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Relief inventory modelling with stochastic lead-time and demand

Rubel Das *, Shinya Hanaoka

International Development Engineering, Tokyo Institute of Technology, Tokyo, Japan

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ABSTRACT

The irregular demand and communication network disruption that are characteristics of situations demanding humanitarian logistics, particularly after large-scale earthquakes, present a unique challenge for relief inventory modelling. However, there are few quantitative inventory models in humanitarian logistics, and assumptions inherent in commercial logistics naturally have little applicability to humanitarian logistics. This paper develops a humanitarian disaster relief inventory model that assumes a uniformly distributed function in both lead-time and demand parameters, which is appropriate considering the limited historical data on relief operation. Furthermore, this paper presents different combinations of lead-time and demand scenarios to demonstrate the variability of the model. This is followed by the discussion of a case study wherein the decision variables are evaluated and sensitivity analysis is performed. The results reveal the presence of a unique reorder level in the inventory wherever the order quantity is insensitive to some lead-time demand values, providing valuable direction for humanitarian relief planning efforts and future research.

1. Introduction

Logistics research and practice is usually applied in the context of commercial logistics (Kovacs & Spens, 2009). Recently, humanitarian logistics (HL) has gained attention because it is uniquely different from commercial logistics (CL), particularly in the context of appropriate relief delivery (e.g. water, medicine, and shelter) to disaster survivors. Thomas's (2003) study on logistics management revealed that the progress of HL research is thirty years behind that of CL, and several studies have compared and contrasted the characteristics of the two (Balcik & Beamon, 2008; Van Wassenhove, 2006). However, as Whybark (2007) has argued, humanitarian logistics inventory management (HLIM) is thus far neither well researched nor clearly understood.

Table 1 summarizes the differences between commercial and humanitarian inventory management. Commercial logistics inventory management (CLIM) has the characteristics of a static network that focuses on product distribution and gathers historical data for demand forecasting. In contrast, HLIM, according to Whybark (2007), is a social inventory that aims to meet the needs of disaster survivors in a timely fashion; as such, its demand-forecasting model is based on quick assessment. For both CLIM and HLIM, lead-time (i.e., the interval between the placement of an order and the arrival of ordered goods) is a controlling factor for inventory modelling. However, HLIM's driving forces, such as philanthropy and human suffering, necessitate a new model.

According to an internal report of the International Federation of Red Cross and Red Crescent Societies (IFRC), the current lead-time during earthquake relief operation is unacceptably long. The comparison of inventory management factors in Table 2 shows that the Indian Ocean tsunami relief response lead-time was 30 days; in comparison, the lead-times for the Pakistan and Yogyakarta earthquake relief operations were significantly reduced. As humanitarian relief lead-time is governed by several factors (e.g. transportation, order preparation, and order delivery), its duration cannot be predicted with certainty. In addition, it appears that logistic costs (e.g. items, transport, and storage cost) comprise a significant share of the total cost of earthquake relief operations. Therefore, these factors should inform the formulation of a new HLIM model for large-scale earthquake relief operations.

There have been some key studies on disaster operations management; for example, Altay and Green (2006) provided a holistic review of mathematical models in disaster operations management until 2004, while Galindo and Batta (2013) developed an extensive review of recent progress in the field. Additionally, though many studies emphasize the importance of HLIM (Kovacs & Spens, 2009; Whybark, 2007), few studies have paid serious attention to quantitative inventory modelling in this context. Beamon and Kotleba (2006) addressed the problem of man-made emergencies (i.e., war and conflict) and demonstrated the problem of uncertain demand for static lead-time in times of war. In contrast, Ozbay and Ozguven (2007) analyzed the inventory problems associated with supporting hurricane survivors living in shelters. Having assumed that lead-time-demand (LTD) is a multivariate normally distributed parameter, they examined the effects of the

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* Corresponding author. Tel./fax: +81 3 5734 3468.
E-mail address: rubeldas@tp.ide.titech.ac.jp (R. Das).

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Table 1
Properties of commercial and humanitarian inventory management.

	Commercial inventory	Humanitarian inventory
Demand forecasting	Historical data	Quick assessment (Sheu, 2007)
Network structure	Predetermined	Dynamic
Fleet size	Unlimited	Limited
Inventory type	Strategic inventory	Social inventory (Whybark, 2007)
Preferred acquisition	Low-cost source	Nearest source
Benefit of inventory	Higher service level	Saving human lives
Out of stock	Scheduled arrival	Finding the responsive supplier

Table 2
Inventory management factors in earthquake (EQ) relief operation of IFRC. *Source:* Cuckow, 2006 (tabulated from Gatignon, Van Wassenhove, & Charles, 2010)

	Indian Ocean Tsunami (2004)	Pakistan EQ (2005)	Yogyakarta EQ (2006)
Order lead-time (requisition to delivery) in days	30	23	16
% Of appeal items mobilized and delivered at 2 months	55%	38%	74%
% Of logistics cost at 8 months (items + transport + storage value)	–	86%	87%

changing parameter. However, according to Eppen and Martin (1988), ‘the normality assumption of lead-time-demand is unwarranted, in general, and this procedure can produce a probability of stocking out that is egregiously in error’.

