Can Simulation Prevent Companies from the Bullwhip Trap?

New Approaches to Model the Bullwhip Effect with the Aid of Excel and High-Level Petri Nets

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***Abstract*—There exist many explications for phenomena in logistics – one of them is the so called bullwhip effect. It explains ups and downs in turnovers in a supply chain if demands and offers of the participants are not synchronized. While previous work on the simulation of the bullwhip effect was intended to explain it in general, surprisingly little research has been conducted with focus on how to make these simulations available for companies. In doing so, simulation based forecasts could reduce storage and production costs significantly, prevent companies from getting stuck in the bullwhip trap, and thus enable significant savings. This paper, in contrast, demonstrates how to develop models of the bullwhip effect for a given scenario with the aid of Excel and with a novel, freely accessible modeling and simulation environment for high-level Petri nets, and compares the findings. Companies can use both approaches and adapt them easily to their specific problem. Hence, this paper has two major outcomes: The models themselves but also an explanation on how to find such models.**

***Keywords*—Logistics; Bullwhip effect; Modeling; Simulation; Excel; Petri nets; Savings.**

I. Introduction

Many companies strive to reduce their internal costs. But in addition, there is another significant potential for savings through a better understanding of the market and coordinated communication with the other market participants. How high this savings potential is can exemplary be explained using the *bullwhip effect (BWE)*: Strong fluctuations in terms of production and sales of the participants in a supply chain can be observed, which lag behind current market developments.

Although phenomena such as the bullwhip effect are known, this knowledge rarely has any practical impact on business decisions. Appropriate simulation models could change that. But entrepreneurs need both suitable models and software to be able to carry out the corresponding simulations. This enables savings in production and logistics as well as a significant contribution to increasing sustainability in supply chains. For this, however, practitioners need guidance on how to proceed methodically and which tools they can use for this.

This paper answers the question how to develop a simulation for the bullwhip effect in a step-by-step approach in correspondence with the phase model of Figure 1 with commonly available tools. It may therefore serve as a source for practitioners to apply the findings to their own business. A detailed description of an imagined scenario is the starting point where the actual process and the business rules which trigger procurement and production are the most important components.

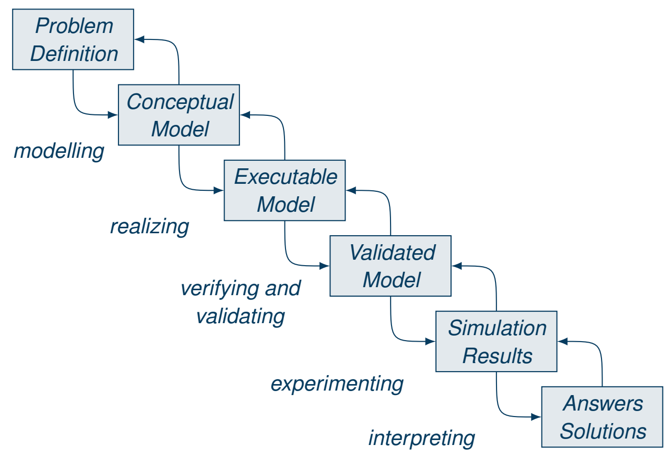

Figure 1. Phases of a Simulation Study adapted from [1].

An Excel based simulation model served as a conceptual model. For each simulation period distinct calculations had to be defined. Although this was a helpful step to understand the problem, this solution does not scale very well. Interested readers are invited to ask for the original Excel file. Afterwards, a Petri net model was developed as an executable model. Also here, interested users are invited to ask for the model and to test it with the aid of the tool which is free to use for academic purposes. Both, Excel and Petri net solutions were used to validate each other. What must not be underestiamated is the need for a meaningful visualization of the simulation results to solve the problem.

This paper is organized as follows: Section II explains the bullwhip effect and discusses former work on its simulation. Section III introduces a supply chain scenario for which simulation models have been developed in Excel as described in Section IV and with the aid of high-level Petri nets as described in Section VI. Since modeling and simulation of Petri nets highly depends on the tool used, Section V is inserted in between, introducing Petri nets and the Process-Simulation.Center (P-S.C). Finally, in Section VII visualization is addressed as a major topic to enable decision making based on the simulation results. A summary and an outlook are given in Section VIII.

