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Bullwhip Effect Study in a Constrained Supply Chain

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Abstract

Well organized supply chains are one of the best ways to compete in today's marketplaces. For make-to-stock production systems the production plans and activities are based on demand forecasting, which is one of the key causes of the bullwhip effect (BE). BE is the inherent increase in demand fluctuation up the supply chain and produces excess inventory and poor customer service. In the paper we simulated a simple three-stage supply chain using seasonal (SM) and deseasonalized (DSM) time series of the market demand data in order to identify, illustrate and discuss the impacts of different level constraints on the BE. The results are presented for different overall equipment effectiveness (*OEE*) and constrained inventory policies. At higher *OEE* level manufacturers have less variability in production processes; the BE is stronger in DSM than in SM.

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Keywords: Supply chain; bullwhip effect; simulation; capacity constraints

1. Introduction

Supply chain management (SCM) is one of the most important and developing areas. It includes basically demand fulfilment, demand planning and supply planning. It integrates internal and external logistics across many manufacturers, suppliers, distributors, retailers, and transportation providers to increase productivity and to obtain a competitive advantage for all parties involved. The objective of supply chain management is to provide a high velocity flow of high quality, relevant information that will enable suppliers to provide an uninterrupted and precisely timed flow of materials to customers. The idea is to apply a total systems approach to managing the entire flow of information, materials, and services from raw materials suppliers through factories and warehouses to the

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end customer. Design of supply chain networks includes network configuration and related operational decisions.

The original motive of SCM was "elimination of barriers between trading partners" in order to facilitate synchronization of information between them [1]. But in real business this idea became lost. Where is the main problem? Supply chain performance depends on the operation of all members in a supply chain, where each member's basic objective is the optimisation of its own performance. Such behaviour of members can lead to less optimal whole chain performance. Members of a supply chain are used to compete and not to co-operate; they don't share information about products, customers, inventories, production capacities, costs and other business processes. So the members don't know much about the real market situation and the efficiency in their chain. They just repeat five basic activities in their supply chain: buy, make, move, store and sell.

Simulation is a very powerful and widely used management science technique [2] for the analysis and study of supply chains. The most important types are: spreadsheet simulation, system dynamics, discrete-event simulation, and business games.

The bullwhip effect represents the phenomenon of demand distortion where orders to supplier tend to have larger variance than sales to the buyer and this distortion propagates upstream in an amplified form.

In the paper we are giving a brief literature review of publications dealing with the bullwhip effect (section 2), continued with the presentation of the data used in the model (section 3) and our analysis of the influence of level constraints in the modelled supply chain (sections 4 and 5). Finally, section 6 contains a conclusion of the work and the future work.

2. Literature review

Numerous studies focused on identifying the bullwhip effect in examples from individual products and companies, starting in '70s [3-5].

Alony and Munoz reviewed the various methods of modelling the dynamics of supply chains [6]. They examined the limitations of modelling methodologies (analytical, agent-based, simulation) and suggested a combined discrete event and continuous simulation modelling approach. Pujawan investigated how different supply chain policies and different operating environments affect schedule instability in a supply chain [7]. It is shown that schedule instability is propagated up the supply chain and is much affected by the degree of demand uncertainty from the end customers, and that safety stock policy applied by the buyer has much impact on schedule instability.

Disney reviewed a range of methodological approaches to solving the bullwhip problem [8]. Measures for the bullwhip are given. Different types of supply chains (traditional – Fig. 1, information sharing, vendor managed inventory) are described and as a whole it is a general overview including also replenishment policies, forecasting techniques, lead times, costs etc.

Ouyang and Li analysed the propagation and amplification of order fluctuations in supply chain networks (with multiple customers) operated with linear and time-invariant inventory management policies [9]. The paper gives analytical conditions to predict the presence of the bullwhip effect to any network structure and any inventory replenishment policy, using a system control framework for analysing order stability. It provides the basis for modelling complex interactions among suppliers and among customer demands.

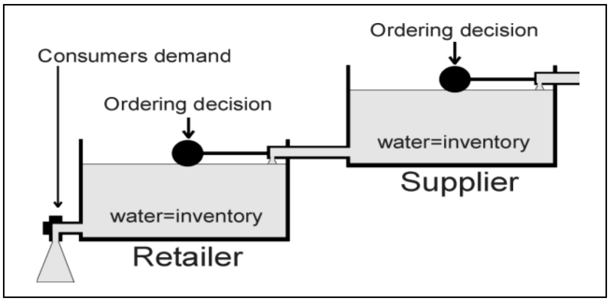


Fig. 1. Schematic of a traditional supply chain [8].

