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Dynamic relief-demand management for emergency logistics operations under large-scale disasters

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ABSTRACT

This paper presents a dynamic relief-demand management model for emergency logistics operations under imperfect information conditions in large-scale natural disasters. The proposed methodology consists of three steps: (1) data fusion to forecast relief demand in multiple areas, (2) fuzzy clustering to classify affected area into groups, and (3) multi-criteria decision making to rank the order of priority of groups. The results of tests accounting for different experimental scenarios indicate that the overall forecast errors are lower than 10% inferring the proposed method's capability of dynamic relief-demand forecasting and allocation with imperfect information to facilitate emergency logistics operations.

1. Introduction

Emergency logistics management has emerged as a globally concerned theme as natural disasters ubiquitously occur around the world. For instance, Cyclone Nargis ruthlessly striking Myanmar coasts on May 02, 2008 accompanied with the military government's anomalous restrictions on foreign aid workers and equipment has reportedly affected about 2.5 million people who urgently needed aids to survive. This is followed by a 7.9 magnitude earthquake hitting Sichuan, the southwestern China on May 12, 2008, which has raised not only the worldwide shock about the news of thousands of victims trapped under the ground but also the growing awareness of the issues on emergency logistics and rescue, particularly for urgent relief-demand management.

Dynamic relief-demand management is the key to the success of emergency logistics operations under the condition of large-scale natural disasters. In reality, the difficulty of relief-demand management is rooted in the uncertainties of relief-demand information due to the following phenomena. First, unlike business logistics (BL) where consumers themselves are the demand information provider, the relief demander (i.e., disaster-affected people) may not be the same as the relief-demand information provider in the emergency logistics context. Instead, those on-the-spot reporters, rescuers and charities usually act as the main information sources; thus, leading to the asymmetry of relief-demand information. Second, the relief-demand information sources are diverse, and usually provide the data under chaotic conditions without the aid of decision support tools and enough time for verification. Furthermore, the relief-demand information needed for emergency logistics is a kind of area-based demand information, i.e., the aggregated relief demand associated with each affected area, rather than the disaggregate demand information which is conventionally treated in business logistics. Such demand, to a certain extent, features uncertainties, and is hard to be approximated using historical data. The aforementioned relief-demand information issues have caused serious impact on the performance of relief-demand management, as

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observed in the recent catastrophes such as the Chichi earthquake in Taiwan (1999), the tsunami in the Indian Ocean (2004), the hurricane Katrina in the US (2005), and the Myanmar cyclone (2008). Apparently, real-time relief-demand forecasting underlines the challenge of dynamic relief-demand management in the area of emergency logistics management (ELM).

Despite the urgent necessity of dynamic relief-demand management, there is no straightforward demand model available for the above issue. Instead, most of the existing demand models appear to be limited to general cases for business operations. From the literature review, we illustrate several related subjects associated with typical models in the following for further discussion.

In operations research and related application areas, the theory of time-series processes appears to be the most flexible to model demand dynamics over time. Therein, methods such as the AutoRegressive and Integrated Moving Average (ARIMA), exponential smoothing models, and independent identically distribution (IID) models have been widely used to deal with various problems of dynamic demand forecasting (Wei, 1990; Box et al., 1994; Aviv, 2003; Gilbert, 2005; Zhang, 2006). The common feature of these efforts is that the forecasts of time-varying demands have certain correlations with their historical values characterized in either linear or nonlinear forms with the dynamic evolution of the mean value of demand over time. Particularly, the previous literature adopts the first order autoregressive processes to deal with the demand variations under the impact of SCM phenomena, e.g., the bullwhip effects (Lee et al., 1997; Chen et al., 2000) and information sharing (Gavirneni et al., 1999; Lee et al., 2000; Raghunathan, 2001). Further, some researchers take into account the temporal heterosedasticity of demand variance, thus evolving sophisticated models such as Generalized AutoRegressive Conditional Heteroscedasticity (GARCH) processes for dynamic demand forecasting (Baganha and Cohen, 1998; Gilbert, 2005; Zhang, 2006).