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II. Related Work on the Bullwhip Effect

Various definitions of the term BWE exist in literature. In general, the BWE can be described as a volatile gap between a company's orders and its suppliers expectation which increases in the up- and downstream of a supply chain. Typically, the BWE is considered concerning the variables order volume, inventory, lot size, and production capacity [2].

The drivers of the BWE are manifold: An increased demand due to a delayed information is called *Forrester effect*, while order bundling within a player is found as *Burbridge effect*. The *Houlian effect* describes a situation where participants expect a possible bottleneck of their suppliers and therefore declare a higher demand as necessary. Finally, the *promotion effect* results from price fluctuations [3]–[5]. Often behavioral and psychological factors of the decision makers in the supply chain have a major impact on the degree of volatility [6].

There exist several approaches to simulate the BWE. But [7][8] criticize that most authors use rather simple supply chains which consist only of two to four stages with one player on each stage. This means an unacceptable level of abstraction for practical applications.

Other approaches to simulate supply chains are conjoint with high entry barriers for potential users [9]. exemplary, [10] use a genetic algorithm to consider cost and liquidity management of supply chains. [11] use an adaptive network based fuzzy inference system (ANFIS) trained with the production information of a beverage producer. Companies can hardly adopt such methods because their modes of action are in-apprehensible for IT laymen.

Thus, companies use software technologies to accelerate the information flow and production speed in the hope of avoiding or at least reducing the BWE, instead of using the knowledge concerning the bullwhip effect. In 2020, 45% of the asked companies use inventory and network optimization tools and another 44% will adopt these tools within the next five years. Robotics and automation, which can be used to speed up reactions on changing demands, are recognized as the technologies with the highest potential (above 60%) [12].

From the authors' perspective, these technologies result in local and isolated improvements. Their impact on the entire supply chain remains vague. The methods and tools used in this paper to model the BWE, however, enable practitioners to understand the causality within a simulation model, adapt the models to their own needs, and to develop confidence in the simulation results.

III. Simulation Scenario

The presented simulation of the bullwhip effect is conducted at the example of an imagined scenario (see Figure 2), where consumers' demands pull goods through a supply chain which also consists of retailers, producers and raw material suppliers.

Figure 2. Stages of the supply chain scenario.

The scenario considers production and trading of shampoos called *Aloe*, *Chai*, *Coco* which are kept simple: They consist of bottled soap and odor of various ratio (see Figure 3). The focus is on the flow of the bottles. For other raw materials there would be similar results, hence they are omitted here.

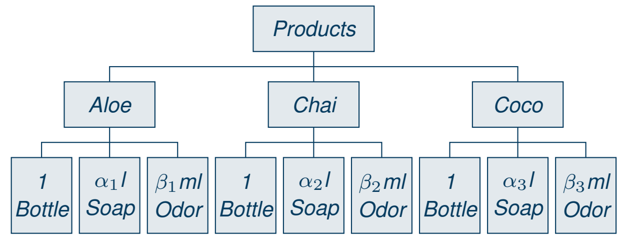

Figure 3. Product Tree.

Products and raw materials are produced on demand. After selling products to the consumers out of their stocks, retailers fill up their stocks when they reach their specific reorder level. For this, the producers have to empty their stocks and eventually order raw material from their suppliers for the production of new products for upcoming requests. Also, the producers use reorder levels to calculate their specific demand.

There exist 8 retailers named *Ali*, *Ede*, *Glo*, *Lid*, *md*, *Pha*, *Rew*, and *Ros*. (and probably German readers assume which real retailers the authors had in mind). Each of them offers all three products and procures them from 6 producers called *Body*, *Head*, *Neck*, *Hand*, *Knee*, and *Foot*. Each producer produces one of the mentioned products and has exclusive contracts with one or more retailers. The sourcing matrix in Table I shows the relations between the different partners.

