Ti* periods. The length of *Ti* is always some integral multiple of the base period (Wadhwa et al. 2009). Unlike the classical OUT policies, smoothing replenishment rules are order policies in which the entire deficit between the OUT level and the available inventory is not recovered in a review period (Boute et al. 2008). For each review period, the quantity 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 (Cannella and Ciancimino 2010). The amount of the gaps to be recovered is regulated by the decision parameters known as *proportional controllers*. The *inventory proportional controller* modulates the recovery of the on-hand inventory gap and the *work in progress proportional* controller determines the recovery of the pipeline inventory gap (Cannella et al. 2011). When the inventory proportional controller is equal to the work in progress proportional controller, the smoothing replenishment rule lies well within the stable regime with extremely satisfying behaved dynamics response (Deziel and Eilon 1967; Disney and Towill 2006). According to Lalwani et al. (2006), this policy consists of a range of production and inventory control systems with five main components: a forecasting mechanism, a set of time values, an inventory feedback loop, a work in progress feedback loop and a target net stock setting. A notorious family of smoothing replenishment policies is the inventory and order-based production control system (Towill 1982; John et al. 1994). Recently, the benefit of this policy has been shown through theoretical studies (Boute et al. 2007; Wright and Yuan 2008; Papanagnou and Halikias 2008; Chen and Lee 2009; Zhou et al. 2010; Hussain and Drake 2011; Adenso-Diaz et al. 2012), as well as empirical researches (Dooley et al. 2010; Potter and Disney 2010). However, as we mentioned in Section 1, most of this studies do not consider the impact of this order policy on the customer service level of the supply chain partners.

3. 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 through first-order nonlinear differential equations (Riddalls et al. 2000; Kleijnen 2005). This approach is commonly known as system dynamics (SD) (Forrester 1961), which deals with the problems of modelling high-level, non-linear systems with complex feedback. Common software applications for SD include STELLA (Isee Systems, Inc., Lebanon, NH, USA), Vensim (Ventana Systems, Inc., Harvard, MA, USA), Powersim (Powersim Software AS, Bergen, Norway) and iThink (Isee Systems, Inc., Lebanon, NH, USA). (Yuan and Ashayeri 2009; Trappey et al. 2012).

Following relevant and well-known supply chain studies (see, e.g. Sterman 1989; Beamon and Chen 2001; Dejonckheere et al. 2003; Machuca and Barajas 2004; Jakšič and Rusjan 2008; Wright and Yuan 2008; Hussain and Drake 2011), the supply chain is modelled under the following assumptions.

1. *K*-stage production–distribution serial system.
2. Each echelon in the system has a single successor and a single predecessor.
3. Unconstrained production–distribution capacity. No quantity limitations in production, buffering and transport are considered.
4. Single product. Aggregate production plans are assumed.
5. Non-negative condition of the order quantity. Products delivered cannot be returned to the supplier.
6. Backlogging is allowed as a consequence of stockholding; as in each echelon, the backlog is fulfilled as soon as on-hand inventory becomes available. Therefore, orders not fulfilled in time are backlogged, so that inventory remains a positive or null value.
7. Unlimited raw material supply. Orders from echelon i = 1 (manufacturer) are always entirely fulfilled in time.
8. 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.
9. 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.

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 C_{i-1} immediately become work in progress (Equation (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) (Equation (2)).

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

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

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

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

Table 1. Notation.

Model variables and parameters for stage or echelon i			
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_i	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}	Angle of inclination of the linear regression of ORVrR Dejonckheere et al.'s (2004) curve
μ_O	Steady state value of the order rate	ϑ_{PCII}	angle of inclination of the linear regression of IVrR Dejonckheere et al.'s (2004) curve
Indices			
i	Echelon in the serial system	K	Total number of echelons
T	Time horizon	P	Position of ith echelon

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

Equation (4) even 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 Equation (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, $I_i(t-1) = 0$ (Ciancimino et al. 2012).

Equation (5) models the exponential smoothing demand forecast rule, where the value of α reflects the weight given to the most recent observation $d_i(t–1)$.

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

Equation (6) models assumption 5, the non-negativity condition of order quantity.

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

Equation (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 (Equation (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 2010). This typology of order policy is also known as APVIOBPCS (automatic pipeline variable inventory and order-based production control system (Dejonckheere et al. 2003). The value of β is between 0 and 1, where $\beta = 1$ is equivalent to standard OUT policy, and $\beta = 0$ to a make-to-order policy. The higher the value of β, the greater the fraction of the discrepancy recovered between gap between the target on-hand inventory and the current level of on-hand inventory. In this case, a moderate smoothing strategy is implemented, that is, the smoothing replenishment rule tends towards to a classic OUT. On the contrary, the lower β, the lesser the fraction of the discrepancy recovered between gap between the target on-hand inventory and the current level of on-hand inventory. In this case, an intense smoothing strategy is realised.

