On bullwhip-limiting strategies in divergent supply chain networks

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Abstract: The amplification of demand variation in a supply chain network (SCN) is a well-known phenomenon called the bullwhip effect. This effect generates a large volume of inefficiencies as it moves a greater number of units than necessary, increases stock and generates stock-outs. There are two different approaches for avoiding and/or limiting this detrimental phenomenon that have received attention in the literature: Collaboration and information sharing in SCNs on one hand, and the adoption of smoothing replenishment rules on the other. The effectiveness of both approaches have been often analyzed only for "serial linked" SCNs, which is a supply network structure rarely found in real-life. In order to give an insight of how these techniques would perform in more generic SCNs, a divergent SCN has been benchmarked against the classical serial SCN. The computational experience carried out show that the bullwhip effect can be considerably reduced by collaboration or the smoothing replenishment rules in divergent SCNs, but it always performs worse than the serial SCN due to its inherent complexity.

Keywords: Bullwhip Effect, Smoothing Replenishment Rule, Information Sharing, Serial Supply Chain, Divergent Supply Chain, Simulation.

1. INTRODUCTION

Managing a Supply Chain Network (SCN) is a dynamic decision task shown to be prone to systematic errors, collectively referred to as the bullwhip effect (Lee et al. 1997, Cantor & Katok 2012). This effect refers to the phenomenon occurring when the orders from the supplier have larger variance than the ones from the customers, i.e. variance amplification (Strozzi et al. 2012). This is known to inevitably lead to excessive inventory investment, poor customer service, lost revenues, misguided capacity plans, ineffective transportation, and missed production schedules (Chen et al. 2012). As a consequence, this effect increases the cost of operating the SCN. Indeed, it has been estimated that a potential 30 billion dollar opportunity exists in streamlining the inefficiencies of the grocery supply chain, which has more than 100 days of inventory supply at various nodes in its supply chain (Subramanian et al. 2012).

The Bullwhip Effect is commonplace in contemporary SCNs (Li & Liu 2013) and, as reported by Ali et al. (2012), any further contribution in this area is of considerable importance to SCN practitioners.

Research related to the bullwhip effect in SCNs has a long tradition which can be broadly divided into three streams (Nepal et al. 2012). The first stream of research focuses on determining the impact of forecasting techniques employed by SCN players on the bullwhip effect. The other two streams of research in the bullwhip effect analysis include an examination of the impact of operations management parameters (such as ordering policy, inventory management policy, and production variation and batching) and SCN dynamics (such as information sharing) on the bullwhip effect (Nepal et al. 2012). The latter streams have mainly focused on the dampening techniques to reduce this detrimental phenomenon.

Specifically, two different approaches for avoiding and/or limiting the bullwhip effect have received attention: collaboration and information sharing in the SCN and the adoption of the smoothing replenishment rules (Cannella & Ciancimino 2010).

Information sharing is the practice of making strategic and operation information available for other partners of the network. It creates visibility along the network and helps suppliers to plan their replenishment and delivery schedules (Prajogo & Olhager 2012). Information sharing is regarded as one of the main drivers to improve or even optimize the overall SCN performance (Voigt & Inderfurth 2012). More specifically, by using information sharing, SCN members can manage their inventory on the basis of customers' demands, thus removing or mitigating harmful problems resulting from the bullwhip effect (Cho & Lee 2011).

A smoothing replenishment rule is a (*S*, *R*) policy in which the entire deficit between the *S* level and the available inventory is not recovered in a review period (Boute et al. 2009). 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 (Cannella et al. 2011). As reported by Wang et al. (2012a) this ordering policy was found to mimic real-life decisions made by players of the Beer Game, Sterman (1989). The rationale for the smoothing replenishment rule is to limit the tiers' over-reaction/under-reaction to changes in demand (Cannella & Ciancimino 2010). This policy is able to solve the detrimental consequence of the adoption of the classical Order-up-to (OUT), as it is well recognized that this policy may lead to the bullwhip effect (Disney & Towill 2003a, Wei et al. 2013).

The aforementioned studies attest that there is scientific evidence that the practices of information sharing and smoothing replenishment rules lead to a reduction of the bullwhip effect. However, when quantitatively assessing the efficacy of these bullwhip avoidance strategies, most of the studies are confined to the classical mono-echelon structure, or the two-echelon supply chain (Bhattacharya & Bandyopadhyay 2011). Even though many researchers have argued that the results obtained for a single-echelon environment should work in a multi-echelon environment, it has been shown recently that this assumption does not necessarily hold (Cattani et al. 2011). Similarly, in studies devoted to analyse the impact of bullwhip reduction strategies in multi-echelon SCNs, it has been adopted a "serially linked" echelon structure (Sterman 1989, Disney et al. 2004a) (i.e. Retailer, Wholesaler, Distributor and

Manufacturer). This modeling assumption is also adopted because it is assumed that any SCN can be simplified to a serially linked SCN. In fact, by modeling each echelon as a transfer function (please see Dejonckheere et al. 2003, Dejonckheere et al. 2004, Disney and Towill 2003a, Disney and Lambrecth 2008, among others), two parallel echelons can be simplified to a single echelon. Even though several countermeasures to the bullwhip effect have been studied and implemented in real businesses using this modeling assumption, it is seldom verified in real SCNs (Bhattacharya & Bandyopadhyay 2011). In fact, as recently advocated by Moser et al. (2011), and Xuan et al. (2011), it would also be interesting to assess the dynamics of SCNs with multi-retailers condition that better reproduce the real-world SCNs, such as the divergent or arborescent SCN (Beamon & Chen 2001). This structure is characterized by a tree-like structure, where every stock point in the system receives supply from exactly one higher level stock point, but can supply to one or more lower level stock points (Hwarng et al. 2005).

In summary, to the best of our knowledge, there is a lack of consistent studies and experimental reports assessing the bullwhip dampening features of the information sharing and smoothing replenishment rule in divergent SCNs and, in general, in no-serial SCNs. Thus, there is the need of study the impact of these strategies on SCNs characterized by more than one member in the same level of the supply chain. Motivated by these observations, the aim of this paper is twofold: (1) to analyze the impact of these bullwhip reduction strategies on a divergent SCN and (2) to compare this impact with the effect of these techniques on the widely used serial SCN.