TABLE I. SOURCING MATRIX: RETAILER, PRODUCER, PRODUCT

	Ali	Ede	Glo	Lid	md	Pha	Rew	Ros
Aloe	Body	Head	Neck	Body	Head	Neck	Body	Head
Chai	Hand	Knee	Hand	Knee	Hand	Knee	Hand	Knee
Coco	Foot	Foot	Foot	Foot	Foot	Foot	Foot	Foot

All raw material is delivered by one supplier since the focus here is on the bullwhip effect for retailer and producer.

The simulation runs over 12 periods. All stocks of retailers and manufacturers are initialized with 150% of their reorder levels as shown in Table II. Retailers have access to their global storage so local storages are not considered.

TABLE II. INITIAL STOCKS (IS) AND REORDER LEVELS (RL) OF THE RETAILERS FOR THREE PRODUCTS (IN THOUSANDS)

		Ali	Ede	Glo	Lid	md	Pha	Rew	Ros
Aloe	**IS**	105	105	90	105	105	90	105	105
	RL	70	70	60	70	70	60	70	70
Chai	**IS**	120	90	120	82.5	120	90	120	82.5
	RL	80	60	80	55	80	60	80	55
Coco	**IS**	82.5	105	75	90	82.5	105	75	82.5
	RL	55	70	50	60	55	70	50	55

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As summarized in Table III, the total consumption varies seasonally from 700.000 to 1.400.000 bottles over all products and their market share varies from 25% to 60% of the total depending on the success of the marketing campaigns.

TABLE III. MARKET (IN THOUSANDS) AND SHARE PER PERIOD

Period	Total market	Product distribution Aloe	Chai	Coco
1	1.000	60%	20%	20%
2	1.200	25%	50%	25%
3	800	25%	25%	50%
4	1.000	33%	33%	34%
5	700	60%	20%	20%
6	1.400	25%	25%	50%
7	1.000	25%	25%	50%
8	800	33%	33%	34%
9	1.200	60%	20%	20%
10	700	25%	50%	25%
11	1.300	25%	25%	50%
12	900	33%	33%	34%

Table IV shows the fluctuating market shares per Retailer across the 12 phases.

TABLE IV. RETAILERS' MARKET SHARE PER PERIODS

Period	Retailer distribution Ali	Ede	Glo	Lid	md	Pha	Rew	Ros
1	12%	12%	10%	18%	15%	11%	14%	8%
2	10%	11%	11%	15%	18%	11%	10%	14%
3	9%	10%	12%	13%	11%	17%	14%	14%
4	8%	8%	14%	9%	19%	12%	10%	20%
5	14%	19%	8%	11%	11%	19%	8%	10%
6	12%	12%	10%	18%	15%	11%	10%	14%
7	10%	11%	11%	15%	18%	11%	10%	14%
8	9%	10%	12%	13%	11%	17%	14%	14%
9	8%	8%	14%	9%	19%	12%	10%	20%
10	14%	19%	8%	11%	11%	19%	8%	10%
11	12%	12%	10%	18%	15%	11%	14%	8%
12	10%	11%	11%	15%	18%	11%	10%	14%

These assumptions allow to calculate the specific demand of each product for all retailers in every period. Table V shows exemplary the demand for each product in the first period.

TABLE V. RETAILERS' DEMAND FOR THE DIFFERENT PRODUCTS AT THE EXAMPLE OF PERIOD ONE (IN THOUSANDS)

Retailer	Ali	Ede	Glo	Lid	md	Pha	Rew	Ros
Aloe	72	72	60	108	90	66	84	48
Chai	24	24	20	36	30	22	28	16
Coco	24	24	20	36	30	22	28	16

The supply chain can be simulated period-wise, where each period is divided into the following phases:

1) Retailers fulfill the demands of their consumers if possible. This reduces their stocks. Unfulfilled demands are backlogged and deferred to the next period.
2) Retailers order products from their producers (e.g., *Ali* orders *Aloe* from *Body*) when their stocks decrease below their reorder level. The order amount is the difference between reorder and current level multiplied by a nervousness-factor which is set to 2 in the following. Unfulfilled amounts are deferred to the next period.
3) Producers satisfy the orders out of their stocks in the sequence given by the retailers' names. Unfulfilled demands are backlogged and deferred to the next period. The production is restricted by the amount of bottles in the raw material stocks of the producers.
4) If bottle stocks sink below individual reorder levels, new bottles are ordered as described above.
5) The production of bottles is assumed to be unlimited.

