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Decision Support

Balancing pre-disaster preparedness and post-disaster relief

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ABSTRACT

Challenges associated with resource allocation to mitigate and recover from natural and man-made disasters inspire new theoretical questions for decision making in the intertwined natural and human world. Disaster loss is determined not only by post-disaster relief but also the pre-disaster mitigation and preparedness. To examine the decision making process at ex ante and ex post disaster stages, we develop a two-stage dynamic programming model that optimally allocates preparedness and relief expenditures. We analytically and numerically solve the model and provide new insights by sensitivity analysis.

1. Introduction

Natural disasters have caused enormous damage to human beings and the economy. After Hurricane Katrina, the US government sought 105 billion dollars for repairs and reconstruction, and the total economic losses were about 250 billion dollars (King, 2005). Global natural disasters caused 350 billion dollars in losses in 2011 (Holm & Scism, 2011).

Disaster management is usually decomposed into four phases: mitigation, preparedness, relief, and recovery (Lindsay, 2012). Mitigation is the effort to reduce loss of life and property by lessening the impact of disasters. Typical efforts of mitigation are organizing resources, identifying the characteristics and potential consequences of hazards, and insurance. Preparedness refers to measures taken to prepare for and reduce the effects of disasters. Preparedness efforts include improving the effectiveness of emergency response by developing a preparedness plan in strategic, operational, and tactical tiers, early warning systems, and public training for disaster risks and responses. Relief refers to the process of responding to a catastrophic situation, providing humanitarian aid to persons and communities who have suffered from some form of disaster. Typical efforts of relief are saving lives, protecting property and environment such as the search and rescue of human beings, and repairing and reconstructing houses. Losses caused by disasters can be reduced by not only post-disaster relief and recovery but also pre-disaster mitigation and preparedness.

The mitigation and preparedness for disasters are studied in social (Messias, Barrington, & Lacy, 2012), political (Gerber, 2007) and legal (Command, 2008) contexts, such as improving the national preparedness for citizens (Conroy, 2008), integrating community/individual behaviors for disaster preparedness (Campasano, 2010), and the derivation of preparedness measurement (Covington & Simpson, 2006). Jongejan, Helsloot, Beerens, and Vrijling (2011) conduct a cost-benefit analysis to the worthiness of preparedness. Preparedness is defined in terms of the probability of capacity exceedance to account for the response effectiveness in both densely and sparsely populated regions. Kunreuther, Grossi, Cyr, and Tao (2001), Chang (2003) and Ganderton (2005) use cost-benefit analysis to investigate the worthiness and effectiveness of mitigation via comparing the cost of mitigation and the reduction of loss and business interruption time. King (2005) and Bank and Gruber (2009) report a lack of preparedness in private sectors such as small businesses. Coffrin, Hentenryck, and Bent (2011) study how to store power system supplies in the pre-disaster stage to maximize the expected power flow across all the disaster scenarios.

FEMA (2014) provides a platform to guide the public and private sectors on preparing for and recovering from disasters. There are many types of natural disasters, such as floods, tornadoes, hurricanes, thunderstorms and lightning, winter storms and extreme cold, drought, extreme heat, severe weather, space weather, earthquakes, volcanoes, landslides and debris flow, tsunamis, and wildfires. The mitigation and preparedness for each type of disaster could be different. For example, flooding may be caused by torrential rains, and lead to high reservoir water levels. Correspondingly, the preparedness for flooding includes the prediction of the weather, the warning system of the water level, and the reinforcement of the dam.

Disaster relief is also studied. For example, Chia (2006) analyzes disaster relief from the perspective of large-scale system engineering. Cagnan, Davidson, and Guikema (2006) study how the joint

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Table 1
Comparison of this paper and prior researches on both preparedness and relief.

Reference	The variable of disaster magnitude	Type of hazard	Trade-off between preparedness and relief	Analytical solutions obtained
El-adaway and El-Anwar (2010); Kramer (1995)	Continuous and discrete	General		
Fiedrich et al. (2000)	Continuous	Earthquake		
Elbakidze and McCarl (2006)	Constant	Animal disease	√	
Tean (2006)	Constant	General		
Dodo et al. (2005)	Constant	Earthquake		√
Mete and Zabinsky (2010); Miller-Hooks et al. (2012); Rawls and Turnquist (2010)	Discrete	General		√
This research	Continuous and discrete	General	√	√

probability distribution of post-earthquake electric power restoration for a certain number of customers in a certain time window varies throughout the Los Angeles area. Altay and Green (2006) summarize the applications of operations research and management science to disaster management. Karlaftis, Kepaptsoglou, and Lambropoulos (2007) investigate the fund allocation strategy for bridge network recovery after natural disasters by maximizing bridge improvement and minimizing the cost. Stephenson and Bonabeau (2007) suggest that the government could capitalize the technology of communication devices and networks to partner with citizens to efficiently prevent and respond to disasters. Yushimito, Jaller, and Ukkusuri (2012) propose a Voronoi diagram approach to locate the post-disaster distribution centers. The objective is to minimize the social cost which is a function of the population size and the distance from demand points to distribution centers. Haghani and Afshar (2009) propose a mathematical model to describe the integrated logistics operations in response to natural disasters.