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

Target inventory TI_i (Equation (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 (Equation (12)) is the product of the forecast of the order from the subsequent echelon and the local lead time λ_i.

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

4. Performance metrics

We adopt a recent framework for the analysis of the bullwhip effect (see Cannella et al. (2013)). It is based on a two-criterion assessment–'internal process efficiency' and 'customer service level' – is developed along this article. The framework is designed to assess both individual (single member) and systemic (whole supply chain) performances. Data collection and calculation methods, update and monitoring mechanisms as well as related procedures for each metric used are detailed via a set of metrics, whose reduction reflects improved cost-effectiveness of members' operations as followings.

4.1. *Order rate variance ratio*

This metric (Equation (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, ORVrR is a quantification of the instability of orders in the network (Cannella and Ciancimino 2010):

$$\mathrm{ORVrR}_i = \frac{\sigma_{O_i}^2/\mu_{O_i}}{\sigma_d^2/\mu_d} \tag{13}$$

4.2. *Inventory variance ratio*

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

(Equation (14)). An increased inventory variance results in higher holding and backlog costs, and increasing average inventory (AI) costs per period (Disney and Lambrecht 2008).

$$\mathrm{IVrR}_i = \frac{\sigma^2_{I_i}/\mu_{I_i}}{\sigma^2_d/\mu_d} \tag{14}$$

4.3. *Average inventory*

Average inventory (Equation (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 for example 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), Dellino et al. (2010).

$$\mathrm{AI}_{m,i} = \frac{1}{T}\sum_{t=0}^{T} I_i(t) \tag{15}$$

4.4. *Bullwhip slope*

Dejonckheere et al. (2004) presented a study on the dynamic behaviour of multi-echelon replenishment rules in a four-tier supply chain. They adopted the ORVrR 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 ORVrR interpolating curve is representative of strong bullwhip propagation, more intense than in a linear trend Cannella and Ciancimino (2010). 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. 2012). To extend Dejonckheere et al.'s (2004) inferring technique to a general case, a statistical analysis of the curve could be performed for both ORVrR and IVrR.

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 $\vartheta_{\mathrm{ORVrR}}$ as the angle of inclination of the linear regression of ORVrR in Dejonckheere et al.'s curve, p_i as the position of *i*th echelon, Bullwhip Slope is formalised in Equatioin (16).

$$\text{Bullwhip Slope} = tg\,\vartheta_{\mathrm{ORVrR}} = \frac{K\cdot\left(\sum_{i=1}^{K} p_i\cdot \mathrm{ORVrR}_i\right) - \left(\sum_{i=1}^{K} p_i\right)\cdot\left(\sum_{i=1}^{K}\mathrm{ORVrR}_i\right)}{K\cdot\left(\sum_{i=1}^{K} p_i^2\right) - \left(\sum_{i=1}^{K} p_i\right)^2} \tag{16}$$

4.5. *Zero replenishment*

For (*S, R*) order policies, the zero replenishment (ZR) phenomenon is defined as the event in which, in a review period *R*, a tier does not place any order (Cannella and Ciancimino 2008). An order pattern characterised by a significant number of ZR phenomena is known in the 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 ZR phenomenon could be an indicative of an erroneous excessive dimensioning of previous orders. The ZR metric (Equation (18)) is the total amount of the ZR phenomenon occurrences in the observation period *T*. The metric is used to measure timely and pondered reactivity and scalability of tier's operations (Cannella and Ciancimino 2012.

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

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

4.6 *Mean backlog*

Mean Backlog (MB) is representative of customer service level. This metric is derived by the backlog (Equation (3)) that represent a cumulative measure of undelivered goods to the final customer. The magnitude of this metric shows how a generic echelon is able to fulfil customer (internal customer or consumer) orders.

$$\mathrm{MB}_i = \frac{1}{T}\sum_{t=0}^{T} B_i \tag{19}$$

5. Experimental design and results

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 and the initial values of the state variables and safety stock factor refer to the setting of Sterman's (1989) traditional supply chain model.

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 controllers 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 assumed demand $d(t)$ is a multi-step function demand shock. This demand pattern 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. In order to contrast the scenarios, Figure 1 depicts the ORVrR measures using the echelon position as independent variable, according to Dejonckheere et al. (2004). Furthermore, we report the equation of the trend line for each supply chain configuration and consequently the angle of inclination of the linear regression of Dejonckheere et al.'s (2004) curves.

