Knowledge-Based Systems 89 (2015) 126–133

Contents lists available at ScienceDirect

Knowledge-Based Systems

journal homepage: www.elsevier.com/locate/knosys

4PL routing optimization under emergency conditions

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ARTICLE INFO

Article history:
Received 14 January 2015
Received in revised form 19 June 2015
Accepted 25 June 2015
Available online 30 June 2015

Keywords:
4PLROP
Emergency logistics
3PL
Uncertainty theory
Chance-constrained programming
Cumulative prospect theory

ABSTRACT

Routing optimization is one of important problems in fourth party logistics (4PL) management. Under emergency conditions, effectively describing uncertain parameters for routing optimization entails major challenges because of a lack of historical data. Hence, this paper studies a fourth party logistics routing optimization problem (4PLROP) with uncertain delivery time under emergency conditions. A novel 4PLROP uncertain programming model (UPM) under emergency conditions is proposed by describing the uncertain delivery time as an uncertain variable based on the uncertainty theory (UT) first. Then, to justify the advantage of UPM for addressing this problem with little historical data, UPM is compared with the stochastic programming model (SPM) in which the uncertain delivery time is described as a stochastic variable based on probability theory. The comparison results show that the UPM solution can satisfy the belief degree constraint, which is used to describe the customer delivery time requirement, whereas the SPM solution cannot. Finally, numerical examples are used to verify the effectiveness of the proposed method. The results also suggest the proposed model's advantages.

1. Introduction

One serious problem in logistics industry is emergency logistics management. Disasters result in huge demands; however, limited resources are available. The process of planning, managing, and controlling the flow of those resources to provide relief to affected people is called emergency logistics [1].

In recent years, because a number of disasters happen occasionally yet deliver great loss to human beings, emergency logistics has attracted increasing attention [2]. Many researchers have devoted efforts to studying this field. Altay and Green [3] and Galindo and Batta [4] provide a holistic review of the use of OR/MS methods in disaster operations management (DOM) and categorize the research into three classes: model development, theory development and application development. Caunhye et al. [5] summarize that the key challenges to emergency logistics planning compared with the business logistics case are the additional uncertainties, complex communication and coordination, the harder-to-achieve efficient and timely delivery, and the limited resources often overwhelmed by the scale of the situation.

In this paper, we focus on these challenges and attempt to solve them from two perspectives. One perspective regards how to coordinate those limited resources to service more affected people timely and effectively. The other regards how to describe and handle those uncertainties accurately and efficiently under emergency conditions.

In an emergency, coordination involves many issues, such as obtaining valid information, the scattered distribution of limited resources and capacities, complex communication and the coordination between logistics providers [5]. These are important reasons restraining the effective operation of emergency logistics. To address this challenge, fourth party logistics (4PL), which has inherent advantages in integrating complementary resources and optimizing the supply chain, can be used.

Internationally, the logistics industry is considered the arteries and the basis of national economic development. Logistics outsourcing is now a mainstream business. In logistics outsourcing, logistics services are outsourced to special enterprises known as third party logistics (3PL) [6]. In recent years, 3PL's integration and promotion steps have accelerated. At the same time, 3PL providers' professional service capabilities have markedly increased. However, most 3PL providers mainly provide transportation and warehousing services. These providers lack cooperation, and their complementary resources have not been effectively utilized. Thus, the integration and management of these 3PL providers to benefit supply chain members and optimize the supply chain presents a difficult and urgent problem.

To overcome the limitation of 3PLs, 4PL, which strives to integrate and manage the logistics chain, emerged. Andersen

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http://dx.doi.org/10.1016/j.knosys.2015.06.023
0950-7051/

Consulting first introduced the concept of 4PL and provided a widely accepted definition in 1998 [7]: "It is an integrator that assembles the resources, capability, and technology of its own organization and other organizations to design, build, and run comprehensive supply chain solutions."

As a supply chain integrator, 4PL meets the need of modern logistics and has attracted the focus of many researchers. Current studies mainly focus on four aspects. First, certain researchers focus on the conceptual study and discuss the inevitabilities and advantages of 4PL [8]; they reveal that 4PL is emerging as a breakthrough solution to modern supply chain challenges [9,10]. Second, other researchers focus on the performance evaluation of 4PL and 3PLs [11,12]. Third, coordination between 3PL and 4PL is also studied, such as contract design [13,14] and the assignment problem [15]. Fourth, certain literature [16–20] focuses on routing optimization in a 4PL network. Furthermore, the fourth party logistics routing optimization problem (4PLROP) is a fundamental and unavoidable problem in a 4PL's actual operation. The core problem is to manage and optimize the distribution process from the source to the destination; this directly relates to the operational efficiency. The 4PLROP includes two main aspects, i.e., route selection and the 3PL provider's selection; this increases the problem's complexity. Many issues lead to difficulty in finding solutions: a complex network, customers' various requirements, a complicated and fickle environment, etc. Chen et al. [21] apply a multi-graph to 4PL and determine its brevity and effectiveness advantages. They establish a directed graph model with multi-dimensional weight for the optimization problem involving the concurrent selection of the route, transportation method and 3PL providers. Huang et al. [22] study the 4PL problem with soft time windows, in which cost, time, transportation capacity, and the 3PL provider's reputation are considered. In these studies, the delivery time is mainly assumed to be a deterministic number. However, for an emergency, delivery time is not a deterministic number for types of uncertainties, such as weather, traffic, and human uncertainty. The appropriate description of the delivery time is important.

