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Humanitarian relief chain: Rapid response under uncertainty

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ABSTRACT

The recent worldwide devastations have reemphasized the importance of rapid response for saving life. Relief supplies must arrive *on time* and in *adequate* quantities. Coordination in a relief chain is complex because of the uncertainties associated with disaster intensity, strike probability, infrastructure-disruption, and the actual damage. The relief effort must weigh the expected social value against delivery delays, and costs of logistics. We explore a 2-stage proactive/reactive approach where response time and relief amounts are decided *ex post* (after disaster occurs), and the prepositioned inventory is determined *ex ante* (before disaster occurs). Our major findings are: (i) the response quantity and time must be adjusted to imputed social value, but differently at different disaster intensities and cost structures, and in different communities, (ii) disaster intensity can be categorized into ranges that reveal whether rapid response and/or large relief quantity would be appropriate in each range, (iii) effectiveness of the relief strategy decreases as the disaster intensity increases, and (iv) in scenarios with limited budget, it is possible to earmark a unique budget for real time relief operations, that ensures maximization of social value.

1. Introduction

Large scale disasters can lead to a massive loss of life, dislocations, and loss of livelihood. Humans perish from multiple causes such as drowning, fire, and lack of food and medicine. They also suffer from hunger, pain, and illness while waiting for supplies to arrive. The human misery is of great concern as natural disasters have become more severe in the recent time (Stecke and Kumar, 2009). As the National Climatic Data Center points out, "Extreme events are occurring with greater frequency and in many cases with greater intensity" (Rudolf, 2010). Natural disasters cause the most destruction per year, as they are more frequent than other types of disasters (Whoriskey and Hsu, 2006). Estimates of damage from hurricane Katrina exceed $125 billion (Finkle, 2005).

Relief efforts, organized in real time, rely heavily on the logistics infrastructure (Knemeyer et al., 2009). In most cases a combination of different modes of transportation such as air-drops and "last mile" deliveries that use light vehicles are employed. Coordination of relief can be chaotic, as it is extremely hard to assess what supplies are needed and where (Chakravarty, 2005). However, in comparison to prepositioned inventory, real time relief faces reduced risk of resource underutilization. Chakravarty (2011) studies a contingent approach where reactive response is triggered only when the disaster intensity exceeds a threshold value.

In proactive approaches, the reserve of prepositioned inventory acts as a hedge against damages and it can be used immediately after a disaster strikes. For example, the relief organizations and the national governments make advance plans for life-sustenance (shelter, food, and medicine), support personnel, and equipment (FEMA, 2009). However, prepositioning of large inventories can be risky, as assets might be underutilized (Beamon and Kotleba, 2006). This suggests the need of a coordinated approach, integrating prepositioned inventory with real time deliveries. In principle, this would be similar to the 2-stage replenishment in a commercial supply chain (Fisher and Raman, 1996), albeit with some differences.

Unlike a commercial supply chain, humanitarian relief must cope with a huge social cost of victims perishing from the combined effects of shortages and delivery delays. As some of the victims may not survive, the demand for supplies is "perishable" in time, the rate of demand-decay decreasing in human survival rate. Nevertheless, the fact that humans can survive a short time without supplies provides a window of opportunity to rush the supplies to the affected site, and therefore the survival time must be incorporated in decision making. This enables the value of rapid response to be factored in. Not only does the prepositioned inventory generate social value, additional lives saved using real time deliveries add to this value. This is an area that has received scant attention from researchers. Another issue not studied fully is how a reactive strategy may be calibrated to the disaster-intensity.

In this research we study the impact of rapid response on improving human survival. Specifically, we are interested in the optimal mix of prepositioning of inventory, and rapid response through real-time delivery. Thus the relief provider must decide

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the quantity of supplies that must be procured proactively and allocated to potential disaster sites, quantities that must be rushed to the sites after a disaster strikes, and the speed of response in real-time. To model rapid-response, we incorporate the delivery time in defining the demand for supplies and the cost of logistics. This enables us to express the optimal delivery quantity as a function of delivery time. We study how the response options are impacted by the intensity of the disaster, and how the response time and quantity interact from a strategic perspective. Although our analysis (with some modification) can be applied to any disaster, we use natural disasters such as hurricanes as the frame of reference and orient our model to it.

1.1. Related research

Supply chain issues such as coordination, capacity, inventory, and pricing have been studied extensively in the literature over the last 15 years (Cachon, 2003). That notwithstanding, the attention paid to supply chains for disaster management with its unique characteristics, has been scanty. As Beamon (2004) points out, a humanitarian supply chain must cope with a surge in demand for essential supplies, equipment, and manpower in an imperfect marketplace. Deliveries of critical supplies get delayed due to damage to the logistics infrastructure. In addition, as relief networks are formed in haste, they need to deal with "deficit of trust" (Tatham and Kovacs, 2010). Note that, unlike a commercial supply chain, consumers of relief supplies are not customers in the traditional sense; they are victims who account for high social costs.