To fulfill these research objectives, we first model a classical four-echelon serial SCN structure (i.e. 1 Retailer, 1 Wholesaler, 1 Distributor and 1 Manufacturer) as in Chatfield et al. (2004), and a new complex multi-echelon SCN (i.e. 8 Retailer, 4 Wholesaler, 2 Distributor and 1 Manufacturer), and we perform a comparative analysis between the two SCNs for four scenarios, i.e. (1) classical OUT, no info-sharing; (2) smoothing replenishment rule, no info-sharing; (3) classical OUT, info-sharing; (4) smoothing replenishment rule, info-sharing.

To perform the analysis we adopt the shock lens input demand as described in Towill et al. (2007). This approach can be viewed as a “crash test” or a “stress test”, i.e.: studying the system performance under an intense and violent solicitation test to determine the resilience of a given SCN structure (Cannella & Ciancimino 2010). SCNs are modeled using SCOPE, a multi-agent based simulation platform.

The results confirm that the bullwhip avoidance features of the strategies are also significant for the arborescent SCN. Furthermore, we encounter several differences in the dynamic behavior between the serial SCN and the arborescent SCN, particularly for the no information sharing under OUT scenario. In general, the divergent SCN performs always worse than the traditional structure. However, the discrepancies in performance between the structures can be considerably reduced by the adoption of the two bullwhip avoidance strategies analyzed. Thus, we show how these strategies not only reduce the bullwhip effect in SCNs but also increase the robustness of complex SCNs.

The rest of the paper is organized as follows: Section 2 presents a literature review. Section 3 describes the methodological approach. Section 4 presents the serial SCN and the divergent SCN to be modelled. Section 5 presents the metrics system employed to compare the SCNs and the design of experiments. Section 6 presents the results together with their discussion. Section 7 includes the findings and managerial implications, while in Section 8 the conclusions and future research lines are pointed out.

2 LITERATURE REVIEW

The role of information sharing and the smoothing replenishment rule has been largely demonstrated in literature. Concerning the former, there is a common agreement that enforcing co-operation between supply-chain participants is an effective tool to increase SCN performance (Audy et al 2012, Stanck et al. 2011, Hall & Saygin 2012). This practice allows eradicating variability in SCNs, preventing costly dynamic distortions such as the “bullwhip” (Lee 2010), and spreading the operational risk (Cristopher & Holweg 2011).

At the operational level, SCN collaboration concerns with the alignment of decisions amongst SCN partners in their planning and inventory management. This alignment is enabled by the exchange of information in the SCN (Stadtler 2009). Firms can share real-time market demand data for the generation of conjoint forecasting, or even real-time information on inventory levels and in-transit items for centralized replenishment activities. In any case, each member of the SCN is able to generate order patterns based not only on the information at a local level, but also on further data incoming from partners. This visibility allows limiting the classical information distortion of the traditional SCN (Prajogo & Olhager 2012).

Perhaps the information sharing strategy studied in the literature is the so-called Information Exchange Supply Chain (Holweg et al. 2005). Unlike in a traditional SCN, in this collaborative structure all echelons receive information on market demand in the information exchange and include this information in the order policy. Thus, retailers and suppliers order independently, yet they exchange demand information and action plans in order to align their forecasts for capacity and long-term planning.

Regarding smoothing replenishment rules, these have been designed to avoid the side-effect of the OUT policy, which is the most commonly used order policy in practice (Teunter & Sani 2009). It is well-known that the classical OUT policy minimizes inventory fluctuations, but may lead to increasing the bullwhip effect (Wei et al. 2013). In fact, whatever forecasting method is used (simple exponential smoothing, moving averages or demand signal processing), OUT 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). A notorious type of these policies is the Inventory and Order Based Production Control System (IOBPCS) family of smoothing replenishment rules (Coyle 1977, Towill 1982). In the last decade, several variations of this family have been developed (e.g. Cannella et al. 2011), such as the Automatic Pipeline Variable Inventory and Order Based Production Control System (APVIOBPCS) by Dejonckheere et al. (2003). In this rule, the order is generated by satisfying the expected demand during the risk period and to recover two gaps. The first gap is that between a variable target net stock value and the current level of inventory. The second is the gap between a variable target pipeline inventory and the current level of pipeline inventory. This variable target level is updated at each review time on the basis of the expected demand during the risk period.

Table 1 summarizes the contributions on the impact of information sharing and smoothing replenishment rules in terms of bullwhip effect. The contributions are classified according to the adopted order rule (classical OUT policies or smoothing replenishment policies), typology of collaboration between partners (traditional SCN or information sharing SCN), and the typology of SCN structure (e.g. serial and non-serial).

In general, all these studies unanimously agree on the benefits of bullwhip avoidance strategies. However, as reported in the previous section and can be easily checked in Table 1, most of these reported studies are confined to the classical mono-echelon structure or the serially-linked SCN. In addition, the few studies based on the non-serial SCN modeling assumption investigating the dynamics of information sharing and demand amplification phenomenon (see e.g. Wang et al. 2011, Chen et al. 2012, Hall & Saygin 2012, Li & Liu 2013) do not report any insight on the different impact of the smoothing replenishment rules and/or the information sharing practice on a classical serial SCN structure and on a divergent SCN structure.

