The influence of risk pooling and allocation policies on supply chain performance

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Abstract

The bullwhip effect suggests that the variability of orders increases as we move upstream in the supply chain. Its existence and negative impact on supply chain performance has mutually been recognized in academia and industrial practice. We use system dynamics modelling and simulation to study the impact of structural supply chain dimensions and allocation policies on increasing order variability. We show, that a linear supply chain structure leads to a significantly higher increase of order variability then a network structure with multiple entities per tier. Moreover, we show, that allocation policies do not have a significant impact on this effect.

Keywords: Bullwhip effect, Supply chain structure, Allocation policy

Introduction

The bullwhip effect suggests that the variability of orders increases as we move upstream in the supply chain (SC) (Lee et al., 1997). Corroborated by experimental (e.g. Sterman, 1989a), empirical (e.g. Hammond, 2008), analytical (e.g. Sucky, 2009) and simulation-based (e.g. Chatfield, 2013) research, its existence and negative impact on SC performance has mutually been recognized in academia and industrial practice (Lee et al., 2004). In a seminal paper by Lee et al. (1997), the authors list four primary causes of the bullwhip effect: 1) demand signal processing, 2) order batching, 3) price fluctuations and 4) shortage gaming. In later research, other potential causes including SC structure have been described (Paik & Bagchi, 2007). Based on Lambert & Cooper (2000), we distinguish three structural dimensions of a SC: 1) horizontal structure, 2) vertical structure and 3) horizontal position of the focal company. Horizontal structure refers to the number of tiers across the supply chain; i.e. the length of the SC. Vertical structure refers to the number of entities per tier; i.e. the width of the SC. Horizontal position refers to the position of the focal company within the SC. It can be far upstream towards the initial source of supply, far downstream towards the ultimate customer or any combination in between (Lambert & Cooper, 2000). As the concept of a focal company is generally connected to an asymmetric power distribution of different members in the SC, we do not consider horizontal position of the focal company as a structural dimension in our research but focus on horizontal and vertical structure. First, we introduce a system dynamics model used to study the influence of horizontal SC structure. We then alter this model to a more complex setting required to study the impact of vertical SC structure.

This step also requires the introduction of an allocation policies, i.e. a policy that governs the distribution of product in periods of short supply. We study the influence of a total of three different allocation policies on increasing order variability in combination with vertical SC structure.

Design/Methodology/Approach

We use system dynamics modelling and simulation. Our basic model is a linear, five tier SC with one entity per tier. This model is based on Sterman (1989a) and Kirkwood (1998) and is a model representation of the well-know and studied beer distribution game.

Figure 1 - Basic SC Model

Ordering or production in each tier is based on an anchoring and adjustment heuristic including adjustments of stock and supply line in each tier of the supply chain (conceptualized and parameterized as in Sterman, 1989a). The only difference in our model is the pattern of final customer orders. While Sterman (1989a) and the classical beer distribution game use a step function demand pattern of 4 cases until period 4 and 8 cases from period 5 onwards, we use a normally distributed demand with an expected demand of 8 and a variance of 4. Moreover, we cap the distribution at 0 to prevent negative demand and at 16 to keep the distribution symmetric, respectively. In a second version, the model is altered to reflect 2 entities at the distributor, wholesaler, retailer and final customer tiers.

Figure 2 - Modified SC Model

The normally distributed demand of the two final customer entities are changed to an expected value of 4 and a variance of 2. Anchoring values of the anchoring and adjustment heuristic in the distributor to retailer tiers are halved from 12 to 6. While the delivery relationship in the basic model was one-to-one between each tier, the modified model comprehends a one-to-two delivery relationship between factory and distributor tier. This necessitates the introduction of a policy on the allocation of product from factory to distributors in periods of short supply, i.e. an allocation policy. We introduce a total of 3 allocations policies: 1) uniform, 2) priority-based and 3) backlog-based. While the former two are based on Cachon & Lariviere (1999) and Chen & Zhang (2013), the latter is based on our work. In a uniform allocation policy both distributors receive the same share of available supply. In case one of the distributors requires less then this share, the remaining quantity is allocated to the other distributor on top of his initial share. Priority-based refers to an allocation policy, in which distributor I has a higher allocation priority over distributor II and hence receives all available supply if required. Whatever is left after the requirements of distributor I have been fulfilled, is being allocated to distributor II. Backlog-based, finally, refers to an allocation policy in which the priority as described above, is dynamically determined by the size of the backlog of the distributors; the distributor with the higher backlog has the higher priority for the respective period.