Glatzel et al. [10] described the bullwhip effect problem on many practical cases from global manufacturing industry aspect with the emphasis to find new ways of thinking and decision making to assure enough flexibility in business. Cachon et al. made observations and evaluated the strength of the bullwhip effect in U.S. industry [11] using official data from period 1992-2006. They did not observe the bullwhip effect among retailers and among manufacturers, but the majority of wholesalers amplified. They explained also that highly seasonal industries tend to smooth demand volatility whereas nonseasonal industries tend to amplify.

Chen and Lee [12] developed a set of formulas that describe the traditional bullwhip measure as a combined outcome of several important drivers (finite capacity, batch ordering, seasonality). They discussed the managerial implications of the bullwhip measurement and showed that an aggregated measurement over relatively long time periods can mask the operational-level bullwhip. Duc et al. [13] quantified the bullwhip effect, the variance amplification in replenishment orders, for cases of stochastic demand and stochastic lead time in a two-stage supply chain. They investigated the behaviour of a measure for the bullwhip effect with respect to autoregressive coefficient and stochastic order lead time. Sucky focused in his work [14] on measuring the bullwhip effect taking into consideration the network structure of supply chains. He shows that the bullwhip effect is overestimated if just a simple (two stage) supply chain is assumed and risk pooling effects are present. The strength of the effect depends on the statistical correlation of the demands. Ouyang and Daganzo [15] presented a control framework to analyse the bullwhip effect in single-stage supply chain under exogenous Markovian uncertainty. They derived robust analytical conditions that diagnose the bullwhip effect and bound its magnitude. The results are useful for prediction of performance in uncertain operating environments.

Shaikh and Khan quantified twenty factors responsible for the bullwhip effect [16]. Their study is based on Middle East situation; the data were collected using a survey form. The most critical factors observed are Substitution products (Competition) and Seasonal effect.

Agrawal et al. analysed a two stage serial supply chain [17]. They studied the impact of information sharing and lead time on bullwhip effect and on-hand inventory. It is shown that some part of bullwhip effect always remain after sharing both inter- and intra-stage data and that the lead time reduction is far more beneficial. Bray and Mendelson analysed the bullwhip by information transmission lead time based on public companies' data from years 1974-2008. Shorter reaction times cause significantly more troubles regarding bullwhip [18].

Oyatoye in Fabson [19] explored the simulation approach in quantifying the effect of bullwhip in supply chain, using various forecasting methods. They emphasized a problem of inadequate information in a supply chain. Kelepouris et al. studied how specific replenishment parameters affect order variability amplification, product fill rates and inventory levels across the chain [20]. Short lead times are essential for the efficient operation of the supply chain. They investigated also how demand information sharing can help towards reducing order oscillations and inventory levels in upper nodes of a supply chain. The model represents a simple two-stage supply chain with real demand data. Tominaga et al. investigated the influence of safety parameters for inventory control policy (safety stocks) on bullwhip effect and its relationship to costs and total profit, with present demand uncertainty in the modelled supply chain [21]. Csik and Foldesi tested the problem of bullwhip effect by adoption of an inventory replenishment policy involving a variable target level, where all other common causes were excluded [22]. Safety stock was proportional to the actual demand. They proposed a new production plan, which guarantees the stability of the entire supply chain. Nepal et al. presented an analysis of the bullwhip effect and net-stock amplification in a three-stage supply chain considering step-changes in the production rates during a product’s life-cycle demand [23]. The simulation results show that performance of a system as a whole deteriorates when there is a step-change in the life-cycle demand. Authors in [24] demonstrate some other supply chain optimization methods.

3. Data and model presentation

Our study is dealing with single product / multi-level supply chain using real market demand data with present variability (demand with moderate linear trend, we calculate with seasonality and deseasonalized). Information (orders) in the chain flow on a weekly basis. We have collected a time series of the market demand data with seasonal characteristics for 48 weeks (periods), shown in Fig. 2 where we added the deseasonalized values for the time series.