	ORDER POLICY		SCN COLLABORATION		SCN STRUCTURES	
	Classical OUT	Smoothing OUT	Traditional	Information sharing	Serial	Non- serial
Chen et al. 2000	√		√	√	√	
Disney & Towill 2003a		√	√		√	
Disney & Towill 2003b		√	√	√	√	
Dejonckheere et al. 2003	√	√	√		√	
Chatfield et al 2004	√		√	√	√	
Dejonckheere 2004	√	√	√	√	√	
Disney et al. 2004a		√	√	√	√	
Disney et al. 2004b		√	√		√	
Machuca & Barajas 2004		√	√	√	√	
Shang et al. 2004	√		√	√	√	
Warburton 2004		√	√		√	
Byrne & Heavey 2006	√		√	√	√	
Disney et al. 2006	√	√	√		√	
Hosoda & Disney 2006	√	√	√	√	√	
Kim et al. 2006	√		√	√	√	
Lalwani 2006	√	√	√		√	
Boute et al. 2007		√	√		√	
Chen, Disney 2007	√	√	√		√	
Disney et al. 2008	√	√	√	√	√	
Hosoda et al.2008	√			√	√	
Jakšič & Rusjan 2008		√	√		√	
Kim, Springer 2008		√	√		√	
Caloiero et al. 2008		√	√		√	
Kelepouris et al. 2008	√		√	√	√	
Wright & Yuan 2008		√	√		√	
Agrawal et al. 2009	√		√	√	√	
Chen & Lee 2009		√	√	√	√	
Cannella & Ciancimino 2010		√	√	√	√	
Yuan et al. 2010		√	√	√	√	
Bottani & Montanari 2010	√			√	√	
Sari 2010	√		√	√	√	
Hussain & Drake 2011		√		√	√	
Cho & Lee 2011	√		√	√	√	
Barlas & Gunduz 2011	√	√	√	√	√	
Cannella et al. 2011		√	√	√	√	
Yang et al. 2011		√	√	√	√	
Wang et al. 2011	√		√	√		√
Babai et al. 2011	√			√	√	
Kristianto et al. 2012	√	√		√	√	
Ali et al. 2012	√		√	√	√	
Adenso-Diaz et al. 2012	√	√	√	√	√	
Chen et al. 2012	√			√		√
Ciancimino et al. 2012		√		√	√	
Hosoda & Disney 2012	√			√	√	
Wang et al. 2012a		√	√		√	
Wang et al. 2012b		√	√		√	
Zhang & Wang 2012		√	√		√	
Strozzi et al. 2012		√	√		√	
Hall & Saygin 2012	√		√	√		√
Trapero et al. 2012	√			√	√	
Cannella et al. 2013		√	√	√	√	
Wei et al. 2013		√	√		√	
Garcia Salcedo et al. 2013	√		√	√	√	
Li 2013	√		√	√		√

Table 1: Literature review

3 METHODOLOGYCAL APPROACH

Simulation has rapidly become a significant methodological approach to theory development in the literature focused on strategy, organizations and SCN management, due to its ease for modeling and its capability of handling the dynamics and stochastic behavior of the inter-related SCN processes (Chan and Prakash, 2012). Furthermore, simulation models are useful for measuring the bullwhip effect (Min and Zhou, 2002). Particularly, multi-agent-based distributed simulation turns to be one of the most effective tools to model and analyze SCNs because there is a natural correspondence between SCN participants and agents in a simulation model (see Swaminathan et al. 1998, Julka et al. 2002, Dong et al. 2006, Chatfield et al. 2001, Govindu & Chinnam 2010, Long et al. 2011, Chatfield et al. 2012, and Chatfield 2013 among others).

SCOPE is an agent-based SCN simulator presented by Dominguez & Framinan (2013) for modeling and simulating different processes related to the order fulfillment process in SCNs, allowing an easy modelling of real-scale SCNs. Every company in the model can be set up with different policies and parameters for different business functions. The simulator was implemented in Java and uses Swarm (a well-known software platform for agent-based system development). The multi-agent paradigm allows flexible configurations of the system, and we have exploited this characteristic to model and simulate our scenarios (see Section 4).

SCOPE has been validated by contrasting the results obtained from the simulations that have been carried out on a SCN previously modeled by other authors. More specifically, in Dominguez & Framinan (2013), a four-stage serial SCN has been modelled and the results (amplification of the standard deviation of orders) obtained by SCOPE are compared with those provided by Chen et al. (2000), Dejonckheere et al. (2003) and Chatfield et al. (2004).

	Amplification Ratio		
Stage	**Chen et al. (2003)**	**Chatfield et al. (2004)**	**SCOPE**
Retailer	1.89	1.90	1.90
Wholesaler	3.57	3.59	3.53
Distributor	6.74	6.70	6.66
Factory	12.73	12.84	12.58

Table 2: Validation of SCOPE

Table 2 summarizes the validation. In the light of the results, we conclude that SCOPE can be considered a validated platform for the subsequent computational experience.

4 SIMULATED SUPPLY CHAIN NETWORK SCENARIOS

In our experiments, we model a serial supply SCN, and a divergent SCN. The serial SCN is identical to that of Chatfield et al. (2004). It has four stages (i=1,..,4), with one factory, one distributor, one wholesaler and one retailer (Figure 1). The lower node places orders with the next upper node and this node fills these orders. The customer does not fill orders and the factory places orders with an outside supplier. A detailed description is provided in Chatfield et al. (2004).

A divergent SCN is characterized by a tree-like structure, where every stock point in the system receives supply from exactly one higher level stock point, but can supply to one or more lower level stock points (Hwarng et al., 2005). The divergent SCN modeled has to be similar to the serial SCN structure of Chatfield et al. (2004) in order to facilitate a comparative analysis. Hence, the resultant divergent SCN has the same number of stages (horizontal complexity). The divergent topology is modeled by an increasing number of nodes per stage (vertical complexity) through the SCN. Due to the prospective nature of this work, the resultant divergent SCN must have the minimum complexity, and so, the structure of the SCN maintains the vertical symmetry with each node supplying two nodes downstream (see Figure 1).

The following characteristics are common to all the scenarios, and are based on Chatfield et al. (2004):

- **Customers Demand**. Each customer demand (*C*,*j*) follows the same normal distribution with mean $\mu_{C,j}$, estimated by $\overline{D}_{C,j}$, and variance $\sigma^2_{C,j}$, estimated by $s^2_{C,j}$.
- **Lead Time.** The lead time of a node *(i,j)* L_{ij} is stationary, independent and identically distributed, with mean $\mu_{L_{ij}}$ estimated by $\overline{L}_{ij}$, and variance $\sigma^2_{L_{ij}}$estimated by $s^2_{L_{ij}}$.
- **Forecasting**. To estimate the incoming demand ($\overline{D}^t_{ij}, s^2_{D^t_{ij}}$), each node uses a *p*-period moving averages (*MA*(*p*)) and a *p*-period moving variances (*MV*(*p*)). To estimate the lead time ($\overline{L}^t_{ij}$), each node uses running averages (i.e. "all data" approach).

