Planning rail hazmat shipments in the presence of random disruptions

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Railroad is one of the primary transportation modes for hazmat shipments in North America. However, the current academic literature has not studied the impact of disruption on rail hazmat shipments. This study proposes a bi-objective two-stage stochastic program that makes use a of new measure of risk to plan rail shipments in the presence of random disruptions.

Key words: railroad transportation ; disruption management ; bi-objective stochastic optimization

1. Motivation

Hazardous materials (hazmat), though harmful to humans and the environment, are integral to the industrial lifestyle and thus need to be transported in significant volumes. In North America, railroad is not only the primary mode for moving (non-bulk) hazmat shipments but also crucial to the economic growth of the entire continent, and hence the associated infrastructure is deemed critical (US DHS, 2018). Consequently, disruptions induced either by nature or man-made threats would have serious adverse impact. However, given the potential for spectacular events, most of the academic and industry initiatives have focused on the assessment and management of risk from hazmat shipments (Batta and Kwon, 2013). Thus, there is a need to study disruption to railroad operations, especially since such events are not infrequent (Kroon, Maroti and Nielsen, 2014; Azad, Hassini and Verma, 2016). It should be evident that the resulting risk management methods and optimization techniques should not only incorporate disruptions but also prescribe contingency plans for rail hazmat shipments. However, implementing such techniques is challenging because of two reasons: first, both the risk and the cost elements would tend to increase during disruptions since safe and economic routes might not be available; and second, it is difficult to evaluate the effectiveness of contingency plans because of the inherent trade-off between upfront cost to the railroad operator versus the possible mitigation (of risk and cost) resulting from the disruption.

2. Problem Statement

We study the tactical planning problem faced by a railroad operator that regularly transports non-hazmat and hazmat freight between different pairs of origin-destination yards, and needs to ensure that demand is satisfied before the specified due dates. We adopt a scenario approach to generate disruption due to its demonstrated ability to model random disruptions and to develop pre- and post-disruption contingency plans (Snyder et al., 2016). To sum, *the objective is to prepare shipment plans in the presence of disruptions such that both hazmat risk and transport cost are minimized.*

3. Approach

We propose a bi-objective two-stage stochastic program to address the interests of the two stakeholders, i.e., the regulatory agencies and the railroad companies. We use expected consequence as the measure of transport risk, and the information about the service legs impacted in a disruption is captured via the two-stage stochastic program with recourse. More specifically, the 1st stage decisions to be taken before the disruption event comprise determining the number of trains of different types, and proactively adding extra capacity to the service legs. Occurrence of disruption triggers the 2^{nd} stage decisions (i.e., reactive), which entails re-routing rail shipments and fulfilling proportion of demand through third party.

Risk Objective: The first objective is to minimize the total risk from routing container with hazmat cargo, while accounting for random disruptions at service legs. Given that different hazmat risk would result from the disruption of different service legs under various scenarios, we introduce a new measure of risk that has two components, i.e., expected risk and variability in risk. Note that the introduction of the second component would discourage considering solutions with low average risk but high variability and encourage solutions with low variability. The presence of absolute term resulted in a non-linearity, and an equivalent linear form was developed.

Cost Objective: The second objective is to minimize the expected total cost, which has four components: cost of transporting containers; cost of fulfilling demand through a third party; cost of adding extra capacities on service legs; and, fixed cost of operating trains of different types.

Optimization Program: It is pertinent that the first-stage decisions only require determining the cost of adding extra capacities on service legs, and the fixed cost of operating trains of different types. The second-stage problem triggered by the disruption of one or more service legs yields a bi-objective problem, where the risk objective requires minimizing the sum of expected risk and variability in risk, and the cost objective requires minimizing expected cost of transporting containers and the cost of fulfilling demand through a third party. The resulting optimization program has to be solved over the following set of constraints: demand fulfilment; providing enough train

capacity to move shipments; adding extra capacity, if necessary, to service legs; completing delivery before the specified due dates; and, limiting the percentage of demand that can be met by the third party. The resulting mathematical model was an MILP, and was solved using an augmented σ-constraint approach that has proved to be extremely efficient in generating (an approximation of the) Pareto solutions in multi-objective combinatorial optimization problems (Mavrotas and Florios, 2013).

Case Study: The proposed optimization framework is applied to a problem instance generated using the realistic infrastructure of a Class 1 railroad operator, in mid-west United States, that was introduced in Verma, Verter and Gendreau (2011). There are 25 yards in the network, which are connected by 31 train services traversing 53 service legs. To conduct focused analysis, we generate 54 scenarios, i.e., disruption of each of the 53 service legs, plus the condition to simulate normal operation.

4. Results

For expositional reasons, we will organize the results under the following headings: risk-cost tradeoff; benefits of considering variability in risk; sensitivity analysis of first-stage decisions; and, benefits of contingency plans.

Risk-Cost tradeoff: A total of 24 non-dominated solutions were generated. The Min Cost entailed a cost of \$39.3 million and exposed 78.0 million people whereas the Min Risk solution resulted in a cost of \$51.6 million and exposed 12.6 million people. We also show that an emphasis on risk shifts an increasing proportion of demand fulfilment task to the third party, which in turn transfers the commensurate hazmat risk away from railroad network to that of the third party. Thus, an interesting trade-off between (capacity) cost and hazmat risk has been uncovered.

Benefits of considering variability in risk: We investigate the benefits of considering variability in the risk objective by varying the weights attached to expected risk and variability in risk. The resulting analyses demonstrate how incorporating variability factor could potentially reduce variability in risk without major increase in expected risk. This could be a very valuable tool for both the railroad industry and the regulators who deal with low probability – high consequence hazmat events. Note that the primary role of variability in risk is to measure the variation in hazmat risk because of disruptions, and thus a significant decrease in this measure implies that the hazmat risk will become more stable around the expected risk, irrespective of disruption scenarios.

Sensitivity analysis of first-stage decisions: We examine how the first-stage decisions (i.e., number of trains, and extra capacity) are influenced by the risk attitude of the decision maker. The resulting analyses facilitated the following insights. First, across all scenarios, extra capacity is added to only 17 of the 53 service legs, which deem them essential to the proper functioning of the

given railroad network. Second, three service legs (around Chicago) receive higher extra capacity because a number of train services use these service legs, and thus the larger capacity addition facilitates movement of a higher number of railcars through these service legs. Third, eight service legs are chosen for capacity addition, even when there are no disruptions since doing so would also reduce hazmat risk under normal operating conditions because extra capacity is being added to safer links.

Benefits of contingency plans: We show the benefits of using the third-party logistics strategy, and assume that doing so transfers the hazmat risk to the transport network of the third party.

5. Conclusions

Through numerical experiments, we can conclude the following. First, hazmat risk in the railroad network can be reduced in one of the three ways: proactively adding extra capacity on safer links; re-routing hazmat shipments through longer but safer rail-links following disruption; and, employing third party logistics services to move hazmat shipments following a disruption. Second, incorporating variability factor could potentially reduce variability in risk, which in turn could be a very valuable tool for both the railroad industry and the regulators who deal with low probability – high consequence hazmat events. Third, cost savings is higher from adding extra capacity vis-à-vis re-routing railcars, and hence the former should take precedence over the latter as a contingency plan. Finally, safer service legs are chosen for capacity addition even in the absence of disruptions, because that would help cope with disruptions and also reduce hazmat risk under normal operating conditions.

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