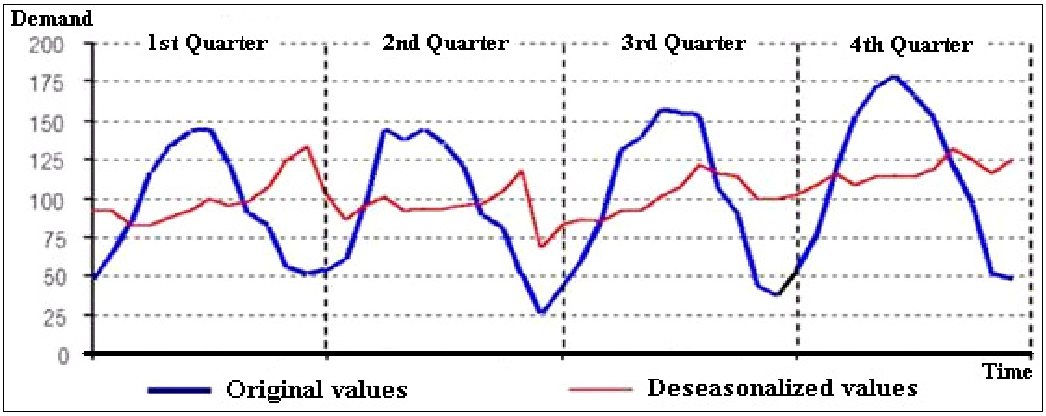


Fig. 2. Market demand of the product (original and deseasonalized values).

Statistical analysis shows that we have 48 data, minimal demand is 26, and maximal demand is 179. Average demand is 102; mode 97, standard deviation is 43 (for original demand) and 11 (for deseasonalized demand).

Deseasonalization is performed using the chain indexing method. In all models (SM - seasonal model and DSM – deseasonalized model) the 48 periods with continuous reviewing were simulated. The simulation model comprises a three-stage supply chain consisting from single retailer, manufacturer and supplier (Fig. 3).

The simulation spreadsheets are designed in Microsoft Excel software (file size: 270 kb). For inventory policy, as one of the level constraints, we chose the min-max inventory policy but only for manufacturer stage in the supply chain. Manufacturer will place order to its supplier in predetermined review period. The order size is the difference between the required production level and the effective inventory level at the review time. Effective level is quantity of work in progress, net stock level plus backorder quantity:

$$\text{Order} = \text{required production level} - \text{work in progress} - \text{net stock level} + \text{backorder quantity} \quad (1)$$

Inventory level is defined as:

$$MIN\ inv.\ level = SS \cdot Sf \quad (2)$$

where: *SS* – safety stock, *Sf* – safety factor.

$$MAX\ inv.\ level = MIN\ inv.\ level - INVlf \quad (3)$$

where: *MIN inv. level* – minimum inventory level, *MAX inv. level* – maximum inventory level, *INVlf* – inventory level factor within limits (1 … 2).

Considering *Sf* the *SS* is defined at limit where the minimum inventory level satisfies production rate and capacity utilization planed according to retailers demand. Usually the processes are planned at 85 % of OEE where production output totally complies with retailers demand and capacity utilization meets 100 % (later in Fig. 4a).

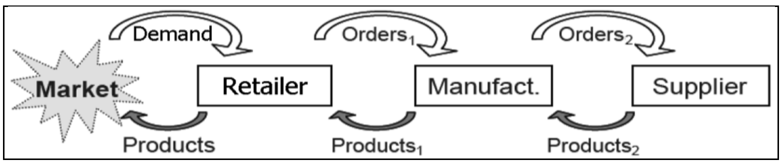


Fig. 3. Presentation of a three-stage supply chain.

Considering the aforementioned for the second level constrain we chose the *OEE* factor, which is considered in manufacturer and supplier lead time. Total lead time is the time taken by the demand and order to be processed to the retailer – one review period. It consists of manufacturer and supplier lead time.

$$Lm = \frac{Tm}{OEEm} \tag{4}$$

$$Ls = \frac{Ts}{OEEs} \tag{5}$$

$$L = Lm + Ls \tag{6}$$

$$PR = \frac{D}{L} \tag{7}$$

$$CU = \frac{PR}{maxPR} \times 100 \tag{8}$$

where: *Lm* – manufacturer lead time, *Tm* – manufacturer production lead time, *Ls* – supplier lead time, *Ts* – supplier production lead time, *L* – total lead time, *PR* – production rate, *D* – retailer's demand, *CU* – capacity utilization (in %).

