Journal of Environmental Management 91 (2010) 2148–2162

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Resolution of an uncertain closed-loop logistics model: An application to fuzzy linear programs with risk analysis

Hsiao-Fan Wang*, Hsin-Wei Hsu

Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Taiwan, ROC

ARTICLE INFO

Article history:
Received 27 September 2009
Received in revised form
16 April 2010
Accepted 14 May 2010
Available online 12 June 2010

Keywords:
Fuzzy number
Interval programming
Green supply chain
Mean and mean square imprecision index
Risk analysis
Trade-off analysis

ABSTRACT

With the urgency of global warming, green supply chain management, logistics in particular, has drawn the attention of researchers. Although there are closed-loop green logistics models in the literature, most of them do not consider the uncertain environment in general terms. In this study, a generalized model is proposed where the uncertainty is expressed by fuzzy numbers. An interval programming model is proposed by the defined means and mean square imprecision index obtained from the integrated information of all the level cuts of fuzzy numbers. The resolution for interval programming is based on the decision maker (DM)'s preference. The resulting solution provides useful information on the expected solutions under a confidence level containing a degree of risk. The results suggest that the more optimistic the DM is, the better is the resulting solution. However, a higher risk of violation of the resource constraints is also present. By defining this probable risk, a solution procedure was developed with numerical illustrations. This provides a DM trade-off mechanism between logistic cost and the risk.

1. Introduction

Given the limited energy and resources, sustainability has become an important topic in environmental protection in recent years. The Green Supply Chain (GSC) management is now suggested as an efficient tactic to achieve this goal. On the basis of the 3Rs, recycling, reuse, and recovery in GSC management, a green company puts in effort to prevent any wastage of materials from the life cycle of a product. Therefore, closed-loop logistics are required to facilitate the 3R processes.

The closed-loop logistics for a green company consists of two parts: the forward logistics and the reverse logistics. Apart from the conventional logistics, GSC has an additional role called *dismantlers*, which allow green logistics to operate with the additional functions of recovery and recycling. Schultmann et al. (2006), Baumgarten et al. (2003), and Lu et al. (2000) have discussed this issue in detail.

The uncertainty embedded in reverse logistics has been a challenge for GSC managers. For the conventional supply chain, the uncertain demand has affected the inventory level, production amounts, and the logistics. The uncertain factors of the reverse supply chain are more complex than those of the forward supply chain. Apart from the uncertain demand, the values of recovery rate and landfilling rate pose difficulties in estimation, yet both contribute to the major factors of the reverse logistics management (Kongar, 2004; Listes, 2007; Salema et al., 2007).

Incorrect estimation and judgment based on uncertain information will cause a high risk of loss. Thus, in this study, the uncertain factors of demand, rates of recovery, and landfilling along the reverse logistics will be considered to support more realistic decisions of logistics and facility locations. This is concluded from the deterministic model of Hsu and Wang (2009). Owing to the capability of fuzzy presentation to engage uncertain patterns, fuzzy numbers will be used to describe these uncertain factors. Thus, fuzzy mathematical programming will be adopted for modeling.

Fuzzy programming has been discussed with different viewpoints in the literature. Among these, the statistical approach towards possibility is a way to synthesize fuzzy information. In the framework of fuzzy programming, possibilistic mean and mean square imprecision index will be formulated in this study to transform the proposed fuzzy mathematical model into a crisp form to facilitate efficient computation and analysis. Furthermore, because of such uncertainty, there is a risk caused by violating the estimated resource constraints. Therefore, risk analysis will be conducted so that the decision makers (DMs) can trade off between the expected cost saving and resource utilization based on their perceptions towards the GSC management in question.

* Corresponding author. Tel.: +886 3 5742654; fax: +886 3 5722204.
E-mail address: hfwang@ie.nthu.edu.tw (H.-F. Wang).

0301-4797/$ – see front matter
doi:10.1016/j.jenvman.2010.05.009

After reviewing the theoretical background on the analysis of GSC management in uncertain environments, including modeling and defuzzification procedures discussed in Section 2, a mathematical programming model of the green supply chain logistics will be introduced. Then, the solution process and risk method of interval programming after transferring fuzzy numbers into interval numbers will be proposed with specifications in Section 3. A numerical example of an uncertain GSC will be presented in Section 4. Finally, in Section 5 and 6, the discussion and conclusion will be drawn.

2. Literature review

This section focuses on the uncertain issues of GSC management raised in the literature. After the basic knowledge of uncertain environment, the resolution methods will be discussed.