Since this scenario has several and widespread parameters, it can be adapted to many real-world situations.

IV. Simulation with the Aid of Excel

When developing a conceptual model of the BWE with Excel, it was the aim to keep the calculations technically as simple as possible. Hence, no VBA was used with the consequence that each modification of a stock, the calculation of order amounts and of backorders had to be mapped with the aid of individual data cells.

The challenges of this approach are to keep all calculations of comparable concepts consistent and to chain the calculations of a given period with its previous one. Beside the simplicity with respect to possible modifications of the model, the calculation of the twelve periods occurs instantly.

Several data sheets for products, periods, demands, retailers and producers were built as follows:

Product contains product master data to extend calculations for more complex product recipes in the future.

Period contains the assumed situation per period described by market share per product and per retailer.

Demand uses *Period* data to charge the demand of the consumers for a specific product sold by a retailer per period.

Retailer uses *Demand* to change the initial stock of and the demand for a specific product for each retailer. Then, the stock level after fulfilling the consumers' demands and a possible backlog of unfulfilled demands are calculated. The purchase volume equals the difference between current stock and reorder level multiplied with the nervousness factor, if the stock is below the reorder level. The calculation of the following periods is conducted in a similar way except for the initial stock per period which is derived from the previous one. Since 12 periods are considered for 8 retailers, the calculation stretches over more than 100 rows and within the rows stand out three column blocks for each product.

Producer is set up in a similar way like *Retailer*. Product and retailer data are used to fulfill the initial demands of the retailers. Supply conflicts between retailers are avoided by serving them in alphabetical order. Also the producers' stocks after delivery are calculated and a possible backlog is build up. If a producer's inventory is below the reported level, it produces enough to replenish the inventory, multiplied by the nervousness factor. This is only restricted by the amount of available bottles.

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Finally, bottles are ordered if the bottle amount is below the reorder level, again multiplied by the nervousness factor. It is assumed that the producer of the bottles can always fulfill this demand.

The calculation of the following periods is conducted in a similar way, and complexity of the sheet *Producer* is similar to that of the sheet *Retailer*.

In addition to these calculation sheets, also sheets with graphical dashboards have been established to observe changes concerning the BWE if parameters like the initial stocks, demands, reorder levels, or nervousness factors change. This makes the simulation experimental.

Although it was easy to get started with the Excel model, it became worse with the number of periods, products, and retailers that had to be added to the sheet until the scenario setting had been reached. One reason for this is that it is difficult to include well readable comments to the excel sheets. Also changing delivery policies like the order in which retailers are served by the producers must be implemented cell by cell, since it is difficult to centralize such decisions. Hence, it must be stated that it is almost impossible to develop scalable models for the BWE in Excel. Nonetheless, for the described problem size it is a good alternative and helped to validate the results of the Petri net model explained next.

V. Petri Nets and the Process-Simulation.Center

Petri net models are used to analyze and simulate dynamic systems. Their main benefit is the ability to describe concurrency in a natural way and concurrent actions are not forced into a schedule. Hence, they are beneficial for the definition of business processes and supply chains [13][14]. One popular and currently widely discussed application of Petri nets in business process management is Process Mining [15][16].

Originally, Petri nets are defined as Place/Transition nets (P/T) with anonymous tokens indicating a system's state [17], but concepts like Predicate/Transition nets (Pr/T) and Colored Petri Nets (CPN) also support the representation of high level information [18]–[20]. Demanding models of high-level Petri nets need appropriate software for modeling and simulation.