In this paper, for *bullwhip effect measure*, the following equation is used:

$$BE = \frac{VAR(Order)}{VAR(Demand)} \tag{9}$$

If the value of *BE* is equal to one, then the order and demand variances are equal. Bullwhip effect is present in a supply chain if its value is larger than one. Where value of bullwhip is smaller than one it is assumed to have a smoothing scenario, meaning that the orders are less variable than the demand pattern.

Verification of the outputs of the model was done by tracing the values produced by the simulation and verifying them by hand using the mathematical equations from the model.

In real environment, because of various deviations in production process, the process is hardly 100 % smooth. Therefore the *OEE* level is taken into account. The *BE* level equal to one is more theoretical because the difference between order variability and demand pattern is always present. We also assume that higher order variability and strength of the *BE* can be reduced with proper inventory level policy. Some other assumptions in the model:

- The three-stage supply chain is working with a decentralized information sharing policy, where each stage calculates its demand forecast, based on the orders it gets from the downstream stage.
- Inventory control is based on continuous review ordering policy, where a new order is placed when the inventory level drops to the minimum inventory level.
- At manufacturer stage the inventory levelling policy is performed.
- Backorders are allowed, thus if one of the inventories cannot fulfil the whole order, it will keep the shortage amount as a backorder to be fulfilled as soon as it gets a new replenishment.
- Time series model: retailer performs autoregressive AR(1) model with $0 < \varphi < 1$ for the demand pattern and manufacturer performs exponential smoothing with $0 < \alpha < 1$ for demand forecasting.
- The *OEE* level is considered at manufacturer and supplier lead time to fulfil the orders.
- The review period is equal to total lead time.
- Week is the basic time unit in the model. One order per period (one order per week) is presumed for each stage in the chain.
- The simulation starts with a stock amount equal to minimum required inventory level.
- If the inventory stock exceeds the target level, then no order is performed in that period.

4. Simulation

The aim of the simulation is to investigate the phenomenon of the bullwhip effect and identify the impact of different level constraints. The simulation model demonstrates the successive situation in 49 weeks. In the next two subsections the results of the supply chain model for different *OEE* and inventory levels are presented.

4.1. Case 1: Equal OEEm and OEEs (85 %), and inventory policy with defined SS and planed Sf and INVlf

Production processes are planed at *OEE* of 85 % and *CU* of 100 % where *PR* meets the required amount of demand. Metter to this, there have to be chosen enough effective inventory policy with sufficient *SS,* efficient *Sf* and *INVlf.* Presence of deviation (*OEE* level) in production process causes bigger order variability than demand pattern, which results in higher *BE* than 1. Case 1 (Fig. 4a) indicates stronger *BE* in DSM. Because of constant demand and unsteady production process, stock fluctuates more easily, which means more frequent order variability. Because of this phenomenon the difference between order and demand variances is higher. In order to reduce the *BE* on reasonable level effective inventory policy have to be performed. DSM requires higher *Sf* and lower *INVlf* than SM. That means more limited inventory level at higher values. Because of more limited inventory the orders vary frequently at lower amplitude (Fig. 4b). Simulation also indicates that cost effciency of supply chain in SM is higher (because of lover inventory level).