In Table 2, we report the values of IVrR, AI and MB by echelon (columns) and by proportional controller configuration (rows).

Zero replenishment is reported in Figure 2. (some explanation)

Finally, Figure 3 reports the trade-off analysis between order rate variance, inventory level and customer service level for increasing the values of the proportional controller (β_k, $k = 1, 2, 3, 4, 5$).

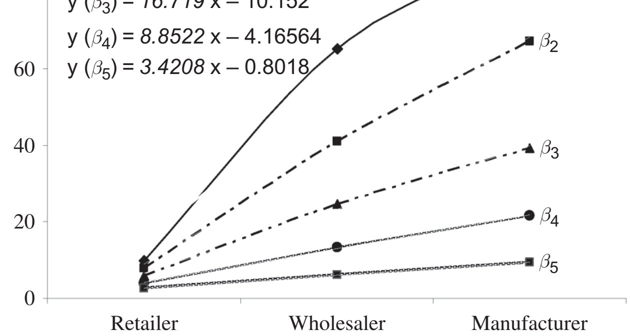

Figure 1. Order rate variance ratio and bullwhip slope.

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

First, ORVrR 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 three echelons present a progressive slope reduction from the no-smoothing condition ($\beta_1 = 1$) to the high smoothing ($\beta_5 = 0.2$). 'High' 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 'low' level reflects an intense smoothing of the discrepancy between actual and target levels of net stock and pipeline stock. Inventory variance ratio and AI (Table 2) show the same trend that ORVrR: 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 in both 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 supply chain, and in a higher stability of the supply chain in terms of orders and inventory levels. 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 ZR for the design β_5 in the retailer is equal to the optimal theoretical value and indicates a high operational scalability and responsiveness.

Finally, backlog reports peculiar results. By increasing the magnitude of the proportional controller, we note a decrement in the customer service level at retailer stage. In particular, we note the MB increasing from 0.9 to 2.68 shifting from the no-smoothing condition ($\beta_1 = 1$) to the high smoothing ($\beta_5 = 0.2$). On the contrary, we note an

Table 2. Inventory variance ratio, average inventory and mean backlog.

	Inventory variance ratio			Average inventory			Mean backlog		
	Retailer	Wholesaleraler	Manufacturer	Retailer	Wholesaler	Manufacturer	Retailer	Wholesaler	Manufacturer
β_1	10.60	76.14	44.20	22.3	53.0	65.1	0.90	6.65	11.38
β_2	8.08	47.92	31.92	21.3	39.3	53.9	1.05	6.22	9.33
β_3	6.73	23.80	23.58	20.6	29.7	42.3	1.31	5.85	7.38
β_4	6.82	10.29	15.36	20.4	23.4	33.7	1.79	5.64	5.55
β_5	7.91	8.30	8.96	20.3	21.5	28.4	2.68	5.70	3.85

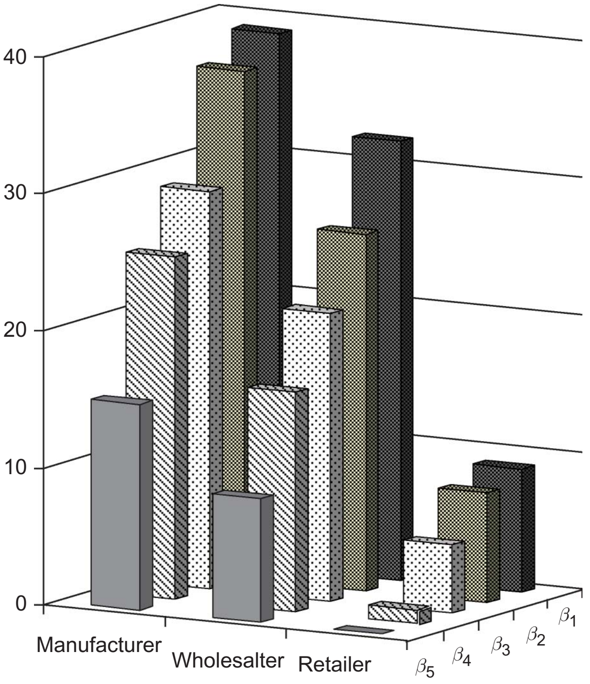

Figure 2. Zero replenishment.

opposite behaviour at the highest level of the chain, i.e. the manufacturer. In fact, for this stage, the results reveal a reduction of the MB from 11.38 to 3.85, shifting from the no-smoothing condition (β_1 = 1) to the high smoothing (β_5 = 0.2).