The *Process-Simulation.Center (P-S.C)*, which is introduced next, supports P/T and Pr/T nets. The Pr/T net concept is realized in such a way that places have an assigned data type and can be used in analogy to tables in a database. Functions encoded on transitions and edges may process this data. Data which is spread over several places can be joined into a single data record. Own types for date and time are substructures for the simulation of processes in production and logistics and enhance the approaches to timed Petri nets [21].

In contrast to relational algebra and, hence, SQL, in P-S.C the processing of tuples on places is serialized. The reason for this design choice is that in business and production processes work items are also treated one after another. The concrete sequence is decided upon locally by the transitions of the net and its marking [22].

Moreover, the P-S.C can be used to connect the process view on a system with other views. Process maps may combine different processes with each other and express the strategic value of a specific process as a primary, support, or management process. Also, the organizational structure of an institution can be combined with the Petri net view by arranging the process nodes in swim lanes of the corresponding responsible organizational units. Organizational charts complete the functions of the P-S.C [22].

It is worth mentioning that for a better readability the P-S.C draws nodes in such a way that their labels can be presented within. To further strengthen visual clues of their functionality, nodes can be provided with symbols [22].

The dearth of current Petri net tools, the quaint user experience of most of the still working ones and the unique approach of using textual programming instead of drag-and-drop modeling in combination with the added functionality are the main reasons for the implementation of the P-S.C [22].

VI. Simulation with the Aid of Petri Nets

Figure 4 shows the Petri net model of the described scenario. Swimlanes are used to separate the model into three parts, called *Exchange*, *Supply Chain and Phases*, that interact in order to simulate a period with the following five phases:

Phase 1 In the first phase transition *Buy Shampoo* realizes the transfer of goods from retailers to consumers. It is enabled as long as there is unfulfilled demand for the current period, which is coded in the token information on place *1. Phase*. For this place, *Demand* contains the demand information for all periods and place *Retailer Dashboard* encodes the initial stocks at the beginning and later the achieved stocks as the simulation proceeds. Delivered goods are coded on place *Bought*.
Transition *next* below from *1. Phase* initiates the next phase, if transition *Buy Shampoo* is no longer enabled.

Phase 2 The second phase occurs when the corresponding place is marked with the number of the current period. Now the retailers order shampoo if the stocks are below the reorder level. At the same time, the producers' stocks of finished goods are emptied. For this, the current stocks of the producers are encoded on place *Producer Dashboard*. Delivered goods are coded on place *Delivered*.
When transition *Order Shampoo* is no longer enabled, transition *next* below of *2. Phase* fires and phase 3 begins.

Phase 3 The third phase simulates the production of new shampoo, restricted only by the number of available bottles. Therefore, only the producer information must be considered. The produced amount is stored on place *Produced*.
When transition *Produce Shampoo* is no longer enabled, transition *next* below of *3. Phase* fires to begin phase 4.

Phase 4 The fourth phase simulates the re-stocking of the bottles if the current stocks are below the reorder level. It is assumed that the producers of the bottles have infinite supply available.
When transition *Deliver Bottles* is not enabled anymore, transition *next* behind *4. Phase* fires and the last phase of a period begins.

