Effects of vendor-managed inventory on the bullwhip effect

Dr. Susanne Hohmann received her master’s degree from the Ruhr University of Bochum. From 2001 to 2004 she worked as a research assistant at the Institute of Production and Industrial Information management at the University Duisburg-Essen, Essen Campus. Since 2006 she has been working as Project Manager at HAVI Global Solutions. Her main research interests lie in Supply Chain Management, Operations Research, Production Planning and Control Systems. She was awarded several prizes for her dissertation on the bullwhip effect.

Prof. Dr. Stephan Zelewski teaches business management with a focus on production Management at the University of Duisburg-Essen. He holds a chair for Production and Industrial Information Management at the faculty of Economics at the campus of Essen. He also is a member of the Institute of Business and Economic Studies (IBES), the Institute for Computer Science and Business Information Systems (ICB), as well as the Centre for Logistics & Traffic (ZLV). His work scope and main research interests include production management, especially logistics and supply chain management, the use of modern computer technologies in the area of production management, operations research and game theory, knowledge management and artificial intelligence and their operational applications (especially knowledge-based systems and multi-agent systems), production theory as well as philosophy of science (especially constructions of economic theories from the perspective of the non statement view).

For further information please visit: http://www.pim.wiwi.uni-due.de/team/stephanzelewski/.

Dr. Susanne Hohmann, née Keller *
Veronikastrasse 53d
45131 Essen
Germany
phone: + 49 201 / 79 888 30
e-mail: uni.hohmann@googlemail.com

Prof. Dr. Stephan Zelewski
University of Duisburg-Essen, Campus Essen
Institute for Production and Industrial Information Management
Universitaetsstrasse 9
45141 Essen
Germany
phone: +49 201 / 183-4007 (secretary’s office)
fax: +49 201 / 183-4017
e-mail: stephan.zelewski@pim.uni-due.de

* Corresponding Author
ABSTRACT
The bullwhip effect means that demand variability increases as one moves up the supply chain. In the following article the bullwhip effect is quantified for each part of the supply chain which is presupposed to consist of a producer, a wholesaler, a retailer and a consumer. After considering the causes of the bullwhip effect, it will be shown with the help of a nonlinear optimization model to what extent the bullwhip effect can be reduced using vendor-managed inventory (VMI) as one concept of Collaborative Planning, Forecasting and Replenishment (CPFR). In contrast to other studies in this field the reduction of the bullwhip effect will be accurately quantified for each part of the supply chain.

Keywords: bullwhip effect, demand distortion, simulation models, supply chain management, quantitative analysis, vendor-managed inventory, CPFR

MOTIVATION
The bullwhip effect in supply chains represents a long recognised phenomenon in the area of logistics. The material flows of the supply chain’s participants do not correspond to the consumer demand, which, known as “demand pull”, is the decisive factor in the supply chain. The chance of a smooth running of the supply chain in view of the material and information flow is missed on a regular basis as soon as the bullwhip effect occurs. The occurrence of the bullwhip effect leads to raised costs in the supply chain (McCullen & Towill, 2002, p. 169; Reddy, 2001, p. 59).

The reduction of the bullwhip effect and therefore the reduction of raised costs in the supply chain lead to an increased profitability of business. Estimations suggest the increase of profitability of business may be up to 8.4 – 20.1 % (McCullen & Towill, 2002, p. 169) or up to 10 – 30 % (Metters, 1997, p. 89).

The use of vendor-managed inventory (VMI) is based on a close cooperation between the producer and the participant that has point of sales data at their disposal. With this coalescence of supply chain parts the appearance of some causes that lead to the bullwhip effect can be prevented (Richardson, 2004, p. 19; Waller, Johnson, & Davis, 1999, p. 183). This article provides a multi-dimensional analysis of the different causes of the bullwhip effect, its impact on the different supply chain parts and its counteractions. It will, therefore, be exactly shown what impact the bullwhip effect has on the supply chain and to what extent the bullwhip effect can be reduced in each part of the supply chain by using vendor-managed inventory. This detailed approach adds a holistic, quantitative analysis to the existing literature and enables the prediction and reduction of the bullwhip effect.

Vendor-managed inventory is chosen as the concept of CPFR which implies the closest collaboration between producer and retailer.

The appearance of the bullwhip effect can be attributed to five reasons in total: Demand distortion, misperceptions of feedback, batch ordering, price fluctuations, and strategic behavior. Keller, 2004.

In this paper, we concentrate on two of these causes, demand distortion and misperceptions of feedback, because they are especially related to the examined topic of VMI. The analysis of these two causes provides the best approach to VMI’s efficiency evaluation. First, however, the conceptual principles will be explained.