6. Findings

The outcome of this work reveals several important features of the smoothing replenishment rule. First of all, the output of the simulation confirms the efficacy of the demand and inventory smoothing in terms of bullwhip effect reduction, in particular for the upstream partners of the chain. In fact, we note how the manufacturer is able to reduce the inventory variability approximately to 78% (see Table 2), with respect to the supply chain based on the classical OUT inventory policy. Essentially, the upstream stages noticeably reduce a range of unnecessary costs – investment in extra capacity, over time, agency, sub-contract costs, obsolescence – due to the unstable production schedules produced by the high variability of the order placed by downstream stage. This outcome is also supported by the empirical study performed at Tesco – the largest UK grocery retailer – by Potter and Disney (2010). The authors report that Tesco's replenishment system was found to increase the daily variability of workload by 185% in the distribution centres. In order to improve the performance, they recommended the introduction of a proportional controller into the ordering policy for high volume, long-life products. These products accounted for 65% of the total sales value of Tesco UK. Thanks to the adoption of a smoothing replenishment rule, the variability in workload has been reduced to approximately 75% of the sales variability. The change created a stable working environment in the distribution system

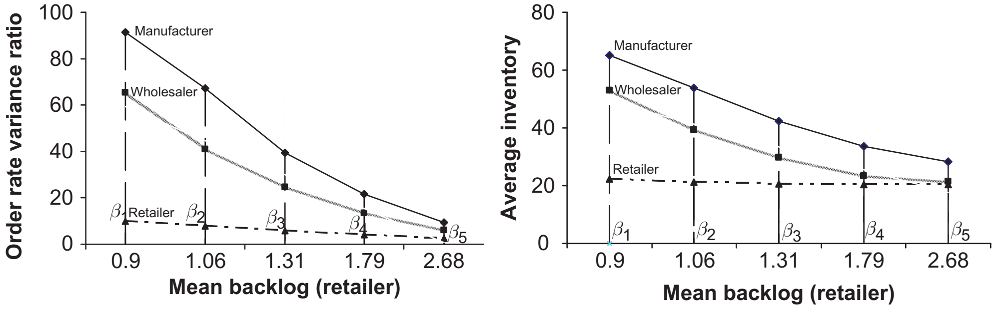

Figure 3. Trade-off between operational performance and customer service level.

and reduced distribution and warehousing costs by an estimated £28m per year.

Analogously, results show how the manufacturer hardly reduces the MB with more smoothing. To the best of our knowledge, this is a new contribution in the bullwhip effect that supports a significant implication for the designing and management of supply chain network. In fact, it is reasonable to consider that an intense smoothing at each stage of the chain allows a reduction of the potential penalty costs of late-delivered and cancelled orders at the upstream stages. Thus, for a manufacturer, the smoothing of demand and inventory is not only beneficial, in terms of operational costs (holding, under-capacity or over-capacity utilisation, sub-contracting, overtime, agency work, and obsolescence), but also in terms of reduction of the penalty costs.

On the contrary, by analysing the performance of the retailer, we can appreciate an opposite trend with respect to the upstream echelon. First of all, the magnitude of the reduction of the bullwhip effect or of the inventory variability is considerable inferior lesser with respect to the manufacturer. In fact, by shifting from classical OUT configuration to the most intense smoothing scenario, there is a reduction of the inventory variability of the 25% against the 78% of the manufacturer. This magnitude of this improvement in inventory stability can be noticed even for the other internal operational performance. However, if we analyse the result of the customer service level at the retailer stage, we note a counter-tendency with respect to the trend discussed up to now. In fact, results show a considerable increment in the main backlog for an intense smoothing.

In order to explain this peculiar phenomenon, we use a hydraulic analogy (Cannella and Ciancimino 2010). In fact, inspired by Holweg et al. (2005), we consider that an inventory control policy can be viewed like as a valve of and hydraulic system. The proportional controller tuning can be viewed one of the regulator of this valve. In a hydraulic system, an imminent alteration of the flow rate can generate a phenomenon known as ‘water hammer’ (Allevi 1902), a threatening shock wave propagating in the pipeline. A water hammer can cause the conduit to break if the pressure of the fluid is high enough. The remedy to the water hammer consists in reducing the fluid pressure. However, reducing excessively the flow rate can impede to reach in time the desired fluid level to the user (Cannella and Ciancimino 2010). Analogously, in supply chain, in order to limit the propagation of the bullwhip effect it is possible to reduce the amount of placed orders in upstream direction by increasing the magnitude of the smoothing replenishment rules. Nevertheless, an exaggerate order rate smoothing can cause the customer service level to degenerate. Thus, this opposite trend between the operational performance (e.g. bullwhip effect and inventory level) and the customer service level at retailer stage is due to the fact that an exaggerate order rate smoothing can impede to reach in time the desired product for the customer. On the contrary, this effect is eliminated at the higher stage of the chain because the upstream partner benefits from a reduction of the incoming order placed by the downstream stage, thus they are equivalent amount of the order size and avoid stock-out phenomenon for the upstream partners in the chain.

