

Herlyn, Wilmjakob

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# The Bullwhip Effect in Expanded Supply Chains and the Concept of Cumulative Quantities

Wilmjakob Herlyn

## Abstract

The bullwhip effect is a recurring problem in expanded supply chains and one of the most discussed problems in the last years. The word “bullwhip” describes the increasing variability (amplitude) of demand in a supply chain. This logistic phenomenon is observed at the interfaces between the partners during the transition of demand. Many authors see the reason for the bullwhip effect in the distortion of information and the separate calculation of dependent demand. This paper investigates the question whether the concept of cumulative quantities can tackle or even avoid the bullwhip effect.

First the concept of cumulative quantities and order calculation are explained. Then a common production and material flow structure of the expanded supply chain is defined that is mandatory for lead time calculation between preceding cumulative curves of dependent demand. The results are demonstrated on a chart by a simple example with a constant Master Production Program. Thereafter the constant Master Production Program is changed into a sporadic one and the consequences for the cumulative curves of dependent demand and order calculation are explained. Then some special factors like additional demand are analyzed that influence cumulative curves and order calculation in expanded supply chains. At least a resume is given and some conclusions are made.

**Keywords:** concept of cumulative quantities, preceding cumulative curves, bullwhip effect, expanded supply chains

## 1. Introduction

"The bullwhip effect occurs when the demand order variability's in the supply chain are amplified as they moved up the supply chain. Distorted information from one end of a supply chain to the other can lead to tremendous inefficiencies" (s. Lee Hau et al 1997, p. 93). The bullwhip effect was discovered for consumer goods where customer demand fluctuates widely, the market demand is anonymous and difficult to predict. Therefor many studies and papers focused primarily on the area of distribution logistics (cf. Arnold et al. 2008, p. 29 ff., Cachon, 2007, Hongchun, 2011, Lee Hau et al. 1997a, Warburton, 2004).

Nowadays an increasing number of original equipment manufacturers (OEM) won't longer produce to stock (BTS) but to customer order (BTO). Therefor the procurement logistics and supply chain play an increasingly important role and not the distribution chain. This applies mainly for companies that manufacture complex technical products with a wide range of variants and a lot of components. The globalization of the world economy has the consequence that multinational companies build production sites on all continents and spread out their supplier network, whereby the suppliers spread out their network too. Thereby the number of cooperating firms and material flow interfaces are growing steadily and "the problem of demand order variables in enterprise-wide value-added systems" increases (s. Göpfert, 2013, p. 29) and can provoke a bullwhip effect. "The solution of the bullwhip effect appears simple. All cooperating companies in the supply chain must have direct access to the demand information of the end customers and replace their current practice of independent planning of production and stocks on available resources and capacities in the supply chain through a global view." (s. above p. 30). This paper investigates the question whether the concept of cumulative quantities (CQ) is suitable to struggle or to avoid the bullwhip effect as far as possible so the above postulation can be fulfilled.

## **2. The concept of cumulative quantities**

### **2.1 The calculation of cumulative curves**

The concept of cumulative quantity (CQ) starts with the calculation of 'cumulative curves' (CC) for the final products that are stored in the Master Production Plan (MPP). The cumulative curve is created by the singular values for final products in the time-units of a timeline. The cumulative quantity for a time-unit in the timeline is calculated by adding all previous values up to the obtained time-unit. The result is a more or less rising curve (s. Heinemeyer, 1992, S. 163 ff.). The time-units in the timeline has to be normalized by a 'production calendar', which transfers the Gregorian calendar data into an equidistant calculation calendar. This means: every calendar day without working hours is removed or marked as "free day" and all calendar days with work reduction or shortage has to be congruently 'cut'. This is mandatory to allow a correct lead-time calculation in the supply chain (see below). This normalization of the timeline also applies to different time-units in the timeline like shifts or hours or what else.

