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Stochastic optimization for investment in facilities in emergency prevention

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ABSTRACT

A coordinated approach is developed to integrate three preventive measures (i.e. building reinforcement, reinforcement of road networks, and facility location of relief supplies), with the objectives of minimizing budgets and risk-induced penalties. The Conditional Value-at-Risk is employed as a decision-making tool to evaluate diverse decisions of prevention based on the degree of risk aversion. Based on a real-world case of an earthquake, a series of scenarios were designed, and the applicability of the proposed model was studied. The coordinated approach for investing preventive measures is cost-efficient in helping reduce the impact of disaster on society.

1. Introduction

A major earthquake can cause a great number of casualties, homeless victims, and loss of property. The main reason is due to the collapse of buildings. Other reasons may include, but are not limited to, poor transportation network conditions, unsatisfactory location of relief supplies, and an overall shortage of relief supplies, which altogether serve to restrict the performance of relief logistics. In China, the earthquake-resistant criteria of buildings are defined by the Ministry of Housing and Urban–Rural Development (MHURD). Decisions on disaster prevention for road networks and relief supplies management are the responsibility of the Transportation Ministry and Ministry of Civil Affairs, respectively. Case studies from the earthquakes, which occurred on May 12, 2008 and April 14, 2010 in Wenchuan and Yushu (in China), reveal that a lack of efficient integration between the related entities ultimately magnified the casualties and homeless victims.

The response to large-scale emergencies is a cooperative process that requires the active and coordinated participation of a variety of functionally independent agencies operating in adjacent regions (Aedo et al., 2010). Related studies are mainly limited to the qualitative analysis of multi-agent coordination (Gonzalez, 2010; Schulz and Blecken, 2010). Multi-agent coordination activities have not been properly incorporated into operation research models in previous literature (Galindo and Batta, 2013). Therefore, incorporating coordination activities into operation research models may be a valuable venture in the pursuit of improved emergency prevention. Of course not all emergency events, particularly natural disasters, can be prevented. However, a coordinated approach for reinforcing buildings, improving the reliability of the transportation network, and strategically locating facility and storing relief supplies for optimal operations in the emergency prevention phase, may nevertheless help mitigate the risk of loss of life, injury, and property in the future.

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There are number of specific civil engineering methods for reinforcing buildings' construction. Yet most research focuses on qualitative analysis and resources management in the context of disaster housing recovery, such as recovery approaches either donor-assisted or owner-driven (Andrew et al., 2013), and the role of social capital (Mukherji, 2014), etc. Diaz et al. (2015) developed a system dynamics model to study the supply problem of reconstruction material in an affected area, and described the behavior of material resources in the housing reconstruction and recovery planning in a catastrophic event. Kumar et al. (2015) proposed a system dynamics model to reproduce and explore the issue of labor force (e.g., construction workers) management. They specifically analyzed the impact of a disaster on labor for the housing recovery, and rebuilding of a devastated region.

Roads are important for providing assistance in the form of transportation of relief supplies, and of injured people after a disaster. Efficient strengthening road network and repair of damaged roads is indeed essential. At a strategic level, most research focuses on investment decisions for strengthening road networks (e.g. decreases the likelihood of link failure), and for reducing post-disaster response time (Peeta et al., 2010; Du and Peeta, 2014). At the operational level, there is some literature focusing on the rapid repair of damaged roads. Yan et al. (2014) employed a time–space network flow technique to construct a logistical support scheduling model under stochastic travel times.

Strategic facility location has received considerable attention, with such study specifically on the storage of medicine, food, and water (Rawls and Turnquist, 2010; Rennemo et al., 2014). Coordinated decision-making on road recovery and relief supply distribution (Liberatore et al., 2014) more broadly is however increasingly becoming a more interesting area of research. Ceselli et al. (2014) presented a model to study the problem of efficient distribution of drugs through the simultaneous and coordinated use of distribution centers and vehicles. Wang et al. (2014) constructed a nonlinear integer open location-routing model for relief distribution obstacles, with consideration of travel time, total cost, and reliability with separate delivery. Most literature on investment just focuses on decisions of road network or facility location of relief supplies in the disaster prevention or recovery phases. However, to the best of our knowledge, related literature on the reinforcements for building construction nevertheless remains scarce.

Operation research models could be used as a decision-making tool that has the potential to help managers save lives and money, maintain the criteria of fairness and maximize the use of limited resources in disaster management (Torre et al., 2012). To lessen the lasting impact of an earthquake on society, this paper has developed a coordinated approach to integrate measures of buildings reinforcement (BR), reinforcement of road networks (RRN), and facility location of relief supplies (FLRS) with the objectives of saving budgets and reducing risk-induced penalties. Depending on, but are not limited to BR, RRN, and FLRS, can potentially mitigate the risk of loss of life, injury, and property.

Risks cannot be ignored in disaster prevention, and indeed they figure prominently and inevitably in disaster management. Yet there has already been a lot of work in safety (Xia et al., 2011), reliability (Lin et al., 2013; Edrissi et al., 2015) and risk (Dijkstra et al., 2002; Barbudo et al., 2012). To decrease the loss in the worst-case scenario, Kelle et al. (2014) applied p-reliable regret criterion for the pre-positioning decision, which is a trade-off between the expected value and the min–max regret criteria. They proposed disregarding the lowest-chance scenarios and considering only the higher chance scenarios up to a total probability of p chosen close to 1. That entails that the planner can choose from a portfolio of solution plans by varying the value of p. Although our work does not attempt to present a more sophisticated model of risk estimation than previous researchers, this study is trying to present a decision-making approach for assisting disaster managers in making decisions with a degree of risk aversion, as opposed to relying on experience and cognition.

A popular risk measure, i.e., Conditional Value at Risk (CVaR) may be an effective method for quantifying the degree of risk aversion. CVaR measures the mean excess loss at a certain confidence level, and commonly is used to measure risk in finance. Rockafellar and Uryasev popularized CVaR by two widespread papers (Rockafellar and Uryasev, 2000, 2002), and is increasingly becoming popular for assisting in decision analysis in emergency response. Ahmadi-Javid and Seddighi (2013) introduced CVaR to quantify the risk-measurement policies for location-routing problems with disruption. Sawik (2014) integrated supplier selection and customer order scheduling in the presence of supply chain disruption risks, where CVaR is employed as a risk measurement.

Compared to other related literature in disaster prevention and post-disaster recovery, this study is unique due to the following distinctive features.

(1) We aim to propose two features make the model closer to the real situation. A research region is subdivided into several locations for studying optimal decision-making on earthquake-resistant measures. Survival probability is used to represent the reliability of road networks. For each decision on earthquake-resistant, survival probabilities of the roads yield different results in different scenarios.
(2) As a holistic consideration, BR, RRN, and FLRS are formulated in a two-stage stochastic programming model. In accordance with the costs for reinforcing buildings, road networks, and the cost for purchasing, holding, and transporting relief supplies, the penalties incurred in the form of death, injury, and shortage of relief supplies are utilized to assess the efficacy of preventive measures. The tradeoffs between budgets and risks are studied based on the quantification of risk impacts.
(3) Based on real data from earthquakes in Lushan, China, the uncertainties in epicenter locations and seismic intensity at affected locations are characterized by using a scenario planning approach. Furthermore, CVaR is utilized to evaluate diverse decisions of BR, RRN, and FLRS, based on the degree of risk aversion on the part of disaster management. There are only a handful of studies that use CVaR for risk management in emergency logistics.