CONCEPTUAL PRINCIPLES

THE BULLWHIP EFFECT
The phenomenon bullwhip effect means that goods and information do not pass through the supply chain in the required quantity and to the required point in time. Thus, the supply chain management does not result in a cost-optimised and just-in-time coordinated supply. The first academic description of the bullwhip effect is usually ascribed to Forrester (Forrester, 1972, p. 21). Forrester assumes lead times to be an immanent part of dynamic systems. Lead times occur between different parts of a system due to handling of material and information. Forrester analyses different variables like stock, production and lead times and demonstrates the effects of changes in the system. He states that it is common in practice, and validated by empirical
data, for variance of orders to far exceed the variance of consumer demand. This effect is amplified at each stage in the supply chain (Forrester, 1972, p. 22). These variations had up to this point been regarded as inevitable, as they were said to be caused by external influences (Forrester, 1972, p. 22). Forrester contradicts this by showing that the variations are caused by lead times. In practice the bullwhip effect is simulated by the well-known “beer game”. The result of this game is that the simulated costs are ten times higher than the benchmark costs (Sterman, 1989, p. 328).

The distribution of orders in the “beer game” is characterized by three factors which are graphically shown in figure 1.

- Oscillation: Order and inventory quantities are dominated by large amplitude fluctuations.
- Amplification: The amplitude and variance of order quantities increase steadily from customer to producer.
- Phase lag: The order rate peaks later as one moves from the retailer to the producer.

The shortest arrows represent the bullwhip effect and the phase lag of the retailer respectively. The longest arrows represent the bullwhip effect and the phase lag of the producer respectively.

This increasing amplitude of order quantities is also well-known in practice. The most popular case is that of Procter & Gamble, who faced this amplitude with their brand Pampers despite the constant demand of diapers (Lee, Padmanabhan, & Whang, 1997a, p. 546; Lee, Padmanabhan, & Whang, 1997b, p. 93). The orders do not coincide with the actual consumer demand. The variability increases as one moves up the supply chain: the bullwhip effect occurs (Dejonckheere, Disney, Lambrecht, & Towill, 2003, p. 567).

The bullwhip effect can be defined as the increase of variability (measured by variances) of orders related to the variability of consumer demand. Material and information do not flow steadily through the supply chain. The orders seem to be hit by a whiplash. Thus, the quantity of stock is too high (Lee et al., 1997b, p. 93). Moreover, the rapid (“just in time”) satisfaction of consumer needs cannot be guaranteed any more.

The rapid, cost-minimised and flexible satisfaction of consumer needs with high-quality goods is the objective of supply chain management. This objective is in jeopardy as soon as the bullwhip effect occurs. The members of the supply chain run the risk of losing the consumer to competitors (McCullen & Towill, 2002, p. 169).

**VENDOR MANAGED INVENTORY (VMI)**

Measures taken against the merely locally spread information in the supply chain, leading among other things to the bullwhip effect, include the diffusion of information. Basically, this means to take into account which information is shared in which manner with whom. Each member of the cooperation has to benefit from the sharing of information. The degree of information sharing increases with the amount of members and information (Schönslaben, 2000, p. 33; Lau, Huang, & Mak, 2004, p. 23).

The coordination between firms can either only include the sharing of information or it can also include the delegating of certain activities to the partner (Yu, Yan, & Cheng, 2001, p. 116; Dong & Xu, 2002, p. 75), for instance VMI. Using VMI means to share information concerning planning and forecasting, and furthermore to collaborate with a view to the replenishment of stock (Karolefski, 2002, p. 19). The stock is replenished based on current sales data instead of forecasting methods with huge safety stock (Sabath, Autry, & Daugherty, 2001, p. 91). The vendor accounts for the quantity of stock and the method of replenishment. For example, each morning he is informed of the quantity of stock and the point of sales data and delivers the required goods in the afternoon (Fisher, 1997, p. 112; Raghunathan & Yeh, 2001, p. 406).

The retailer shifts the responsibility for the stock to the vendor. In return, the retailer provides point of sales data (for the topic of one producer with several VMI-customers see Robins, 1995, p. 42). VMI seeks to reduce administrative complexity and costs of stock in increased service level (Holmström, 1998, p. 1; Waller et al., 1999, p. 184). The retailer benefits from VMI due to the decreasing uncertainty regarding their being supplied with goods. The vendor may benefit from VMI by being able to place a larger assortment of his goods at the retailer’s. Moreover, the vendor does not rely on his forecasts of consumer demand any longer as he now knows the actual consumer demand (for this and for further information about a decision support system for VMI see Achabal, McIntyre, Smith, & Kalyanam, 2000, p. 433; for studies into the impact of VMI on the bullwhip effect see Disney & Towill, 2003a, p. 625; Disney & Towill, 2003b, p. 199).

