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Impact of demand changes and supply chain's level constraints on bullwhip effect

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A B S T R A C T

During an aggravated economic situation many companies have to deal with various situations that present demand distortion and changes in production processes. As a result orders to suppliers fluctuate upstream of the supply chain in amplified form. This phenomenon is called the bullwhip effect, which is one of the more interesting and developing problems within supply chain management. This undesirable effect produces excess regarding inventory, problems during production planning and poor customer services. In this paper we experimented with two special cases in a simple four stage supply chain with the level constraints represented by the overall equipment effectiveness (*OEE*) level: Case 1 – stable demand with single 5 % change and ideal *OEE* level, and Case 2 – stable demand with single 5 % change and *OEE* level changes upstream of the supply chain. The results of spreadsheet simulation are shown in the tables and charts. The impact of slight demand distortion and level constraints within the supply chain on the bullwhip effect was evident. The comparison of the results showed that when deviations in production processes are present the higher bullwhip effect occur at different stages within the supply chain and depending on the situation do not have to occur at stages within the supply chain with the lowest *OEE* levels.

A R T I C L E I N F O

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1. Introduction

In modern days, one of the most interesting and developing problems that supply chain management has had to face is the bullwhip effect (*BE*). The bullwhip effect represents the phenomenon of demand distortion where orders to suppliers have larger variance than sales to the buyer and this distortion propagates upstream in an amplified form [1]. These demand variability amplification might not be as a consequence of changes in the downstream demand but generated within the supply chain [2].

The main problem of such situation is that supply chain performance depends on the operation of all members in a supply chain, where each member's basic objective is the optimization of its own performance. Members of a supply chain are used to compete and not to co-operate; they do not share right information about products, customers, inventories, production capacities and other business processes [1]. The final effect of these issues is reducing competitive advantage of supply chain and each integrated member itself. Therefore companies increasingly find that they must rely on effective supply chain to successfully compete in the global market.

To become one of them, they must understand the causes of the *BE* and its consequences. One way to achieve this knowledge is to study the *BE* in a controlled environment. In this paper we are using spreadsheet simulation, which is widely used management science technique for the analysis and study of supply chain.

We are considering make-to-stock production system. The orders are supplied by stock inventory, in which the policy emphasizes the immediate delivery of the order. We assume that the customer expects that delays in the order are inexcusable, so the supplier must maintain sufficient stock [3]. Besides demand forecasting and ordering policies which are two of the well-known causes of the bullwhip effect, we are also considering demand changes of end customer (market) and overall equipment effectiveness (*OEE*) as a representative indicator of level constraints in supply chain.

The organization of the paper is as follows. In the next section we give a brief literature review of the *BE*. In section 3 the details of the investigated model of a four-stage supply chain are presented. We present a case with decreased demand pattern and ideal *OEE* level (the same at all stages) and a case with decreased demand pattern and different *OEE* levels at all stages. Section 4 analyses and discusses the presented cases with an extension of case 2. Concluding remarks are given in the final section.

2. Literature review

Numerous studies were developed in order to identify and describe the bullwhip effect. In our previous publications [4, 5] the literature review about related work regarding *BE* from its first observations including causes and consequences has been presented [6-8]. In our latest publication regarding *BE* the literature review about simulation modelling of supply chain has been presented [1]. In this paper we have summarised several studies from the last five years.

Disney reviewed a range of methodological approaches for solving the bullwhip problem [9]. Measures for the bullwhip are given. Different types of supply chains 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 [10]. 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.

Glatzel et al. [11] described the bullwhip effect problem on many practical cases from global manufacturing industry aspect with the aim to find new ways of thinking and decision making to assure enough business flexibility. Cachon et al. made observations and evaluated the strength of the bullwhip effect in U.S. industry [12] 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 also explained that highly seasonal industries tend to smooth demand volatility whereas nonseasonal industries tend to amplify.

Chen and Lee [13] 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. [14] 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 [15] 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 [16] 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 [17]. 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 [18]. 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 [19].

Oyatoye and Fabson [20] 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 [21]. 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 [22]. Csík and Földesi 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 [23]. 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 [24]. The simulation results show that performance of a system as a whole deteriorates when there is a step-change in the life-cycle demand.

Tapero et al. highlighted that the demand variability might not be as a consequence of changes in the downstream demand but being generated within the supply chain [2].

3. Model presentation

The objective of this paper is to illustrate and discuss the impact of demand changes and level constraints in supply chain on the bullwhip effect. The results (*BE*, changes in order sizes and stocks) for all stages in a supply chain are compared.