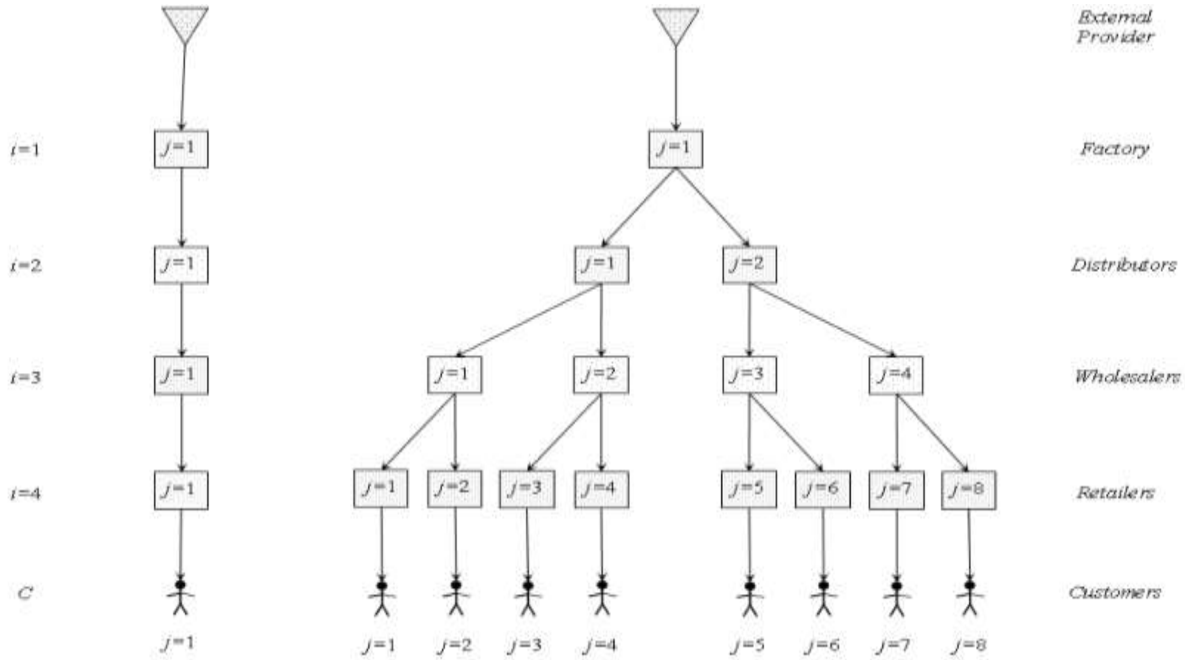


Figure 1. Serial SCN and Divergent SCN under comparison.

On these SCNs, we analyze four scenarios using different techniques to avoid the bullwhip effect as described below:

Traditional SCN with classical OUT policy

The traditional SCN under OUT policies is arguably the most studied SCN configuration in bullwhip literature. Each member generates an independent production–distribution plan on the basis of incoming orders from the direct customer (Holweg & Disney 2005). Thus, retailers forecast the customer demand on the basis of market consumption, while the up-stream echelons only take into account for their replenishment downstream incoming orders (equation (2)) in the risk period (Zhou et al. 2010). In this scenario, the order O_{ij}^{t} (equation (1)) is generated to recover entirely the gap between the OUT level and the inventory position (Cannella et al. 2011), defined as the the net stock (NS_{ij}^{t}) plus the inventory on order but not yet arrived or work in progress (WIP_{ij}^{t}) by Disney & Lambrecth (2008). More specifically, the OUT level S_{ij}^{t} (equation 3) equals the expected demand during the risk period (equation 4) and a safety stock to cover higher than expected demands during the same risk period (equation 5). The risk period is equal to the forecasted lead time ($\bar{L}_{ij}^{t}$) plus the review period *R* (Disney & Lambrecth 2008).

$$O_{ij}^{t} = S_{ij}^{t} - inventory\ position \tag{1}$$

$$X_{ij}^{t} = \sum_{k=0}^{L+R} D_{ij}^{t+k} \tag{2}$$

$$S_{ij}^{t} = \bar{X}_{ij}^{t} + z s_{X_{ij}^{t}} \tag{3}$$

$$\bar{X}_{ij}^{t} = \left(\bar{L}_{ij}^{t} + R\right)\bar{D}_{ij}^{t} \tag{4}$$

$$s_{X_{ij}^{t}}^{2} = (\bar{L}_{ij}^{t} + R) s_{D_{ij}^{t}}^{2} \tag{5}$$

Traditional SCN with smoothing replenishment rule

Similarly to the previous scenario, the information flow consists of the transmission of members' orders upstream. However, in this case, each member generates in every review period *R* an order quantity to recover only a fraction of the gap between the OUT level and the inventory position (Cannella & Ciancimino 2010). The amount of the gap to recover is regulated by the decision parameters *β* and *γ*, known as proportional controllers (Disney et al. 2007). These parameters enable to alter the dynamic behavior of the SCN (Disney & Lambrecht 2008).The resultant order policy is shown in equation (6):

$$O_{ij}^{t} = R\bar{D}_{ij}^{t} + \beta_{ij}\left(z\sqrt{\left(\bar{L}_{ij}^{t} + R\right)s_{D_{ij}^{t}}^{2}} - NS_{ij}^{t}\right) + \gamma_{ij}\left(\bar{L}_{ij}^{t}\bar{D}_{ij}^{t} - WIP_{ij}^{t}\right) \tag{6}$$

We note from equation (6) that the order quantity O_{ij}^{t} is the sum of three components: (1) a forecast on the order from the subsequent echelons, (2) a smoothed inventory gap, and (3) a smoothed work in progress gap.