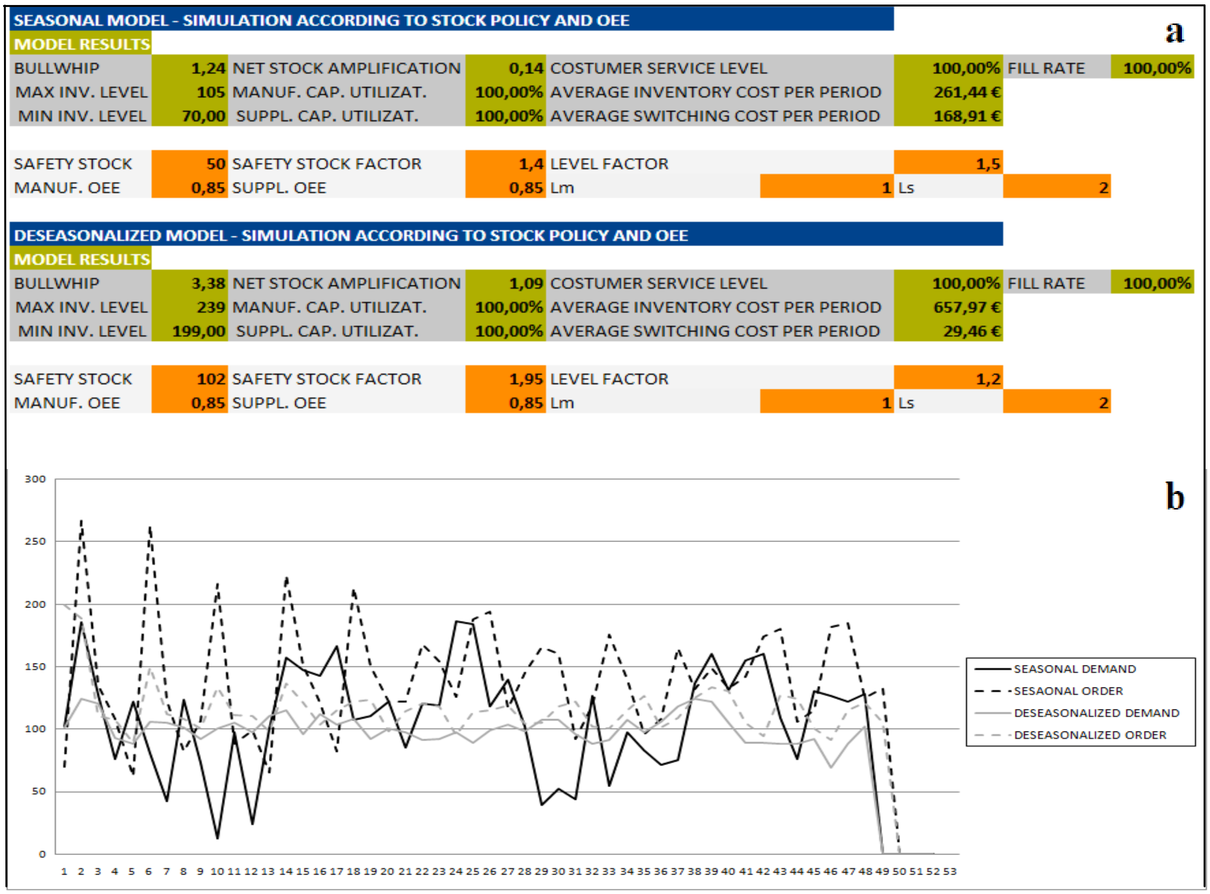


Fig. 4. (a) model results at *OEEm* and *OEEs* of 85 %; (b) case 1 bullwhip effect comparison of models.

