European Journal of Operational Research 250 (2016) 855–864

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Decision Support

A two-stage resource allocation model for lifeline systems quick response with vulnerability analysis

C. Zhang[a,b], X. Liu[a,b,*], YP. Jiang[b], B. Fan[c], X. Song[d]

[a] *Department of Industry Engineering, Shanghai Jiaotong University, P R China*
[b] *Department of Industrial and Systems Engineering, National University of Singapore, Singapore*
[c] *School of International and Public Affairs, Shanghai Jiao Tong University, China*
[d] *School of Mathematics, University of Portsmouth, UK*

ARTICLE INFO

Article history:
Received 17 April 2014
Accepted 13 October 2015
Available online 19 October 2015

Keywords:
Decision support systems
Quick response
Resource allocation
Two-stage programming
Vulnerability analysis

ABSTRACT

The internal complexity of lifeline systems and their interdependencies amplify the vulnerability of external disruptions. We consider lifeline infrastructures as a network system with supply, transshipment, demand nodes and arcs constructed between node-pair for conveying service flows. The complex interactive network system can be modeled as multi-layered graphs, whereby the power network depends on the gas network linked through the gasified power plants. Similarly, the water network depends on both quality and quantity of power supply. A successful emergency rescue can make lifeline infrastructures more resilient against natural disasters and unexpected accidents. This study focuses on a resource allocation and schedule problem to restore the most critical components quickly in the multiple interdependent lifeline infrastructures under disruptions. The key objectives of quick response model include reducing the overall losses caused by the accidents, and restoring system functions as quickly as possible. The Resource Allocation Model (RAM) for rescue was formulated as a two-stage mixed-integer programming, in which the first stage problem aims to minimize the total losses, while the second stage problem is to optimize resource allocation for rescue service within the rescue time horizon using the proposed heuristic algorithm in polynomial complexity. In the meantime, those tasks/components to be repaired are selected by the proposed vulnerability analysis method to guarantee the optimal whole network efficiency, and then put them into the Resource Allocation Model. The simulation results demonstrate that the proposed approaches are both efficient and effective to solve the real-life post-disaster resource allocation problem.

1. Introduction

In the past century, the infrastructures of urban cities have faced immense strains as a result of dramatic growth in population. Correspondingly, the increasing complexity and interdependencies of lifeline infrastructures pose new challenges for security and operations management because of their large-scale, nonlinear, and time-dependent properties. Such lifeline systems are often considered as a network system consisting of supply, demand, and transshipment components (nodes and arcs) including electric power, gas, water supply, food, telecommunications, and transportation, to provide platforms for service delivery. The complexity nature of the network makes the lifeline systems vulnerable to failures, which may cause widespread negative consequences. It has being becoming the most susceptible part for the economic, social, and environment development in all cities (Aven, 2011; De Sherbinin, Schiller, & Pulsipher, 2007; Murray, 2013).

The occurrence of several cascading failures in the past typically causes huge property loss and significant restoration cost (Chai, Liu, Zhang, & Baber, 2011; Collier & Lakoff, 2008). For example, in July and August of 1996, the Western US grid experienced outages affecting 11 of the US States and 2 Canadian Provinces. More recently in December 1998 blackout in San Mateo cascaded to affect 2 million people in the San Francisco Bay Area. Therefore, the cities should take all feasible measures to strengthen their response capabilities to ensure essential services. From the viewpoint of sustainability, a city cannot achieve the goal of sustainability if the operations of its lifeline network are vulnerable (Turner et al., 2003; Turner II, 2010).

In the ensuing sections, we shall elaborate on the existing researches, which focus on the survivability of systems under nature disasters or man-made accidents (Kamissoko, Zaraté, & Pérès, 2014; Murray, Matisziw, & Grubesic, 2007; San Martin, 2007). The first stream of the research mainly focuses on malicious attacks and network interdiction problems based on the complex network topology

---

[*] Corresponding author at: Department of Industrial Engineering management, Shanghai Jiaotong University, 800 Dongchuan Road, Min-Hang District, Shanghai 200240, P R China. Tel.: +65 6601 4089; fax: +65 6601 4089.
E-mail address: x_liu@sjtu.edu.cn (X. Liu).

http://dx.doi.org/10.1016/j.ejor.2015.10.022
0377-2217/

methods (Azaiez & Bier, 2007; Hausken, 2011; Rocco, Ramirez-Marquez, Salazar, & Yajure, 2011). The second stream studies the network flow problems under disruptions (Garg & Smith, 2008; Sorokin, Boginski, Nahapetyan, & Pardalos, 2013), which is formulated as IO model that could effectively evaluate the performance of the whole network at each time period. The third stream focuses on network vulnerability analysis including network design and operations against blackout based on the network topology, which is largely used to identify the critical components in the network (Alguacil, Arroyo, & Carrión, 2010; Fiedrich, Gehbauer, & Rickers, 2000; Zio, Golea, & Rocco S., 2012).

The approaches used to solve the post-disaster resource allocation problem include applied statistical and probabilistic models combined with multi-objective programming, two-stage model and dynamic model (Samuel & Guikema, 2012; Shan, Wang, & Li, 2012; Srdjevic, Srdjevic, Blagojevic, & Suvocarev, 2013; Yan & Shih, 2009; Yatesa, Battab, Karwanb, & Casasc, 2012). Specifically, Barbarosoǧlu and Arda (2004) proposed a two-stage stochastic programming model to plan the transportation of vital first-aid commodities to disaster-affected areas during emergency response; Lee, Mitchell, and Wallace (2007) formulated a mixed integer model to design optimal responding strategies for emergencies with the objective of minimizing cost; Scaparra and Church (2008) identified the most cost-effective way of allocating protective resources among the facilities of an existing but vulnerable system using bi-level programming in such a way that the impact of the most disruptive attack on the unprotected facilities is minimized; Cavdaroglu, Hammel, Mitchell, Sharkey, and Wallace (2013) formulated a service restoration and job scheduling in interdependent systems; and Wex, Schryen, Feuerriegel, and Neumann (2014) proposed and compared several heuristics for allocating available rescue units to incidents with the objective of minimizing the sum of completion times weighted by severity.