Another way of representing LTD is to discretely assess the properties of lead-time and demand. Most inventory models generally assume that either demand or lead-time is a deterministic parameter. While studies on stochastic demand with constant (or zero) lead-time are a popular research area in inventory modelling (Kouvelis & Li, 2008; Kouvelis & Tang, 2012; Moinzadeh & Nahmias, 1988), studies on stochastic lead-time with constant demand have attracted less attention (Bookbinder & Cakanyildirim, 1999; Zipkin, 1986). Therefore, there is a need to bridge these two research streams to analyze scenarios where the stochastic relief demand and the stochastic lead-time are combined to calculate the expected LTD (i.e., multiplication of lead-time and demand).

With this in mind, we attempt to explore the difference between CLIM and HLIM, with a particular focus on large-scale earthquake disasters where both demand and lead-time are stochastic. In this study, we propose an HLIM model that combines decisions about the reorder level (RL), order quantity, the probability of a stock-out per cycle, the expected shortage cost per cycle, and the expected holding cost per cycle, with the assumption of stochastic lead-time and stochastic demand following a large-scale earthquake.

Accordingly, this study presents a stochastic HLIM approach in a two-stage relief supply chain to support decision-making during the relief response phase. More specifically, the proposed approach uniquely includes two distinct features:

1. We propose a model to estimate LTD, average inventory per cycle, and cycle length for stochastic demand and lead-time for HLIM.
2. Due to the distinctive feature of relief logistics, we incorporate exigent orders and systematic orders to minimize expected relief shortage.

The remainder of this paper is organized as follows. In the model (Section 2), we introduce the formulations of the expected LTD, average on-hand inventory, and expected shortage per cycle, as well as an algorithm for a multi-product system. This section also determines the optimum order quantity using a first-order differential equation. Then, in the case study (Section 3), we discuss a numerical example, a parametric programming-based solution, and its analysis. Finally, in the conclusion (Section 4), we summarize the outcome and the contributions of this study.

2. The model

2.1. System characteristics

Fig. 1 shows the two-stage system for distributing relief to disaster survivors; it is a simplification of a relief operation system used after the Tohoku earthquake in Japan. There are two stocking points: the first stocking point, located at the earthquake-affected area, is known as the point-of-distribution (POD); the second stocking point, located at an unaffected area, is called the central warehouse in this study.

In this two-stage supply chain model, the POD follows a continuous inventory review strategy to place orders with the central warehouse. It is assumed that the central warehouse is capable of delivering the requested amount of relief. The on-hand inventory at POD at the time of order placement with the central warehouse is r_1, which is expected to meet LTD. The placing of an order at the inventory level r_1 is called a ‘systematic order’ in this case. If the inventory level at POD reaches the threshold limit before the arrival of the systematic order, the logistics manager places an additional order—called an ‘exigent order’—in an effort to prevent shortages. Thus, the threshold limit of the inventory at POD is r_2. Then, without losing generality, the limit of the two inventory levels is $0 \leqslant r_2 < r_1$.

When lead-times are stochastic, orders may not be received in the same sequence as they were placed. This phenomenon, known as an ‘order crossover’, complicates analysis. To address this problem, it is usually assumed that orders do not cross in time (Hadley & Whitin, 1963; Kaplan, 1970; Tijms & Gronevevelt, 1984) or that not more than one order is outstanding at any point in time (Moinzadeh & Nahmias, 1988). This study assumes that an exigent order will arrive earlier than a systematic order; since an exigent order is delivered by an expediting service (e.g. by air or special convoy) rather than systematic services, it incurs a higher cost than that of a systematic order. The exigent supply source is assumed to be within the affected country or in a nearby country.

In this study, we explore a strategy to prevent shortage without having to resort to an exigent order. For the purposes of analysis, we assume an infinite time horizon for the relief operation. While all relief operations in practice have a termination point, our model assumes the relief operation will continue as long as there is relief demand, and internally adjusts the decision variables as demand changes. It should be noted here that the assumption of infinite time horizon affects only the modelling formulation, since no order

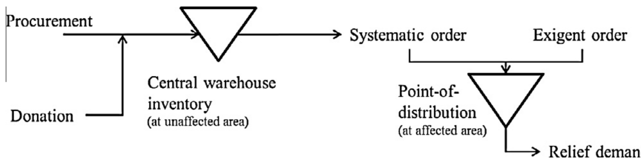

Fig. 1. The schematic representation of an earthquake relief inventory model.