**RELEVANT LITERATURE**

This paper provides an extensive and exact quantification of the bullwhip effect for each part of the supply chain which cannot be found in supply chain...
literature so far. From our point of view it is however essential to quantify the bullwhip effect separately for each member of the supply chain because only in this way effects of supply chain improvements can be thoroughly evaluated. This is due to two reasons: First, the analysis for each supply chain member allows a detailed analysis which member benefits most from measures against the bullwhip effect. This could be of importance for further investigations such as optimal allocation of efficiency gains in supply chains. Second, it allows an evaluation of the supply chain structure, e.g. if each member is really necessary for the supply chain or if it may lead to inefficiencies such as the wholesaler in our example for VMI.

The success of measures taken against the bullwhip effect will be quantified in the same way. This quantification is represented separately for each cause leading to the bullwhip effect. Our model reflects 40 periods rather than only 2 or 3 periods like models used in the relevant literature because we wanted to prove our results with a model based on mid-term conditions.

In the following, the relevant literature, which all present important contributions to the quantitative analysis of the bullwhip effect, is briefly reviewed and differences to this paper are highlighted.

QUANTIFICATION OF THE CAUSES OF THE BULLWHIP EFFECT

Metters (Metters, 1997) assumes the necessity to forecast demand. The purpose of his paper is to demonstrate the significance of the bullwhip effect estimated in the increase of demand variance on the one hand and in the effects on overall business profitability on the other hand. He uses a dynamic programming model to compare the costs of various production policies. He minimises costs, consisting of the sum of production, expected holding and excess demand penalty costs and discounted future costs, minus the effect of revenue. He then estimates the excess costs of the bullwhip effect by comparing the optimal solution costs under different parameter settings. Profits can be gained by eliminating the bullwhip effect (Metters, 1997, p. 98).

The starting point of Metters is the same as in this paper: the costs minimization. In contrast to this paper, he does not quantify the bullwhip effect for each part of the supply chain but only for the supply chain as a whole and only concentrates on one cause of the bullwhip effect, the demand distortion. This paper deduces the bullwhip effect to two specific causes to analyze the effects of vendor-managed inventory properly.

Lee and colleagues (Lee et al., 1997a) reduce the bullwhip effect to four causes (of the two causes examined in this paper, Lee and colleagues only mention “demand distortion”). They focus on the retailer of the supply chain whose analysis is, according to the authors, applicable for each other member of the supply chain as well. The retailer’s demand is serially correlated. Lee and colleagues formulate a costs minimization problem including the discounted holding and shortfall costs. They, therefore, establish a theorem stating that under certain conditions the variance of retail orders is strictly larger than the variance of retail sales. Furthermore, it says that the variance of retail orders strictly increases with the replenishment lead time.

Lee and colleagues choose costs minimization as initial starting point, which is the same as this paper. Yet they imply the existence of a normally distributed demand model unlike the forecast model in this paper. The bullwhip effect is not defined as the ratio of the variance of consumer demand to the variance of the members’ orders. Lee and colleagues only seek to show the inequality of the variance of orders to the variance of the previous demand. They only consider two periods in order to define the bullwhip effect. The authors owe the proof of the bullwhip effect for further periods. As already mentioned, Lee and colleagues do not differentiate the bullwhip effect for each member of the supply chain. This paper chooses a broader approach.

A part of this paper is related to the paper of Zäpfel and Wasner (Zäpfel & Wasner, 1999) and presents enhancements to their approach. They provide equations to define the relation of the supply chain members and their behavior. This distinction of equations leads to a modelling in which the various reasons of the bullwhip effect and the measures taken against it can be described by behavior equations. Zäpfel and Wasner derive a model from these equations which, however, is not presented in their paper. With the aid of software they find solutions to the model under different parameter settings for α, β and γ. Compared to the aforementioned paper of Lee and colleagues they do not provide a general mathematical proof for the existence of the bullwhip effect. Instead, the bullwhip effect is presented graphically in form of mathematical instances. Zäpfel and Wasner do not analyse the development of the bullwhip effect for each member of the supply chain either. In contrast to the paper of Zäpfel and Wasner, we distinguish three components of lead time: time for production, transport lead time, and information lead time. Moreover, the objective includes the costs of over delivery, i.e. tardiness.