### **2.2 Order calculation based on cumulative curves and the control loop principle**

The determination of order quantities in the concept of CQ bases on the control loop principle. Each particular cumulative target quantity in a time-unit is compared with the cumulative actual quantity. Based on the target-actual deviation a control mechanism (this is the software for requirement demand calculation) determines the regulator: the order of delivery or production. If the actual cumulative value falls below the cumulative target value an order is generated in the level of the measured deviation. In other words: an order is triggered only at the point (time-unit) where the cumulative target curve exceeds the actual cumulative curve (s. fig. 1). If the actual cumulative value exceeds the target value no order is generated.

For regulation also a certain lot size, a time-oriented algorithm or another logistic control mechanism can be used. If a lot size has to be taking in account then the

order quantity normally exceeds the target value. This 'event' acts only at the concerned time-unit because the next following order is only then generated when the next cumulative target quantity is lower the cumulative order quantity. This leads to a certain temporarily variability and fluctuation in the short run but in the long run it can't lead to a bullwhip effect. It has to be noticed that the new calculated orders are at the same time used for creating the cumulative in the future so we can build the target-actual deviation and calculate new orders also for the future (s. Chap. 2.3).

In general the magnitude of order variability and fluctuation depends firstly on the granularity of the timeline, secondly on the amount of required quantities and thirdly on the lot size for transportation or production. These factors have obviously no substantial influence to the principle method of calculation and will not be treated in detail here.

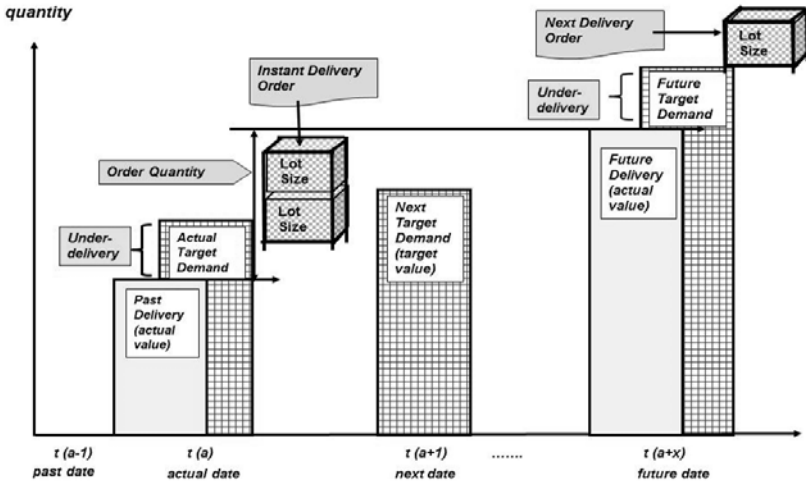


Fig. 1: Calculation of delivery orders (simple example)

The control loop principle includes the automatically adjustment of over- and under-delivery or over- and underproduction, no matter what the reasons for the differences are. This includes subsequent changes in the MPP, customer order

definition and product documentation. Also the cleanup of errors is included in the next requirement demand calculation run. These errors can be mistakes, failings and deficits in the processes and the documentation like: failing in the BOM-data, errors in product order definition, inaccurate or late data collection, mounting of false component or incorrect termination of technical changes. These casual factors can't predict and lay outside the normal process and procedures, but they lead to a change in the cumulative target or actual curve. Such retroactive changes and corrections are obvious intended and necessarily taken in account in the control loop principle for exactly requirement demand calculation and lead to 'certain' fluctuations in cumulative target curve and especially for the instant or next order.

### **2.3 Preceding cumulative curves in supply chains**

The cumulative target curve for final product orders in the MPP is the starting ground for the calculation of the required demand for all components (single parts, assemblies, units, raw parts). The calculation of the dependent demand requires to determinate a common production and material flow structure (PMF-structure) for the entire supply chain. An oriented material flow can be described by an ideal Boolean interval algebra, where an interval within maps a certain section or stretch in the supply chain (cf. Herlyn, 2012, p. 131 ff.). An interval can represent any kind of production or transportation, also a stock area or whatever is needed. The beginning of an interval is always defined by a 'counting point' (CP) and the end is bounded by the CP of the next following interval. Between two following intervals no lack or overlapping does exist so that the PMF-structure maps the entire supply chain concisely and consistently. Each interval can be divided into subintervals and so on, whereby these subintervals don't have any lacks or overlapping too.