Information sharing SCN with classical OUT policy

In this scenario, the information flow consists of the transmission of members' orders upstream and of the sharing of market demand. Thus, a generic echelon generates the order quantity not only on the basis of the incoming orders from the direct customers, but also on the basis of market demand. Hence, unlike the traditional SCN, all members compute the OUT level and orders by considering the end-customer demand (equations (7) and (8),). For the serial SCN it is assumed that the end-customer demand is equal for all members. On the contrary, in the divergent SCN, the end-customer demand used by a generic echelon has to be related to its specific position in the chain. More specifically, a generic node (*i*,*j*) has to consider the orders placed by all the customers that are linked to this specific node as the market demand. A node (*i*,*j*) is linked to a customer (*C*,*j*) if the former can trace a path through linked downstream partners to the latter. Herein, we define this information "shared demand", and for a node (*i*,*j*) it is computed as the sum of the shared demand of its downstream linked partners ($j=p$) (equation 7).

$$ShD_{ij}^{t} = \sum_{j=p} ShD_{i+1,j}^{t} \tag{7}$$

$$O_{ij}^{t} = \left(\bar{L}_{ij}^{t} + R\right)ShD_{ij}^{t} + z\sqrt{(\bar{L}_{ij}^{t} + R)s_{ShD_{ij}^{t}}^{2}} - NS_{ij}^{t} - WIP_{ij}^{t} \tag{8}$$

Information sharing SCN with smoothing order policy

In this scenario we adopt simultaneously information sharing and the smoothing replenishment rule (equation (9)). Thus, we modify equation (6) by adding the "shared demand" (equation (7)), obtaining the following order policy:

$$O_{ij}^{t} = ShD_{ij}^{t}R + \beta_{ij}\left(z\sqrt{\left(\bar{L}_{ij}^{t} + R\right)s_{ShD_{ij}^{t}}^{2}} - NS_{ij}^{t}\right) + \gamma_{ij}\left(ShD_{ij}^{t}\bar{L}_{ij}^{t} - WIP_{ij}^{t}\right) \tag{9}$$

5 METRICS AND EXPERIMENTS DESIGN

First proposed by Chen et al. (2000), the Order Rate Variance Ratio (Φ) is the most widely used measure to detect the bullwhip effect (Cannella et al. 2012), measuring the internal process efficiency and indicating how each node performs in the SCN. More specifically Φ provides information on potential unnecessary costs for suppliers, such as lost capacity or opportunity costs and overtime working and subcontracting costs. This is a demand-independent measure, allowing the comparison between both SCNs, which have different demands. It is computed as the ratio of the order variance at a generic node ($\sigma^2_{O_{ij}}$, estimated by $s^2_{O_{ij}}$) to the order variance of the market demand (σ^2_d, estimated by s^2_d) (equation (10)).

Nevertheless, measuring the internal process efficiency at the individual level (single stage) is insufficient as it only accounts for the individual performance of each link in the SCN separately (Cannella et al. 2012). Therefore, a network measure is used as a complementary measure of Φ. The Bullwhip Slope (*BwSl*) summarizes all the ratios obtained for each stage in a single measure (the slope of the linear interpolation) allowing a complete comparison between different SCNs at the network level (equation (12)). A high value of the slope indicates a fast propagation of the bullwhip effect through the SCN, while a low value speaks for a smooth propagation. The slope metrics can give an important and concise overview of the properties of a n-echelon SCN both in terms of bullwhip and inventory stability with just one value instead of the n values required using Φ (Cannella et al. 2013). By aggregating individual performance measures into a single index of overall performance (Wong and Wong 2008), these metrics are able to measure the potential benefit of partnership, collaboration and information productivity of suppliers, enabling fast feedback and continuous improvement (Cannella et al. 2013).

The above mentioned metrics are easy to apply to a serial SCN, but there is one important difference when applying them to a divergent SCN, as each stage contains one or more than one nodes. In the serial SCN the parameter required to compute the different metrics on each stage (i.e. order variance) is taken from the only node in the stage. In the divergent SCN, it is necessary to find an aggregate measure for the whole stage. To obtain this measure, the orders of every node j in the stage i (O_{ij}) are considered at the same time and added, resulting in an aggregate order pattern for the stage i: $AO_i = \sum_{j=1}^{n_i} O_{ij}$. Following the same procedure, the aggregate demand market pattern is obtained: $Ad = \sum_{j=1}^{n_C} O_{Cj}$. Then, the aggregate variance of each stage ($\sigma^2_{AO_i}, \sigma^2_{Ad}$) can be estimated ($s^2_{AO_i}, s^2_{Ad}$), and Φ_i is calculated as $\Phi_i = s^2_{AO_i}/s^2_{Ad}$. In view of the fact that all the customer demands are assumed to be independent and that each node places orders independently, the aggregate variance in each stage *i* is the sum of the variances of orders of each node *j* in the stage *i* ($\sigma^2_{O_{ij}}, \sigma^2_{O_{Cj}}$), estimated by ($s^2_{O_{ij}}, s^2_{O_{Cj}}$), and thus, the calculation of Φ_i is formulated as equation 11. All these metrics are summarized in Table 3.

Order Rate Variance Ratio			Bullwhip Slope	
Serial SCN	$\Phi_i = \frac{s^2_{O_i}}{s^2_d}$	(10)	$BwSl = \frac{K\sum_{i=1}^{K} p_i\Phi_i - \sum_{i=1}^{K} p_i \sum_{i=1}^{K}\Phi_i}{K\sum_{i=1}^{K} p_i^2 - (\sum_{i=1}^{K} p_i)^2}$ K is the total number of echelons. p_i is the position of the *i*th echelon.	(12)
Divergent SCN	$\Phi_i = \frac{\sum_{j=1}^{n_i} s^2_{O_{ij}}}{\sum_{j=1}^{n_C} s^2_{O_{Cj}}}$	(11)		

Table 3. Metrics for measuring the bullwhip effect.

In order to tune the proportional controller we adopt the design proposed by Disney & Towill (2006). More specifically, the experimental level of the two parameters are related to lead time according to the following relation: $1/\beta_{ij} = 1/\gamma_{ij} = \bar{L}^t_{ij} + R$. This design has been tested by several simulations and analytical environments and it presents an extremely well-behaved dynamic response (Disney & Towill 2006). Other parameters of the SCNs are set as in Chatfield et al. (2004), i.e.: review period $R = 1$, safety factor $z = 2$, *p*-period $p = 15$, lead time is assumed to be gamma-distributed with mean 4 time units for all nodes in the SCN and 0 for customers, with a coefficient of variation $c.v. = 0.50$.

Following the simulation procedure indicated in Chatfield et al. (2004), each experiment consists of 30 replications of 700 periods, with the first 200 periods of each replication removed as a warm-up used to set up the system. The results obtained from the replications are averaged for each experiment. Metrics are calculated after the impulse time (*t*=450). In Table 4 we report a summary of all sets of experiments.