In contrast with the aforementioned time-series based demand models, real-time relief-demand forecasting must overcome more issues in demand uncertainties, as mentioned previously. Furthermore, its problem nature stems from the lack of previous demand information. This may lead to the difficulty in tracing the time-varying relief demand pattern merely using time-series data processing mechanisms. In brief, the existing time-series based demand models appear unsuitable for real-time relief-demand forecasting addressed in this study.

Despite the recent emergence of emergency logistics management that has increasingly drawn researchers' attention, most of the pioneering works appear to aim at addressing the issues of relief supply and distribution contingent on the plausible assumptions in terms of relief demands. Yi and Kumar (2007) propose an ant colony optimization (ACO) based heuristics, which decompose the original emergency logistics problem into two decision-making phases: the vehicle routes construction and the multi-commodity dispatch in disaster relief distribution. Therein, they treat wounded people, vehicles, and relief as commodities, and then solve such a multi-commodity network flow problem using the proposed ACO meta-heuristic algorithm. Based on certain idealistic assumptions with respect to disaster information acquisition and communication to simplify the disaster contextual background, Tzeng et al. (2007) formulate the corresponding relief distribution problem with a fuzzy multi-objective programming method. Distinctively, they conceptualize the satisfaction of fairness in formulating the multi-objective functions to avoid the possibility of a severely unfair relief distribution to certain affected areas in the relief distribution process. Considering the dynamics and uncertainties of relief demands in the crucial rescue period of a large-scale disaster, Sheu (2007) proposes an emergency logistics co-distribution approach for dynamically responding to the urgent relief demands in the crucial rescue period. The feature of Sheu's methodology is that two types of urgent relief including the daily consuming relief (e.g., water and meal boxes) and daily-used equipment for refugees (e.g., sleeping bags and camps) are considered. Furthermore, Shue conceptualizes the buffer relief demand in the formulation of a simplified dynamic relief demand forecast model. Relatively, Chiu and Zheng (2007) aim to address the issue of dynamically assigning multiple emergency responses and evacuation traffic flows outbound from the affected areas using a proposed cell transmission-based linear model.

Accordingly, this study presents a dynamic relief-demand management model to address the above issue under the conditions of disorder and uncertain relief-demand information sourcing from affected areas during the crucial rescue period of a large-scale natural disaster. Rooted in the techniques of data fusion coupled with fuzzy clustering and TOPSIS, the proposed methodology embeds three mechanisms: (1) dynamic relief-demand forecasting, (2) affected-area grouping, and (3) identification of relief-demand urgency. Here the crucial rescue period refers to the initial three days following the onset of a disaster, which is the most critical period to search and rescue the trapped survivals. Relative to the previous literature, the proposed relief-demand management methodology has the following two distinctive features.

(1) The model is capable of updating the time-varying numbers of survivals trapped in the affected areas so as to approximating the time-varying relief demands through data fusion techniques. Note that in the large-scale disaster contexts, the number of fatalities including the missing people may vary over time upon the severity of the disaster conditions, and meanwhile, the related information may come randomly from diverse information sources in affected areas. As such, the quality (e.g., accuracy) and reliability (e.g., information update frequency) of these multiple information sources appear to be uncontrollable under emergency conditions. Considering both the uncertain and dynamic features of relief demands mentioned above, first we propose to utilize the data fusion technique to deal with multiple sources of information in terms of the number of fatalities randomly collected from a given affected area. This is followed by the estimation of the aggregated relief demands needed in real time by the corresponding survivals. Such a measure is rare in the area of either demand forecasting or emergency logistics management.
(2) To facilitate dynamic relief demand allocation and distribution, the proposed model dynamically groups the affected areas using fuzzy clustering, followed by the identification of group-based relief-demand urgency through the TOPSIS