This is followed by the interval of assembly mounting (Int-AM) followed by the section of unit assembling (Int-UA), whereby the word 'unit' is another expression for a main resp. an essential assembly for the final product. The last section represents the assembling of final products (Int-FA). Each of these main intervals

is divided into two subsections one for production activities and the other for transportation activities. They could be divided in further subsection for more exact calculation but for our purpose this has no substantial relevance.

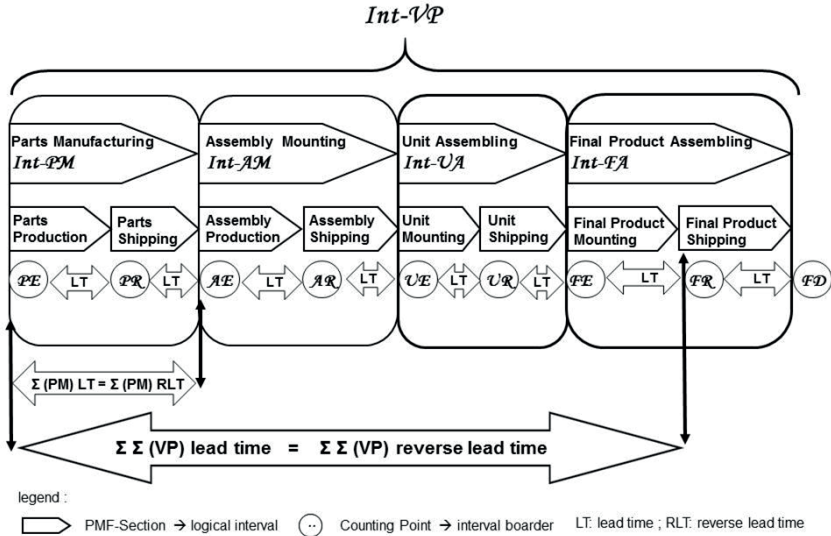


Fig. 2: Production & Material Flow Structure and (Reverse) Lead Time

The requirement demand calculation starts 'at the right' vice versa to the material flow with the cumulative target curve of final products assembling that is referred to the CP "Final Product Ready" (FR), which represents the upper boarder of the PMF-Structure. Thereafter the calculation goes backwards from one CP to the next preceding CP and ends at the counting point "Part Entry" (PE), which represents the lower boarder of the PMF-structure. The requirement demand is calculated step by step backwards to the physical material flow and supports a pull-system-oriented procedure. Hereby the cumulative curve of final products is the dominant curve and the superior boarder for the preceding cumulative curves for the depending demand of all components.

The calculation of preceding cumulative curves is a simple shift by lead time (LT) and is especially adequate continuously production and material flow (cf. Wiendahl, 1997, p. 33 ff.). The LT is defined individually for each PMF-section. The LT from one CP to the next one is used as the Reverse Lead Time (RLT) for backwards calculation. The single LT's of preceding intervals can be added up so that the total LT for a component is the sum of the LT's for all concerned intervals. To calculate e. g. the entire RLT for a single part from 'Parts Entry' (PE) up to the end of final product assembly (FR) the single LT's of all PMF-sections the part passes through have to be added. The more detailed the PMF-structure is described finer and the smaller the PMF-sections are defined the better are the LT determined and the more accurate will be the result of the requirement calculation.

The chart below (s. fig. 3) shows a typical progress and shape of several preceding cumulative target curves based on a MPP with constant production of 50 items per day. Until 'today' 300 final products are cumulative produced and at the end of the cumulative curve for 850 final products have passed the counting point (FR). The cumulative curve at the counting point 'Parts Entry' (PE) represents the "earliest" target demand in time and the curve for the counting point 'Final Products Ready' (FR) represents the "latest" target demand. Between these 'corridor' you can see the cumulative curves for the other counting points like 'Parts Ready' (PR), 'Assembly Ready' (AR), 'Unit Ready' (UR) and the 'Final Product Entry' (FE). In our example we suppose a continuous material flow without lot sizes so the cumulative curve for final products is shifted along the timeline. Only the last cumulative curve for 'Parts Entry' has some little kinks because of lot size for delivering. In this case the delivery order is calculated with a lot size of 40 items and the curve is exceeded at the time-unit, where the required target demand is lower than the actual demand. The impact of a lot size works only temporarily at some certain time-units and doesn't cause an increasing whipping up in the demand of the supply chain. It has to be noticed that in case of a huge lot size that exceeds the cumulative curve in the long run the order calculation has to be adjusted. An extremely lot size or an extremely