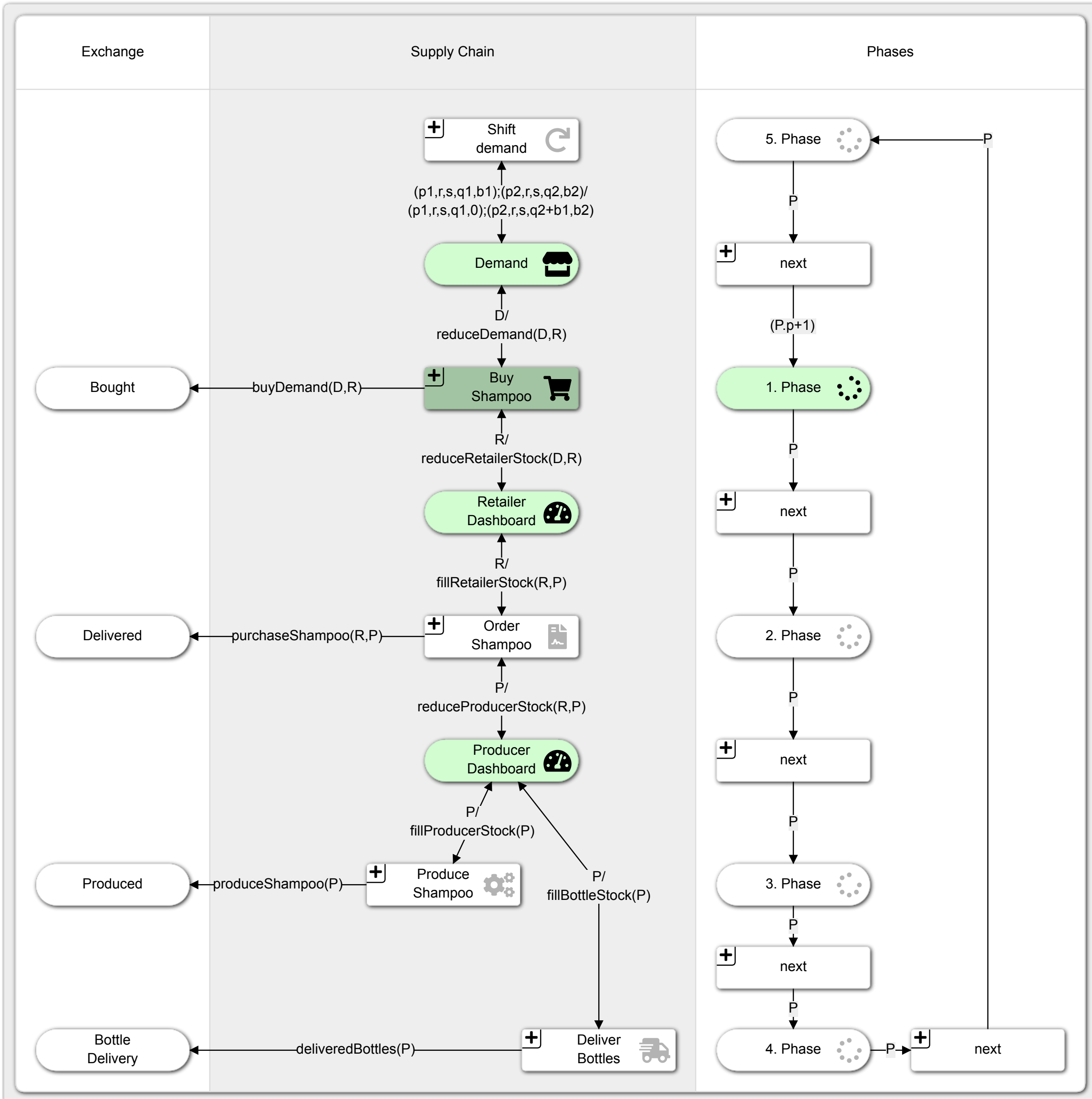

Figure 4. Petri net model of the scenario's supply chain.

Phase 5 The final phase takes unfulfilled demands of former periods and copies them to the upcoming one. If all backlog information are copied, the transition below *5. Phase* increments the period counter by one and the next period starts with its first phase.

Figure 5 shows exemplary how the (initial) marking of place *Demand* can be operated within the tool.

At the end of the simulation run, the P-S.C exports the entire set of reached markings for further analytics.

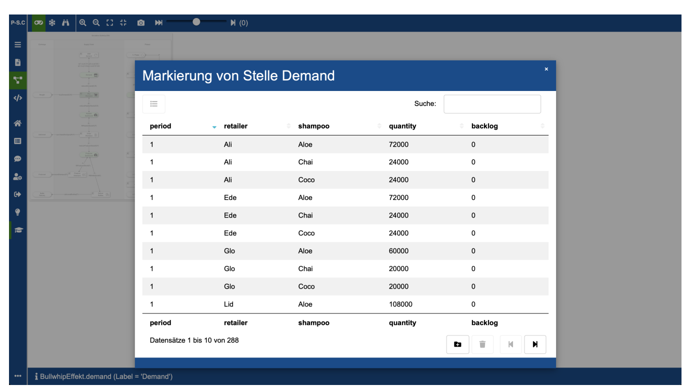

Figure 5. Screenshot showing the initial marking of place *Demand*.