Chen and colleagues (Chen, Ryan, & Simchi-Levi, 2000) seek to show the impacts of different forecasting methods and different distributed demands on the forecast of demand. They begin with a positively correlated demand which is partly estimated by exponential smoothing. Chen and colleagues estimate the variance qEX of retail orders (Chen et al., 2000, p. 273) and relate it to the variance of demand. An increase of this ratio, and thus an in-
crease of the bullwhip effect, may be ascribed to three factors of influence: (1) the lead time \( L \), (2) the smoothing parameter \( \alpha \), and (3) the correlation parameter \( \rho \). The larger the lead time and the larger the smoothing parameter, the larger the bullwhip effect is. Thus, a retailer facing long lead times must choose a small smoothing parameter in order to reduce the bullwhip effect. The impact of correlation parameter \( \rho \) depends on the correlation of demand: negatively correlated demands lead to higher variability than positively correlated demands. To continue, Chen and colleagues analyse the impacts of “demand distortion” on demands with linear trend. The trend parameter is estimated with exponential smoothing including a second smoothing parameter \( \alpha_2 \). The bullwhip effect increases with the use of \( \alpha_2 \), a fact that is linked to the need to estimate an additional parameter and therefore, to cope with additional uncertainty concerning the forecast of demand.

Next, Chen and colleagues compare the increase in variability for two forecasting methods, moving average (MA) and exponential smoothing (EX). They consider the impact of the forecasting methods on correlated demand and on demand with linear trend. The comparison of moving average for correlated demand (MA) and demand with linear trend (MAT) leads to the result:

\[
\text{var}(q_{\text{MAT}}) \geq \text{var}(q_{\text{MA}})
\]

Chen and colleagues conclude from the comparison of both forecasting methods, with EXT for exponential smoothing and demand with linear trend:

\[
\text{var}(q_{\text{EX}}) \geq \text{var}(q_{\text{MA}}) \quad \text{and} \quad \text{var}(q_{\text{EXT}}) \geq \text{var}(q_{\text{MAT}})
\]

Contrary to this paper and the previously quoted literature, the starting point of Chen and colleagues for quantifying the bullwhip effect is not costs minimization. They rather quantify retail orders, estimate their variances and relate them to the variance of consumer demand. The bullwhip effect is represented as this ratio. It is important to note that the bullwhip effect is not shown for more than one period of time. Converse to Chen and colleagues, we use in addition to the correlation parameter \( \rho \) and the lead time \( L \), the smoothing parameter \( \alpha \) and the parameter \( \beta \) and \( \gamma \). The parameter \( \beta \) and \( \gamma \) which give the ratio of how the already ordered but not yet delivered quantities are taken into account for stock evaluation. It is to be emphasised that Chen and colleagues, too, only prove the bullwhip effect for just one part of the supply chain.

The “beer game” of Sterman (Sterman, 1989) is the starting point for the analysis of the “misperceptions of feedback”. He conducts empirical tests in the form of the game. The results show that most subjects fail to account adequately for the supply line. It is probable that only a fraction of the supply line is taken into account. This leads to over-ordering and instability. Sterman does not show a mathematical model to prove the existence of misperceptions of feedback. He provides only empirical results for the parameters. Sterman shows the results of the “beer game” for each part of the supply chain.

**QUANTIFICATION OF MEASURES AGAINST THE BULLWHIP EFFECT**

Measures against the bullwhip effect are mostly only verbally described in the relevant literature but not quantified (e.g. Lee et al., 1997b, p. 98). Very few researchers have attempted a quantification of measures, in particular VMI, as can be seen in the following literature review.

Disney and Towill (Disney & Towill, 2003a; Disney & Towill, 2003b) examine the impact of VMI on the producer. They distinguish various reasons for the bullwhip effect. The bullwhip effect caused by the reason “demand distortion” is, like in this paper, defined as the ratio between variances of orders and variances of consumer demand. The traditional supply chain management and VMI are compared with difference equations. Disney and Towill conclude that the bullwhip effect can be reduced by half. The bullwhip effect is only estimated for the producer and again not for each member of the supply chain as in this paper.

Jakšič and Rusjan (Jakšič & Rusjan, 2008) investigate the effect of replenishment policies on the bullwhip effect with the help of a transfer function analysis used in control engineering. They show that for a simple supply chain consisting of a manufacturer and a retailer there is no bullwhip effect for certain replenishment policies. They do not specifically refer to VMI.

Wright and Yuan (Wright & Yuan, 2008) quantify the mitigation of the bullwhip effect by ordering policies and forecasting methods for a four-stage supply chain. They do not analyse the effects of VMI.