Findings

Our first model demonstrates an increasing variability of orders upstream the supply chain. Based on Chen et al. (2000) we measure the bullwhip effect in each tier of the supply chain by the ratio of orders placed variance in relation to orders received variance. Moreover, bullwhip effect of the entire SC - as a systemic measure - is measured as factory production order variance in relation to final customer order variance. Table one summarizes order variance and bullwhip effect induced in each tier of the SC as well as overall.

Table 1 - Variances and Bullwhip Effect

	Final Customer	Retailer	Wholesaler	Distributor	Factory
Order Variance	3,79	8,56	25,69	56,73	96,05
Tier Bullwhip Effect		2,26	3,00	2,21	1,69
SC Bullwhip Effect	25,34				

The overall bullwhip effect of the SC is equal to the multiplication of the individual tier-induced bullwhip effects. In our model the systemic bullwhip effect, i.e. the production order variance of the factory in relation to final customer order is 25. Generally, we can say that for each additional tier with a tier-induced bullwhip effect of >1, the overall SC bullwhip effect will be amplified. A tier with an induced bullwhip effect of <1 can be thought of a SC that is actively smoothing ordering or production quantities. This strategy is particularly interesting for companies with a highly seasonal demand profile (Cachon, 2007). Figure 3 illustrates the increasing order variability from final customer to factory.

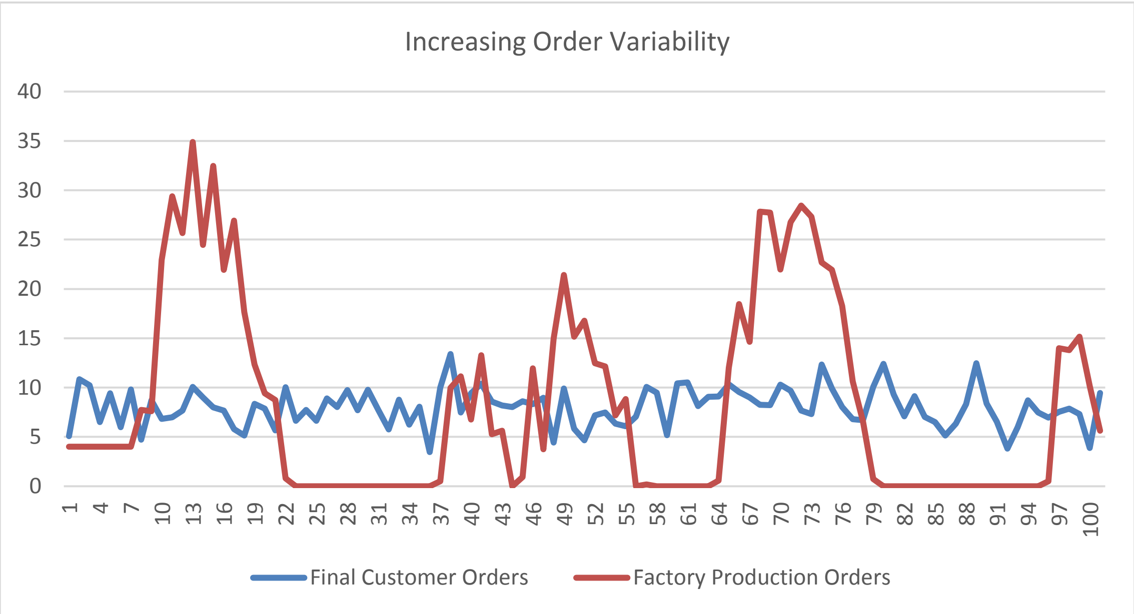

Figure 3 - Increasing Order Variability

SC performance is measured in terms of backlog and inventory cost. Net inventory is calculated as inventory – backlog. The cost of backlog is 1$/period and inventory cost is 0.5 $/period (Sterman, 1989a). Table 2 summarizes SC performance in terms of cost.

Table 2 - Supply Chain Performance

	Final Customer	Retailer	Wholesaler	Distributor	Factory
Tier Cost [$]	N.A.	559	1099	1719	1987
SC Cost [$]	5364				

The results show, that the cost of each tier increase in line with the order variability received. From Retailer to factory, SC cost nearly quadruple. In our extended model, we disaggregated the customer to distributor tiers and run the simulation with a total of 3 different allocation policies between distributor and factory tier. To keep comparability between both models, we then aggregated the orders of both entities per tier and calculated the aggregated variance. Table 3 summarizes the simulation results. Order variance of final customer to distributor tier is calculated based on the aggregated orders to both entities per tier.