Furthermore, since the resource allocation problem could be generalized to the unrelated parallel machine scheduling problems, many heuristic algorithms could also be used to solve the resource allocation problem (Lin, Pfund, & Fowler, 2011; Su & Lien, 2009; Yeh, Lai, Lee, & Chuang, 2014).

However, in the existing resource allocation studies, there are two problems that require further discussion. The first is that the objective of most models only focuses on minimization of the overall costs (Brown, Carlyle, Salmerón, & Wood, 2005; Shen, 2013; Zhang & Peeta, 2011), while studies focus on minimization of the completion time is by far limited (Faraj & Xiao, 2006; Wex et al., 2014). The total losses could not be solely measured in terms of costs because the consequences as a result of accidents are hard to be assessed, in other word, it doesn't make sense to trade off the costs and the restoration time. Therefore, during the rescue time horizon, the minimization of the restoration time should take priority for stakeholders in their decision-making process. The second problem is that in the accidents, the interconnectivities of the lifeline network may trigger cascading failures, which can result in the amplifications of the overall losses, therefore, the whole network efficiency shall be considered as the most important metric during the resource allocation assessment procedure. In this study, we consider the emergency allocation problem with limited resources and restoration time for the lifeline systems with the consideration of the whole network efficiency. To solve the resource allocation and scheduling problem, we utilize the network system vulnerability analysis method to sort those critical components to be repaired, and then put them into the two-stage mixed integer model formulated.

This paper is organized as follows. Section 2 presents the lifeline emergency resource allocation model, which is formulated as a two-stage programming. Section 3 presents the proposed algorithms to solve the two-stage programming. Section 4 demonstrates the computational results and some discussions. Conclusions are detailed in the final Section.

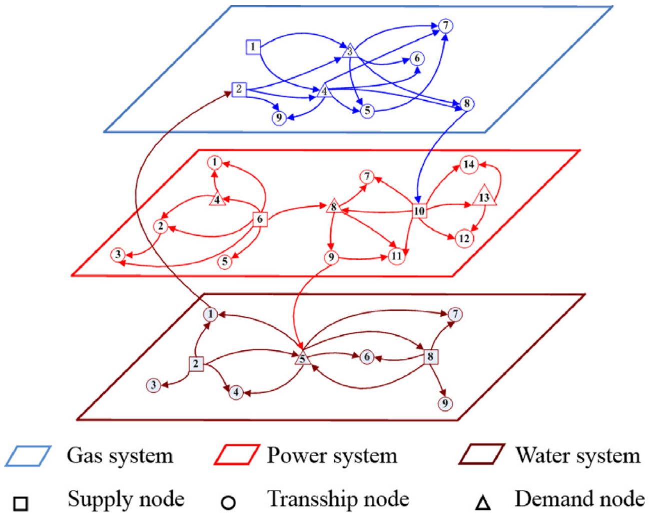

Fig. 1. Interdependent multi-layered lifeline systems network.

2. Two-stage resource allocation model

2.1. Problem description

In the study, we focus on lifeline systems with three sub-systems, which include gas, power, and water systems, whereby the power network depends on the gas network through the gasified power plants, and the water network depends on both quality and quantity of power supply. Thus, there exist functional connections among the different layers, which means the supply layers are too important to trigger the demand layers failure if any disruption happens. Meanwhile, the network is composed of supply, transshipment, and demand components in each layer as shown in Fig. 1.

Such three-layered network could be denoted as a directed graph $G(A, V)$ with nodes $v_n \in V (n = 1, 2, \ldots, N)$, and directed arcs $a_i \in A (i = 1, 2, \ldots, I)$ which connect service flow within each layer and between the node-pair $(v_m, v_n) \in P$, where P represents the set of node-pair. Moreover, a_i^r $(r = 1, 2, \ldots, R')$ represents the rth destroyed arcs with $a_i^r \in \mathbb{R}$; accordingly, $v_n^r (r = R' + 1, R' + 2, \ldots, R)$ represents the rth destroyed nodes, with $v_n^r \in \mathbb{R}$. In other word, the destroyed components include all destroyed arcs and nodes, which belong to destroyed components set $\mathbb{R}$. For rescue tasks, we have rescue team $k\,(k \in K)$, each rescue team has different capabilities to repair the destroyed components as each rescue team can be a group consisting of technicians with different skills.

The rescue procedure is that the top-layer decision makers give orders to rescue teams, and then rescue teams have to meet the requirements of the task. In this study, we stand on the rescue teams' point of view, the goal is to take time priority against restoration costs because of the time sensitive character in emergency case to optimize the efficiency of the whole lifeline system. To achieve the goal, we first select critical destroyed components $a_i^r \in \mathbb{R}$ to be repaired to ensure the maximization of lifeline system network efficiency within rescue time horizon T, and then, we assign the determined tasks $\mathbb{R}$ from top-layer decision makers to each rescue team $k\,(k \in K)$ within the time horizon T.

2.2. Notations and variables

In order to facilitate our explanation, the following notations and variables will be used throughout this paper.

Parameters

u_i	capacity of arc a_i
u'_n	capacity of transshipment node $v_n \in V_{n=}$