low demand needs a 'special treatment' for limitation. That means it has to be ensure that the actual order curve doesn't exceed the target curve in the long run, especially at the run-out of demand.

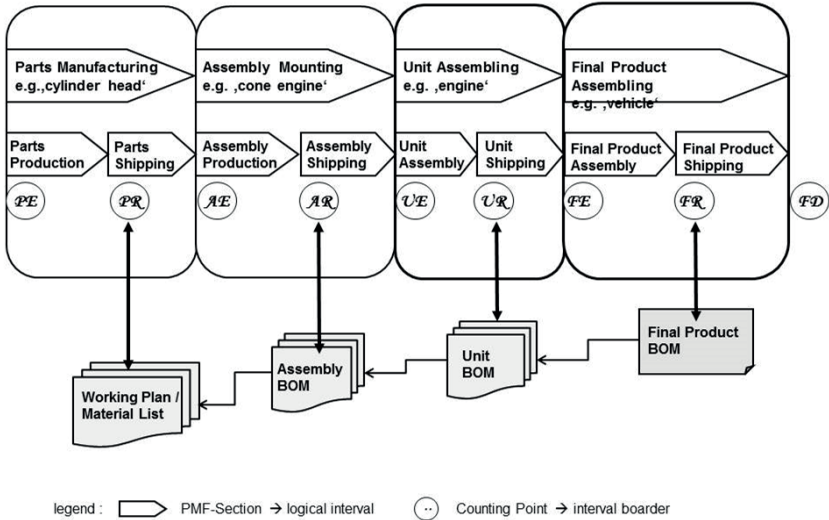


Fig. 3: Cumulative curves for a constant Master Production Program

Because the LT is an attribute for a PMF-interval and not for a PMF-object the LT must be transferred to each PMF-object that passes the concerned PMF-interval. Every change of the LT for a specific interval (or subinterval) can instantly be transmitted to all of the concerned PMF-objects. So no more additional data input for each single PMF-object in the master data is necessary. This powerful method is especially important for a complex product with many variants and a lot of components.

### 2.4 Changes in the Master Production Program

There are two types of changes in the MPP that have different impacts on cumulative curves of the final product and the preceding cumulative curves. The first type changes only the distribution of final products in the MPP inside a certain

time-window whereby the cumulative amount at the end of the time-window remains the same. Such a change can often be observed in companies with BTO-Production where the sequence of the final products is optimized or adjusted because of different events. The limitation of a time-window is not a precondition and no restriction for the method but only done for better demonstration. In the next example the constant distribution in the MPP is changed into a more or less sporadic distribution of the final products (s. fig. 4). That means that on some days none or only a few final products were produced and on some other days a bigger amount of final product were manufactured. In the consequence you can observe same days where the cumulative quantities of two or three cumulative curves are equal. The reason is that the lead time of a PMF-section is shorter than the days without production therefor none of the concerned items are in this PMF-section. In the middle of the timeline you can see a big increase (860

□ 1260) at

results from the strong rise of final production of 200 items in two days (450 □ 650). Some other little changes come from the lead time of the preceding PMF-sections.

This fictive example can be handled separately but here it is done for a better understanding of the method. In practice the described change from a constant to a sporadic distribution of final products in the MPP can happen vice versa. This can be seen properly by final products with a lot of options and very different customer orders, where a balancing of the assembly line is necessary.

The second type changes not only the mix of product variants or the distribution of final products but the total amount of final products at the end of the defined time-window. So the MPP is not only temporarily but substantially revised. Those changes can be observed if there are not enough real customer orders in the MPP and the MPP is filled-up with fictive customer orders.