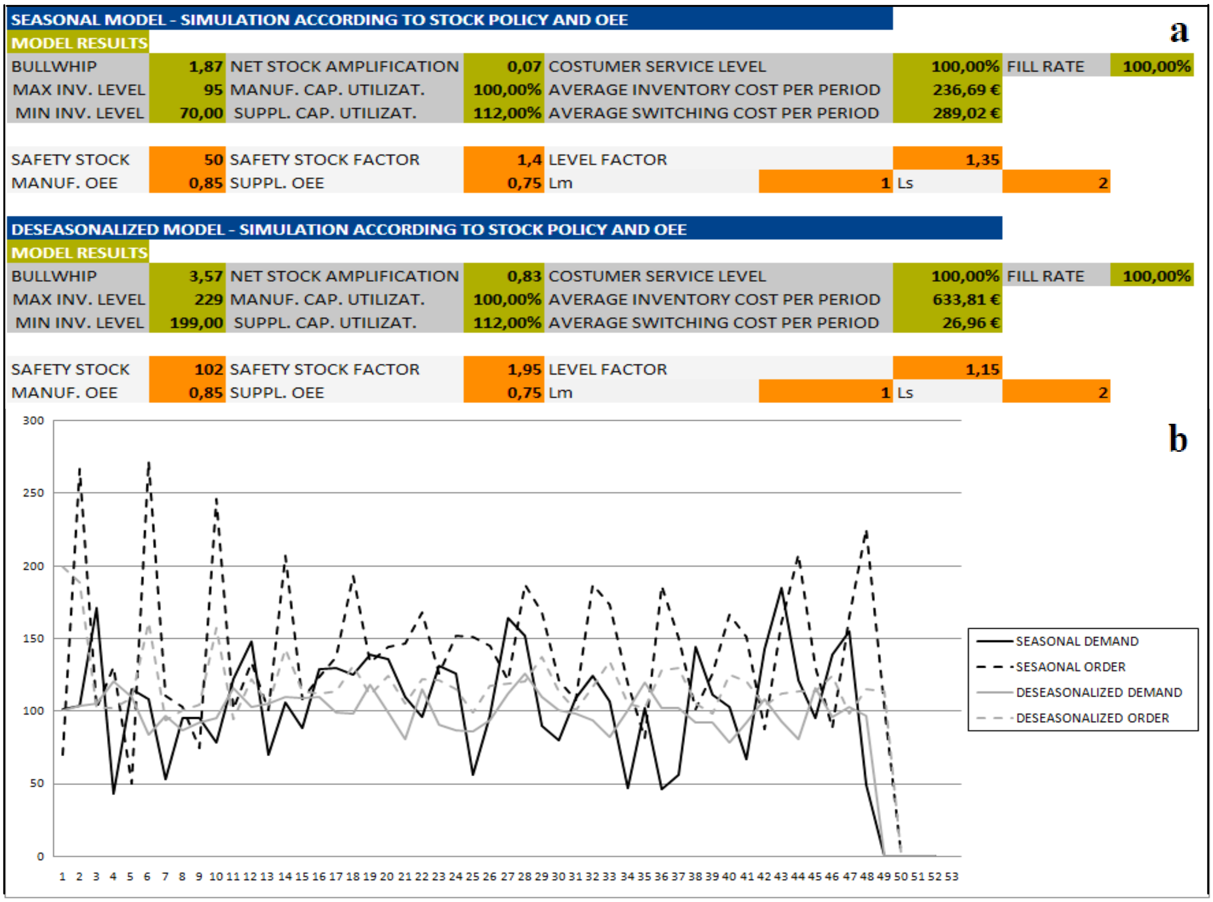
4.2. Case 2: Different OEEm and OEEs (85 %, 75 %) and changed inventory policy with defined SS and variation of Sf and INVlf

Different levels of *OEE* at downstream stages in a supply chain daily occur in real environment. Downstream stage has higher deviations in production processes; that leads often to inefficient material supply. Incoming inventory level fluctuates more at upstream stage which leads to backorders and higher order variability.

In case 2 (Fig. 5a) simulation results indicate more frequent inventory fluctuation, due to downstream backlogs. Therefore in both models the net stock amplification and *BE* was stronger than in case 1. To reduce the strength of *BE*, reducing order variability has to be performed. For this matter the inventory level has to be optimized. In case 2 the *INVlf* in both models was decreased, which reduces the interval between min-max inventory levels.

Due to more unsteady stock fluctuation, changes are more frequent, which is more evident in DSM. With inventory optimization the amplitude of stock fluctuation was reduced. In DSM net stock fluctuates frequently with lower amplitude at higher level. Therefore the stock amplification is higher. Due to more limited inventory level the order variability is frequent at lower amplitude, leading to stronger *BE* in DSM (Fig. 5b).

Usually manufacturer cannot influence on supplier problems in production process, but the inventory can be stabilized with adapted inventory policy, with changing and properly defining *Sf* and *INVlf* for optimum min-max inventory levels and for reducing *BE*.



SEASONAL MODEL - SIMULATION ACCORDING TO STOCK POLICY AND OEE

MODEL RESULTS

BULLWHIP	1,87	NET STOCK AMPLIFICATION	0,07	COSTUMER SERVICE LEVEL		100,00%	FILL RATE		100,00%
MAX INV. LEVEL	95	MANUF. CAP. UTILIZAT.	100,00%	AVERAGE INVENTORY COST PER PERIOD		236,69 €			
MIN INV. LEVEL	70,00	SUPPL. CAP. UTILIZAT.	112,00%	AVERAGE SWITCHING COST PER PERIOD		289,02 €			
SAFETY STOCK	50	SAFETY STOCK FACTOR	1,4	LEVEL FACTOR		1,35			
MANUF. OEE	0,85	SUPPL. OEE	0,75	Lm	1	Ls		2	

