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The impact of the supply chain structure on bullwhip effect

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ABSTRACT

The aim of this paper is to study how the structural factors of supply chain networks, (i.e. the number of echelons, the number of nodes and the distribution of links) impact on its dynamics performance (i.e. bullwhip effect). To do so, we systematically model multiple structures according to a robust design of experiments and simulate such structures under two different market demand scenarios. The former emulates a stationary condition of the market, while the latter reproduce the extreme volatility and impetuous alteration of the market produced by the current economic recession. Results contribute to the scientific debate on supply chain dynamics by showing how the advocated number of echelons is not the only structural factor that exacerbates the bullwhip effect. In particular, under a sudden shock in market demand, the number of nodes and the divergence of the supply chain network affect the supply chain performance.

1. Background and motivation

Bullwhip Effect (BWE) refers to a progressive increase in order (demand) variance as order information passes upstream in a Supply Chain (SC) [1]. BWE is the responsible of inefficiencies in terms of total costs increase, profitability deterioration, increased inventory holding costs, and higher cost of capital [2–5]. Nowadays, about two-thirds of firms are affected by the BWE (see e.g. [6,7]. Thus, BWE continues to be one of the most widely investigated phenomena in modern-day SC management research [8,9].

Among the streams of research dealing with BWE, an important one has focused on showing its existence and on identifying its possible causes [10]. Among the different root causes that have been identified (please see Section 2), the 'number of echelons' or 'number of channel intermediaries' [11] is considered a root cause that explicitly depends on the structure of the SC. In fact, there is a common agreement on the existence of a positive correlation between the reduction of the intermediate stages in the SC and the reduction of the BWE [12,13,11,14–16]. For this reason, the reduction of channel intermediaries and the adoption of reduced SCs (such as the direct channel, or "the Dell model") [11] have been promoted as effective strategies to mitigate BWE.

However, SCs are usually networks or global networks [17]. Hence, the number of echelons only represents an indicator of the structure of the Supply Chain Network (SCN). The structure of the SCN, defined as the arrangement of the various SCN nodes [18] is a critical decision for managers that is becoming increasingly complex [19]. In general, three main factors determine the structure of the SCN and consequently also the material flow from the raw materials stage to the final customer stage [10]: (1) the number of echelons, (2) the number of facilities at each echelon, and (3) the number of links between

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the locations. These elements may have a dramatic effect in terms of cost, customer satisfaction, ability to respond to market changes, and ability to innovate and bring new products to the market [19].

Among these three elements, published works have only explicitly investigated the impact of one of them, i.e. the number of echelons in the BWE. Probably the reason is that most scientific works dealing with the BWE are confined to the classical single-echelon, dyadic, or serially-linked configurations [10,20,18]. In these configurations it is not possible to assess the impact of the aforementioned structural factors on the BWE, with the mere exception of the serially-linked configuration, where it is possible to quantify only the effect of the number of echelons. However, recent studies (see e.g. [21] and [22] show how different SCN configurations with the same number of echelons may have different SCN performances. Thus, there is a need to assess the impact of all SCNs structural factors on performance.

To the best of our knowledge, the potential relationship between key structural factors and the BWE is almost unknown, with the exception a few anecdotal reports which, however, do not provide information on the impact of the different factors in the BWE (see e.g. [16]. Motivated by these considerations, the aim of this paper is to quantify the impact of the SCN structure (i.e. the number of stages, the number of facilities at each stage, and the number of links between the locations) on the BWE. To do so, we simulate the dynamic response of several configurations in one of the most widely used SCN typologies in real businesses: the divergent SCN [23]. This configuration is characterized by a tree-like structure, where every stock point in the system receives supply from exactly one higher level stock point, but can supply to one or more lower level stock points [24]. Consumer-oriented industries, such as cell phone manufacturers, appliances, electronics, and computer industries often adopt this typology of SCN [25]. To identify the structural factors having a statistically significant impact on the BWE, we perform a full factorial set of experiments by varying these factors under identical SCN operational parameters (e.g. lead times, safety stock factors, demand forecast factors, etc.). Furthermore, in order to increase the robustness of the analysis, we adopt the framework for studying the BWE proposed by Towill et al. [26]. More specifically, we adopt two input demand patterns, i.e. the variance lens and the shock lens. The former aims at inferring on the performance of SCNs for a stationary input demand. The latter aims at inferring on the performance of SCNs for an unexpected and intense change in the end customer demand. This type of demand has been adopted in theoretical BWE studies in order to model the extreme volatility and impetuous alteration of the market produced by the current economic recession [27]. The simulation platform used in our work is SCOPE [126], a multi-agent system (MAS) based software platform for the simulation of complex SCNs.

Results for the variance lens show that the factor 'number of echelons' has a high impact on the BWE while the number of nodes and the divergence of the SCN have a low impact, which is in line with the results found by other authors. However, for the shock lens, in addition to the number of echelons, the number of nodes and the divergence of the SCN also have a significant impact on the BWE. More specifically, as the levels of the structural factors increase, the BWE increases with different trends. In fact, BWE quickly (exponentially) increases as the SCN shifts from a low number of echelons to a high number of echelons, but the increase is smoother with the number of facilities in each echelon and with the divergence of the SCN. Also, there is an important interaction between the number of echelons and the divergence of the SCN in this scenario. Finally, we prove how BWE is very sensitive to the structure of the SCN under a sudden shock in customer demand.

The rest of the paper is organized as follows: Section 2 presents a literature review. Section 3 describes the structural elements of SCNs and the inherent structural characteristics of divergent SCNs. In Section 4 the SCN model is presented. Section 5 briefly describes the software platform used for computer simulation. Section 6 includes the design of experiments and Section 7 shows the results numerical analysis. Finally, Section 8 presents the implications of the research and Section 9 contains the conclusions and future research lines.

2. Literature review

The identification of the root causes of the BWE is an important stream in SCN literature and has long been of interest for industrial practitioners and academics [28]. In this context it is possible to distinguish two schools of thought, i.e. the System Thinking school, and the Operations Managers' school [29]. The former, focused on the behavioral causes, is mainly interested in the "systemic" nature of the SCN, reflecting a holistic perception of the causes of the BWE. The Operations Managers' school focuses on the operational causes. Thus, it concentrates on single elements rather than on the whole system. Both schools have largely contributed in suitably defining causes and remedies for the BWE. Thanks to these efforts, during the last decades several classification frameworks have been proposed. Undoubtedly Lee et al. [30] provided the seminal work that defined the BWE and identified the well-known five causes [11]; Zotteri, 2012). A further relevant framework was proposed by Geary et al. [31]. The authors identified 10 published causes of BWE, based on the works by Mitchell [32], Wikner et al. [33], and Lee et al. [30].

Bhattacharya and Bandyopadhyay [20] identify 19 causes, 16 of them operational and 3 behavioral. Operational causes include demand forecasting [34,35], order batching [36], price fluctuation [37,38], rationing and shortage gaming, lead time, inventory policy, replenishment policy, improper control system [39,40], lack of transparency [41,42], number of echelons [12,13], multiplier effect, lack of synchronization [43], misperception of feedback [44], local optimization without global vision [11], company processes [45,46] and capacity limits [47]. The behavioral causes cover neglecting time delays in making ordering decisions [48], lack of learning and/or training [49,50], and fear of empty stock/customers' baulking behavior [51,52]. A recent classification of the BWE causes is provided by Lin et al. [28].