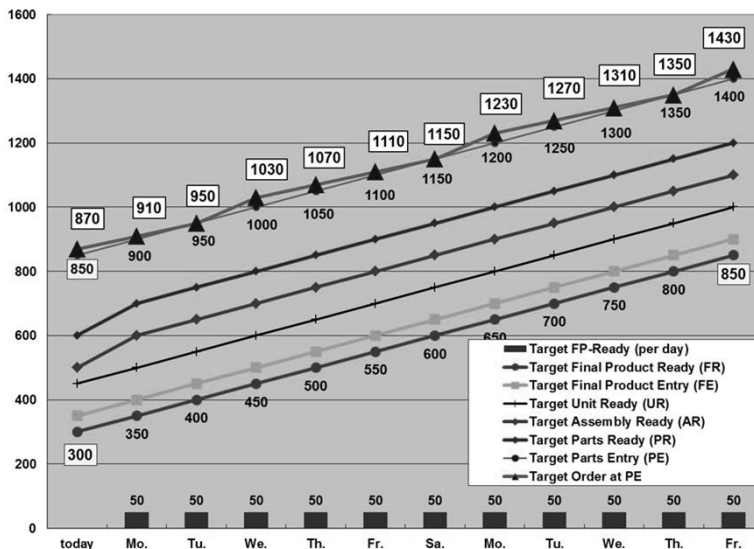


Fig. 4: Cumulative Curves for a 'sporadic' distribution of final product

As soon as there are real customer orders the fictive orders will be substituted. Some BTO-Manufactures have a special systematic to handle this type of change (s. Herlyn, 2012, p. 202 f.). Because the concept of CQ still works in the same manner and therefore no extra examples are developed here. Of course the change from a constant to a sporadic product distribution in the MPP can happen vice versa. This can often observe as assembly-line balancing properly by products with a lot of options and very different customer orders. So the results for the cumulative curves and the order calculation are vice versa too.

## 2.5 The influence of product structure and BOM-Data for dependent demand calculation

For the calculation of cumulative demand it is mandatory to have a Bill of Material (BOM) in which the product structure and the relations between the components are documented. This BOM-data are necessary to disaggregate the final product into its components. This is a precondition to transmit the superior demand of

final products to the upper demand of its components. The product structure must match with the PMF-Structure and can be referenced at the counting points in the PMF-structure. In our case there are Counting Points that represents the end of manufacturing activities so that four BOM's are required (s. fig. 5).

If a component is used more than once at a certain usage point the quantity is multiplied by the 'usage factor' in the BOM.

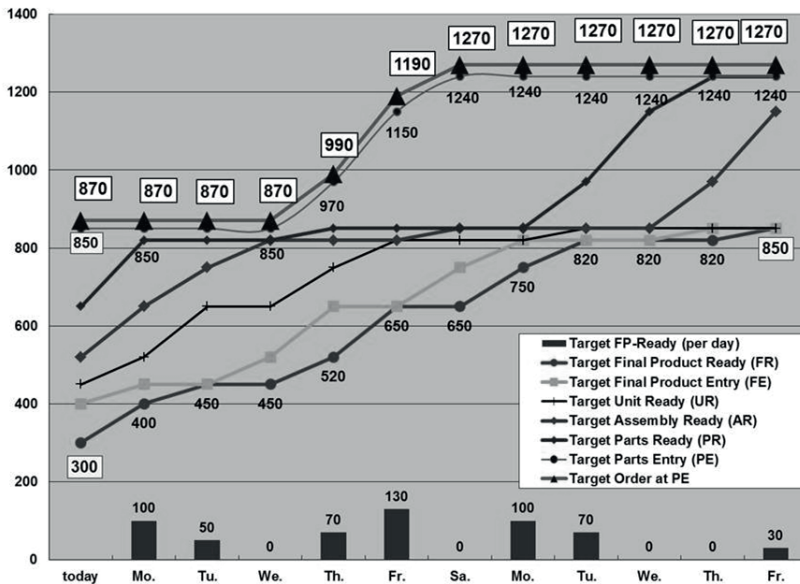


Fig. 5: Product Structure with linkage to the PMF-Structure

The cumulative curve is expanded proportionally but the characteristic shape of the curve remains. If a component has more than one usage point in same observed PMF-section than several curves build a common cumulative curve at the concerned counting point. Such components are often 'standard parts' like screws, bolts, washer, plugs etc. These are normally components that don't belong to a specific product variant, so the common cumulative curve is a mixture of quite different curves. In this case it is a huge effort to trace back all and every