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VII. Visualization of the Bullwhip Effect

The classic bullwhip effect is manifested by pronounced fluctuations in inventory levels upstream in the supply chain. Besides, different views of what is happening are possible. Visualizations are suitable for addressing different perspectives within or interdependencies across the supply chain. To see the bullwhip effect of a product in the supply chain, viewers look into the participants' warehouses. The data for this is a CSV-export generated by the P-S.C at the end of the simulation.

Figure 6 provides a first view: The four 3D area graphs in the diagram represent the summed inventory per stage of the supply chain: Light green $\hat{=}$ retailer stock, green $\hat{=}$ producer stock I (finished goods), dark green $\hat{=}$ producer stock II (raw material). All eight retailers offer *Aloe* in their portfolio, but this product is manufactured by only three producers.

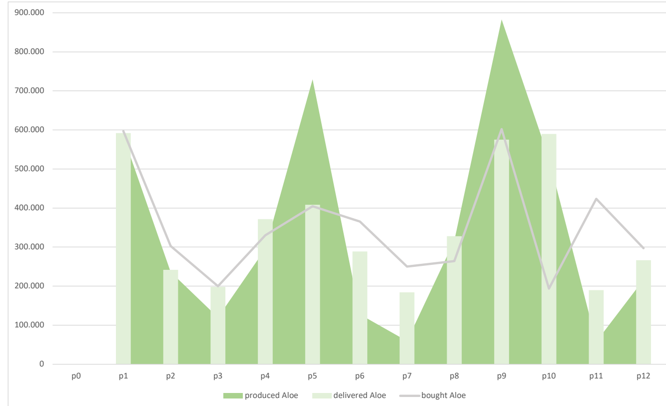

Figure 7. Activity of the product *Aloe*.

The stocks of *Body*, *Head*, and *Neck* and of the eight retailers reach a similar level. Increased sales between periods 3 to 5 (from 200k to 404k shampoos sold) have a well visible impact for the upstream participants in the supply chain.

Period zero represents the initial values in the warehouses when no sales of the products have taken place yet. The gray area chart ($\hat{=}$ bought goods) starts in the first period. This graph also shows the amount of goods actually sold in order to classify the stage-wise inventory level of the supply chain. Further, the bought goods act as an anchor value and could be the benchmark in a customer-oriented supply chain.

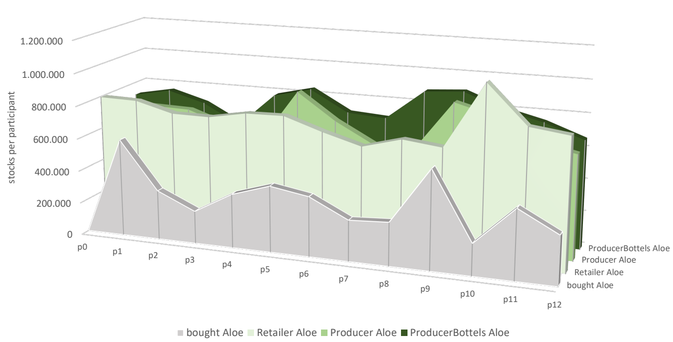

Figure 6. Bullwhip effect for the product *Aloe*.

It is worth taking a look at the respective ordering and production behavior shown in Figure 7. Fluctuations between purchased, delivered, and produced products become more relevant upstream in the supply chain, as described in the BWE literature.

The focus in Figure 7 is on the changes in inventories of the product *Aloe*. Based on the general popularity of the product's consumer group, the number of shampoos supplied and produced is also adjusted here. The gray line shows the actual demand for shampoos. The light green bar reflects the articles delivered to the retailers and the filled dark green line shows the number of shampoos produced. Again, period zero represents the initial stocks: No products are demanded or produced at that moment.