**THE BULLWHIP EFFECT AS A RESULT OF “DEMAND DISTORTION” AND “MISPERCEPTIONS OF FEEDBACK”**

**DESCRIPTION OF CAUSES**

This analysis is based on a simple supply chain consisting of a producer, a wholesaler, a retailer and a consumer. The consumer starts the flow of material and information with his demand. Each stage of the supply chain has to forecast demand regularly as the consumer demand is not constant over time. The members of the supply chain assume positively correlated demand to forecast the de-
demand of the next period. The members of the supply chain are only in the possession of local information. They are not in the possession of global information concerning actual consumer demand. Consequently, each member is only in the possession of local information concerning the demand of their immediate customer. The information of consumer demand is only available for the retailer (Lee et al., 1997b, p. 95, for further studies on coordination with demand stimulation see Xiao & Luo & Jin, 2009 or Huang & Gangopadhyay, 2004, for the impact of coordinated decisions in supply chains see Núñez-Muñoz & Montoya-Torres, 2009).

The firms need to interpret orders of their customers in order to derive consumer demand with the aid of forecasting. Based on forecasting, each firm releases an order to the upstream firm in the supply chain. The firms use exponential smoothing as a forecast method. The forecast is updated each period after knowing the actual order quantity of the downstream firm.

The orders consist of three parts, i.e. (1) material to replace expected loss from stock as a result of the current demand, (2) material to reduce the discrepancy between the desired and the actual stock, and (3) material to maintain an adequate supply line of unfilled orders. Obviously, the orders are not only based on actual demand but also on safety stocks. The extent to which the orders reflect demand is not evident for the upstream firm that uses this order to deduce consumer demand. Hence, the upstream firm has to deal with uninterpretable information. As a consequence of safety stock and the resulting misperceptions, the order is higher than consumer demand. The upstream firm tends to augment its own orders on its own account, as it is not willing to run the risk of not being able to satisfy the apparently increased consumer demand.

Consequently, the quantity of orders increases as one moves up the supply chain due to added safety stocks at each stage. The quantity of orders of upstream firms is much higher than consumer demand. The height of consumer demand, however, is only known by the retailer (Franso & Wouters, 2000, p. 78; Lee et al., 1997b, p. 95; Posey & Bari, 2009).

Nevertheless, it is important to note that this keeping of safety stocks is a consequence of rational behavior of each supply chain member. The topic of rational behavior was introduced by Lee and colleagues (Lee et al., 1997a, p. 552). The rational behavior of individuals, though, leads to increasing variances of orders, as only parts of the supply chain are optimised. The supply chain as a whole is not optimised. Thus, the bullwhip effect occurs.

"Misperceptions of feedback", leading to the bullwhip effect, are closely related to "demand distortion" as there are identical reasons leading to their respective occurrence. The cause "misperceptions of feedback" is based on two reasons: (1) Locally spread information results in the use of forecast methods and (2) the three-partite structure of orders, as mentioned above, hampers the derivation of consumer demand. When analysing "demand distortion" we focus on the demand forecast of firm k in period t, whereas when analysing "misperceptions of feedback" the emphasis is put on material of firm k in period t to reduce the discrepancies of desired and actual stock as well as the material of firm k in period t to maintain an adequate supply line of unfilled orders..

**QUANTIFICATION OF CAUSES**

At first, relations between supply chain members are presented in form of definition equations. It is shown how information and material flow through the system, how these flows connect supply chain members and where these flows lead to changes in stock and demand. The relations between supply chain members assume premises (Zäpfel & Wasner, 1999, p. 297) which are valuable for all following analyses:

- Each member has a stock at his disposal (we suppose there are no capacity restrictions; for the topic of capacity restrictions see Cachon & Lariviere, 1999).
- There are lead times for information and material.
- Each order has to be completed as quickly as possible. Orders remain until they are completed (for the impact of this assumption on the bullwhip effect see Chen et al., 2000, pp. 272, 277, where it is demonstrated that this assumption does not influence the bullwhip effect).
- The objective is to minimise costs, consisting of costs for stock, costs for shortfall and costs for over delivery (costs for over delivery is often added to costs of stock) (Zäpfel & Wasner, 1999, p. 306). In this paper, costs for over delivery are separated from costs of stock.

The definition equations of each member of the supply chain are represented in figure 2 (following Zäpfel & Wasner, 1999, p. 299 and Keller, 2004, p. 25).

It can be seen that the producer has input of material. The inflow in period t presents the quantity of produced goods in period t-m. Each member has a stock consisting of safety stock plus changes in stock in the current period. Because of the lead time members include the quantity of orders which has already been released but has not yet arrived. The quantity of outstanding orders is estimated to maintain an adequate supply line. Thus, this quantity may not be too large in order to make sure that the incoming goods are still required.