DESEASONALIZED MODEL - SIMULATION ACCORDING TO STOCK POLICY AND OEE

MODEL RESULTS

BULLWHIP	3,57	NET STOCK AMPLIFICATION	0,83	COSTUMER SERVICE LEVEL		100,00%	FILL RATE		100,00%
MAX INV. LEVEL	229	MANUF. CAP. UTILIZAT.	100,00%	AVERAGE INVENTORY COST PER PERIOD		633,81 €			
MIN INV. LEVEL	199,00	SUPPL. CAP. UTILIZAT.	112,00%	AVERAGE SWITCHING COST PER PERIOD		26,96 €			
SAFETY STOCK	102	SAFETY STOCK FACTOR	1,95	LEVEL FACTOR		1,15			
MANUF. OEE	0,85	SUPPL. OEE	0,75	Lm	1	Ls		2	

Fig. 5. (a) different *OEEm* (85 %) and *OEEs* (75 %), with variations of *INVlf* and *Sf*; (b) case 2 bullwhip effect comparison of models.

4.3. Comparison of the results for both cases

Simulation results (Table 1) indicate that in case 2 in DSM the *BE* is strongest due to higher order variability at constant demand pattern. Case 2 is more likely in the real environment, where with proper inventory policy the *BE* was reduced.

Table 1. Comparison of *BE* and coefficient of variance (*COV*) for both cases.

		Case 1	Case 2
	BE_{SM}	1,24	1,99
	BE_{DSM}	3,38	3,45
Demand	COV_{SM}	0,32	0,29
Orders	COV_{SM}	0,35	0,35
Demand	COV_{DSM}	0,019	0,028
Orders	COV_{DSM}	0,108	0,078

For 100 % delivery compliance of a supply chain in SM, lower inventory level is needed. In both cases coefficient of variance (*COV*) is higher in SM due to less limited inventory policy and seasonal characteristic of time series. Because of higher order variability the order coefficient of variance for both models is higher than demand coefficient of variance due to presence of *OEE* levels downstream the supply chain.

5. Discussion

Two cases of seasonal and deseasonalized models have been investigated, regarding the link between changing constraints parameters (overall equipment effectiveness and inventory policy with variable safety factor and inventory level factor) and bullwhip strength.

We have find out that *OEE* level on downstream stages has a significant influence on inventory fluctuation and order variability in the supply chain. Higher deviation in production process (lover *OEE* factor) causes more frequent stock fluctuations. This brings frequent order variability and stronger BE at constrained inventory level policy.

The *PR* and *CU* are better when *OEE* increases. At higher *OEE* level manufacturers have less deviation in their production processes. Consequently orders to suppliers are more constant and more aligned with demand pattern. Therefore BE strength is lower. Because of constant demand pattern in DSM and non-steady manufacturer and supplier production rate, orders in DSM will vary more frequent than in SM. Consequently at planed *OEE* level the BE will be stronger in DSM than in SM.

Considering *OEE* level in DSM, higher *SS* is needed. When material flow is steadier than expected, level of *OEE* will be higher than 85 %, meaning lead time decreases and *CU* will be under 100 %. When level of *OEE* decreases below 85 % then lead time increases and *CU* will be more than 100 % (e.g. more than 15 shifts per week). Stock consumption is more changeable at lower *OEE* level.

6. Conclusion

New forms of organizations such as extended enterprises and networked enterprises (also called supply chain networks) appear and they are quickly adopted by most leading enterprises. In order to be successful, performance and expected benefits have to be carefully evaluated and balanced. This paper aims to analyze the bullwhip effect for supply chains.

Results of spreadsheet supply chain simulation indicate that *OEE* level and inventory level downstream the supply chain have a significant impact on order variability and its frequency through the chain. At higher *OEE* level there is less deviation in production processes. Efficient inventory policy enables that orders to suppliers are more constant and aligned with the retailer demand. In this case the bullwhip effect and net stock amplification will be lower.

At predicted demand increase of variability in production process causes decreasing *OEE* level. Without adjustments in inventory policy, the bullwhip effect and stock amplification will increase. In terms of supply chain efficiency that mean inefficient deliveries. Considering *OEE* level and constant demand pattern in the DSM, more frequent order variability is required. Bullwhip effect is stronger in DSM. Simulation results also indicate more cost effective SM than DSM at the same level of costumer delivery compliance, because of lower required inventory lavel.

Our future research will be focused to more complex suplly chains (networks) with multiple products, sharing the same suppliers, incorporating other real restrictions and combinations of stock keeping policies.

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