We consider periodic review system in discrete time. We present a four-stage single-item supply chain where a manufacturer (M) is served by three tiers of suppliers (S1, S2, and S3; see Fig. 1). The results were obtained by the means of spreadsheet simulation [5]. The spreadsheets are designed in Microsoft Excel (file size 25 kb), so they are user-friendly and easy to understand.

There are no stock capacity limits, no production limits and one order per period is presumed for each stage in the chain. Order sizes are rounded and governed by the following relationship [5]:

$$\text{Order size} = 2 \times \text{demand} - \text{starting stock} \quad (\geq 0) \tag{1}$$

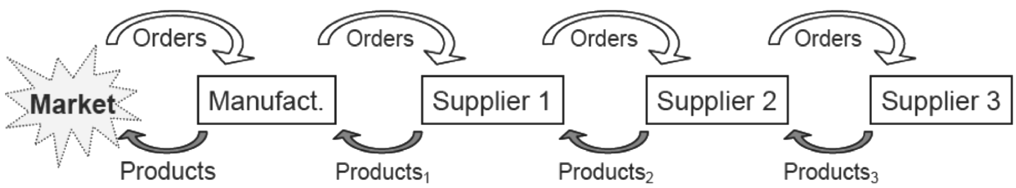

Fig. 1 Presentation of a four-stage supply chain

In this simple case orders and deliveries are made in the same period. For stock keeping policy we assume that all stages in the chain work on the principle that they will keep in stock one period's demand [5].

$$SS_i = D_{i-1} \tag{2}$$

where:
SS_i – Starting stock in i^{th} period
D_{i-1} – Demand in previous period (i – 1)

We considered that each stage in supply chain has its own deviations in production process (level constraints – availability, performance, quality), which are reflected through *OEE* level. *OEE* takes into account three *OEE* factors: Availability, Performance, and Quality; it is calculated by multiplication of their values (each between 0 and 1). For this matter the *OEE* level must be observed at production planning. In our case the production rate equals order size with *OEE* level taken into account:

$$PR_i = \frac{O_i}{OEE} \tag{3}$$

where:
PR_i – Production rate in i^{th} period
O_i – Order in i^{th} period

When *OEE* level is equal one, there is presumed that we have no level constraints. In such case order quantity and production rate are equal.

In this paper, for bullwhip effect measure, the following equation is used [25]:

$$BE = \frac{VAR\ (Order)}{VAR\ (Demand)} \tag{4}$$

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 [1].

4. Case studies

4.1 Case 1: Decrease in demand for 5 %, *OEE* level is 100 %

In this case the *OEE* level has been integrated. The market demand has been running at a rate of 100 items per period, but in period 2 the demand reduces to 95 items per period and keeps that value in other periods [5]. With this case we want to demonstrate that at only 5 % change in demand and despite of full *OEE* of 1 at all stages, production rates (orders) and stock begin to fluctuate through the supply chain (see Figs. 2 and 3). The *BE* will occur (see Fig. 4). The situation at supply stages is shown in Table 1.

Table 1 Changes of production orders and stock levels along the supply chain – case 1 (Excel snapshot)

		Manufacturer		Supplier 1		Supplier 2		Supplier 3	
Period	Market demand	Production rate	Stock (start/finish)	Production rate	Stock (start/finish)	Production rate	Stock (start/finish)	Production rate	Stock (start/finish)
1	100	100	100	100	100	100	100	100	100
			100		100		100		100
2	95	90	100	80	100	60	100	20	100
			95		90		80		60
3	95	95	95	100	90	120	80	180	60
			95		95		100		120
4	95	95	95	95	95	90	100	60	120
			95		95		95		90
5	95	95	95	95	95	95	95	100	90
			95		95		95		95
6	95	95	95	95	95	95	95	95	95
			95		95		95		95
VAR	**4**	**10**	**5**	**54**	**11**	**377**	**52**	**2818**	**346**
BE		**2,40**	**1,23**	**5,42**	**2,19**	**6,95**	**4,66**	**7,48**	**6,64**
	OEE	1		1		1		1	

