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Collaborative forecasting, inventory hedging and contract coordination in dynamic supply risk management

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ABSTRACT

We examine the intertemporal and decentralization effects on managing disruption risks in a supply chain with lost sales and fixed transportation cost. The disruption risk is continuously monitored via collaborative forecasting based on *advance supply signals*—such as financial health and operational viability. We first develop a Markov model to capture the nonstationary, volatile, and dynamic nature of the forecast evolution. We then integrate the forecast into a dynamic programming for inventory hedging under three hierarchies. We derive an easy-to-implement coordination contract and a simple policy structure that facilitates ex ante strategic planning and ex post dynamic execution. The optimal strategy is driven by properly balanced adaptiveness, resilience and intertemporal imperatives. It outperforms the conventional inventory hedging and lean management by reducing premature inventory holding in good times, and timely ramping up safety stock ahead of looming disruptions. The proposed subsidy contract can effectively address double marginalization and information concealment problems via risk sharing, power preserving, and Pareto improving. We show that dynamic forecast is valuable for high margin products, moderate fixed cost, and low demand volatility. Without coordination, mandating supply information sharing can exacerbate supply disruptions. The three instruments are strategic complements and most effective when deployed jointly. This research highlights the importance of integrating forecast, inventory, and contract instruments in managing supply risk dynamically. It also explains two rationales—the resilience and information imperatives—behind recent trends of onshoring and vertical integration.

1. Introduction

For companies with a global footprint, recent years have not been kind to their supply chains.[1] To better manage supply risks in this turbulent time, many of them begin to closely track the status of their suppliers, including their production progression (Gaukler, Özer, & Hausman, 2008), quality performance (Choi, Blocher, & Gavirneni, 2008), financial health (Babich, 2010), etc. These *advance supply signals*, though noisy and volatile, contain rich information on suppliers' likelihood of operational disruptions, bankruptcy, and hence their availability (Gao, Yang, Zhang, & Luo, 2015). If properly maintained and utilized in forecasting, they can greatly leverage companies' ability to predict future supply, and enhance their risk preparation and response capability.[2] For most companies, however, these activities are generally ad hoc and have not been systematically integrated into their risk management strategies. The academic literature is also sparse on how to model and utilize advance supply signals.

Our work is motivated by dynamic supply risk management in decentralized supply chains. Three factors complicate the problem. First, the nature, likelihood, and magnitude of supply risks evolve dynamically over time, which requires real-time monitoring, longer

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[1] For example, Hurricane Katrina in 2005 shut down transportation in the Gulf Coat for days, paralyzing the supply chain of United Technologies Corp. (UTC). The 2011 Japan earthquake shattered auto industry, disrupting the production of Toyota, Honda, and Ford for weeks (Archstone Consulting, 2011). The 2011 Thailand floods crippled the production of major hard-drive suppliers (e.g., Western Digital and Seagate), inflicting severe parts shortages and financial losses on downstream purchasers. For example, the UK set-top boxes maker Pace shares dropped by 12 percent; PC maker Dell shares fell by 5.4 percent (Makan & Simon, 2011).

[2] For example, UTC, a Fortune 100 aerospace manufacturer, relies on lean management and sole-sourcing strategy for many highly specialized components. Thus any single supply disruption can have catastrophic implications. The cost of switching suppliers is extremely high, and the impact of missed deliveries can be financially crippling and can even affect national security. To manage suppliers proactively, UTC implemented SBManager—a real-time supplier monitoring system developed by Open Ratings Inc. (SupplyChainBrain.com, 2005). The system uses predictive technology to constantly track advance signals from UTC, its suppliers, and the third-party data to determine the dynamic risk profile of each supplier. In 2004, the system warned UTC of the potential bankruptcy of a key casting supplier, giving UTC precious head-ups to increase inventory buffer and avert a disaster (Bacheldor, 2005).

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planning horizons and dynamic execution capabilities.[3] Second, the decentralized structure leads to incentive misalignment and uncoordinated decision making, which necessitates coordination devices. Third, the stressed suppliers are often reluctant to share with the buyers the information on their vulnerability and reliability. All three factors can severely exacerbate supply risks.

This paper has four objectives: (1) to model the nonstationary, volatile, and dynamic nature of advance supply signals; (2) to integrate this advance information into real-time risk management process and identify the main determinants of the optimal hedging strategies; (3) to develop a coordination mechanism that ensures collaborative forecasting and efficient decision making; and (4) to characterize the role of dynamic forecast, inventory hedging, and contract coordination in dynamic risk management.

Specifically, we study a dynamic inventory hedging problem in a single product, one-supplier-one-buyer supply chain. The supplier is vulnerable to supply disruptions. During disruptions, no replenishment is possible. The supplier tracks the advanced signals on his risk level; different risk levels entail different disruption or recovery probabilities. Depending on the nature of the relationship, he may or may not share the forecast with the buyer. In each period the supplier first updates the forecast using newly available signals, then replenishes the buyer at fixed and variable transportation costs if operational. Afterwards the customer demand arrives and the buyer sells as much as possible. Unsatisfied demand is lost and the leftover inventory incurs holding cost. Both parties seek to maximize their individual expected total profit.