single curve. But both cases are although no reason for a bullwhip effect. In addition there are some factors that can't be determined exactly for example: mounting with selective need, mounting of alternatives parts or producing parts with stochastic results. In this case the concerned cumulative curves have to be calculated as bundle to adjust the curves. This should here not further be investigated.

## **2.6 Splitting and merging of material flow**

Beside the described demand calculation the splitting in material flow and demand (e.g. several suppliers or manufacturers) and the merging of material flow and demand (e.g. different product variants) cause changes in the shape and height of the preceding cumulative curves.

If there is a splitting in the PMF the cumulative curve has to be split into the different sections and in the consequence the demand is divided. For this a rule is needed which describes the specific regulation for 'splitting'. This rule can be a quotation of orders or another alternation of delivery and production. As a consequence of this the order quantities have more or less peaks and lows at certain point in the timeline. This depends on the gradient of the cumulative curve and the height of the lot size. In any case this is not a reason for a bullwhip effect but only an inherent procedure in the concept of CQ.

In the next charts the actual delivery orders for two suppliers A and B with a delivery quotation (splitting) of '70:30' percent are shown. For both the lot size for delivery order is 40 items. The chart 6 shows the order-line for the constant MPP (s. fig. 6) therefore the order-line is also very constant. Because the lot size is a little bit below the daily demand, there are only two orders of 80 items.

The orders for sporadic MPP follow the sporadic MPP. The peak you can see in the middle covers the peak of the final production therefore it is not a bullwhip effect but a normal reaction (s. fig. 7).

# The Bullwhip Effect in Expanded Supply Chains

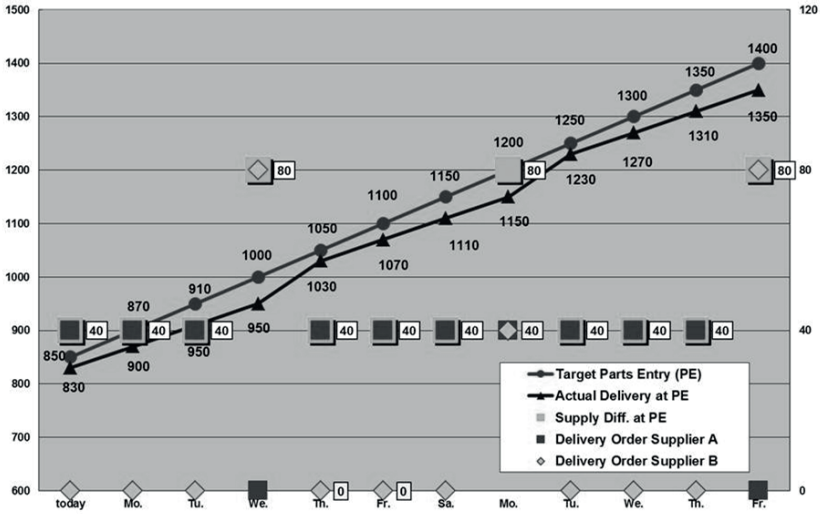


Fig. 6: Delivery order splitting for the constant MPP (cf. fig. 3)