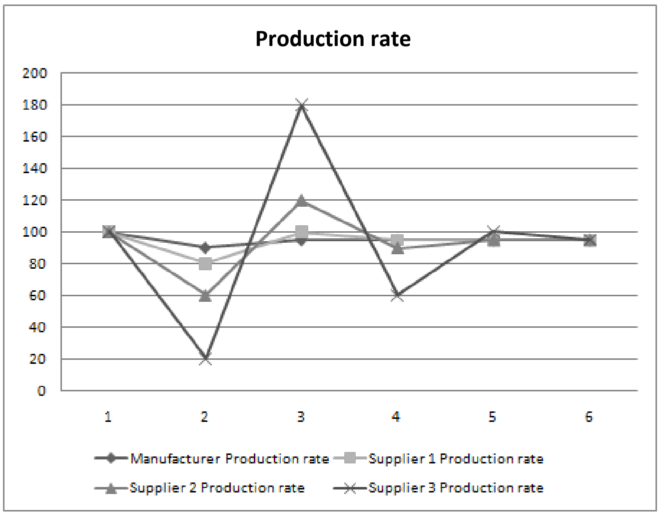

Fig. 2 Production rate in the supply chain for 6 periods – case 1

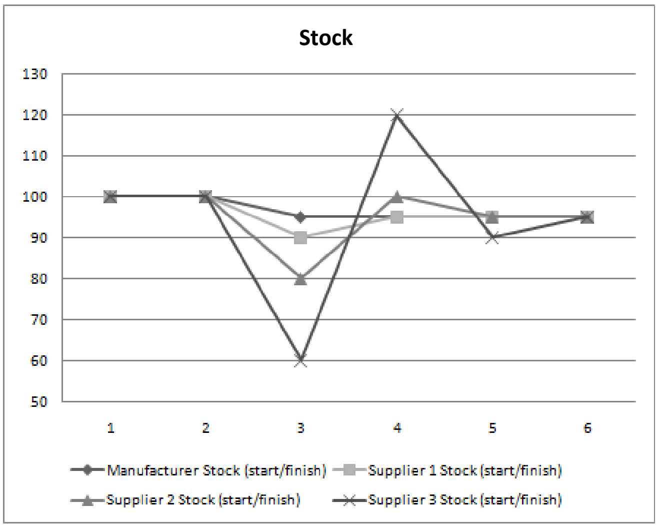

Fig. 3 Stock level in the supply chain for 6 periods – case 1

The fluctuation of production rate (*PR*) has occurred after the 1st period: 5 % change in demand has produced at M in the 2nd period the 10 % change in production rate, and in the following 4 periods 5 %, which is the same as the market demand; at S1 first 20 % decrease and after that in periods 4, 5, and 6 the 5 % decrease (stable); at S2 and S3 the production even more fluctuate. The consequence of demand and order variability reflects in *BE* occurrence (see Fig. 4). *PR* on all four stages in the supply chain is different. *PR* fluctuates the most at S3 with minimum rate in the 2nd period (20 items per period) and maximum in the 3rd period (180 items per period). Average of all *PR* is 94 items.

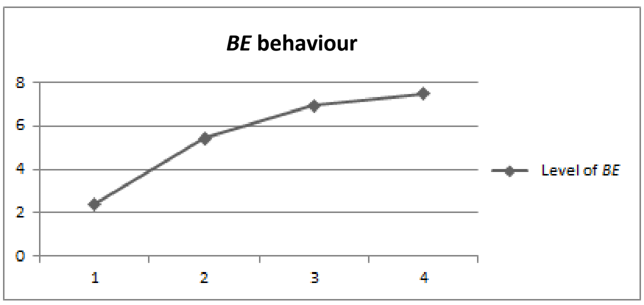

Fig. 4 *BE* value for all 4 stages – case 1

As expected the stock level on all four stages in supply chain is different too. Again the stock the most amplify at S3 with minimum level in the 3rd period (60 items on stock) and maximum in the 4th period (120 items on stock). Average items on stock are 95. Stock amplification rump up through the chain.

Thus ideal *PR* at all four stages, order variability occurs because of slight demand decrease (only for 5 %). The *BE* in supply chain has occurred. The level of *BE* is rising upstream the supply chain. The lowest level of *BE* (2,4) is at the beginning of the supply chain at M (stage 1).

4.2 Case 2: Decrease in demand for 5 %, different *OEE* levels at all four stages

For market demand we used the same logic as in case 1. With this special case we want to demonstrate the impact of different *OEE* levels (85 %, 80 %, 75 %, 80 %, given for all stages from M to S3) and deviation in demand on *BE* behaviour in the supply chain. The situation at all stages is shown in Table 2.