The symbols used are:
k  index for members
    t  index for periods
    m  time of production
    n  lead time of material because of picking, packaging and transport
    i  lead time of information
    \( x^i_t \) quantity of production of the producer in period \( t \) (\( k = 1 \))
    \( x^k_t \) quantity of orders of member \( k \) in period \( t \) for \( k = 2,3 \)
    \( Z^k_t \) inflow in stock of member \( k \) in period \( t \)
    \( A^k_t \) outflow of stock of member \( k \) in period \( t \)
    \( L^k_t \) amount of stock of member \( k \) at the end of period \( t \)

\( L^k_\ast \) safety stock of member \( k \)
\( \Delta L^k_t \) gap between desired and actual stock of member \( k \) in period \( t \)
\( M^k_t \) amount of outstanding goods of member \( k \) in period \( t \)
\( M^k_\ast \) desired level of outstanding goods of member \( k \)
\( \Delta M^k_t \) gap between desired and actual amount of outstanding orders of member \( k \) in period \( t \)
\( F^k_t \) shortfall quantity of member \( k \) in period \( t \)
\( H^k_t \) over delivery quantity of member \( k \) in period \( t \)
Figure 2. Definition equations of supply chain members.
The causes for the occurrence of the bullwhip effect are considered using several behavior equations. They are composed of two factors: the order of the downstream member and the own demand of the previous period. The current demand is derived from these two factors except for the exogenous consumer demand.

The behavior equations are demonstrated in figure 3 with the following used symbols:

- \( N^k_t \): demand forecast of member \( k \) for period \( t \)
- \( \alpha, \beta, \gamma \): parameters, where \( 0 \leq \alpha, \beta, \gamma \leq 1 \) and \( \gamma \leq \beta \)

The parameters are explained below.

The behavior equations of the members reflect the characteristics of the “demand distortion”.

Each member is forced to forecast consumer demand with the help of incoming orders of downstream members. The members use exponential smoothing (for the common use of exponential smoothing as forecast method compare Hyndman, Koehler, Snyder, & Grose, 2002) with the two parameters: orders of downstream members arriving with phase lag and own demand of the previous period.

The choice of parameter \( \alpha \) indicates the smoothing of amplitudes in order quantity \( N^k_t \) of member \( k \) for period \( t \). A large \( \alpha \) implies a greater consideration of orders of downstream members \( x^{k+1}_{t-1} \) than of own demand \( N^k_{t-1} \) in the previous period \( t-1 \). On the one hand, this results in the opportunity of quick alignments, on the other hand, in the risk of overestimating non-representative orders (Zäpfel & Wasner, 1999, p. 301).

Based on the forecast of the current period each member releases an order to the upstream member consisting of three components:

- satisfaction of current demand forecast \( N^k_t \),
- adjustment of changes in stock \( \Delta L^k_t \) and
- maintaining the supply line with consideration of the outstanding orders \( \Delta M^k_t \).

In order to determine the quantity of orders \( x^k_t \) of member \( k \) (\( k = 2 \) or 3) in period \( t \) or the quantity of production \( x^1_t \) of the producer (\( k = 1 \)) in period \( t \), it is necessary to reduce the demand forecast \( N^k_t \) in the respective behavior equation of member \( k \) by changes in stock \( \Delta L^k_t \) and by maintaining the supply line concerning outstanding orders \( \Delta M^k_t \). These reducing influences are weighted by the parameters \( \beta \) and \( \gamma \) to demonstrate the perceptions of changes in stock and of outstanding orders, respectively. A large \( \beta \) means quick alignment to changes in safety stock as changes in stock increase the quantity of orders in the current period. A large \( \beta \) may lead to excessive adjustments in stock although this is not justified by increased orders of the downstream member. A solitary adjustment of stock due to stock changes would mean that members release orders without regard for the outstanding orders. Yet the outstanding orders are already part of stock changes. Orders would be released twice or even more often. To prevent this double ordering the outstanding orders have to be taken into account by introduction of parameter \( \gamma \). Parameter \( \gamma \) is closely related to parameter \( \beta \) as the outstanding orders are a part of stock changes. The ratio of \( \gamma \) to \( \beta \) represents the part of outstanding orders which is consciously perceived by the members. \( \gamma = \beta \) means that there is no misperception of feedback, the outstanding orders are weighted like the stock changes so that double ordering does not occur (Mosekilde, Larsen, & Sterman, 1991, p. 209). A closer consideration of these two parameters follows. Regarding “demand distortion”, we assume that these parameters are fixed, based on empirical average values (Mosekilde et al., 1991, p. 212).
Figure 3. Behavior equations for the “demand distortion”

