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A Generalized Nash Equilibrium network model for post-disaster humanitarian relief

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ABSTRACT

We develop a Generalized Nash Equilibrium network model for post-disaster humanitarian relief by nongovernmental organizations (NGOs). NGOs derive utility from providing relief supplies to victims of the disaster at demand points in a supply chain context while competing with each other for financial funds provided by donations. The shared constraints consist of lower and upper bounds for demand for relief items at the demand points to reduce materiel convergence or congestion. This game theory problem is reformulated as an optimization problem and numerical examples and a theoretical case study on Hurricane Katrina given.

1. Introduction

The number of disasters has doubled globally since the 1980s with the associated costs of the damage and losses estimated at an average $100 billion a year since the turn of the century (Watson et al. (2015)). Notable natural disasters have included Hurricane Katrina in 2005, the Haiti earthquake in 2010, the triple disaster in Fukushima, Japan in 2011, consisting of an earthquake, followed by a tsunami and a nuclear meltdown technological disaster, the second worst nuclear disaster since Chernobyl in 1986; Superstorm Sandy in 2012, tropical cyclone Haiyan in 2013, and the earthquake in Nepal in 2015 (cf. Nagurney et al. (2015)). Slow-onset, long-lasting disasters have included the political and humanitarian disaster of the Syrian refugee migration crisis, which escalated in 2015 and is continuing (The Economist (2015)). The Ebola crisis in West Africa, which peaked in 2015, and was the largest such outbreak in history, is an example of a health response disaster (cf. Boseley (2015)).

The number of people that are being affected by disasters is also increasing (see Nagurney and Qiang (2009)), posing challenges to disaster relief organizations, including nongovernmental organizations (NGOs). According to Kopinak (2013), humanitarian aid represents a commitment to support vulnerable populations that have experienced a sudden emergency and require assistance. She notes that distinct humanitarian relief organizations may have individual mandates, goals,

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strategies, and associated activities, but the majority operate under a single, common, humanitarian principle: to protect the vulnerable by decreasing morbidity and mortality, to reduce suffering, and support the quality of life. Nevertheless, Kopinak (2013) recognizes that many stakeholders believe that humanitarian aid has not been successful in delivering on these due to a lack of coordination, which results in duplication of services. Moreover, NGOs, such as the Red Cross, rely on donors for financial support and, hence, compete with one another for financial donations. Consequently, there are unique challenges in the important humanitarian aid for disaster relief domain. On the supply side, the main challenge is to secure the donations needed for disaster response and the sustainability of their organizations; whereas, on the demand side, the challenge presents itself as fulfilling the victims' needs while avoiding wasteful duplication and congestion in terms of logistics (cf. Nagurney et al. (2011, 2012) and the references therein).

For example, Barrett and Novack (2015) in the compilation of the Forbes list of the 50 largest charitable organizations in the United States, noted that the Salvation Army, was the second largest charitable organization, and received private donations of $2.12 billion, in its last reported fiscal year, ending September 30, 2014. World Vision, number 11 on the Forbes list, received $832 million in the fiscal year prior, and the American Red Cross, number 16 on the list, received $736 million in private donations. According to Zhuang et al. (2014), approximately $300 billion are donated to charities in the US each year.

Interestingly, and, as noted by Ortuño et al. (2013), although the importance of donations is a fundamental difference of humanitarian logistics with respect to commercial logistics, this topic has "not yet been sufficiently studied by academics and there is a wide field for future research in this context." Toyasaki and Wakolbinger (2014) developed perhaps the first models of financial flows that captured the strategic interaction between donors and humanitarian organizations using game theory and also included earmarked donations.

In this paper, we construct what we believe is the first Generalized Nash Equilibrium (GNE) model for post-disaster humanitarian relief, which contains both a financial component and a supply chain component. The Generalized Nash Equilibrium problem is a generalization of the Nash Equilibrium problem (cf. Nash (1950, 1951)) in that the players' strategies, as defined by the underlying constraints, depend also on their rivals' strategies.

We utilize a network perspective and focus on decentralized decision-making due to the competition among NGOs for financial funds from donations. Given that the number of registered US nonprofit organizations increased from 12,000 in 1940 to more than 1.5 million in 2012, competition for financial funds is clearly an important issue (cf. Muggy (2015)). Moreover, individual decisions of NGOs as to the delivery of resources affect the entire disaster relief system. For example, within three weeks following the 2010 Haiti earthquake there were 1000 NGOs operating in that country (Schear (2015)).

At the same time, as noted in Arnett and Zobel (2015), research has shown that nonpriority flows in the aftermath of disaster can exceed 50%. The flow of supplies, general donations (solicited or unsolicited), and equipment that travels to the site of the disaster is known as materiel convergence (Fritz and Mathewson (1957)). For example, weeks following the 2004 tsunami, the Colombo airport in Sri Lanka was flooded with humanitarian cargo, much of which was nonpriority cargo, which negatively impacted both airport operations and created pressures on warehousing storage. Months afterwards, many of the items remained unclaimed (Thomas and Fritz (2006)). Having superfluous supplies also poses hardship on relief workers (see Hechmann and Bunde-Birouste (2007)). Holguin-Veras et al. (2012), in turn, noted that post the Haiti 2010 earthquake, news media attention of insufficient water supplies in Haiti resulted in massive donations of water to the Dominican Red Cross, resulting in a depreciation of such local goods. Port-au-Price was also saturated with both cargo and gifts-in-kind, so that shipments from the Dominican Republic had to be halted for multiple days. Following the once in 1000 year flood that hit South Carolina in mid October 2015, resulting in more than 19 deaths, a call for bottled water, resulted in too much bottled water donated, shortly thereafter. As a consequence, rescue workers struggled with surplus pallets of it (GoUpstate.com (2015)). The flood of donated inappropriate materiel in response to a disaster is sometimes called the second disaster.

Importantly, our GNE model ensures that demands are met at demand points but not at the expense of overprovision, which results in waste, and an ineffective allocation of resources (Fritz and Mathewson (1957), Thomas and Fritz (2006)) and congestion (Haghani and Oh (1996), Nagurney et al. (2015)). We accomplish this through the imposition of common, that is, shared, constraints among the NGOs with respect to the amounts of the relief item needed at the demand points, in the form of lower and upper bounds on the demands. Such constraints may be imposed by a regulating body in the form of a government or a higher level coordinating humanitarian organization.

The novelty of our GNE network framework captures the following:

1. The nongovernmental (NGO) relief organizations compete for financial funds from donors who respond to the visibility of the organizations at the disaster points. Their utility functions consist of a financial component and a supply chain component.
2. The NGOs, in addition to their individual constraints, face common upper and lower bound demand constraints at each demand point so as to reduce both congestion and materiel convergence, while satisfying the demand.
3. We demonstrate that the GNE model, because of its special structure, can be transformed into an optimization problem, and one does not need to utilize, for example, quasivariational inequality theory (cf. Bensoussan (1974), von Heusinger (2009), and Fischer et al. (2014), and the references therein) for formulation, analysis, and computations.
4. We provide an easy to implement and effective computational procedure, which yields closed form expressions for the product flows and the Lagrange multipliers associated with the supply and demand bound constraints at each iteration.