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Flexible supply chain planning based on variable transportation modes

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ABSTRACT

This paper investigates the application of diverse transportation modes for a global supply chain (SC) in stochastic environments. The motivation of our paper is to investigate the idea of enabling a global flexible SC with disruptive risks in making it less vulnerable by applying diverse transportation modes which is also our first contribution. The flexibility stems from the fact that transportation modes with a low-speed transportation contain latent time buffers that can be used by accelerating transport activities. This represents a promising approach to make supply chains (SCs) more flexible and to establish an additional degree of freedom in order to manage stochastic events like minor disruptions or serious catastrophes. In this paper, a stochastic programming model for a multi-stage multi-product SC is developed. SC partners, including multiple suppliers, a processing center, two assembling centers, multiple distribution centers and retailers, are incorporated into the model. The second contribution of this paper is that different types of possible future catastrophic disruptions are quantified and included in the model. SC catastrophic disruptions like transportation delays or the fact that a SC node is disrupted by a serious catastrophe are stochastic factors of our model. The model is solved by using *PySP*, a specific modeling and stochastic programming framework. In order to show the quality of solutions of the stochastic programming model (SP solutions), a large amount of scenarios is generated to simulate the real case for each instance. The expected SC costs for these scenarios will be evaluated based on SP solutions and wait-and-see solutions, which are benchmarks. In addition, decision makers with neutral, optimistic and pessimistic attitudes regarding the occurrence of disruptions are also simulated and evaluated in the computational experiments. Managerial insights are concluded from computational results. The most important conclusion is that proper transportation mode planning enables a flexible global supply chain. Further conclusions like the quality of stochastic solutions and solutions of simulating decision makers with neutral, optimistic and pessimistic attitudes, as well as the most beneficial transportation modes in SCs with uncertain environments are proposed based on the computational results.

1. Introduction

For a long time, SC risk typically has been ignored by managers in practice since most SC risks are hard to forecast. There still exists no general strategy which is inexpensive and effective to handle SCs in stochastic catastrophic environments. Without rapid responses and right decisions, complete SCs may break down if particular SC nodes or transportation links suffer a catastrophe. Nokia's huge success compared with Ericsson's great loss after a fire in a fabrication line of Philips on 17 March 2000 is a typical example (Chopra and Sodhi, 2004). From then on, researchers pay more attention on both risk management and SC risks.

There are some qualitative and quantitative models about SC risk management such as Guericke et al. (2012). They present the application of postponement strategies, which refers to transferring manufacturing steps of a product towards the end of a SC as an effective strategy for dealing with demand uncertainty. However, most quantitative models for managing SC risks focus on operational risks. In contrast, disruption risks such as earthquakes, tsunamis, floods, storms etc. are normally disregarded (Tang, 2006a; Wilding et al., 2012; Heckmann et al., 2015; Ho et al., 2015). In order to close this research gap, our motivation is to provide SC executives decision support by quantifying SC disruption risks and modeling SCs in stochastic environments.

Flexible transportation is introduced as a SC disruption mitigation strategy by Tang (2006b). But this strategy has not been

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investigated in detail. A diversification of transportation modes provides an opportunity to generate latent time buffers which can be activated in case of disruption events. The time buffers are generated by a transport mode which is characterized by a low-speed transportation. In this case, the buffers come into operation by switching from a low-speed transport mode to a high-speed transport mode. If the buffer time is sufficiently long, this approach makes SCs more flexible to avoid huge losses after catastrophic events. In reality, the approach can be found in the concept of slow steaming, too, where in the normal case the speed of transport is less than the original operating speed.

Flexible SCs are able to adapt effectively to disruptions in supply and changes in demand whilst maintaining customer service levels (Stevenson and Spring, 2007). In this paper, flexible SCs can be achieved by using variable transportation modes in two steps: The first step is to determine the transportation mode for each product on each transportation link. Buffer time should be preserved by using low-speed transportation modes. The second step is to eventually switch to a faster transportation mode after a disruption event happens in order to save transport time for adopting alternative plans. The decision of the second step depends on the location and severity of the disruption event. Furthermore, it also depends on the decision of the first step. The focus of this paper is on the question of how to determine the best transportation mode for each product on each transportation link in uncertain environments. A two stage multi-scenario SC model is built based on this problem. Progressive Hedging (PH; see the Appendix), which is proposed and theoretically proved as a method to be convergent by Rockafellar and Wets (1991) for multi-scenario problems, is used to solve the problem instances for this model. PySP (Watson et al., 2012), which provides a framework of using PH for multi-stage multi-scenario problems, is used to get solutions. In order to evaluate the most powerful solution technique, we apply PySP with different values of a specific parameter ρ, which is an inherent parameter of the PH approach. Solutions of diverse groups of instances are analyzed in order to determine a beneficial first stage decision. This decision tends to support the identification of a common transportation mode for different types of products as well as for different transportation links. The results of our numerical analyses reveal basic ideas about the best solution technique and the most advantageous SC transportation modes which provides decision support to SC executives.