It can be seen that different *OEE* levels cause extreme fluctuation of production rate through the supply chain. 5 % change in demand and decrease of *OEE* level has produced at M in the 1st period 4 % change in production rate over initial value and then in the following periods even greater change (9 %); at S1 first 28 % increase and after that over 30 % over the initial value; at S2 and S3 the production rates fluctuate extremely. The consequence later is that S3 has to produce in the 2nd period 350 % more items than at the initial market demand.

PR on all four stages in the supply chain is significantly different (Fig. 5). *PR* of all members is never met. Due to minimum deviation in market demand and good *OEE* level (85 %) the *PR* of M fluctuate at the lowest rate around average of 109 items. Fluctuation of *PR* rump up through the chain form M to S3, where is the highest fluctuation around average of 242 items and with maximum of 473 and minimum of 184 items.

Table 2 Changes of production orders, stock levels and *OEE* levels along the supply chain – case 2 (Excel snapshot)

		Manufacturer		Supplier 1		Supplier 2		Supplier 3	
Period	Market demand	Production rate	Stock (start/finish)	Production rate	Stock (start/finish)	Production rate	Stock (start/finish)	Production rate	Stock (start/finish)
1	100	100	100	100	100	100	100	100	100
			100		100		100		100
2	95	106	100	140	100	239	100	473	100
			95		106		140		239
3	95	112	95	147	106	206	140	216	239
			95		112		147		206
4	95	112	95	140	112	176	147	184	206
			95		112		140		176
5	95	112	95	140	112	186	140	245	176
			95		112		140		186
6	95	112	95	140	112	186	140	233	186
			95		112		140		186
VAR	**4**	**24**	**5**	**291**	**27**	**2127**	**357**	**15543**	**2492**
BE		**5,81**	**1,23**	**12,02**	**5,33**	**7,30**	**13,10**	**7,31**	**6,98**
	OEE	0,85		0,8		0,75		0,8	

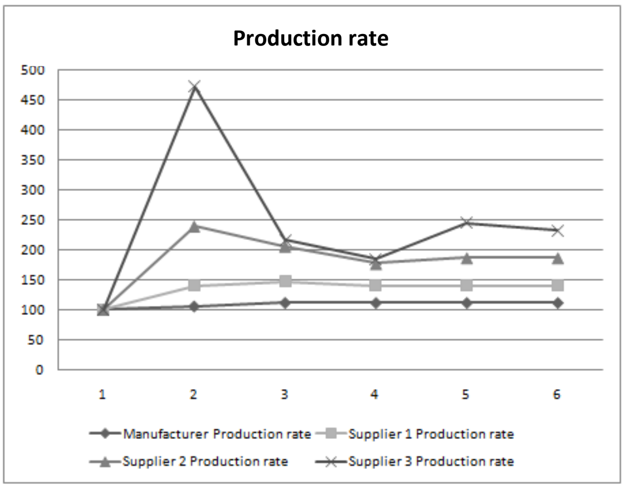

Fig. 5 Production rate in the supply chain for 6 periods – case 2

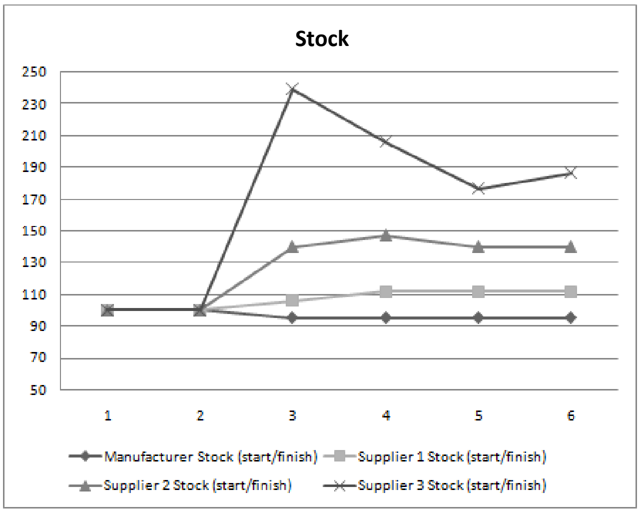

Fig. 6 Stock level in the supply chain for 6 periods – case 2

Stock level on all four stages in supply chain is also significantly different (Fig. 6). Stock of all members is never met. Due to minimum deviation in market demand and good *OEE* level (85 %) the stock of M fluctuate at lowest rate around average of 96 items. Fluctuation of stock rump up through the chain from M to S3, where is the highest fluctuation around average of 182 items and with maximum of 239 items in the 3rd period.