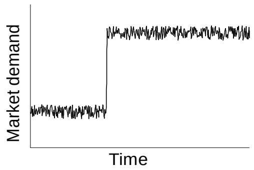
Demand Pattern	Structure of the SCN	Order Policy	Metrics
	Serial SCN	Traditional order-up-to	*Φ* *BwSl* t ∈ [450-700]
$N(50, 20^2)$ t ∈ [0-449]		Order-up-to + Smoothing	
$N(100, 20^2)$ t ∈ [450-700]		Order-up-to + Information Sharing	
		Order-up-to + Smoothing + Information Sharing	
	Divergent SCN	Traditional order-up-to	
		Order-up-to + Smoothing	
		Order-up-to + Information Sharing	
		Order-up-to + Smoothing + Information Sharing	

Table 4. Summary of experiments.

6 RESULTS AND DISCUSSION

The numerical output of the experiments is presented. Data are collected and the metrics discussed in the Section 5 are herein used to assess performance of the SCNs. In order to contrast the scenarios, we plot the Order Rate Variance Ratio measures using the echelon position as independent variable, according to Dejonckheere et al.'s notation (2004) (Figure 2). Differences between the serial SCN and the divergent SCN are plotted in Figure 3. Finally, in Table 5 we report the values of the Order Rate Variance Ratio by echelon (columns) and by SCN configuration (rows). Furthermore, in order to concisely compare the different scenarios, we also report in Table 5 the values of the bullwhip slope for every SCN configuration and the differences between the serial SCN and the divergent SCN. To test the statistical significance of the scenarios, we calculate the 99%-confidence interval for each one. The confidence intervals are presented next to the *Φ* and *BwSl* values in Table 5. The values obtained show that all the scenarios simulated are statistically different.

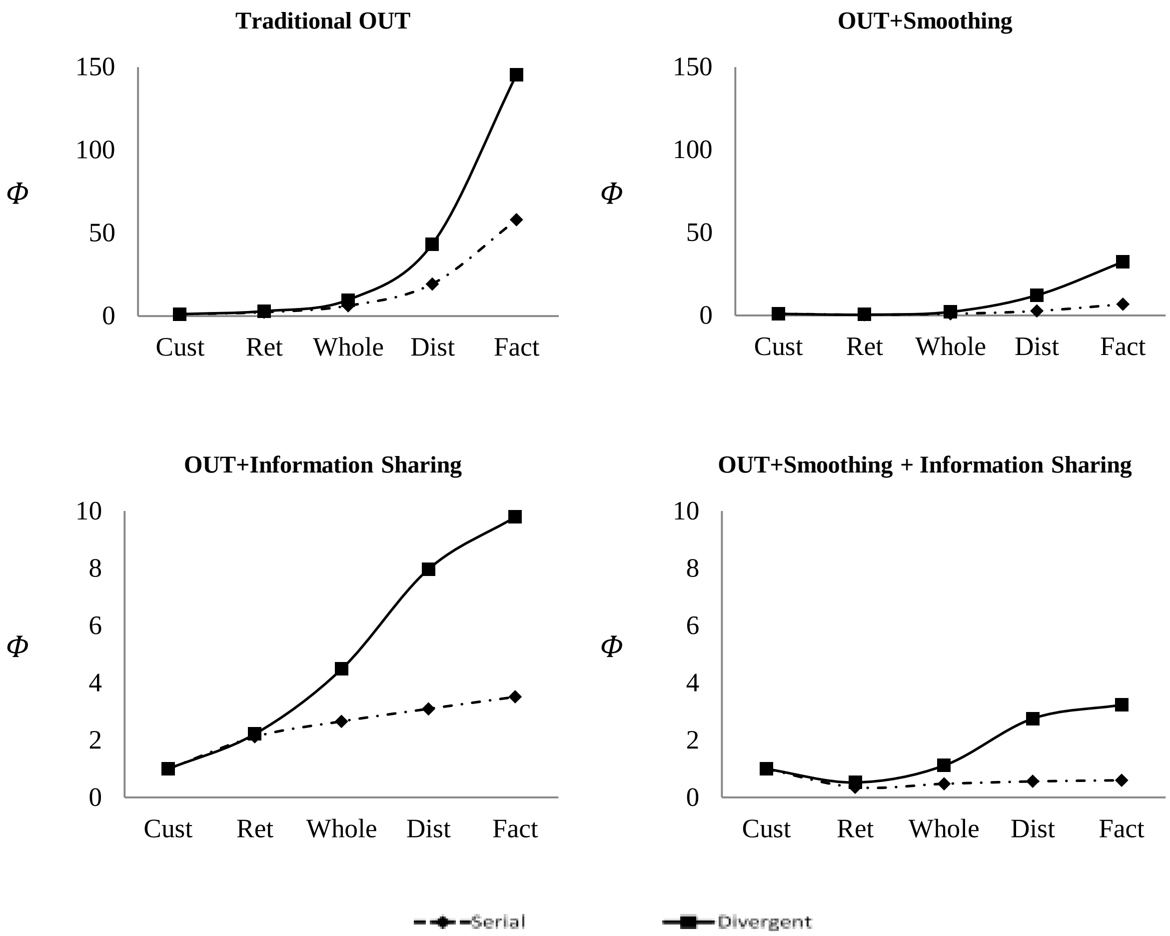


Figure 2. Φ for the different bullwhip limiting strategies.

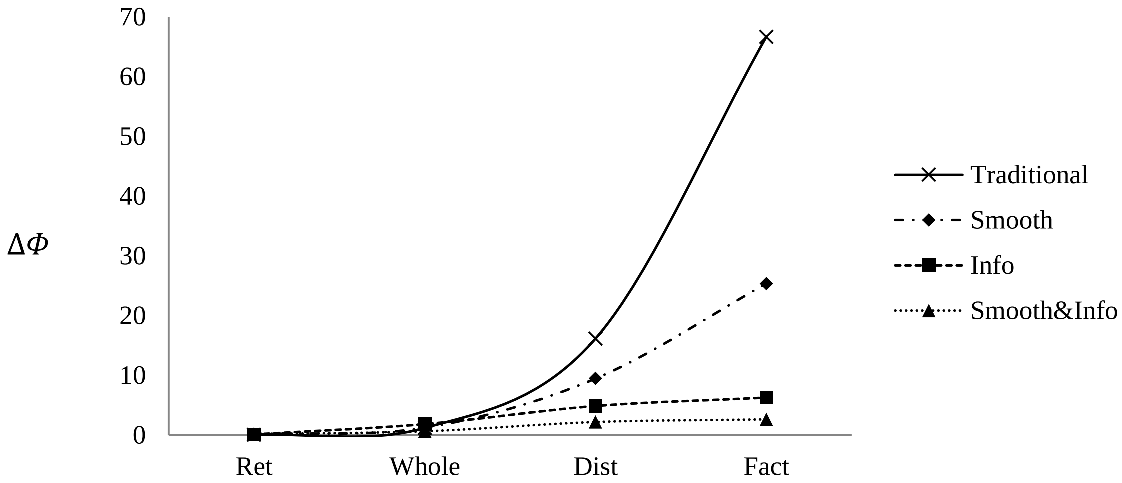


Figure 3. Φ differences between serial and divergent SCNs for the different bullwhip limiting strategies.

