



A human experiment on inventory decisions under supply uncertainty

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ABSTRACT

Controlled human experiments are adopted in this paper to investigate the impact of supply uncertainty on buyers' inventory management. The experiments aim at assessing the impact of one specific source of supply chain uncertainty, namely stochastic lead times, on inventory holdings and the extent of the bullwhip effect. Three experimental treatments are run within the framework of the beer game manipulating variability in demand and in lead times. Results confirm that the bullwhip effect arises in all experimental treatments and that the variance of orders is higher under stochastic lead times. Analysis of players' behaviour in the course of the game suggests that players react to higher uncertainty by holding fewer inventories, a behaviour consistent with the predictions of some psychological models of choice under ambiguity.

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1. Introduction

An increasing degree of complexity characterises the supply chains of many sectors (Esposito and Passaro, 2009). Among the causes of such a trend are outsourcing, the enlargement of supplier networks, increased dependence on supplier capabilities, shorter product life-cycles, and international market and production expansion (Wagner and Neshat, 2010). Further, as firms try to reduce costs through the rationalisation and reduction of the supply base, the aim to secure a stable flow of materials has become more difficult to achieve (Harland et al., 2003). As a consequence of both higher complexity and leaner supply chains, the instability of supply chains and supply uncertainty have increased (Geary et al., 2006).

A paradigmatic representation of supply chain instability is the Bullwhip Effect (BWE). The BWE is generally triggered by demand uncertainty (Forrester, 1958), and it entails that, as external demand passes through the SC from the downstream to the upper levels of the chain, the variance of orders is amplified. This behaviour can imply substantial costs in terms of stock-out as well as inventory holding and obsolescence costs, thus worsening the performance of the SC.

While the impact of demand variability on SC instability and performance has been explored in several studies (Croson and Donohue, 2006; Steckel et al., 2004; Gupta et al., 2002; Sterman, 1989), the impact deriving from supply-side sources of uncertainty

has received less attention, in spite of the fact that some authors have posited that a reduction in SC instability is best enabled via implementation of the principles of smooth material flow, and by decreasing actual or perceived shortage risk (Geary et al., 2002, 2006).

A small number of numerical simulations (Chatfield et al., 2004; Truong et al., 2008) has investigated the effects of supply uncertainty on the extent and consequences of SC instability by making supply uncertainty operational through stochastic lead times, one of the most relevant supply-side sources of uncertainty. These studies have shown that, generally, stochastic lead times contribute to worsen SC instability.

While numerical simulations can throw light on how rational and optimising agents can react to SC uncertainty, they cannot fully account for deviations from rationality or limited cognitive abilities of SC managers. In this direction, experimental research on human subjects in neighbouring disciplines to Operations Management has shown that decision makers apply heuristics in processing tasks characterised by uncertainty (Kahneman and Tversky, 1974), and that they may use these heuristics as a way “to live with risk” (Gigerenzer, 2002). Further, decision makers exhibit biases in processing probabilistic information, since they distort probabilities of outcomes even when they are objectively known (Kahneman and Tversky, 1979) and, according to the domain of outcomes (costs vs. revenues), they might dislike/prefer uncertainty (Ellsberg, 1961; Wakker, 2010).

Controlled human experiments have gained importance as a methodology for the study of SC instability since Sterman's (1989) finding that the BWE is a problem arising as a consequence of human decision making and stemming from the amplification of unanticipated changes in demand, and from a biased perception of the flows in transit through the SC pipeline.

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In the face of varying types and degrees of SC uncertainty, managers' risk mitigation actions depend on their individual attitudes, on their perceptions of the likelihood of supply disruptions, and on the degree of confidence they assign to available risk information (Ellis et al., 2010). Thus, there are grounds for positing that under supply uncertainty heuristics and biases used in assessing probabilities of outcomes affect either the size of the BWE, or inventory holdings and inventory policies, or both, in ways which might be at odds with the predictions of numerical simulations. Further, since heuristics may develop through time in repeated tasks, it is relevant to provide insight into the way individuals adapt their decisions as they experience a highly variable environment. This analysis can hardly be carried out in the field because of lack of sufficient control, thus suggesting that human experimentation may prove a useful tool to explore the effects of supply uncertainty on the BWE formation and SC costs (Bendoly et al., 2006; Ancarani and Di Mauro, 2011).

To the best of our knowledge, a test of the impact of supply uncertainty on SC performance using human subjects is still lacking. In this paper, we apply human experiments with the aim to study the behaviour of members of a SC in the face of lead time uncertainty, and contrast the performance of a SC with stochastic lead times with that of a SC with deterministic lead times. We carry out the study within the framework of the beer distribution game, which reproduces a serial supply chain with four echelons (retailer, wholesaler, distributor, and factory).

Two research questions are investigated:

1. What is the impact of supply uncertainty on supply chain instability, as measured by the BWE, and on supply chain performance, as measured by SC costs?
2. How do SC managers react to supply uncertainty in terms of ordering decisions and inventory holdings?