It can be seen that M's orders to the S1 (and further up the supply chain) reflect demand fluctuation far more drastically than we can expect from the single market demand change. This indicates the volume of *PR* variance. Small movements at the end of the supply chain trigger exponential movements down the chain. Suppliers ramp up in order to prevent stock-outs. These fluctuations in production rates and orders have significant influence on *BE* behaviour in the supply chain (Fig. 7).

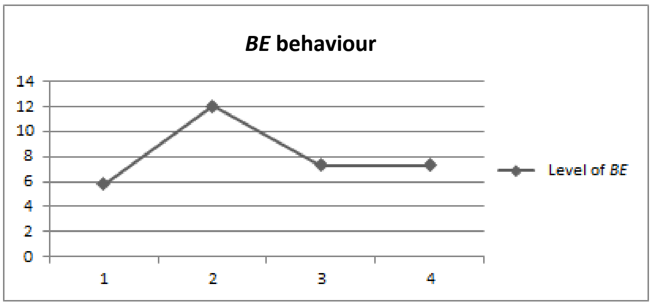

Fig. 7 *BE* value for all 4 stages – case 2

5. Analysis and discussion

Relations between orders variances (in our cases the production rates) and demand for all members of the supply chain are summarized in Table 3. Variance ratios are calculated and represent the level of *BE*. It is clear that the demand variability and level constraints (*OEE*) influence the production rate amplification and the level of *BE*. Case 1 indicates that slight demand variability of only 5 % causes *BE* in the supply chain. That happens even if the *OEEs* at all stages in supply chain are ideal. When deviations occur in *PR*, the situation gets worse. That is indicated in the case 2, where demand stays the same as in the case 1 but *OEE* level has been varied. Such situation implies enormous *BE* for the first supplier (S1). Case 2 indicates that when deviations in production processes are present, the highest *BE* occurs on different stages in the supply chain and must not occur on the stage with the lowest *OEE* level.

Table 3 Variance of *PR* and *BE* comparison

Case	Demand	Manufacturer		Supplier 1		Supplier 2		Supplier 3	
	VAR	*VAR*(M)	*BE*(M)	*VAR*(S1)	*BE*(S1)	*VAR*(S2)	*BE*(S2)	*VAR*(S3)	*BE*(S3)
1	4	10	2.4	54	5.42	377	6.95	2818	**7.48**
2	4	24	5.81	291	**12.02**	2127	7.3	15554	7.31

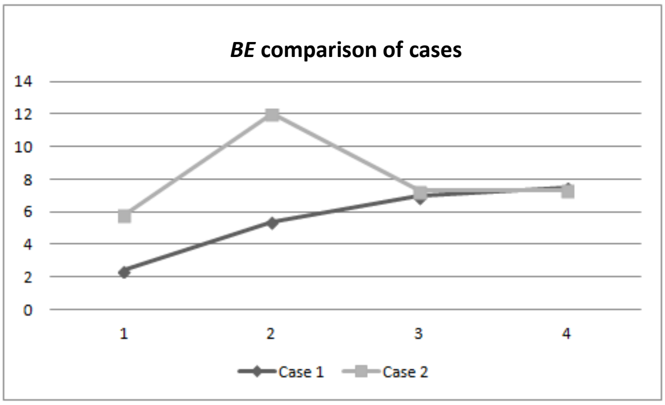

Fig. 8 *BE* comparison for both cases

For all examples the results are shown in Fig. 8. The worst behaviour of *BE* is in case 2, where different *OEE* levels are present. In case 2 *BE* vary the most, from 5.81 at M to 12.02 at S1 and then drops down to 7.31 at S3, what is lower than in case 1. Higher variance ratio implies a wildly fluctuating order pattern, resulting in rapid changes of the production rates in each period (and higher production costs).

Additionally for all stages in the supply chain the ratio between variance of orders and stocks is calculated for all cases (Table 4). Lower ratio means that even smaller changes of orders present quite big changes in necessary stock level. When the ratio is low the dependence between standard deviation of orders and standard deviation of stocks is more sensitive regardless of the (safety) stock level. Simulation indicates, that at S2 the biggest stock amplification (*Samp*) occurs after the stage with the biggest *BE* (where the order and *PR* vary the most – S1), see Fig. 9.