The definition and behavior equations are combined into one model. The objective is to minimise relevant costs $K$:

$$K = \min \left[ \sum_{i=1}^{40} \sum_{k=1}^{3} L_{i,k}^4 + f \cdot \sum_{i=1}^{40} \sum_{k=1}^{3} F_{i,k}^4 + h \cdot \sum_{i=1}^{40} \sum_{k=1}^{3} H_{i,k}^4 \right]$$

This formula is based on the following assumptions and parameters (following Zäpfel & Wasner, 1999, p. 301) which are also utilised when considering the further causes of the bullwhip effect:

- The planning horizon is fixed to 40 periods to show the run of order and stock quantities. One period corresponds to 1 time unit.

### Behavior equations

#### Producer ($k = 1$)

$$N_1^4 = \alpha \cdot x_{i,1}^4 + (1 - \alpha) \cdot N_{i-1}^4$$

$$x_i^1 = \max \left\{ 0, N_i^1 - \beta \sum_{j=1}^{i} (Z_j^1 - A_j^1) - \gamma \sum_{j=1}^{i} (x_j^1 - Z_j^1) \right\}$$

#### Wholesaler ($k = 2$)

$$N_2^4 = \alpha \cdot x_{i,2}^4 + (1 - \alpha) \cdot N_{i-1}^4$$

$$x_i^2 = \max \left\{ 0, N_i^2 - \beta \sum_{j=1}^{i} (Z_j^2 - A_j^2) - \gamma \sum_{j=1}^{i} (x_j^2 - Z_j^2) \right\}$$

#### Retailer ($k = 3$)

$$N_3^4 = \alpha \cdot x_{i,3}^4 + (1 - \alpha) \cdot N_{i-1}^4$$

$$x_i^3 = \max \left\{ 0, N_i^3 - \beta \sum_{j=1}^{i} (Z_j^3 - A_j^3) - \gamma \sum_{j=1}^{i} (x_j^3 - Z_j^3) \right\}$$

#### Consumer ($k = 4$)

$$N_4^4 = x_i^4$$
The order quantities \( x_{i,m-n-1}^k \) to \( x_i^k \) are 4 units per period, so that each member has an initial outflow \( A_0^k \) of 4 units.

Per unit costs \( l \) of stock and per unit costs \( h \) of over delivery are both fixed at 1 monetary unit / (material unit \( \times \) time unit [period]), costs \( f \) of shortfall per unit are assumed to equal 3 monetary units / (material unit \( \times \) time unit [period]).

Time of production \( m \) amounts to 3 periods, lead time of material \( n \) amounts to 2 periods and lead time of information \( i \) amounts to 1 period.

Consumer demand increases in period 1 from 4 units per period to 5 units per period and then remains constant: \( x_i^4 = 5 \) for \( t = 2, \ldots, 40 \).

Safety stock \( L^k \) and the desired level of outstanding goods in the supply line \( M^k \) of the members \( k \) each amounts to 6 units respectively.

Parameter \( \alpha = 0.36 \), parameter \( \beta = 0.26 \) and parameter \( \gamma = 0.09 \) (the choice of this parameters follows empirical average amounts, Mosekilde et al., 1991, p. 212).

The model is solved with the optimization software tool Lingo. The following model will be further used as a reference model for reducing the bullwhip effect.

**Model:** \( \alpha = 0.36, \beta = 0.26, \gamma = 0.09 \):

The order quantities (also including the quantity of production) reflect the typical oscillating amplitude of the bullwhip effect the more one moves up the supply chain (see figure 1 above).

Besides the oscillation of order quantities and the phase lag in amplitudes, we observe that order quantities increase in the supply chain. The bullwhip effect is calculated as the quotient of variance of order quantities of members to variance of consumer demand. The producer’s bullwhip effect is the highest one in the supply chain, whereas the retailer’s bullwhip effect is the lowest one. For exact figures please see table below.

**USE OF VMI**

We now analyse whether the bullwhip effect caused by “demand distortion” and “misperceptions of feedback” can be reduced through the use of VMI. Furthermore, we analyse the extent of the reduction. We introduce two measures against the bullwhip effect. In one measure the wholesaler is included in the supply chain, in the other one he is not. Additionally, the misperception of feedback is prevented from taking place in the second measure without the wholesaler. The wholesaler is not needed due to the concept of VMI.

