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Post-seismic supply chain risk management: A system dynamics disruption analysis approach for inventory and logistics planning

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ABSTRACT

Post-seismic inventory and logistics planning under incomplete and fuzzy information is an important yet understudied area in supply chain risk management. The goal of this paper is to propose a system dynamics model to analyze the behaviors of disrupted disaster relief supply chain by simulating the uncertainties associated with predicting post-seismic road network and delayed information. The simulation results indicate: (1) information delay has different influences over the relief headquarter (the upstream) and the disaster-affected areas (the downstream); and (2) the change of road conditions and shipment schedules have impact on the on-time transportation rate in supply chain management. Furthermore, this paper defined and tested supplies' replenishment solutions combined with three inventory planning strategies and four forecasting methods under different lead time uncertainties. The results show that: (1) a strategy that considers information from both the post-seismic management center and the affected areas can provide a better logistic plan than an one takes information from one side; (2) the smooth-the-trend forecasting method is suitable for inventory and logistic planning when the post-seismic situations are volatile, while the quick-response forecasting method has good performance in stable environments. In addition, this paper proposes decision tree to help decision makers choose the appropriate stocking strategies.

1. Introduction

With the frequent occurrence of disasters and incidents in recent years, there has been an increase in the interest of the international academic community in the challenges of the humanitarian supply chain [1]. Whybark et al. [2] reviewed scholarly journal articles after the January 2010 Haiti earthquake, and suggested that the disaster relief supply chain is a subset of the humanitarian supply chain because its operating environment is extremely uncertain and dynamic. Beamon [3] made a detailed comparison list between disaster relief operations and normal commercial activities, including demand pattern, lead times, distribution network, inventory control, information system, and strategic goals. Consequently, practices that may work well in commercial settings may not be appropriate in disasters responses [2].

Road conditions varied under different geological conditions. After the 2008 Wenchuan earthquake, some roads were damaged or even disrupted for a long period. Some roads were quickly repaired and were destroyed again by aftershocks and secondary disasters, while some others maintained a fluctuating transportation capacity. The transport time of supplies varied in this circumstances. In addition, information regarding demand and material inventories was often delayed and disrupted by dynamic information delay (ID), and was even completely unavailable in some circumstances. Such wide-ranging uncertainties present significant challenges to make the replenishment decisions. However, comparing with the studies on demand forecasting, there has been less studies in the dynamic lead times prediction.

System dynamics (SD) is a popular approach to study such problems for its ability to deal with high levels of uncertainty, causal ambiguity, and complexity. In this paper, we implement an SD model to describe the disaster relief supply chain with dynamic road conditions and ID by combining existing researches on transportation, supply chains, and seismic risk assessment. To evaluate the impact of the environmental factors and the effect of the response decisions, the replenishment solutions are combined with three inventory planning strategies and four forecasting methods, and different scenarios which match solutions with the dynamic circumstances were also suggested. After the analysis of the simulation results, a decision tree is proposed to assist the decision-makers to choose the stocking strategies based on quantified risks after a disaster strikes.

The rest of this paper is organized as follows: Section 2 reviews the related works in supply chain risk management and system

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dynamics disruption analysis. Section 3 defines the research problem and describes the proposed system dynamics model. Section 4 represents the simulation results and discusses how the inventory and logistics planning decision should be made. Section 5 summarizes the paper with conclusions and future research directions.

2. Literature review

Since Lee et al. [4] indentified the bullwhip effect and its causes, lots of studies have been conducted on demand forecasting, information sharing, and coordination among supply chain members. Factors such as variable lead times and/or delayed information transfers are also included in such studies. However, in commercial supply chain research, researchers usually focus on just one of these factors to assure a stable environment in term of lead times. For example, He et al. [5] assumed lead time to be stochastic and measurable; Handfield et al. [6] described lead times as a fuzzy set; and Song and Zipkin [7] compared the performances of a multiple source supply system with different types of lead times that were constant, stochastic, and exogenous. Only a few studies have considered the delay of lead times. For example, Bensoussan et al. [8] studied the ID of an inventory system caused by the instability or failure of a data management system, and they used several stochastic ID and one constant transport delay.

Researchers also made similar assumptions in humanitarian logistic and disaster relief supply chains research. In resource scheduling models in emergency situations, the transport delay is usually set as a fixed value [9,10]. However, in the real-life dynamic situations in disaster areas, according to Özdamar et al. [11], actual vehicle numbers is more accurate in representing the limitations of transport capacity.

