Computers & Industrial Engineering 112 (2017) 274–288

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Component importance for multi-commodity networks: Application in the Swedish railway

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ARTICLE INFO

Article history:
Received 9 May 2017
Received in revised form 2 August 2017
Accepted 3 August 2017
Available online 4 August 2017

Keywords:
Freight transportation
Vulnerability
Importance measure
Multi-commodity network flow
Railway

ABSTRACT

Preparedness and resilience planning for critical infrastructure networks requires evaluating the impact to the network when its components are disrupted. We extend the well-studied problem of component importance measures in single-commodity networks to multi-commodity networks by integrating a flow based multi-commodity optimization model with a multi-criteria decision analysis tool. A three-stage approach is proposed to assess critical component importance with multi-commodity impacts on network vulnerability of one-at-a-time component disruptions. We analyze commodity-specific impacts on network performance of the Swedish railway system to rank critical links with respect to the 20 different commodity types transported in the network. We conclude that the two proposed metrics to measure vulnerability, unmet demand and link usage over 90%, give complementary information regarding the vulnerability of the network. It is further concluded that the approach supports exploration of how the lack of redundancy and capacity in the network can give rise to high levels of unmet demand or increased link usage for specific commodities that are transported in the network, although the overall robustness of the railway system towards single link failures is high.

1. Introduction and motivation

Critical infrastructure systems such as telecommunications, energy, water, and transportation provide essential services to society. Disruptions to these systems can be caused by natural disasters, accidents, and malevolent attacks, and the effects of such disruptions can be felt across infrastructures, modes, and regions (Johansson, Hassel, Cedergren, Svegrup, & Arvidsson, 2015; National Infrastructure Advisory Council, 2015). There is an increasing interest in research and policy "to strengthen and maintain secure, functioning, and resilient critical infrastructure" (Obama, 2013) with multiple stakeholders and with currently a limited ability to adapt to rapidly changing risks (Department of Homeland Security, 2014; European Commission, 2013). In particular, the continuity of the transportation system, which remains especially vulnerable to disruptions due to aging infrastructure (American Society of Civil Engineers, 2013; NAIC, 2015), is critical for societal mobility and economic productivity (European Parliament, 2015).

Transportation infrastructure is fundamental to the modern economy for the flow of goods through spatially large and complex multi-modal networks. In the U.S. transportation system that includes all 50 states, there exists over four million miles of highway, 138,500 miles of rail, 11,000 miles of waterways, and an integrated network of airports (United States Department of Transportation, 2015). In EU-28, similar figures are 73,246 km of motorways and 284,117 km of main or national roads, 216,507 km of rail, 41,862 km of inland waterways and 339 airports (European Commission, 2015). The EU-28 covers the 28 member states of the European Union as well as, when possible, EU candidate countries and the EFTA countries. In 2013, the US moved a daily average of 55 million tons of freight valued at more than $49 billion with trucks carrying the majority of the weight and value of freight (United States Department of Transportation, 2015). The transport and storage service sectors in EU-28 accounted for about 4.9% of total gross value added at basic prices in 2012, €562 billion in total. In 2013 over 3380 billion tonne-kilometres of transport activities were carried out within EU-28, excluding transport to the rest of the world. As in the US, road transport provides the bulk of the activities (49.4%) with rail in second (11.7%) (European Commission, 2015). In both the U.S. and EU, railway networks have experienced a resurgence as an energy-efficient and environmentally friendly alternative compared to

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http://dx.doi.org/10.1016/j.cie.2017.08.004
0360-8352/

road transportation (American Society of Civil Engineers, 2013; EP, 2015). With 42% of major urban highways congested and costing annually over $101 billion in wasted time and fuel, in the US, over $75 billion has been invested in capital to reinforce the railway infrastructure since 2009 (American Society of Civil Engineers, 2013). Similarly, in the EU, European funding instruments invested over €135 billion during the period 2007–2013, with additional national investments by the individual member states, to strengthen the railway infrastructure (European Parliament, 2015). Recent interest in increasing resilience of critical infrastructure systems such as the rail network involves more than the long-standing "patch and repair" perspective on maintenance and requires an understanding of the risks associated with disruptions and identifying system vulnerabilities (European Commission, 2013; NAIC, 2015). With the renewed investment in rail networks, there exists a need to increase the performance of the network for immediate gains in operational efficiency and to increase its resilience for sustained performance.

Generally, resilience can be defined as the ability of a system to withstand, adapt to, and recover in a timely manner from the effects of a disruptive event (Turnquist & Vugrin, 2013). Borrowing language from Henry and Ramirez-Marquez (2012), the lack of ability to withstand and adapt in the short-term to a disruption is reflected in a system's vulnerability. In transportation contexts, network vulnerability describes how disruptions reduce accessibility of network components, resulting in decreased system performance (Berdica, 2002; Chen, Yang, Kongsomsaksakul, & Lee, 2007). Network component vulnerability can be classified by either node vulnerability, the criticality of a node in system performance, or link vulnerability, reduction in system capability after selective link removal (O'Kelly, 2015). We focus here on the vulnerability of a network defined by the magnitude of damage in system performance (i.e., change in commodity flow) when critical links are disrupted (Jönsson, Johansson, & Johansson, 2008). Identifying critical links that have the largest impact on network performance will allow for a targeted resource allocation to the links that make the network most vulnerable to decreased system performance after a disruption. And reducing network vulnerability is the first step in enhancing network resilience.

