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## Destocking, the bullwhip effect, and the credit crisis: Empirical modeling of supply chain dynamics

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## ABSTRACT

In this paper we analyze the strong sales dip observed in the manufacturing industry at the end of 2008, following the bankruptcy of Lehman Brothers and the subsequent collapse of the financial world. We suggest that firms' desire to retain liquidity during these times prompted a reaction characterized by the reduction of working capital, which materialized as a synchronized reduction in target inventory levels across industries. We hypothesize that such a reaction effectively acted as an endogenous shock to supply chains, ultimately resulting in the bullwhip-effect kind of demand dynamics observed. To test this proposition we develop a system dynamics model that explicitly takes into account structural, operational, and behavioral parameters of supply chains aggregated at an echelon level. We calibrate the model for use in 4 different business units of a major chemical company in the Netherlands, all situated 4–5 levels upstream from consumer demands in their respective supply chains. We show that the model gives a very good historical fit of the sales developments during the period following the Lehman collapse. We test the model's robustness to behavioral parameter estimation errors through sensitivity analysis, and the de-stocking hypothesis against an alternative model. Finally, we observe that the empirical data is aligned with experimental observations regarding human behavioral mechanisms concerning target adjustment times.

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### 1. Introduction

The world economy experienced a severe, sudden, and synchronized collapse in late 2008. The magnitude of the drop in global trade was the largest since World War II, it was the steepest in recorded history, and it was synchronized: all 104 nations where data is collected by the WTO experienced a drop in imports and exports during the second half of the year (Baldwin, 2009). Following the public collapse of the financial system (starting with the Lehman Brothers bankruptcy in September 2008), firms all over the world observed substantial demand disruptions; sales plummeted across the board, and panic spread. While many consumer markets remained relatively stable (exceptions being consumer durables and capital goods), the manufacturing sector observed almost instantaneous demand drops (Dooley et al., 2010).

In crises such as these, managers are pressured to improve the financial position of the company at the same time that demand levels are dropping dramatically. This typically leads to strategic

decisions such as reducing inventories (to reduce the level of working capital), downsizing (to reduce operational expenses), and closing manufacturing facilities (to reduce fixed assets). These decisions, however, have substantial operational consequences when demand increases at a later stage: the reduction of inventory levels, workforce, and manufacturing facilities are decisions that require significant time to be reversed. If the situation that triggered such decisions is temporary and demand recovers faster than the speed at which firms can react, lost sales and general problems with inventory management will appear. Knowledge about the underlying dynamics behind the demand slump is therefore needed to avoid costly mistakes.

These underlying operational dynamics are a focus of extensive study as part of the systems-thinking approach introduced by Forrester (1958). This approach centers on the use of System Dynamics as the preferred methodology to replicate and understand the dynamic behavior of complex systems. System Dynamics models explicitly simulate the behavior of individual components pursuing local results, and exploit the structure of the system to model the interactions between these components. In doing so, System Dynamics allows the modeler to decouple endogenous, exogenous, and structural effects.

With regard to supply chain dynamics, observations are generally made that (a) production variance tends to be greater than

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demand variance, and (b) that this difference increases the further upstream a firm is. This has the effect of greatly amplifying demand fluctuations through a supply chain, and has been termed ‘the bullwhip effect’ (Lee et al., 1997a). Analytical studies quantify this effect (Chen et al., 2000); empirical studies show evidence of its existence at a firm level (Metters, 1997; Fransoo and Wouters, 2000; Bray and Mendelson, 2012); and a substantial experimental body of work investigates its causes and possible solutions (Stermann, 1989; Croson and Donohue, 2006). Empirical evidence of the bullwhip effect at higher aggregation levels is, however, ambiguous: conclusive evidence of neither variance amplification nor production smoothing has been found in public manufacturing data (see Cachon et al., 2007, for a study based on U.S data). This apparent incompatibility between the predictions of the theory—supported by experimentation— and high-level observations is, however, explained by the effects of data aggregation. Chen and Lee (2012) show that both product aggregation (whereby multiple items are grouped into categories), and temporal aggregation (whereby information is grouped into quarters) mask the magnitude of the bullwhip effect.