To address these uncertainties in emergency logistics management, many scholars [5] devote research time and effort; some study routing optimization. Yuan and Wang [23] consider that the travel speed on each arc will be affected by a disaster extension. However, they consider changes of delivery time from a deterministic perspective. Considering strong uncertainty under emergency conditions, Sheu [1] and Aharon [24], respectively, study the problem from the perspectives of fuzzy clustering and robust optimization. More related research [25–27] regarding routing optimization describe this uncertainty as a stochastic type. However, for an emergency, the whole logistics delivery process has strong uncertainty, in which the driving factor includes weather, traffic, and human uncertainty, and real decisions are usually made in the state of indeterminacy [28]. In this condition, most of the past data are no longer valid, and the delivery time is difficult to determine for types of noise. Therefore, describing the delivery time reasonably and developing an effective transportation solution with limited resources, is very challenging.

To describe indeterminacy, most literature characterized the uncertainty involved as randomness [25–27] based on probability theory (PT). Probability is interpreted as frequency, because the long-run cumulative frequency is close enough to the probability distribution when the sample size is large enough. However, no samples or not enough samples are available to estimate a probability distribution under emergency conditions; therefore, describing indeterminacy as randomness is not reasonable under this condition. Because of a lack of historical data under emergency conditions, a 3PL provider's delivery time cannot be described as either a deterministic or a stochastic number. Thus, effectively describing delivery time for routing optimization is a problem.

To address this problem, people generally have to invite some domain experts to evaluate their belief degree that events will occur. Nevertheless, human beings usually overweight unlikely events [29,30]. Therefore, the belief degree function will have much larger variance than the long-run cumulative frequency [28]. In this situation, if we insist on addressing the belief degree by PT, counterintuitive results may be obtained [31]. Thus, a new approach, which is based on the belief degree and consistent with human beings usually overweighting unlikely events, called uncertainty theory (UT) [32], is used in our model to describe delivery time. UT was proposed in 2007 and refined in 2010 by Liu [32,33]. This theory effectively solves the problem regarding addressing the belief degree from some domain experts in uncertain environments, whereas PT cannot because no samples are available to estimate a probability distribution. Nowadays, UT has become a branch of axiomatic mathematics for modeling human uncertainty and has been applied to address various problems under incomplete information scenarios [34–36], such as emergency scheduling problems [37], shortest path problems in a transportation network [38], multi-product newsboy problems [39], and uncertain graph problems [40].

In this paper, a novel 4PLROP under emergency conditions is described and formulated based on UT, in which the delivery time is described as an uncertain variable. Then, the proposed uncertain programming model (UPM) is compared with the stochastic programming model (SPM) for the 4PLROP in emergencies. The results show that UPM can guarantee the belief degree of the customer, whereas SPM cannot. Furthermore, numerical examples also show the effectiveness of the proposed method.

The remainder of this paper is organized as follows: Section 2 introduces basic concepts and properties of UT and PT used throughout this paper. Section 3 describes the uncertain programming model of the proposed 4PLROP in detail. Section 4 provides an equivalent model for the proposed UPM, and comparison and analysis with SPM are conducted. In Section 5, numerical examples are used to verify the effectiveness of the proposed method. Finally, Section 6 provides a brief summary of this paper.

2. Preliminary

In this section, basic UT and PT concepts are presented.

Let Γ be a nonempty set, and $\mathcal{L}$ a σ-algebra over Γ. Each element $\Lambda \in \mathcal{L}$ is assigned a number $\mathcal{M}\{\Lambda\}$. In order to ensure that the number $\mathcal{M}\{\Lambda\}$ has certain mathematical properties, Liu [32] presented the following three axioms:

Axiom 1 (*Normality*). $\mathcal{M}\{\Gamma\} = 1$ for the universal set Γ.

Axiom 2 (*Duality*). $\mathcal{M}\{\Lambda\} + \mathcal{M}\{\Lambda^c\} = 1$ for any event Λ.

Axiom 3 (*Subadditivity*). For every countable sequence of events $\Lambda_1, \Lambda_2, \ldots$, we have

$$\mathcal{M}\left\{\bigcup_{i=1}^{\infty}\Lambda_i\right\} \leqslant \sum_{i=1}^{\infty}\mathcal{M}\{\Lambda_i\}.$$

Definition 1 (*Liu [32]*). The set function $\mathcal{M}$ is called an uncertain measure if it satisfies the normality, self-duality, and countable subadditivity axioms.

Definition 2 (*Liu [32]*). An uncertain variable is a measurable function ξ from an uncertain space $(\Gamma, \mathcal{L}, \mathcal{M})$ to the set of real number, i.e., $\{\xi \in \mathcal{B}\}$ is an event for any Borel set $\mathcal{B}$.