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Vulnerability assessment and re-routing of freight trains under disruptions: A coal supply chain network application

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ABSTRACT

In this paper, we present a two-stage mixed integer programming (MIP) interdiction model in which an interdictor chooses a limited amount of elements to attack first on a given network, and then an operator dispatches trains through the residual network. Our MIP model explicitly incorporates discrete unit flows of trains on the rail network with time-variant capacities. A real coal rail transportation network is used in order to generate scenarios to provide tactical and operational level vulnerability assessment analysis including rerouting decisions, travel and delay costs analysis, and the frequency of interdictions of facilities for the dynamic rail system.

1. Introduction

Today, our society depends on its transportation systems more than ever. A large percentage of the products we consume are transported long distances by road, rail, air, or a combination of modes. In addition, many people travel on roads to go to work every day. One of the main risks embedded in transportation systems is the failure of infrastructure elements such as bridges, tunnels, and facilities (ports, rail yards, warehouses, etc.). These elements can fail due to natural disasters, terrorist attacks, or just because they are in bad condition. The impact of these failures includes loss of life, economic loss, increased travel costs and congestion due to rerouting.

Rail transportation is an important and growing component of freight transportation in the United States. The benefits of rail transportation are that it is cheaper and produces less carbon emissions than road transportation. It is also easier to transport heavy loads on rail than on truck. Leaders in transportation are trying to increase the volume of goods transported by rail to alleviate loads on the road network and reduce carbon emissions. Large freight companies also are moving more of their transportation to a combination of rail and road.

There are several aspects of rail transportation that make it different than other transportation modes. First, the operations of a railroad are more centrally controlled than in the road network. That is, train operators have less autonomy to choose their own routes and schedules. Second, compared to road transportation, there is not as much excess capacity in rail transportation. Thus, it is important to consider capacity when routing and scheduling.

Disruptions have a large impact on rail transportation because there are less alternate routes available when a disruption occurs. There are several reason for the lack of alternate routes. First, rail is not as ubiquitous as roads. Second, much of the

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track in the United States is single line track. Thus, only one train can be on the track at a time in either direction. This makes it more difficult to reroute trains after a disruption. Third, the operation of a railyard can be complex and therefore it is difficult for a railyard to accommodate excess capacity. Again, this must be taken into consideration when rerouting.

In this paper, we present a mathematical model for estimating the consequence of a disruption to a rail transportation network in which an interdictor optimally chooses a set of infrastructure elements to attack in order to maximize the total disruption to the network. As a response, after the disruptions, an operator reschedules and re-optimizes trains in such a way that all demands and capacity restrictions are satisfied. In addition to modeling the threat of an interdictor, this model is also used to determine critical elements of the network by identifying the set of elements of the rail network whose unavailability causes the largest consequence. The consequence estimation of disruptions are also taken into account in a unit train transportation system by modeling trains as discrete demand units that stay intact from origin to destination. The model captures the movement of trains in time and space over a finite time horizon. Tracks and railyards in the network have strict capacity constraints for discrete time periods. Given these properties, the proposed mathematical model can be utilized to solve any problem that requires multi-period transportation scheduling under disruptions. Thus, the application is not limited to rail transportation.

Several events in the last 30 years illustrate that the freight rail transportation system in the United States is vulnerable to disruptions. In 1993, flooding of the Mississippi and Missouri rivers caused several railroads to experience delays and cancellations. The estimated total cost of the disruption was $ 182 million (Haefner et al., 1996). In 1996, a merger between Union Pacific and Southern Pacific railroads led to delays for many of Union Pacific's customers (Quillen, 1997). In 2005, a derailment on a main line in Wyoming near the Powder River Basin led to a shortage of coal in many parts of the United States as well as price increases (Bleizeffer, 2005). Finally, after the death of Osama Bin Laden, it was revealed that Al-Qaeda was planning an attack on the rail infrastructure in the United States (Boyd, 2011).

Jespersen-Groth et al. (2009) demonstrates that there are 22 disruptions related to railway infrastructure failure in the Dutch railway network in a day due to technical problems, weather, third parties and other causes, and on average, a single disruption lasts 1.7 h. Preventive maintenance is the first stage of mitigating the risks associated with any type of railway infrastructure failure. It first assesses risks that might cause any damage to regular operations and then proposes maintenance activities to minimize the total destruction. In order to identify the risks embedded in railway infrastructure (usually tracks between two nodes), Åhrén and Parida (2009) develop maintenance performance indicators via benchmarking for railway infrastructures in Norway and Sweden. Different types of reliability functions are used in order to represent the reliability distribution of the railway infrastructure components (see Chen et al. (2013), Podofillini et al. (2006) for a case study in Norway) or to incorporate the potential delays/congestions due to infrastructure breakdown (see Higgins (1998) for a case study in Australia).

The remainder of the paper is organized as follows. Section 2 summarizes basic properties of coal transportation by rail. Then, Section 3 highlights the most relevant studies in the literature focusing on disruptions in rail transportation networks. A formal problem description, the proposed two-stage mathematical model formulation and our solution methodology are presented in Section 4. Section 5 demonstrates the analysis of the computational results obtained by using a real coal supply chain network. Finally, conclusions and future work are described in Section 6.

2. Coal transportation by rail

In this study, we consider rail transportation of bulk commodities such as coal, grain, and scrap metal since they make up a large percentage of the volume transported on rail. In bulk transportation, demand is in terms of entire trains; therefore, there is no need to switch cars at intermediate classification yards. The demand for these commodities is also smoother than the demand for lower volume items. For example, several power plants in the southern United States place a fixed-quantity order every month.

Coal combustion has been commonly used to generate electricity and provide power for many kinds of operations in the United States. In 2008, it was announced that 48.2% of the electricity consumed in the US was produced by the combustion of coal in coal power plants (U.S. Energy Information Administration, 2010). The electricity generated in these plants is being used in many areas such as: hospital operations, vaccine storage, security and surveillance systems, as well as water treatment. Hence, in order to keep this source of electricity safe for such important services in case of a disruption or disaster, operations in the coal supply chain must be secured. Moreover, coal transportation is a good representative of bulk transportation by rail, and therefore a good source of data to test the proposed model, since 70% of coal was transported by rail throughout the U.S. in 2010 (U.S. Energy Information Administration, 2012).

After the coal is mined, it is sent to a processing facility where the coal pieces are crushed into more manageable chunks. The trains typically consist of 125–150 cars loaded with between 110 and 120 tons of coal in each rail car. These trains are dispatched on their routes towards specific power plants. Even though the primary objective in the coal supply chain is to meet electricity demand, reducing the transportation and storage costs of coal as much as possible is also a major consideration. Moreover, optimizing coal inventory control policies in plants might help reduce the risk of electricity shortages, but that is not in the scope of this paper. We only aim to meet the dynamic discrete demands of coal plants under disruptions. In this sense, the current approach can be seen as a just-in-time approach.

Most power plants are designed in such a way that they can only use a single type of coal in order to generate electricity. Hence, there could be serious results of a disruption or a disaster that occurs in the coal supply chain, especially for the areas