Our results show that supply uncertainty, in terms of stochastic lead times, gives rise to a higher variance of orders at every echelon of the supply chain. More intriguingly, we find that, when the SC is characterised by both demand uncertainty and stochastic lead-times, buyers hold fewer inventories, a behaviour that we attribute to an uncertainty loving attitude.

The paper is organised as follows: Section 2 reviews the relevant branches of the literature underpinning the hypotheses tested through the experiment, Section 3 presents the experimental design, while Section 4 develops benchmarks for behaviour in the experiment by means of numerical simulation. Section 5 presents the results of the human experiment. Section 6 discusses the main findings, and highlights implications for SC management and future research. Section 7 concludes the paper.

2. Factors investigated and hypotheses tested

2.1. The beer game and the bullwhip effect with stochastic lead times

The BWE has been widely studied in the context of the so-called "beer game". In the classic beer distribution game (Forrester, 1958) the supply chain consists of four echelons (retailer–wholesaler–distributor–factory). Inventory is managed according to the periodic review inventory model (order-up-to). During the game each i -participant, $i \in [1, \dots, 4]$, at each t -period, $t \in [1, \dots, T]$, places orders, $O_{i,t}$, to the immediate upstream supplier and fills downstream customer's order, $D_{i,t}$. Typically, at each echelon, when a buyer places an order a delay of 1 week (Lead Time of Information—LTI) occurs before this latter is known to the upstream supplier, $D_{i,t} = O_{i-1,t-1}$; a 2 weeks lead time (Lead

Time of Distribution—LTD) is requested to ship orders to the downstream echelon and the same happens to the factory when beer is produced (Lead Time of Production—LTP). At each echelon, goods received at time t , $R_{i,t}$, correspond to those shipped by the upstream supplier 2 weeks before, $S_{i+1,t-2}$. During the game the inventory balance is such that: $I_{i,t} = I_{i,t-1} + R_{i,t} - S_{i,t}$, where $I_{i,t}$ is the on hand quantity ($I_{i,t} \geq 0$); customer orders are filled completely if $I_{i,t-1} + R_{i,t} \geq D_{i,t}$ otherwise $S_{i,t} < D_{i,t}$ and backorders occur, $B_{i,t} = B_{i,t-1} + D_{i,t} - S_{i,t}$.

If the external demand distribution is non-stationary and/or unknown, larger oscillations of orders occur moving upstream the SC, giving rise to the BWE. When the demand distribution is both stationary and known, then no BWE arises if a simple base-stock inventory policy is used, whereby individuals place orders equal to the orders they receive (Chen, 1999).

Most of the extant literature on the BWE has focused on the effect of uncertainty in customer demand, while ignoring the potential impact of supply-side sources of uncertainty on the BWE. More recently, a few papers have addressed the problem of the BWE and of SC performance relaxing the assumption of deterministic lead times. Stochastic lead times complicate the picture of the standard beer game, because in every period the volume of shipments received by the buyer is probabilistic. Further, if shipments in every period are independent draws, order cross-over may occur.

Chatfield et al. (2004) use simulation to investigate the effects of stochastic lead times in a k -node SC. In particular, through a factorial design, the effect of various degrees of lead time variability is crossed with that of four different levels of information quality, and with the absence/presence of information sharing. A normally distributed customer demand is assumed. The first information level refers to the situation in which there is no updating of policy parameters during the game, whereas the other three levels involve some form of updating based on demand and/or lead time historic information. Generally, updating of policy parameters occurs if the distributions of demand and lead times are unknown. When demand and lead time distributions are known, the optimal order-up-to quantity can be chosen in advance. In this instance, stochastic lead times do not generate BWE. However, there is evidence that buyers may use historical information also with known lead times (Chatfield et al., 2004). Updating of policy parameters worsens the BWE, as the variance of lead time increases. In particular, the amplification of order variances is highest when historical information on both demand and lead times variances are used to update inventory parameters, while it is lowest when lead time information is not used, because of misperception of the variability or the belief that lead time variation is not important. Comparable results are confirmed by Truong et al. (2008) assuming either an AR(1) or an ARMA(1,1) model for customer demand.

Kim et al. (2006) present a model with stochastic lead time in which the case of information sharing (customer demand is common knowledge for all echelons of the chain) is contrasted with that of no sharing. Results show that the variance of orders increases nearly linearly in echelon stage with information sharing, and exponentially without information sharing. One managerial implication of this result is that the sharing of information on customer demand by all echelons is an effective way to reduce BWE also under conditions of supply uncertainty. However, information sharing per se does not eliminate BWE.

Heydari et al. (2009) isolate the impact of lead time uncertainty from that of demand uncertainty by simulating a four-stage SC in which customer demand is constant. Results show that uncertainty in lead time increases the variance of orders at each echelon but does not worsen BWE. Further, order variance is positively correlated to the variance of inventory levels and the

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