Existing research in humanitarian relief is focused at two "ends" of a spectrum. At one end are the issues such as organization culture, responsibility, and politics (Dowty and Wallace, 2010; Day et al., 2012; White, 2012), coordination (Balcik et al., 2010), and networking (Oloruntoba and Gray, 2006). At the other end are logistics issues such as routing of delivery trucks (Balcik and Beamon, 2008; Salmeron and Apte, 2010). In between these two extremes are a host of issues that have not yet been addressed adequately (Holguin-Veras et al., 2012). Long and Wood (1995) and Whybark (2007) raise interesting questions: whether the current theories and concepts developed for commercial supply chains are adequate in restoring damaged supply lines, setting up new supply chains "on the fly", and resolving the "last mile" distribution problem. A related important issue, not fully explored, is the need for rapid response. Kleindorfer and Saad (2005) and Lee (2004) make a beginning by outlining how excess capacity, inventory buffers, and flexibility may enable quick response. In our research, we address multiple facets of quick humanitarian response: delivery delays, perishable demand, and logistics cost. Altay and Green (2006), using a sample of manuscripts, point out that analysis of humanitarian issues was non-existent in their sample, and almost all of the response related articles belonged to the "logistics" end of the spectrum referred to above. They also note that only 12% of the manuscripts discussed natural disasters.

Our model – optimal mix of prepositioned and real-time inventory for rapid response – is somewhat similar to the 2-stage production model of Fisher and Raman (1996): an initial capacity built on demand forecast, with the provision for adding capacity when additional information on demand is available. In a similar vein, Cattani et al. (2008) establish conditions for investment in both reactive and proactive capacities (also known as speculative capacity). The above similarities notwithstanding, our model is different in several aspects. First, the reactive procurement decision is made only after the disaster intensity becomes known; second, unsatisfied "customers" do not leave the system; third, the decay in demand is dependent on the human survival function; and fourth the marginal social value is a function of the response time.

It is clear that in an integrated proactive/reactive approach such as ours, the downside and upside risks of prepositioned inventory must be balanced. However, the application of risk management to humanitarian relief is scant (Seshadri and Subrahmanyam, 2005). Related research on risk mitigation is discussed in Chopra and Sodhi (2004) and in Hendricks and Singhal (2005). Tomlin (2006) and Albeniz and Simchi-Levi (2005) have investigated the effectiveness of various mitigation strategies. Stauffer (2003) studies the vulnerability of supply chains to disasters. Lee et al. (2009) describe a dynamic simulation model of disaster logistics.

In Section 2 we discuss issues such as human-survival and logistics cost. The 2-stage response strategy is discussed next in Section 3, and the implications of disaster severity on real time decisions are explore in Sections 4 and 5. In Section 6 we discuss implications of budget constraints. In Section 7 we discuss the implications of our results in implementing the relief strategy, and we conclude in Section 8.

2. Survival, infrastructure, and destruction

We first discuss a framework for studying the impact of human survival rate and logistics time on demand for supplies. This framework is then used in establishing the social surplus.

2.1. Survival

Loss of life may occur instantly at the time of disaster ($t=0$) from causes such as drowning, fire, and suffocation in debris; or later ($t>0$) from delays in receiving supplies. The value of saving a human life is not easy to determine. Landefeld and Seskin (1982) describe two approaches for valuing human life: human capital (HC), and willingness to pay (WTP). While HC estimates the future income potential of an individual, WTP assesses the amount a community would be willing to spend to save a human life. The authors also describe how statistical surveys can be designed for estimating the WTP. In our context, we use WTP as a social cost of disaster relief and we denote it as v_1. The value of v_1 is estimated as \$5.8 million (and rising) by FEMA (Burbank, 2009). Miller (2000) points out that the value of life may vary between countries due to differences in cultural norms or in market forces. OECD (2012) and Viscusi and Aldy (2003) also arrive at the same conclusion.

In structuring a strategy for response, the social value must be weighed against the cost of acquiring and transporting relief supplies. This requires incorporation of the interplay between the quantity of needed supplies and the delays in delivery. We capture this interaction in Fig. 1, where Q is the amount of prepositioned inventory available at time zero (for instant relief), and q is the amount delivered to the site at time τ, where τ is the time to transport supplies to the disaster site. Note that at most Q

	Cumulative Number of Victims Saved
Time $t \le \tau$	Cell A_1 Minimum (demand, Q)
Time $t > \tau$	Cell A_2 Minimum (demand, $Q+q$)

Fig. 1. Response time and quantity.