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Sourcing strategies in supply risk management: An approximate dynamic programming approach

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ABSTRACT

In recent years, supply chains have become increasingly globalized. As a consequence, the world's supply of all types of parts has become more susceptible to disruptions. Some of these disruptions are extreme and may have global implications. Our research is based on the supply risk management problem faced by a manufacturer. We model the problem as a dynamic program, design and implement approximate dynamic programming (ADP) algorithms to solve it, to overcome the well-known curses of dimensionality. Using numerical experiments, we compare the performance of different ADP algorithms. We then design a series of numerical experiments to study the performance of different sourcing strategies (single, dual, multiple, and contingent sourcing) under various settings, and to discover insights for supply risk management practice. The results show that, under a wide variety of settings, the addition of a third or more suppliers brings much less marginal benefits. Thus, managers can limit their options to a backup supplier (contingent sourcing) or an additional regular supplier (dual sourcing). Our results also show that, unless the backup supplier can supply with zero lead time, using dual sourcing appears to be preferable. Lastly, we demonstrate the capability of the proposed method in analyzing more complicated realistic supply chains.

1. Introduction

Over the past two decades, supply chains have become more globally dispersed. As a consequence, the world's supply of all types of products has become more susceptible to disruptions. Some of these disruptions are extreme, although occurring with low frequencies. The closure of the European airspace in 2010 due to an ash cloud from Iceland is an example of an extreme disruption with global implications. In another example, in March 2000, the Philips semiconductor plant in Albuquerque, New Mexico, was hit by a lightening causing a minor fire, which activated the fire sprinkling system destroying the production. The consequences of this minor event were unexpectedly large. The plant supplied semiconductors to both Ericsson and Nokia. Ericsson adopted a single sourcing strategy, had to accept the disruption, and consequently shutdown its production lines. As a result, Ericsson lost 400 million US dollars in potential revenue and its market share decreased from 12% to 9%. On the contrary, Nokia's production suffered little from this crisis. Since Nokia had adopted a multiple sourcing strategy, it could quickly switch its semiconductor orders to other Philips plants, as well as to other Japanese and American suppliers [14]. In 1997, Aisin Seiki was the sole supplier of 98% of the brake fluid proportioning valves (P-valves) used by Toyota Japan. The P-valves are critical as production stops if their supply is hampered. In 1997, a fire completely stopped Aisin's main factory in Kariya. Toyota recovered very quickly by broadening its supplier network [18,30]. As a final example, in August 2005, Hurricane Katrina hit the United States' Gulf coast. Wal-Mart performed well and recovered quickly from disruptions due to its proactive planning for potential disruptions. When Katrina was approaching, Wal-Mart overstocked its nearby distribution centers with items it knew would be needed, and after Katrina struck, it could respond quickly to deliver supplies and hence mitigated the consequences of supply disruption [15]. Nokia, Toyota, and Walt-Mart all acknowledged supply risks and proactively planned for them, and as a result they were able to deal with disruptions and recovered more quickly.

As the examples above show, supply disruptions could result from major events, but can also be caused by less extreme and less global events, such as fires (e.g., the Philips example), strikes, slow shipments, and machine breakdowns. Chopra and Sodhi [5] discuss several supply chain risks that a manager must consider when planning mitigation strategies, and the drivers of these risk categories. They distinguish between disruptions (typically low-probability events with high impact) and recurrent risks such as quality and capacity problems of a supplier. Sheffi and Rice [31] make a similar distinction. In this paper, we evaluate the ability of alternative sourcing strategies to cope with both disruptions and recurrent risks.

Supply risks have a significant impact on the firms who fail to protect against them. However, effective and efficient management

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of supply risks can reduce the negative impact. Tomlin [36] distinguishes three kinds of strategies to manage supply risks: mitigation, contingency, and passive acceptance. Mitigation strategies are those in which the firm takes some action before a risk and so incurs the cost of the action regardless of whether a risk occurs, such as increasing inventory or setting up alternative sources. Contingency strategies are those in which a firm takes an action when a risk occurs, such as contingent sourcing from backup suppliers. Acceptance is used when the cost of dealing with uncertainty through mitigation and contingency strategies outweighs the losses of accepting the consequence of the risks.

Earlier studies have evaluated the performance of alternative sourcing strategies to counter disruptions. However, more extensive evaluations using operational or planning models under more complex conditions are still lacking. Dynamic programming (DP) provides an elegant framework to model multi-period stochastic optimization problems. However, DP faces the well-known three curses of dimensionality, i.e., states, outcomes, and decisions, and cannot deal with practical size problems. Approximate dynamic programming (ADP) emerges as an efficient and effective tool in solving large scale stochastic optimization problems, combining the flexibility of simulation with the intelligence of optimization. Successful applications of ADP can be found in various areas, such as transportation, finance, healthcare, energy, and supply chain management.