In this paper, we argue that firms reacted to the 2008 financial crisis by reducing their working capital targets and, because it was global and synchronized, this reaction introduced a significant shock in the world's supply chains—essentially creating an inventory-driven bullwhip effect. To test our hypothesis, we adopt supply chain modeling, experimentation, and validation methods based on theory from the experimental work by Stermann (1989) and Croson and Donohue (2006)—originally focused on the appearance of the bullwhip effect following demand shocks in a laboratory setting. We develop 4 different supply chain models for a major chemical company in the Netherlands and validate them with demand data from the crisis period. In terms of methodology, our work distinguishes itself from previous studies on inventory dynamics by using extensive empirical data, framing the Lehman Brothers collapse as a natural experiment. We specifically distinguish between the direct estimation of the operational model parameters, such as lead times, and the econometric fitting of behavioral parameters, such as stock adjustment times. In terms of theory, we model aggregates of companies at a particular level of the supply chain in a particular region rather than individual decision makers (as is common in experiments) or firms (as is common in much of the system dynamics literature in supply chain management). The crisis time-frame, through the resulting synchronization in managerial objectives, gives us the opportunity to link aggregate and individual human behaviors.

We show that the combination of declining end-markets and the appearance of a synchronized inventory shock successfully account for a significant portion of the observed long and short term dynamics. Moreover, to increase our confidence in the de-stocking hypothesis, we present an alternative model without the explicit inventory adjustment reaction to the crisis. Our results show that demand drops in the respective end markets were not severe enough to explain by themselves the wild dynamics observed upstream.

In this view, exogenous end-markets drive the overall long-term evolution of sales, while endogenous behavior (such as the inventory decisions taken as a consequence of the crisis) primarily impacts the short term dynamics.

The contribution of this paper to the theory is thus threefold: (1) We identify the 2008 financial crisis as a natural experiment that effectively controls for the masking effects of aggregation. This allows for the usage of a system dynamics framework based on the bullwhip effect literature whereupon we model aggregate echelons. (2) We introduce a de-stocking hypothesis capable of explaining the demand evolution observed by upstream

companies following the bankruptcy of Lehman Brothers. (3) We identify the importance of both consumer end-markets and ordering behavior in the evolution of demand patterns through time. By explicitly modeling separate structural, operational, and behavioral parameters, this study quantifies their contribution to the observed transient behavior and allows for a comparison with results obtained from experimental studies on individual human decision making.

By explicitly modeling the impact of the sudden reduction of inventory targets throughout the supply chain, we highlight the impact that locally rational policies can have on overall supply chain performance. From a managerial perspective, we display the value of supply chain models that propagate end-market, and endogenous, dynamics up a supply chain. Whereas an upstream firm cannot avoid the bullwhip-like dynamics that follow shocks of the magnitude of those observed after the onset of the 2008 financial crisis, it can use turning-point forecasts to support strategic decisions.

The remainder of this paper is organized as follows: In Section 2 we introduce several inventory puzzles present in the economics literature, use these to identify the challenges inherent in the study of inventories as part of aggregate models, and develop our de-stocking hypothesis. Section 3 introduces the methodology and model formulation. We extend prior experimental work and frame our models in the crisis time-period by explicitly modeling the managerial decisions behind the hypothesized reduction of inventory targets at an echelon level. In Section 4, we extend the echelon models to four different supply chains, and use empirical data to calibrate and validate these. We then formulate alternative models—without the de-stocking hypothesis—to study the appropriateness of this hypothesis. We conclude in Section 5 with a series of managerial insights.

## 2. Background and hypothesis development

When looking at the link between inventories and macro economic developments, Blinder and Maccini (1991) point out that interest in inventory behavior seems to follow cycles, not unlike the economy we attempt to explain. Indeed, we observe that research on the role of inventories in the economy peaks throughout history following extraordinary economic happenings such as the post-war period, the late seventies oil crisis, and—relevant to current developments—the financial crisis of 2008.

We refer the reader to Fitzgerald (1997) and Blinder and Maccini (1991) for comprehensive reviews of over 50 years of discussions on inventory theory in the economics discipline and the puzzles they attempt to solve. In his work, Fitzgerald (1997) identifies inconsistencies between theory and data, and the subsequent attempts of researchers to eliminate these discrepancies from their models. Blinder and Maccini (1991) summarize the opposing views of micro and macro economists with regard to the role of inventories: the former discipline sees them as a stabilizing factor, whereas the latter sees them as a de-stabilizing one. Despite these fundamental disagreements, Feldstein and Auerbach (1976) point out, inventory fluctuations have long been recognized as a major endogenous force in American business cycles. In their experience, irrespective of the conceptual contradictions between contemporary models and the real-life processes behind them, most studies of inventory behavior note that about 75% of the cyclical downturn in gross national product (from peak to trough) can be accounted for by the reduction of business inventories. Recognizing these conceptual difficulties, Lovell (1994) reflects upon the inherent challenge of trying to reconcile these views. He poses a series of questions that—for all the body of research available—remain open to this day: “(...) Do firms actually

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