Our main results are summarized as follows. First, we develop a Markov chain model that captures nonstationary, volatile, and dynamic properties of supply signal evolution. The high fidelity of the model allows uneven distribution of availability over time, diverse forecast accuracy, and frequent revision of risk profile. It provides a unified framework to incorporate both historical-data-based statistical forecast and advance-signal-based judgmental forecast. As the model does not rely on specific functional structures, it facilitates designing general and robust mitigation strategies.

Second, we characterize the optimal inventory hedging strategy under three organizational structures—centralized, coordinated, and noncoordinated. Although the inclusion of fixed cost and lost sales captures the essential characteristics of a wide range of applications, it also complicates structural analysis. Despite the problem complexity, we are able to derive strong analytical results on the structure of the optimal strategies.

Third, we propose a coordinating subsidy contract that induces collaborative forecasting and efficient decision making in a dynamic setting. It rectifies many inefficiencies in commonly used contracts (e.g., wholesale, buy-back, inventory return). Three properties of the subsidy contract—risk sharing, power preserving, Pareto improving—drive its superior performance. (1) Risk sharing promotes the buyer to take channel-optimal action by subsidizing overstock and discouraging excessively frequent ordering, thereby eliminating double marginalization deficiency. (2) Power preserving ensures that power balance remains intact, thereby lowering the negotiation barrier and facilitating coordination building. (3) Pareto improving promotes objective alignment and voluntary compliance, thereby fostering collaborative forecasting and truthful information sharing. As such, the subsidy contract effectively addresses double marginalization and information concealment problems—two main challenges in decentralized supply risk management.

Fourth, we characterize the role of dynamic forecast, inventory hedging, and contract coordination in supply risk management. Our model endogenizes the dynamic interactions of the three instruments. They are *strategic complements*—advance supply information has a greater impact on profitability under dynamic hedging strategy and well-coordinated supply chains. By tracing early warning signals dynamic forecast provides real-time risk monitoring capability that facilitates *adaptive*, *resilient* strategy design and dynamic execution: The risk mitigation strategy is planned ex ante in light of the forecasted risk profile, and hence sufficient capacity for emergency can be secured for resilience imperative; it is executed ex post in response to a changing environment, and hence the countermeasures are properly calibrated in timing and magnitude for efficiency imperative. Unlike conventional inventory hedging strategy that hoards large stock for a long time, our adaptive strategy does not raise safety stock *prematurely*, thereby saving on inventory cost. In contrast to some ill-informed "lean" initiatives that push for unguarded operational efficiency by relentlessly slashing needed inventory, our resilience-driven strategy is capable of swift inventory buildup for imminent disruptions, thereby reducing shortage penalty.

2. Literature review

Our work contributes to the literature on *forecasting*, *contracting* and *supply risk management*. In the forecasting literature, collaborative forecasting has been widely credited for improving channel efficiency (e.g., Aviv, 2003, 2007; Chen, 2003; Lee, So, & Tang, 2000). There are two ways to model forecasting evolution. The first uses time series framework, e.g., Martingale Model of Forecast Evolution (MMFE) (Chen & Lee, 2009; Milner & Kouvelis, 2005). The second approach employs Markov models to study forecast evolution in production and inventory problems (e.g., Gao, Xu, & Ball, 2012). Our work follows the second approach but focuses on supply forecast.

Our work contributes to this literature in two aspects. (1) Theoretically, most of the literature considers inventory systems with *demand* forecast under *backorder* without fixed cost; in contrast, we examine settings with dynamic *supply* signals, *lost-sales* and *fixed cost*. In particular, we develop a high fidelity Markov model that captures real-time supply information for execution-level decision making. Despite problem complexity, we derive the optimal hedging strategy and coordination contract—the first such endeavor in the literature. (2) Practically, most of the known results *assume* a static, coordinated structure, and concern hedging demand risk *only*. In contrast, we propose a dynamic coordination contract and derive an easy-to-implement policy that mitigates *both* supply and demand risks.

The central theme of the supply chain contracting literature is how various contract types affect supply chain performance and coordination. Exemplary works include Cachon (2003), Corbett, Zhou, and Tang (2004), Iyer, Schwarz, and Zenios (2005), Özer and Wei (2006), Cachon and Zhang (2006), Burnetas, Gilbert, and Smith (2007), Li and Debo (2009), Zhang (2010), Yan and Zhao (2011), Babich, Li, Ritchken, and Wang (2012), Chen (2013), Gao (2014). This literature mainly focuses on *static* coordination without fixed cost; none of them investigates how dynamic information and fixed cost affect risk mitigation strategies and contracting. As most supply chains operate in dynamic environments and fixed transportation cost is prevalent, the existing literature offers insufficient tools and guidance for actual risk mitigation. Our model incorporates crucial features of fixed cost and dynamic forecast evolution, thereby providing more accurate account of global supply chains. Our subsidy contract can *dynamically* coordinate the supply chain under evolving market conditions. By examining the interplay of three instruments we provide guidance for managers on how to deploy these instruments jointly for effective risk management.

We also contribute to supply risk literature. Recent contributions include Santoso, Ahmed, Goetschalckx, and Shapiro (2005), Altay and Green III (2006), Dolgui and Prodhon (2007), Schütz, Tomasgard, and Ahmed (2009), Yang, Aydın, Babich, and Beil (2009),

[3] For example, the devastating Hurricane Katrina in 2005 first crossed southern Florida as a moderate Category 1 hurricane, then strengthened to a Category 5 over the warm Gulf water, and weakened to Category 3 hurricane when landing in southeast Louisiana.