Our study contributes to the literature in three aspects. First, we provide a DP formulation to model the supply risk management problem at a high level of detail. Second, we design efficient ADP algorithms that allow us to solve large scale problems in reasonable time. Third, this significant reduction of computational time enables us to conduct systematic numerical experiments, providing managerial insights into the effect of alternative sourcing strategies.

The remainder of this paper is organized as follows: in Section 2, we provide a summary of the literature related to supply risk management and ADP. In Section 3, we model the supply risk management problem faced by a manufacturer, providing the flexibility of dealing with both disruptions and recurrent risks. In Section 4, we develop ADP algorithms using aggregation methods. We design numerical experiments to evaluate the performance of ADP algorithms and address some key algorithmic issues in Section 5. Finally, in Section 6, we perform a comprehensive set of experiments to analyze the performance of different sourcing strategies considering the effects of different risk profiles and operational settings. In Section 7, we conclude this paper.

2. Literature review

Tang [35] develops a framework for classifying supply chain risk management research and reviews various models for managing supply chain risks. He distinguishes four approaches to manage supply chain risks: supply management, demand management, product management, and information management. In this paper, we focus on the supply risk management.

In general, in order to mitigate the consequences of supply risk, the nature of the risk needs to be specified, the quantitative impact of the risk needs to be evaluated, and finally the risk mitigation strategy needs to be defined [13]. In order to prepare for disruptions, companies may need to employ an additional supplier and/or increase their inventories [29]. Obviously, this includes a trade-off where the availability of additional suppliers reduces the need to store additional inventory.

Tomlin [36] studies a single product and infinite horizon setting in which a firm can source from two suppliers, one unreliable and another reliable but more expensive. He shows that in the special case where the reliable supplier has no volume flexibility and the unreliable supplier has infinite capacity, a risk-neutral firm will pursue a pure disruption management strategy (mitigation by carrying inventory, mitigation by single sourcing from the reliable supplier, or passive acceptance). He also shows that supplier reliability and the nature of the disruptions are key determinants of the optimal strategy. Schmitt and Tomlin [28] study the performance of diversification and contingent sourcing in an infinite horizon setting. They explore the impact of the number of suppliers, disruption correlation, and spare capacity on the performance of the diversification strategy and the impact of response time and emergency capacity on the performance of the contingency sourcing strategy. They consider fixed cost per period for both unreliable and reliable suppliers and show that the average disruption length has a profound impact on the preferred strategy, with inventory favored for short and more frequent disruptions, contingency sourcing favored for long and less frequent disruptions, and diversification in between. Schmitt and Snyder [27] study an infinite-horizon model, considering one case where a firm only sources from an unreliable supplier subject to disruptions and yield uncertainty, and another case where a second, reliable but more expensive supplier is available. They show that using an explicit multi-period formulation outperforms a single-period approximation. Qi et al. [26] analyze a continuous review model with supply and demand uncertainty and provide structural results that allow them to develop an efficient computational procedure. Burke et al. [3] provide a single-period analysis of sourcing strategies under both demand and supply uncertainty.

There is extensive work on analyzing the optimal inventory policies or determining the optimal lot sizes under different kinds of supply uncertainty. For example, Yano and Lee [38] provide an overview of quantitative approaches for determining lot sizes when production or procurement yields are random. For more details on dual sourcing inventory models, we refer to Anupindi and Akella [1], Parlar et al. [19], Güllü et al. [10], and Lizheng [16]. In general, to obtain the optimal policy analytically, some strong assumptions need to be made. Instead of making restrictive assumptions to obtain structured results, our objective is to evaluate the mitigation and contingency strategies under substantially less restrictive assumptions.

ADP emerges as a powerful tool for modeling and solving large and complex stochastic optimization problems. Powell [20,22,23] provides a nice overview of ADP. Powell [21] gives a comprehensive introduction of the basic ideas of ADP and addresses key algorithmic issues when designing ADP algorithms. Interested readers are also referred to Bertsekas and Tsitsiklis [2] and Sutton and Barto [34].

Successful applications of ADP include transportation, finance, healthcare, energy, and supply chain management. Godfrey and Powell [8,9] use ADP to model and solve dynamic fleet management problems with single period and multiperiod travel times. Numerical experiment shows that ADP is effective on solving both large scale deterministic problems and stochastic problems. Powell et al. [24] use ADP to solve a heterogeneous resource allocation problem with over 5000 drivers and 30,000 loads in a four-day planning horizon. They propose three independent benchmarks and demonstrate that ADP provides high-quality solutions in reasonable solution time. Powell and Van Roy [25] present ADP algorithms to solve high-dimensional dynamic resource allocation problems in transportation and logistics. Simão et al. [32] use ADP to model and simulate the movements of over 6000 drivers for Schneider National in great operational details. By merging mathematical programming with machine learning to solve large scale stochastic dynamic programs, the resulting model is able to closely calibrate against real-world operations and produce accurate estimates of the marginal value of 300 different types of drivers. Nascimento and Powell [17] study a mutual fund cash balance problem, which tradeoffs between being