Order Policy	SCN structure	Φ				BwSl
		Retailer	Wholesaler	Distributor	Factory	
Traditional OUT	Serial	2.655±0.0126	7.732±0.1203	23.453±0.4962	69.539±1.7386	15.790±0.3942
	Divergent	2.690±0.0119	8.923±0.1188	39.595±0.8211	136.196±2.8934	30.730±0.6540
	Δ	**0.035**	**1.191**	**16.142**	**66.657**	**14.94**
OUT + Smoothing	Serial	0.360±0.0015	0.957±0.0058	2.665±0.0221	6.803±0.0655	1.391±0.0150
	Divergent	0.530±0.0021	2.190±0.0246	12.127±0.1899	32.168±0.5706	7.393±0.1324
	Δ	**0.17**	**1.233**	**9.462**	**25.365**	**6.002**
OUT + Information Sharing	Serial	2.120±0.0185	2.657±0.0234	3.093±0.0299	3.508±0.0317	0.599±0.0080
	Divergent	2.219±0.0216	4.488±0.0399	7.970±0.0927	9.793±0.1178	2.334±0.0311
	Δ	**0.099**	**1.831**	**4.877**	**6.285**	**1.735**
OUT + Smoothing + Information Sharing	Serial	0.354±0.0017	0.474±0.0025	0.560±0.0026	0.599±0.0025	-0.060±0.0007
	Divergent	0.528±0.0019	1.116±0.0069	2.756±0.0177	3.236±0.0192	0.670±0.0054
	Δ	**0.174**	**0.642**	**2.196**	**2.637**	**0.73**

Table 5. Numeric results for the shock lens perspective (99% confidence intervals).

In the following subsections, results are analyzed for each scenario.

Traditional SCN with classical OUT policy

The traditional scenario shows the classical exponential trend of the bullwhip effect for the serial SCN, obtaining high values of both Φ and *BwSl*. The result is in line with several studies dealing with the magnitude of bullwhip effect in a traditional SCN under the classical OUT policy (Disney & Lambrecth 2008). Analogously, the divergent SCN shows the same exponential trend, but with higher values of Φ and *BwSl*. By analyzing the differences in order variance ratio between the serial SCN and the divergent SCN, we observe an important differentiation between both SCNs, being $\Delta\Phi = 16.142$ at the distributor stage and $\Delta\Phi = 66.657$ at the factory stage. Finally, we can appreciate how the discrepancy in the bullwhip effect propagation is equal to $\Delta BwSl = 14.94$.

Traditional SCN with smoothing replenishment rule

The smoothing scenario considerably reduces Φ and $BwSl$ for the serial SCN. In the first stages (retailers and wholesalers) there is no bullwhip effect ($\Phi \leq 1$) and then, it start to smoothly increases ($BwSl = 1.391$). As for the previous scenario, we confirm the benefits in term of bullwhip reduction provided by the smoothing replenishment rule. Likewise, the divergent SCN also experiments a considerable reduction of Φ and *BwSl*, but still presents a high value of the bullwhip slope ($BwSl = 7.393$), and hence, it still shows high values of Φ at the last stages. Notice that the high differences between both SCNs observed in the previous scenario have been reduced by the use of this technique.

<u>Information sharing SCN with classical OUT policy</u>

The reduction of Φ and $BwSl$ in the information sharing scenario is higher than in the smoothing scenario for both SCNs. As this technique uses customer demand in the calculation of orders, the first stage (retailers) shows similar values of Φ to those of the traditional scenario for both SCNs. After this stage, Φ starts to increase in a linear trend (not showing the exponential trend of the above scenarios), with a higher slope in the divergent SCN. The differences between both SCNs have been considerably reduced in this scenario, being $\Delta\Phi = 6.285$ at the factory stage and $\Delta BwSl = 1.735$.

<u>Information sharing SCN with smoothing order rule</u>

Finally, the combination of the above techniques obtains the highest reduction of the bullwhip effect for both SCNs. At the retailer stage, we observe similar values to those obtained in the smoothing scenario for the serial SCN, (information sharing does not work in this stage). After this stage, Φ starts to increase approximately in a linear trend (like the information sharing scenario), but with a very low slope due to the reduction caused by the smoothing factor and thus obtaining very low values of Φ in all stages ($\Phi \leq 1$). The divergent SCN presents the same behavior described for the serial SCN, but with higher bullwhip slope and hence, higher values of Φ. However, the discrepancy between both SCNs is very low, with $\Delta\Phi = 2.637$ at the factory stage and $\Delta BwSl = 0.73$.

7 FINDINGS AND MANAGERIAL IMPLICATIONS

The results reveal several important features of the divergent SCN and of the bullwhip avoidance techniques addressed in this study. First of all, the output of the simulation confirms the efficacy of the information sharing and of the smoothing replenishment rule in terms of bullwhip reduction in the divergent SCN. Until now this efficacy had merely been demonstrated for serial SCN models. However, in our opinion, the most significant results provided by this study concern the differences in term of bullwhip magnitude between the serial SCN and the divergent SCN. Actually we note how the divergent SCN structure always performs worse than the serial SCN. We think that this discrepancy can be due to the inherent higher complexity (i.e. higher number of nodes, higher nodes per stage, etc.) of the divergent SCN with respect to the serial SCN. In fact, the market demand impulse causes a massive stock-out situation at the retailer stage, which is then propagated and amplified along the divergent SCN, causing stock-outs in all the stages. While the factory in the serial SCN has to manage the instability caused by the stock-out of only one retailer, the same factory in the divergent SCN has to manage it with the stock-outs of eight retailers. This significant discrepancy observed between both SCNs in the traditional scenario lead us to think that the divergent SCN is inherently more vulnerable to unexpected changes in market demand than the serial SCN and so, less robust.