Identifying the contribution of network components to network vulnerability is a well-studied problem in the reliability engineering literature, where importance measures (IMs) rank components according to their adverse effect on network performance when removed. Such network performance could be evaluated with graph theoretic measures, such as average shortest path distance or closeness centrality (Dunn & Wilkinson, 2012; Tizghadam & Leon-Garcia, 2008; Ukkusuri & Yushimito, 2009), or with flow-based measures, where the importance of a component is determined by how it enables flow in the network (Johansson, Hassel, & Cedergren, 2011; Nagurney & Qiang, 2008; Nicholson, Barker, & Ramirez-Marquez, 2016). Such flow-based IMs have heretofore addressed networks of single commodities, where links enable a single stream between nodes. However, many infrastructure networks, including rail networks, enable the flow of multiple commodities, each of which have different characteristics (e.g., value, size, weight). In rail networks, multiple types of goods are moved throughout the network and represent multiple stakeholders attempting to satisfy commodity-specific demand through a capacitated network. The added complexity of a multi-commodity flow might identify network components that are more important to specific commodities than others, a perspective that is not provided when a single-commodity approach is considered.

As such, this work develops an approach to determine the importance of links in a multi-commodity network. Considering a multi-commodity flow in transportation networks is appropriate due to the regionalization of commodities based on historical movement of goods and the difference in value each commodity might represent. This research proposes an approach that integrates (i) two perspectives on the commodity-specific importance of network links, with (ii) a means to aggregate these two perspectives across all commodities using a multi-criteria decision analysis technique. The main contribution of this paper is a means to identify critical links that integrates both topological characteristics of the network as well as freight volume statistics in an interpretable ranking system for a decision maker. The approach is illustrated with a case study dealing with the multiple commodities that are transported along the rail system in Sweden.

This paper is arranged as follows. Section 2 provides the proposed three-step approach to measuring link importance, including notation, a brief overview of multi-commodity network flow optimization, the proposed network vulnerability performance measures, and an introduction to the multi-criteria decision analysis technique, the Technique of Order Preference Similarity to the Ideal Solution (TOPSIS). In Section 3, an example of the Swedish railway system illustrates the approach. Section 4 offers concluding remarks and areas for future research.

2. Proposed multi-commodity importance approach

This section describes the three-step approach for determining the importance of links in a multi-commodity network, depicted graphically in Fig. 1. In the first step, the model is solved using the classic *minimum-cost multi-commodity flow* (MCMF) optimization framework for baseline (undisrupted) conditions, and resulting commodity-specific performance measures are calculated. Second, links are removed one-at-a-time for each link in the network, and network performance is evaluated for each commodity and compared with baseline performance. Finally, measures are combined across commodities to provide a single ranking of critical links in the network.

2.1. Step 1: Calculating multi-commodity flow

Multi-commodity network flow models, as their name suggests, optimize the flow of commodities across a capacitated network of source (supply) and sink (demand) nodes (Ahuja, Magnanti, & Orlin, 1993), with a wide array of application areas (e.g., transportation, supply chain, communication, disaster relief).

Denote a directed graph by $G = (N, L)$ where N is a set of n nodes and $L \subset \{(i,j) : i,j \in N, i \neq j\}$ is a set of m directed links. Let K denote the number of commodity types, labeled with $k = 1, \ldots, K$ and for each link (i,j). Let c_{ij} denote the overall capacity of link (i,j) and c_{ij}^k denote the commodity-specific capacity of commodity $k \in \{1, \ldots, K\}$ of link (i,j). Let λ_i^k denote the amount of supply of commodity k at node i, and μ_j^k denote the demand of commodity k at demand node j. We define 2 K sets as $\mathcal{S}^k$ and $\mathcal{D}^k$, where $\mathcal{S}^k$ $(\forall k = 1, \ldots, K)$ is a set of source nodes of commodity k, and $\mathcal{D}^k$ $(\forall k = 1, \ldots, K)$ is a set of demand nodes of commodity k. An assumption of the network is that each node can be a sink for one type of commodity and a source for another, but not both a sink and source for the same commodity, $(\lambda_i^k \times \mu_j^k = 0 \text{ if } i = j)$.

To simplify the model, a set of "supersource" and a set of "supersink" nodes $S = \{s_1, \ldots, s_k, \ldots, s_K\}$ and $D = \{d_1, \ldots, d_k, \ldots, d_K\}$, respectively, each consisting of K individual nodes, are introduced to separate the $2 \times K$ sets of sources and sinks for each commodity from the network (Aggarwal, Oblak, & Vemuganti, 1995; Ford & Fulkerson, 1962; Hall, Hippler, & Skutella, 2007; Newman & Yano, 2000). This reduces $2 \times K$ sets of sources and sinks into two sets of K individual sources and K individual sinks. Each