**Measure:** VMI with wholesaler and forecast of producer \( (\alpha = 0.36, \beta = 0.26, \gamma = 0.09) \):

In addition to consumer demand, the producer, in this measure, also uses his own demand forecast from the previous period to estimate the current demand (see behavior equations in the following figure 4). The producer’s bullwhip effect is still high due to coordination of stock. The wholesaler’s bullwhip effect has been reduced.

VMI integrates the producer into the flow of information. Thus, the producer does not have to cope with uncertainty concerning the supply any more.
Figure 4. Behavior equation for measure

“VMI with wholesaler and forecast of producer”
The progress of order quantities is represented in the following figure 5. The order quantities for wholesaler and retailer are mostly identical.

Figure 5. Progress of order quantities with the measure “VMI with wholesaler and forecast of producer” ($\alpha = 0.36, \beta = 0.26, \gamma = 0.09$)

**Measure**: VMI without wholesaler and with forecast of producer ($\alpha = 0.36, \beta = \gamma = 0.26$):
The use of forecast methods and the right perception of outstanding orders ($\beta = \gamma$) leads to a decreased bullwhip effect in the supply chain. The producer’s bullwhip effect is reduced, the retailer’s bullwhip effect does not occur anymore. The wholesaler is thus not needed in VMI, they even lead to increased inefficiency in the supply chain.

The orders per period converge to the fixed order quantity of 5 units per period as can be seen in the following figure 6.

Figure 6. Progress of order quantities with the measure “VMI without wholesaler and with forecast of producer” ($\alpha = 0.36, \beta = \gamma = 0.26$)

The accurate results concerning the bullwhip effect, the quantities of orders and stock as well as costs of the model without measure VMI and costs of the models with measure VMI are represented in the following table.

<table>
<thead>
<tr>
<th>model/measure</th>
<th>bullwhip effect</th>
<th>cumulated order quantities</th>
<th>cumulated stock</th>
<th>costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>model without measure VMI</td>
<td>producer</td>
<td>21.47</td>
<td>215</td>
<td>112</td>
</tr>
<tr>
<td>((\alpha = 0.36, \beta = 0.26, \gamma = 0.09))</td>
<td>wholesaler</td>
<td>11.87</td>
<td>213</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>retailer</td>
<td>6.63</td>
<td>208</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>consumer</td>
<td>1</td>
<td>199</td>
<td>-</td>
</tr>
<tr>
<td>model with measure VMI</td>
<td>producer</td>
<td>23.96</td>
<td>199</td>
<td>211</td>
</tr>
<tr>
<td>((\alpha = 0.36, \beta = 0.26, \gamma = 0.09))</td>
<td>wholesaler</td>
<td>1.95</td>
<td>198</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>retailer</td>
<td>1</td>
<td>199</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>consumer</td>
<td>1</td>
<td>199</td>
<td>-</td>
</tr>
<tr>
<td>model with measure VMI and</td>
<td>producer</td>
<td>1.98</td>
<td>198</td>
<td>8</td>
</tr>
<tr>
<td>without wholesaler</td>
<td>wholesaler</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>((\alpha = 0.36, \beta = \gamma = 0.26))</td>
<td>retailer</td>
<td>1</td>
<td>199</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>consumer</td>
<td>1</td>
<td>199</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Quantified results of model and measures.
IMPLICATIONS

We were able to demonstrate that the use of VMI leads to dramatic reduction of the bullwhip effect in supply chains. The total costs, the quantities of orders, and stock decrease as well. We provided simulation results showing that the extent of reduction increases with the elimination of the wholesaler in the supply chain and with the prevention of misperceptions of feedback.

The use of VMI solves problems concerning coordination within the supply chain. This leads to a significant reduction of the bullwhip effect and thus to an increase in profitability.

With the presented model, the extent of the bullwhip effect can be predicted. A managerial implication could be to use this ability to analyze the efficiency of the supply chain. The modelling and quantification of the counteraction of the bullwhip effect allows the optimization of the supply chain with regards to the described causes of the bullwhip effect.

However, the provided model is restricted to a small supply chain consisting of 3 to 4 parts. A globalized supply chain with more parts being located in different parts of the world will lead to a more complex supply chain and also to a more complex information model due to e.g. lead time aspects of different time zones (for supply chain design see Charu & Grabis, 2009). Another aspect of further investigation could be to strengthen the VMI producer-retailer-relationship with buyback contracts (see e.g. Shi & Xiao, 2008, p. 7). These enhancements might be a starting point for further investigation on the bullwhip effect.

REFERENCES


Lau, J. S. K., Huang, G. Q., & Mak, K. L. (2004). Impact of information sharing on inventory replen-


Figure 1