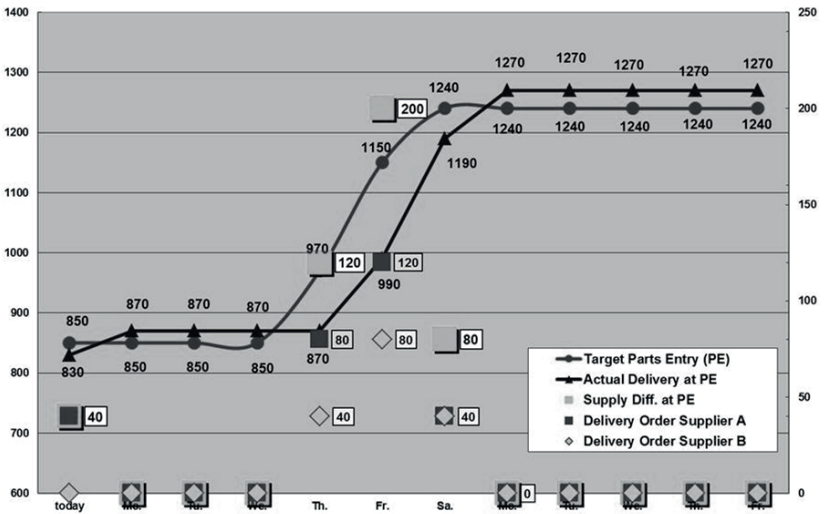


Fig. 7: Delivery order splitting for the sporadic MPP (cf. fig. 4)

If there is a merging in the PMF-Structure, the different cumulative curves (of demand) has to sum up and a new cumulative curve is the result. Therefor it's not easy (e. g. for the partners inside the SC) to recognize the original curves of the superior demand. The original demand can only be traced by all individual cumulative curves. The more complex a product is and the more expanded the supply chain is, the more difficult it is to trace back the dependent demand to the final product though this is not a reason for a bullwhip effect.

### **3. Additional demand to final products demand**

A more or less big factor that influences the shape and height of the cumulative curve are additional demand sources for components of the final products. The mainly additional demand comes from the spare parts, industrial partners or other allied companies of a group. Another additional demand comes from several consumers inside a company. They need components for their internal tasks like Prototyping in the Design Department or Trying-out in the Production Department to check out the manufacturing tools and industrial equipment. Another additional demand is caused by manufacturing of defect and deficient components. Also components were destroyed during or after manufacturing or transportation. Anyhow: All additional demands have to be added to the target demand from the final product. So the additional demand is included in the cumulative target curve and will heighten the cumulative target quantity. The concept of CQ is still working in the same manner and to that fact no bullwhip effect will occur.

It has to be remark: if there is a combination of different additional demand sources for a component it is very difficult to recognize the reason for a concrete actual order. This can only be analyzed by separating the cumulative curve for the several demand sources. There exists no inherent systematic between the demand for components deviated from the MPP and the additional demand. So the preceding cumulative curve are changed in a certain casually way and can cause an unpredictable order change but no bullwhip-effect.

#### **4. Short resume and conclusion**

The globalization of the world economy leads to globally production and procurement networks of multinational companies. Thereby the number of cooperating firms and interfaces are growing steadily and the phenomenon of a bullwhip effect can be observed in the expanded supply chain. A growing numbers of OEM's build their product no longer to stock but to customer order. In this situation a powerful concept for requirement demand calculation is needed for the expanded supply chain.

The concept of CQ is a very simple and robust method for requirement calculation of dependent demand in an expanded supply chain. This concept integrates the control loop principle that is able to avoid a bullwhip effect. It starts with the calculation of the cumulative target curve for final products from the MPP. Thereafter the dependent demand of components is calculated step by step backwards along a common PMF-structure. The results are cumulative curves for all relevant Counting Points in the supply chain. This concept is especially appropriate for continuous flow production and transportation with an ongoing demand of high amounts. Some impacts from outside and inside the company, mainly the additional demand for components, can be integrated into this concept.

To transfer this concept into practice all cooperating partners in the expended supply chain have to use this same concept. As a fundamental base they have to define and use a consistent PMF-structure with common counting points. All partners have to give their target and actual values to their partners. This includes to collect actual data just in time and to use a common communication platform. It doesn't matter if the interfaces between the cooperating partners are inside a group or outside because the PMF-sections and the counting points are only material flow items and not juridical items. Therefore the above postulation can be fulfilled by the concept of cumulative quantities. If the partners work together on this concept the bullwhip effect can be avoided in expanded internal or external supply chains.



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