Additional analysis indicates a decrease of *Samp* and *BE* when *OEE* level increases (for 5 %) upstream the supply chain (at S1 in our case). *Samp* decreases at S2 (stage 3) from 13.10 to 8.43 and *BE* decreases from 12.02 to 8.27 (see Figs. 10 and 11).

Table 4 Ratios between variances of orders and stocks

Case	*Samp*			
	Manufacturer	Supplier 1	Supplier 2	Supplier 3
1	1.23	2.19	4.66	**6.64**
2	1.23	5.33	**13.10**	6.98

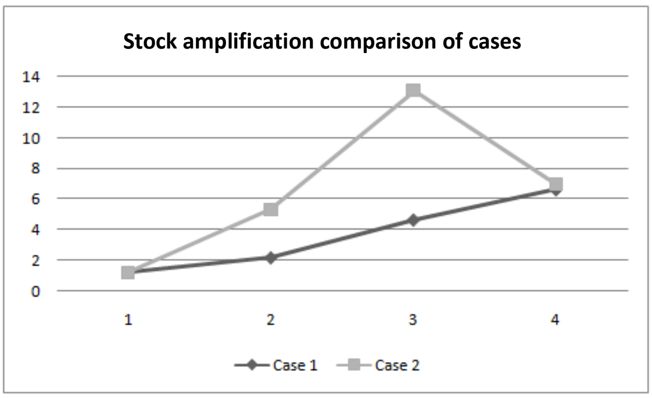

Fig. 9 *Samp* comparison for both cases

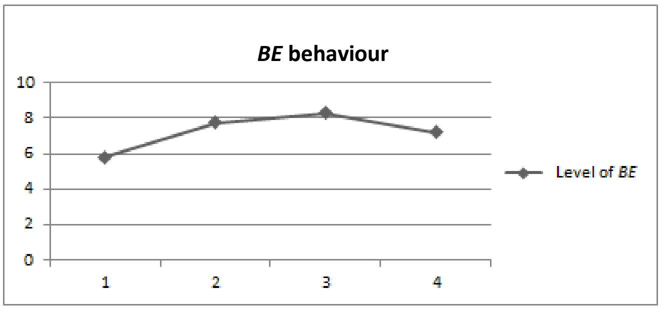

Fig. 10 Extension of Case 2: increase of *OEE* for 5 % at S1 (stage 2) and decrease of *BE* at stage 3

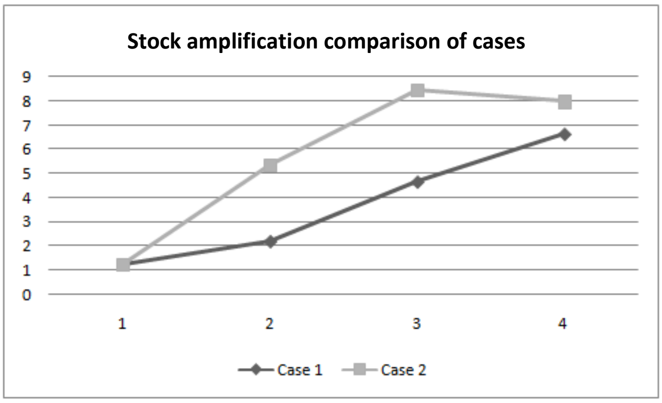

Fig. 11 Extension of Case 2: increase of *OEE* for 5 % at S1 (stage 2) and decrease of *Samp* at stage 3

6. Conclusion

In this paper we have experimented with two special cases of a simple four-stage single-item supply chain using 2 different demand patterns and different *OEE* level. In the first case with decreasing demand (–5 %) the *BE* occurs. When we added the different *OEE* level in case 2, the situation deteriorated. Results are discussed and shown in tables and charts. They illustrate how the parameters of *OEE* induce or reduce the bullwhip effect. In our future work we will define some new criteria for numerical evaluation of the bullwhip effect based on the supply chain simulation parameters and results.

We concluded that demand distortion implies variances in production rates (orders) which increasingly amplified upstream the supply chain. In such cases the bullwhip effect occurs. The bullwhip effect can occur if changes in demand requirements are moving slowly through the chain or large lot sizes and infrequent orders cause lags in information, or insufficient sharing of accurate information is typical. When we integrated the overall equipment effectiveness the situation deteriorated. The main problem of such situation is that supply chain performance depends on the efficiency of operation of all supply chain members, where each member's basic objective is the optimization of its own performance. At small demand changes, simulations indicates, when on all stages in the supply chain the *OEE* is at the same level, the bullwhip effect is low and moderately rising through the supply chain.

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