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Reliable emergency service facility location under facility disruption, en-route congestion and in-facility queuing

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ABSTRACT

The planning of emergency service facility location, especially for those expecting high demand and severe conditions, requires consideration of victims' en-route travel, in-facility service quality, and reliability of these service facilities themselves. This paper first presents a scenario-based stochastic mixed-integer non-linear program (MINLP) model that integrates facility disruption risks, en-route traffic congestion and in-facility queuing delay into an integrated facility location problem. We derive lower and upper bounds to this highly complex problem by approximating the expected total system costs across the normal and all probabilistic facility disruption scenarios. This allows us to develop a more tractable approximate MINLP formulation and a Lagrangian Relaxation (LR) based solution approach. The relaxed sub-problem for location and service allocation decisions is further reformulated into a second-order conic program. Numerical experiments show that the approximate model and LR solution approach are capable of overcoming the computational difficulties associated with the problem. Interesting findings and managerial insights are obtained from a series of sensitivity analyses, e.g., regarding the importance of considering in-facility queuing in location design, and the significance of resource pooling on the optimal facility deployment.

1. Introduction

Frequent natural and man-made catastrophic events highlight the need for a reliable and responsive service network that can effectively mitigate the adverse impacts. Victims of the disaster are likely to impose high service demand (e.g., medical treatment, food and water supply) on emergency service facilities (e.g., shelters, medical centers). There are a collection of apparent yet complicated factors that affect efficiency of emergency service systems. First, the location of emergency service facilities should be properly selected considering the soaring travel demand in the adjacent roadway network (Bai et al., 2011), as heavy en-route traffic congestion may happen. For example, when the 2005 Hurricane Rita hit the Gulf of Mexico (Louisiana and Texas coasts), it induced severe roadway congestion that paralyzed the whole evacuation system (Litman, 2006). Second, as arriving traffic can quickly exceed a facility's service capacity, supply shortage often inevitably occurs and results in queuing, waiting, and other social costs (e.g., for collecting/redeploying and transporting disaster relief

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supplies). After the 2010 Haiti earthquake, for example, thousands of people flocked to a few point-of-distribution centers where emergency supplies (e.g., food and water) were far from sufficient (Jaller and Holguín-Veras, 2013). Third, service facility disruption often occurs during or after disasters, due to infrastructure damage, roadway blockage, water cuts, power outages, and so forth. When this happens, the victims originally heading to these emergency service facilities have to either be reassigned to more distant ones, or even lose service completely. The risk of service facility disruption could dramatically increase social cost which not only endangers life but also exacerbates both en-route traffic congestion and in-facility delay.

There is abundant literature on emergency service facility location, e.g., for emergency medical services (ReVelle et al., 1977; Jia et al., 2007) and emergency service vehicle locations (Ball and Lin, 1993; Beraldi and Bruni, 2009), but most of them typically addressed in-facility queuing only. For example, some literature incorporated queuing theory models, e.g., M/M/1 (Zhang et al., 2009), M/G/1 (Berman et al., 1985), and M/M/n (Larson, 1974, 1975; Zhang et al., 2010). Earlier models attempted to achieve a certain level of service by either providing redundant coverage (Daskin, 1982, 1983; ReVelle and Hogan, 1989; Ball and Lin, 1993) or explicitly considering the queuing aspect (Larson, 1974, 1975; Berman et al., 1985; Marianov and ReVelle, 1996). Recent studies further integrated the impact of in-facility congestion in location–allocation problems to determine the optimal number and location of facilities, their service capacity, and the assignment of victims (Marianov and Serra, 2002; Aboolian et al., 2008; Syam, 2008; Castillo et al., 2009; Corrêa et al., 2009; Aboolian et al., 2012). These models were commonly used for the design of service networks in normal operational contexts (e.g., health-care, banking, or ticket services), or emergency services in disaster contexts (e.g., ambulances, fire stations, shelters and point-of-distribution). Zhang et al. (2009) formulated a preventive healthcare facility location problem and incorporated patients' in-facility congestion as an M/M/1 queue in a nonlinear optimization framework. Later, the same authors extended their model to an M/M/n queue and proposed a bi-level non-linear mathematical program under user equilibrium to improve accessibility of preventive healthcare centers (Zhang et al., 2010). Walking, waiting and safety risks were considered in Jaller and Holguín-Veras (2013) by formulating an approximate optimization model to minimize the total social cost of human suffering in a point-of-distributions network. Minimizing queuing effects was also frequently considered in competitive facility location problems (Marianov et al., 2008; Zhang and Rushton, 2008). Kwasnica and Stavrulaki (2008) explored competitive facility location and capacity decisions by considering queuing delay in a two-stage game model. They conducted a comparative analysis on system equilibrium under three different monopoly conditions.