In addition, a simplification of the model is uncovered here: The production capacity of the producers varies greatly. Fluctuations in demand are compensated for almost equally by this flexibility. Imagine a constant production level of e.g., 400-500k shampoos and in a second step imagine the impact on the producer's inventories in Figure 6. The only limitation in this model is the raw material, which must be ordered first, however, in unlimited quantities.

Basically, these large fluctuations cause uncertainty in capacity and quantity planning for the participants. This also has an impact on the capacities to be purchased in terms of loading space or personnel planning. At this level, all movements at the product level can be seen across all retailers and producers.

The clear picture given by Figure 6 becomes confusing from the perspective of an individual. Figure 8 shows an in- and out-diagram of retailer *Glo's* product *Aloe*. The gray bars represent the product's actual amount of sales and the light green bars represent the shampoos supplied by the producer.

The simulation can be considered as an equivalent to a business planning game. Thus, the expired period is analyzed at the same time as the decisions for the coming period are made, e.g., for the delivery volume. So the stock in the warehouse is replenished with the ordered quantity (minus backlog) at the beginning of each period.

Therefore, for example, the inventory at the retailer *Glo* is never empty, because the backlog is never equal to the ordered quantity, but only parts of it.

In this simulation, the demand for the three products *Aloe*, *Chai*, and *Coco* fluctuates, and so does the planning reliability for all involved parties. It becomes clear that at this level the view of the big picture of the market is missing, which is still given above. How would you act as a retailer *Glo* in a 13th period? Would you adjust the order level or perhaps reduce the order quantity? If you would have a simulation as the described one, you could add all available market information to the simulation to soften negative bullwhip effects.

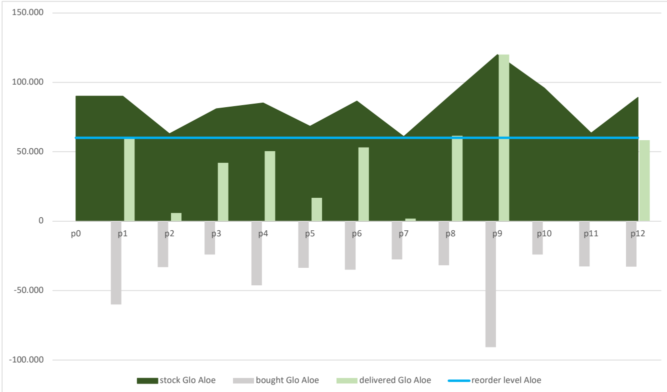

Figure 8. In- and out-diagram of *Aloe* and *Glo*.

VIII. SUMMARY AND OUTLOOK

During the validation phase for this research, the authors found that individual variables such as demand distribution or output data in the market hardly played a role to generate the BWE. Further, the modelers could have imposed much tighter constraints. The simulation model is key. Thus, the models are most applicable to real-world data from enterprise users. Even with the arbitrary numbers, the simulations produce the bullwhip effect, which is clearly visible at the level of an individual participant.

In conclusion, the following lessons can be summarized when running a simulation with Excel:

1) At the beginning, a clear and consistent structure should be developed directly, especially with regard to the interaction between the tables.
2) Calculations with formulas should be kept as simple as possible, because they must be repeated for the various periods, products, retailers and producers.
3) Subsequent changes often lead to errors in the formulas; the four-eyes principle should be applied.

Also for the Petri net simulation lessons could be learned:

1) It took several detours until the clear final structure presented in this paper was found.
2) However, the final solution scales and only the initial data for more periods have to be added. The Petri net structure stays the same.
3) Without a mature tool for modeling and simulation of high-level Petri nets, it is impossible to develop a comparable model and to benefit from this.

Each approach can meet the user at their individual skills and supports the performance of what-if analyses and in running through different scenarios. This is the beauty of these approaches and paves the way for practical use.

But is this enough to protect companies from the bullwhip trap? "Presumably not," because the simulation only takes the user to the heart of the problem: Small changes of the configuration can have a significant impact on the outcome, and incorrect assumptions about the market made by users lead to incorrect predictions regarding the bullwhip effect.

Nonetheless, further research on this topic seems to be reasonable, because this research on bullwhip simulation is only just beginning.

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