Table 3 - Variances and Bullwhip Effect extended model

		Final Customer	Retailer	Wholesaler	Distributor	Factory
Backlog-based allocation policy	Order Variance	3,65	5,88	10,67	23,77	48,74
	Tier Bullwhip		1,61	1,82	2,23	2,05
	SC Bullwhip	13,35				
priority-based allocation policy	Order Variance	3,65	6,05	11,29	24,04	48,30
	Tier Bullwhip		1,66	1,87	2,13	2,01
	SC Bullwhip	13,22				
50/50 allocation policy	Order Variance	3,65	6,02	11,62	24,35	49,66
	Tier Bullwhip		1,65	1,93	2,10	2,04
	SC Bullwhip	13,60				

The results show no significant difference between the allocation policies regarding both the tier induced and overall bullwhip effect. For the 50/50 policy, overall SC bullwhip effect has decreased from 25 to 13 with variance of final customer orders at 3,65 and variance of factory production orders at 49,66.

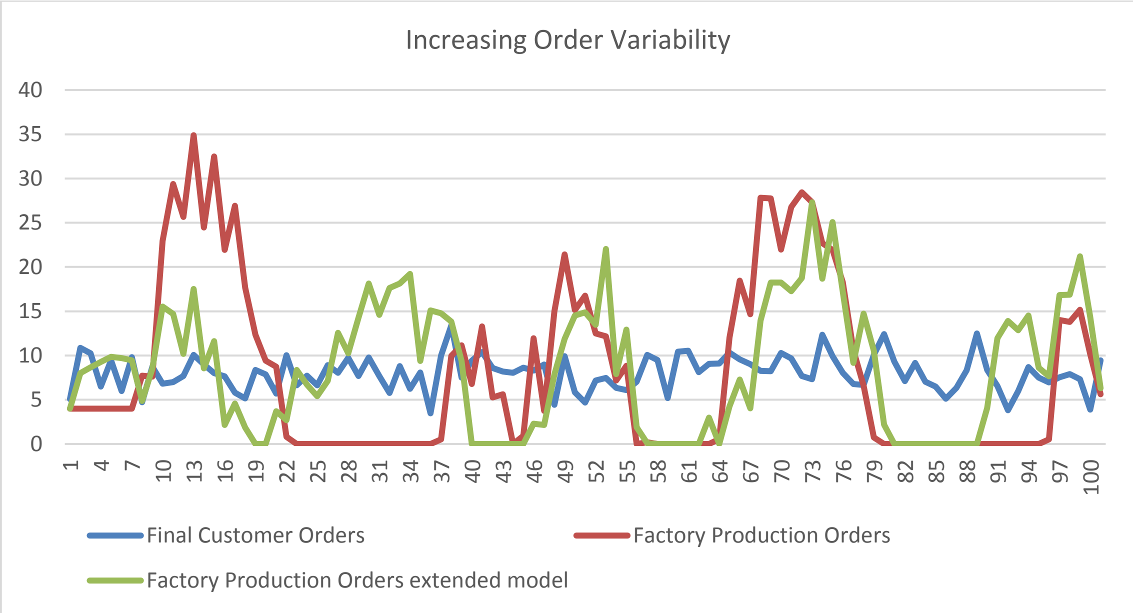

Figure 4 - Increasing Order Variability Comparison

This has a direct impact on SC performance. A nearly overall halved bullwhip effect results in reduced costs of 3532 from initially 5364. A decrease of approximately 35%.

Table 4 - Table 5 - Supply Chain Performance extended model

	Final Customer	Retailer	Wholesaler	Distributor	Factory
Tier Cost [$]	N.A.	580	749	1141	1063
SC Cost [$]	3532				

The reduction of increasing order variability is based on a risk pooling effect between distributor and factory tier. Because both retailers order from the factory the variability of orders to the factory is reduced leading to lower overall SC cost.

Relevance/Contribution

The contribution of our research is twofold. First, it extends the understanding of the impact of the supply chain structure to the bullwhip effect. Using an analytical model, Sucky (2009) showed that it's extent might be overestimated in a linear supply chain structure by neglecting risk pooling effects. His work, however, neglects some of the dynamic aspects and is limited to a two-echelon supply chain. Our work confirms this key finding in a setting with dynamic complexity and four echelons. We also show that the chosen allocation policy does not play a significant role for increasing order variability. Second, our results have direct impact on supply chain network design. While transportation cost, lead times and other factors typically play a role in strategic network design decisions, the effect of supply chain structure on increasing order variability and costs associated with this effect are typically not considered. We, however, believe that they should be considered among other factors. Our research can be extended to more complex structural SC settings.

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