The opposite trend between the customer service level and the operational performance of the retailer and the difference between the global performance of the downstream and the upstream partners of the chain bring us to further concern about the adoption of the smoothing order policy. Basically, the manufacturer hardly reduces AI and inventory variance with more smoothing, on the contrary this approach it cannot be always beneficial for the retailer as the decrease in service level will outweigh the decrease in bullwhip. Thus, it is reasonable that retailers can be discouraged by adopting an intense smoothing. In fact, the bullwhip effect is driving costs at the upstream stage (e.g. the manufacturer or the supplier) and consequently, the downstream stage (e.g. the retailer) may not worry about it (Disney and Lambrecth 2008). As a result, the wholesaler and the manufacturer will receive a volatile demand signal. A potential solution for this dilemma can be represented by the ‘sharing of benefits’ between partners (Audy 2012). In other words, upstream parties have to compensate the downstream party for the advantage they receive. If not, then the upstream party will not apply the appropriate level of smoothing. Thus, the implementation of this inventory strategy should be based on reward schemes. In the information sharing supply chain literature, we can appreciate several studies dealing with the relation between the incentives provided by the manufacturer to the retailers in order to access the customer demand. It has been shown that information sharing can hurt retailers’ interests, and thus the retailers are discouraged from sharing their demand information with the manufacturer. In order to obtain this strategic information, manufacturer tends to rewards retailers (Qian et al. 2012). Analogously, in this work we have proved how supply chain performance can be noticeable improved by appropriately tuning the parameter of the inventory control system. However, this tuning has to be promoted by the manufacturer with the creation of coordination incentive mechanisms in the downstream. This clearly suggests that the benefits gained by each entity when properly shared, makes the collaboration acceptable for everyone (Audy 2012).

7. Conclusions and further research

The aim of this article is to analyse the advocated benefits and shortcomings of the order’s smoothing strategies under the extreme volatility and the impetuous alterations of the market demand produced by the current economic recession. For a standard serially linked traditional supply chain serial observed in a related literature, and based on the SD approach, we simulated five levels of order smoothing as a strategy to scope the bullwhip effect. We studied the system response for two shocks in demand, i.e. a negative pulse and a positive pulse.

A measurement system to assess the supply chain performances was detailed, based on 'internal process benefits' (ORVrR, IVrR, bullwhip slope, AI, and ZR phenomenon), and also including one indicator of supply chain shortcoming named MB.

Results shown how a higher level of smoothing can generally improve the operational performance of the supply chain in terms of bullwhip effect, inventory levels and supply chain stability (orders and inventories), but as other strategies to cope with the bullwhip effect, service level is slowly decreased. In this fashion, the adoption of a smoothing order rule represents a possible strategy to contrast the operational inefficiencies caused by the present impetuous changes in the market demand. However, to implement such a strategy, it must be taken into account that the party furthest downstream should be compensated for its lowered service level.

In terms of future research, we highlight to extend the analysis for more complex supply chains, considering more stages, several parallel sites at each stage and multi-item scenarios (Disney and Lambrecht 2008). Moreover, it is interesting to analyse and evaluate the impact of different supply chain inventory control strategies (as discussed in this article) into supply chain network topologies. The latter observation relies on previous works which showed how inventory control strategy effectively might alter the optimal supply chain network, suggesting the integration of inventory control strategies within standard facility location model to design supply chain networks (see, e.g. Berman et al. 2012; Melo et al. 2009; Daskin et al. 2002; Erlebacher and Meller 2000; Miranda and Garrido 2004; Dotoli et al. 2007; Yin and Khoo 2007).

Considering the results of this study, the next logical step is to analyse smoothing strategies in different supply chain sectors, for example in order to control in a better fashion retailer service level or high-tech distribution network such as tablets or mobile phones. In each sector, one could analyse different intensities of smoothing strategies (proportional controller) at different supply chain stages. Thus, it is possible to obtain similar benefits at the manufacturer, controlling service level at the downstream of its respective supply chain.

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