Our paper is organized as follows. In the next section, a literature review is given and the theoretical background is explained. The investigated problem is illustrated in detail in Section 3. Section 4 contains a presentation of the developed model. Computational results are presented and analyzed in Section 5. The application of our model is provided in Section 6. The paper finishes with the conclusions in Section 7.

2. Literature review

SC risks are classified into operational risks and disruption risks (Tang, 2006a). Operational risks refer to inherent uncertainties such as uncertain customer demand, uncertain supply, and uncertain costs. Disruption risks refer to major disruptions caused by natural and man-made disasters. A typology of risk sources, consisting of environmental factors, industrial factors, organizational factors, problem-specific factors and decision-maker related factors is presented in Rao and Goldsby (2009). Relevant literature about *SC risk management* (SCRM) is collected and classified in, e.g., Tang (2006a), Kouvelis et al. (2006) and Dadfar et al. (2012). Although many qualitative analyses and quantitative models of SCRM exist, most quantitative models for managing SC risk focus on operational risks. In contrast, disruption risks are usually disregarded (Tang, 2006a). Whereas a good portion of the corresponding literature only focuses on demand fluctuations, rather few papers point out how to cope with catastrophic events. Woodruff and Voß (2006) present a first attempt to deploy PH on a SC production planning problem with big bang scenarios.

Postponement strategies provide an additional degree of freedom as well as mitigation options for decision making in stochastic SC environments. Combined with an integration of additional time buffers which may be established by longer standard shipping times, Fan et al. (2014) identify postponement as an effective way to cope with SC disruptions. In that paper, an enumeration is used to get the optimal expected annual SC costs, but the enumeration is only effective for pure binary small scale problems with a limited number of scenarios. Furthermore, the relationships between optimal SC transportation modes and probabilities of catastrophic scenarios have not yet been explored.

Apart from some small problem instances, stochastic optimization problems are notoriously hard to solve. A common approach to deal with stochastic problems in practice is scenario analysis. This approach decomposes a stochastic problem into a number of solvable sub-problems. PH has been applied in solving a number of stochastic programming problems (Voß and Woodruff, 2006), such as network problems (Mulvey and Vladimirou, 1991, 1992; Crainic et al., 2011), fishery problems (Helgason and Wallace, 1991; Wallace and Helgason, 1991), power system optimization (Takriti et al., 1996; Santos et al., 2009), resource allocation problems (Watson and Woodruff, 2011), and lot-sizing problems (Haugen et al., 2001). PH represents a solution technique that determines a solution which performs well for all scenarios of the multi-scenario problem. The algorithm is proved to be convergent for convex problems (Rockafellar and Wets, 1991). It utilizes the variable split form of the multi-scenario program. The non-anticipativity constraints of a stochastic model are integrated into the objective function as penalty and multiplier terms, and are progressively enforced by an iterative procedure (Mulvey and Vladimirou, 1991). In our research, PH is used for solving our stochastic programming model.

Helgason and Wallace (1991) show how to implement a scenario aggregation procedure in a simplified version of PH by solving the individual scenario problems only approximately, using an integrated application of a Lagrangian approach. They propose that solving the subproblems exactly amplifies oscillations of the individual scenarios, which then has to be dampened with stronger penalties. A drawback of this approach is that increasing the penalty slows down the speed of the algorithm. Therefore, exact solutions of the scenario problems are rarely used. Lokketangen and Woodruff (1996) provide a first implementation of general-purpose methods for finding good solutions to multi-stage, stochastic mixed-integer (0,1) programming problems. Tabu search is used for subproblems and PH is used to coordinate blending the subproblem solutions. The method is verified to be effective by computational experiments. They mention that without a good, integer-feasible solution during the initial iteration of PH, the solution will be hardly integer feasible.

In the existing research, PH as a scenario-based decomposition technique is applied in diverse research areas. One controversial issue has been the selection criterion of the penalty parameter of PH. Empirical tests are employed to examine the effect of various internal tactics on the algorithm's performance. Mulvey and Vladimirou (1991) report that the proper choice of a value for the penalty parameter depends on the problem structure. The effects of dynamic penalty adjustments and inexact subproblem solutions are evaluated in this paper. Fan and Liu (2010) propose similar conclusions in their paper. They postulate that on the contrary values of penalty parameters result in a slow convergence towards