A reduction of this discrepancy can be noted for the scenarios characterized by the implementation of one of both bullwhip avoidance techniques. Thus, these techniques are not only able to reduce the bullwhip effect in both SCN structures, but are even able to increase the resilience and the robustness of the divergent SCN. However, there are some differences in the impact of the information sharing and of the smoothing replenishment rule. More specifically, by adopting only the smoothing replenishment rule a significant reduction of the bullwhip effect on both SCNs can be noted, but it is still high in the last stages of the divergent SCN. With this technique, the orders placed by each node are just reduced by the smoothing factor, but are still affected by the demand pattern of the downstream nodes. When the above-mentioned multiple stock-out situation occurs, the high order amplification is reduced (smoothed), but not eliminated. Furthermore, the *BwSl* is high, so a divergent SCN with high number of stages would present high values of Φ. Thus, we can state that the smoothing technique does not work properly for long divergent SCNs under a shock demand.

On the contrary, information sharing performs better than the smoothing, obtaining good values of the bullwhip effect for both SCNs. The benefit of this technique is twofold: 1) nodes can adapt faster to the violent changes in market demand, and 2) the high amplification of orders due the multiple stock-out problem commented above is stopped, because nodes use the customer demand order patterns to update the base stock level instead of the order pattern of their downstream partners. Combining the benefits of the information sharing and the smoothing together, the bullwhip effect in the divergent SCN almost disappears and its propagation is very low (near zero).

From a managerial view point, a significant implication for the designing and management of SCNs has been precisely captured. In fact, to the best of our knowledge, till now, the unique proposed solution in scientific literature to reduce poor dynamics in divergent SCN has been the elimination of channel intermediaries (direct channel, “the Dell model”) (Disney & Lambrecth 2008). In fact, the work of Sodhi & Tang (2011), one of the few papers that have reported some insights on the differences between a serial SCN and a no-serial SCN in terms of their dynamic behavior, reveals that a firm should consider simplifying the SCN structure by reducing the number of levels or by reducing the number of successors (i.e. transforming the current SCN structure into a serial structure) to mitigate the incremental bullwhip effect. In this work, we show how the differences between the divergent SCN and the serial SCN can be considerably reduced by an appropriate implementation of the smoothing replenishment rule and/or the information sharing (see e.g. Figure 4). Thus, we can argue that information sharing and smoothing replenishment rule not only limit the bullwhip effect, even SCN characterized by more than one node in the same layer, but also are able to increase the resilience and robustness of SCNs. By reducing this incremental bullwhip effect we are, in fact, reducing the differences in operation performance between the traditional structure and the divergent structure (merging their dynamic behavior) and hence, increasing the robustness of the divergent SCN without modifying its structure (suppressing nodes).

The above-mentioned result bring us to further concern about the efficient management of the SCNs. Nowadays we are not facing a temporary shock that will quickly pass, but in fact are on the verge of an “era of turbulence”, that will feature higher variance in key business parameters (Christopher & Holweg 2011). Obviously, this context exposes SCNs to tremendous shocks and impetuous alterations of the market (Cannella et al., 2014). Thus, the SCN crash test adopted in this work do not merely emulate the potential response of the real-world SCNs for an extreme and rare condition of the business environment. On the contrary, this response realistically represents the dynamic behavior of the real-world SCNs under the current and the advocated future business environment. In the light of our results, companies should pay more attention with respect to the past decades, when decide to reengineer and even design new SCNs. Consider the case of a company that operates with traditional control strategies and is yet able to perform well in the current market. If this company is willing to enhance their market by covering further geographical positions, probably should increase their distribution, wholesaler and retailer centers. Obviously this would amplify the complexity of the chain structure. As direct consequence, this company would risk to experiment a decrement of the whole operational performance. Thus, the potential benefit provided by the acquisition of new market share can be leveraged by a structurally decaying of the dynamic behavior. On the contrary companies adopting these bullwhip avoidance strategies, such as the external collaboration by information sharing strategies, pursuing the "new supply chain agenda" (see e.g. Stank et al. 2011), would reduce the risk and in any case would be more protected against the effect of the "era of turbulence" than the traditional SCNs.

8 CONCLUSIONS

The literature review reveals that the bullwhip avoidance phase have been focused mostly on serial SCNs structures, not having found many studies considering different SCN structures. However, real SCNs rarely adopt the traditional serial structure, often following a more complex topology. By examining the causes of the bullwhip effect under different SCN structures, researchers would be able to better assess the cause of the bullwhip effect, measure their relative contributions, and thus, make suggestions tailored to a particular SCN structure (Paik & Bagchi 2007).

The present work is a first attempt to explore this research gap by analyzing the impact of some well-known bullwhip avoidance techniques (i.e. the smoothing replenishment rule and the information sharing) on a divergent SCN and by doing a benchmark with the classical serial SCN already analyzed in the literature by several authors.

The analysis has been carried out using the shock lens proposed by Towill et al. (2007), which is a stress-test related to the robustness of the system. Under these conditions, the divergent SCN performs worse than the serial SCN (in terms of bullwhip effect) in all the scenarios.

This bad behavior is caused by the higher complexity of the divergent SCN, which leads to a loose in robustness in relation to the serial SCN.

The best results are offered by the combination of the smoothing replenishment rule with the information sharing. However, the differences between both SCNs still persist, not being completely removed. This fact opens a new research line in developing new techniques which implicitly consider the inherent complexity of divergent SCNs and attempt to totally erase the differences with the serial SCN. These techniques would allow managing a divergent SCN with the same robustness than the classical serial SCN.

This research is limited by the input demand used for the analysis (i.e. the shock lens). Thus, it could be extended by the use of other types of input demand. In this regard, Towill et al. (2007) proposed other two perspectives to detect the bullwhip effect: the variance lens, with a demand based on a level plus noise (see Dominguez et al., 2014), and the filter lens, based on a demand with seasonality.

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