SD models were introduced to describe and analyze the behavior of the supply chain, with different types of delay. Barlas and Gunduz [12] defined three typical ordering policies in an SD model to investigate the structural sources of the bullwhip effect, and explored the effectiveness of information sharing to eliminate undesirable fluctuations. Ge et al. [13] presented an SD model to analyze the bullwhip effect in the supply chain of a supermarket. They compared the system performances of eight scenarios based on different assumptions of ID, demand forecasting, and information sharing. Rubiano and Crespo [14] evaluated the impact of using Internet-based e-collaboration tools in supply chain management. They built an SD model that consisted of four trade partners, and the four types of collaborative approaches among them were compared. In the researches above, unique lead times in material transportation and delay times in order transfer are assumed to be constant for each supply chain member.

SD models have been used to simulate a wide range of disasters, such as road rush-repairs after an earthquake [15,29], coal mine accidents [16,17], and floods [18,19]. For an example, Besiou et al. [20] discussed the advantages of studying disaster relief issues using SD methodology, and took an example of field vehicle fleet management to show how SD captures complexity. However, less studies have been done on selection of inventory planning strategies and forecasting methods in emergency supply chain management. In this research, we will discuss how the replenishment process of emergency supplies could be impacted by the dynamic environmental factors comparing with the traditional supply chain model.

3. Analysis of the problem and the system dynamics model

Suppose there exists a post-seismic area shown in Fig. 1. The shaded part at the left represents mountain area, and the remaining white area represents plain area. The epicenter is located in the mountain area with several disaster-affected towns surrounding it. During a disaster relief operation, supplies must be delivered from the relief headquarters (HQ) to those towns. Thus, a two-stage relief supply chain is established. Unlike the usual commercial supply chain, material and information flows are affected by the earthquake and continual aftershocks, which cause dynamic transport delays and ID. Each town will suffer different degrees of delays because of their geological conditions and distance from the epicenter. The environmental assessment and the decision-making structure are described in this section.

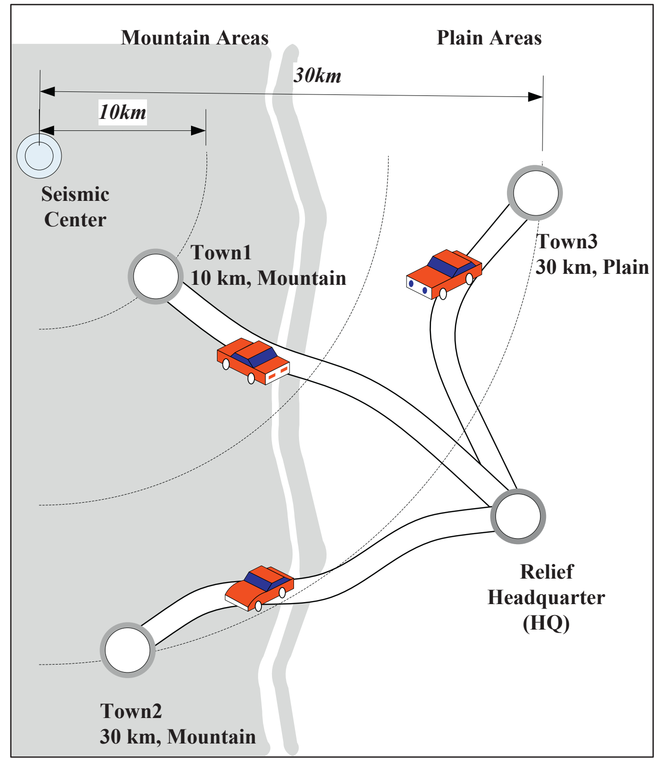

Fig. 1. Environment of post-seismic relief.

3.1. Environmental factors in post-seismic area

3.1.1. Dynamic road capacity

The factors that affect transport conditions can be described in a causal loop diagram as shown in Fig. 2. The damage energy released by the earthquake, measured as peak ground acceleration (*PGA*), will decrease over distance. Continuing aftershocks and secondary disasters like landslides and debris flows increase the level of damage to the road system. These damage types are accumulated and included as a state variable *Road Damage Stack*, which is reduced by the continual attempts at road repair, and are converted dynamically into *Road Capacity Loss*. The *Mountain Factor* aggravates the geological hazards, but decreases the effort of repair. In addition, the greater the *Road Capacity Loss*, the less the *Effective Repair Ability*.

In seismic risk assessment, researchers have developed several models to determine the performance of transportation network systems after large-scale disasters. Shinozuka et al. [21] suggested that bridges are the most vulnerable of all engineered components under seismic conditions, so the assessment of road networks can be simplified to the assessment of bridges. They developed empirical bridge damage fragility curves expressed as log normal distribution functions of *PGA*, which were evaluated using the degradation of the traffic capacities of Los Angeles networks after