Most past studies assumed non-existence of traffic congestion, and transportation cost was simply estimated by shortest-path travel distances. Only in recent years did the impact of traffic congestion on traveler access cost and facility location design gain attention. Bai et al. (2011) and Hajibabai and Ouyang (2013) examined traffic congestion impact and incorporated shipment routing decisions endogenously in supply chain design problems. Hajibabai et al. (2014) extended this idea to incorporate the impact of freight traffic on highway congestion as well as deterioration of pavement infrastructure. Ouyang et al. (2015) integrated continuous traffic congestion and equilibrium into a planar facility location design framework. Traffic routing under congestion was also considered in shelter location planning problems (Sherali and Carter, 1991; Li et al., 2012). Konur and Geunes (2011, 2012) analyzed a two-stage game to characterize the qualitative effects of traffic congestion costs on supply chain activities in a competitive environment.

These existing studies are very relevant, but they did not explicitly capture the occasional unavailability of the involved facilities; i.e., a built facility may become unavailable to customers either due to limited capacity or due to the impact of disasters. Site-specific facility availability and reliability directly affects customer allocation and traffic assignment; if they are incorporated into facility location design, customers will have multi-level service options and traffic assignment will change correspondingly. Omitting the facility disruption impact may result in underestimated transportation cost, low service quality, and high socio-economic penalty (e.g., loss of life and properties).

A related group of literature deals with such reliability issues; i.e., built facilities may be unable to provide service due to facility disruptions (Bundschuh et al., 2003; Snyder and Daskin, 2005) or link failures (Nel and Colbourn, 1990; Eiselt et al., 1996). A number of reliable location models have also been proposed to address possible facility disruption risks problems in various contexts (e.g., Berman et al., 2007; Snyder et al., 2007; Shen et al., 2011; Qi et al., 2010; Friesz, 2011; Friesz et al., 2011; Peng et al., 2011; Wang and Ouyang, 2013). For example, Qi et al. (2010) and Chen et al. (2011) integrated inventory decisions into the reliable location design framework; An et al. (2013) examined the impact of service disruption on the transit-based evacuation pick-up location design; Li and Ouyang (2010b, 2012) explored facility location models for several types of network surveillance sensors under various malfunction risks. In recent years, more complicated facility disruption patterns were also of particular interest, including site-independent (Snyder and Daskin, 2005; Chen et al., 2011; Xie et al., 2015a), site-dependent (Cui et al., 2010), and spatially-correlated facility failures (Li and Ouyang, 2010a; Li et al., 2013; Xie et al., 2015b).

Despite all these efforts in respective areas, to our best knowledge, no previous study has addressed the interrelationship among facility location design, en-route traffic congestion, in-facility queuing delay and probabilistic facility disruption in an integrated framework. Separate considerations of these factors, as in prior studies, may result in sub-optimal decisions or inaccurate cost estimation. The integration of these considerations, as we shall see soon, is motivated by real cases and indeed poses a great challenge. Hence, from the practitioners' point of view, a holistic emergency service network design model, such as the one in this paper, might help develop enhanced engineering guidelines and policies.

To effectively capture en-route traffic congestion and in-facility queuing delay, this paper starts by exploring the victims' traveling and waiting patterns in a scenario-based model. The model determines strategic emergency service facility locations; see the upper layer of Fig. 1. At the same time, it offers system operation strategies such as traffic routing,