Most research focuses on minimizing fatality or monetary loss by considering relief only, especially in a logistics perspective (Fiedrich, Gehbauer, & Rickers, 2000; Rawls & Turnquist, 2010). There is limited research on both preparedness and relief. El-adaway and El-Anwar (2010) propose a comprehensive decision support system for natural disaster investment strategy incorporating stochastic hazards models for disaster losses, multi-agent simulation models, multi-objective optimization models and multi-attribute utility models to minimize cost and maximize equity. Kramer (1995) summarizes various risk modified cost-benefit analysis for disaster mitigation such as game-theoretic analysis, safety-first analysis, mean-variance analysis, and stochastic dominance analysis. Elbakidze and McCarl (2006) study the tradeoff of economic investment on pre-disaster preparedness and post-disaster relief for the potential introduction of infectious animal disease by minimizing the total loss of investment and disease damage. The disease damage is a function of preparedness, relief, and a constant incident severity parameter, while in our paper, the disaster magnitude is generally modeled as a random variable. Tean (2006) proposes a two-stage stochastic programming model to maximize the total expected number of survivors and delivery of required goods, without providing the solution of the model. Dodo, Xu, Davidson, and Nozick (2005) propose a linear model to obtain the optimal earthquake mitigation (preparedness) effort on each square footage of the region during each discrete time period, in order to minimize total costs of the mitigation and expected post-earthquake reconstruction investments. The annual probability of the occurrence of each earthquake is a constant parameter while in this paper the disaster magnitude follows a discrete or continuous distribution. Mete and Zabinsky (2010) use stochastic programming and mixed integer programming to investigate the optimal warehouse location and inventory level of the medical supply in pre-disaster stage, through solving the subproblem of minimizing the expected transportation cost after disaster. Miller-Hooks, Zhang, and Faturechi (2012) set up a two-stage stochastic model to maximize the resilience of a transportation network, which is defined as the expected fraction of demand that can be satisfied for all network arcs after the disaster. In the case study, they compare the expected total post-disaster flow of shipments under the binary combinational scenarios of implementing preparedness, and/or relief. Peeta, Salman, Gunnec, and Viswanath (2010) build and solve a two-stage stochastic programming model to obtain the optimal pre-disaster investment for a highway network. Rose et al. (2007) shows that overall, the pre-disaster investment of one dollar has about four dollars benefit in post-disaster stage for earthquake, flood and wind hazards across US between 1993 and 2003. Table 1 summarizes the features of past research and presents a comparison to the research conducted in this paper. As we can see, past research mostly focuses only on either preparedness or relief. While this paper studies both preparedness and relief, and provides analytical solutions.

The damage of disaster has been categorized as direct or indirect loss; tangible or intangible loss. Tangible losses, such as physical destruction of buildings and equipment, can be evaluated by monetary values . Intangible losses are those that cannot be expressed as universally accepted financial terms such as human, social, environmental and cultural losses. Several methods have been applied to estimate intangible losses such as hedonic pricing methods and travel cost methods (Department of Homeland Security, 2011; Markantonis, Meyer, & Schwarze, 2012). Weitzman (2011) uses multiplicative- and additive-form damage functions as a method to investigate the economic impacts from global warming. In this paper, we propose a damage function that takes into account effects of preparedness and relief besides the disaster magnitude.

The probability distribution of disaster magnitude can be described by normal distribution, exponential distribution, and power-law distribution corresponding to the trend, the extreme, and the breakdown type of disasters, respectively (Pisarenko & Rodkin, 2010). The trend, extreme, and breakdown type of disasters are categorized by the ratio of disaster magnitude to the background level from low, medium to high, respectively. Due to the scarcity of large-scale natural disaster and terrorism, it is challenging to accurately estimate the likelihood of disaster occurrence. Some exploratory methods are used to obtain the probability or distribution of catastrophes, such as Bayesian methods, catastrophe theory, entropy maximization, extreme value theory, modeling, and decomposition (Bier, Haimes, Lambert, Matalas, & Zimmerman, 1999). Based on the research conducted by Starr, Rudman, and Whipple (1976), Clauset, Shalizi, and Newman (2009) and Pisarenko and Rodkin (2010), river floods, hurricane energy, droughts and moderate-term sea level variations are usually described using exponential distribution. Heights of sea waves, drought occurrence, tsunamis, tornadoes' damage swath, flood damage magnitude, and earthquake magnitude and frequency are described using lognormal distribution. The frequency of tornadoes is described using negative binomial distribution. Wind speed and wave heights are described using Rayleigh and Weibull