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Increasing the resilience level of a vulnerable rail network: The strategy of location and allocation of emergency relief trains

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ABSTRACT

This paper examines the optimal location and allocation of relief trains (RTs) to enhance the resilience level of the rail network. Unlike probabilistic approaches, the priority of demand is handled by link exposure measure which considers the operational attributes of links and accessibility to road system. We formulate the proposed model using a bi-objective programming and solve it using an augmented e-constraint method (AUGMECON) combined with a fuzzy-logic approach. The proposed framework is employed to a real-world case study, and analytical results reveal the superiority of the proposed model in providing an economical and effective layout compared to conventional maximal covering model.

1. Introduction

Railway systems are part of critical infrastructures and the main backbone of economic development in every country. During a rail accident, some parts of infrastructure might be damaged, and some passengers injured. In such case, acceleration in the rate of recovery through the movement of relief equipment to disrupted lines, particularly those located in low access areas, is vital. Delayed arrival of relief equipment at disaster sites leads to delayed restoration of rail traffic causing diversion and cancellation of trains. For example, delayed relief operation in a low access tunnel of the south corridor in Iran, between Tang-haft and Andymeshk stations, caused a 41-h line blockage and many train cancellations (Kachoueyan et al., 2016).

In Iran, rescue and relief equipment of railway is provided by a specific emergency rail-vehicle called relief train (RT). Such trains are equipped with medicine and first aid supplies, track components, a crane, re-railing and cutting equipment along with some technicians working with them. An RT in Iran consists of open wagons containing ballast, flat wagons holding traverses, a tank wagon for firefighting, a heavy rail crane, and a passenger wagon for technicians (see Fig. 1). In case of emergency, RT should be available at the disaster site with the least response time. However, locating RTs in stations is subjected to operational constraints such as preference of operating personnel, availability of crews, and nearness to repair depots. Moreover, RTs should be allocated to demand locations with high emergency priority where the relief coverage for the whole network is provided.

In this paper, we address the problem of location and allocation of RTs in the rail network to reduce the response time to vulnerable points of the network. Through such strategy, our aim is to make the rail system resilient enough to mitigate the disastrous impact of extreme events and to restore it to normal status immediately. Resiliency is defined as the ability of a transportation network to recover from a disruption and return to normal function within a “reasonable” time frame (Snelder et al., 2012). Optimal location and allocation of emergency relief equipment throughout the rail network can greatly reduce the response time to vulnerable links after an extreme event and consequently the time needed to return to normal functioning, and thus enhance the resilience of the

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Fig. 1. Relief train and its components (Source: own pictures).

system.

The vulnerability analysis concerns the consequences of failing components of the system where the estimation of demand probability is not feasible. The consequences usually concern life, health and environment. If these issues are assigned monetary values, consequences can also be expressed as costs. Among vulnerability studies, Nagurney and Qiang (2012) introduced the network performance efficiency measure as the average throughput on a network with a given demand vector. With such measure, they investigate the importance of network components by studying their impact on the network efficiency through their removal. Khademi et al. (2015) developed a vulnerability analysis for transportation system at a major population center in a geographic area prone to earthquakes. Bababeik et al. (2017) also proposed the increased cost of routing and scheduling in case of a multi-link blockage in a railway network. Mattsson and Jenelius (2015) introduced the concept of conditional vulnerability to show how resilience and vulnerability can be framed. In our study, we suggest an alternative term, *link exposure*, for vulnerability. Link exposure is defined as how much an important link of the network is in urgent need to be provided by emergency facilities when disruption occurs. In our application, the accessibility of an important link to road as a backup system to transfer relief facilities determines its criticality. Link importance, in turn, reflects the crucial role of any link in the performance of the network. In our application, it is measured by a set of attributes influencing the performance of the rail network. A major difference of our study with previous vulnerability works is that they evaluated critical components by calculating the general costs after the removal of those elements while the current study utilizes link importance index to identify critical components of the network in terms of the need for emergency facilities when disruption occurs.

In literature, quantitative research in emergency response has tackled two distinct areas: (1) models for emergency logistics planning, and (2) models for routine emergency relief. The first category deals with location and distribution of facilities which come into use after a rare event like earthquake or hurricane while the next category demands high frequent facilities such as ambulance, police, or fire services. In the first category, Caunhye et al. (2012) provided a comprehensive survey on emergency logistics operations and classified models further into two main sets: (a) facility location, and (b) relief distribution and casualty transportation. One of the most popular techniques to deal with the emergency facility location problem is the applications of the covering location models (Li et al., 2011). The first emergency facility location covering model was the location set covering problem (LSCP) proposed by Toregas et al. (1971). Belardo et al. (1984) used a maximal covering location problem (MCLP) to site resources for maritime oil spills. Balcik and Beamon (2008) also used an MCLP to preposition relief supplies, concerning capacity constraints. However, the LSCP and MCLP have two drawbacks: first, when a facility is called for service, demand points under its coverage are not covered by it anymore; second, they assume that a demand point is covered only when it can be reached within a specific predefined distance by at least one facility. Recently, some researchers have proposed gradual covering models to relax the assumption of coverage within a fixed distance. Berman et al. (2003) applied a level of partial coverage by considering the coverage decay function for the formulation of uncapacitated facility location problem. Karasakal and Karasakal (2004) developed a partial coverage version of maximal covering location problem and applied Lagrangian Relaxation to optimize it. Gradual coverage models still have a limiting assumption as each demand point is covered only by one facility which leads to solutions that require more facilities to cover the same amount of demands. In other words, it causes facilities to be concentrated in specific parts of the network. To cope with this challenge, the cooperative behavior of facility location in covering demand has recently been considered by researchers. Cooperative coverage framework is a new trend which aims to combine (cooperate) facilities to provide coverage (Li et al., 2011). In this paper, we replaced