2.1. Uncertain green supply chain management

Ever since Fleischmann et al. (2000) pointed out that product recovery has reversed the product stream as the consequence of management, its design remains rigorously complicated because of the high uncertainty in many aspects. To cope with the uncertain demand, Mahadevan et al. (2003) have assumed that a Poisson distribution is installed in their inventory model in order to remanufacture the returned products. To incorporate logistics, the differences of forward and reverse supply chains were studied by Kongar (2004) and a comparison was summarized and is shown in Table 1. In addition, the table shows the difficulties in the high level of uncertainty embedded in a reverse supply chain.

The high complexity and necessity in application have become a challenge. As such, many research undertakings have been carried out. Among them, Listes and Dekker (2005) have developed a stochastic programming model by taking account of the uncertain demands of the product recovery network design in different locations. Then, Listes (2007) and Salema et al. (2007) have focused on the uncertainty issues in the reverse logistics with specific scenarios. However, the lack of generality prevented them from using their results in general applications.

Researchers then resorted to different approaches taken from different viewpoints. For instance, Zikopoulos and Tagaras (2007) investigated how the profitability of the reuse activities was affected by uncertainty associated with the quality of returned products. Biehl et al. (2007) used the experimental design to analyze the uncertain impact of reverse logistics, which confirmed the high degrees of uncertainty in the collection rates, the landfilling rates, the availability of recycled production inputs, and the capacities in the reverse channel.

In summary, it can be concluded that the basic difference between the conventional and green supply chains is the uncertainty as shown in Table 1. Among them, demand, landfilling, and recovery rates are the basic factors that contribute to the uncertainty in management (e.g., Biehl et al., 2007; Zikopoulos and Tagaras, 2007; Kongar, 2004). On the subject of logistics, past research used different cases to cope with the specific uncertainty and thus lacked generality (Listes, 2007; Salema et al., 2007) while another group failed to discuss the *closed-loop* scenario. In order to overcome these problems, this study is based on the *closed-loop* model of Hsu and Wang (2009) and applies fuzzy programming to cope with the three major uncertain factors. To introduce the method of the study, the literature for the methods of dealing with uncertainty will be discussed in the next subsection.

2.2. The methods for resolving uncertainty

Depending on the properties of the problems, uncertain optimization can be formulated by stochastic programming, gray programming, fuzzy programming, or other procedures. Dippon (1998) cited that stochastic programming needs a large amount of data and more calculation steps to solve a problem. On the other hand, gray programming is used when the patterns of the data are uncertain and clearly disjointed (Davila and Chang, 2005; Bass et al., 1997). The main difficulties in the GSC problems are that their uncertainties are caused by their complex data relations so much so that their pattern distributions cannot be well classified, that is, they overlapped. Therefore, prediction of the recycled items with their quantities and analysis of the reused possibilities is difficult, which leads to the uncertain design of logistic plans. For the green logistics, the random phenomena of the recycled amount and content often makes the agents difficult in scheduling the vehicle fleet for collection, and thus their experience and perception become an important reference for such management. Due to this kind of intrinsic uncertainty in estimation from an expert's experience, fuzzy set approach is adopted for coping with this imprecision ["Precisiation of meaning via translation into PRUF," Cognitive Constraints on Communication, Vaina and Hintikka, 1984, (eds.), 373–402, Dordrecht: Reidel] and fuzzy programming is attempted for the resolution of this problem.

The fuzzy mathematical programming was initiated by Bellman and Zadeh (1970). Consequently, depending on which fuzzy parameter was considered, various forms were developed (e.g., Tanaka et al., 1974, Zimmermann, 1976) with different solution procedures (e.g., Rommelfanger, 1996, Bass et al., 1997). For proper trend of development, Inuiguchi and Ramik (2000) have discussed the advantage and disadvantage of fuzzy programming. They found out that fuzzy programming can be solved easily by transforming into a crisp program. However, from the optimality viewpoint, it lacked the appropriate interpretation of fuzzy objective function, therefore, fuzzy programming methods are unable to communicate uncertainty directly into the optimization process, as well as into the resulting solutions. These concerns were extended to the comment of Chiang (2001) in which he pointed out that without statistical analysis conducted in a fuzzy programming the confidence interval of the solution cannot be referred.

From the literature, it can be realized that the "defuzzification" process commonly adopted in the solution procedures of a fuzzy programming has brought about the issue of how to retain the complete information after defuzzification. Different approaches

Table 1
Comparison of Forward and Reverse Supply Chain (Kongar, 2004).

Forward supply chain	Reverse supply chain
Easier to forecast	Harder to forecast
Profit benefit orientated	Environmentally benign product benefit orientated
Distribution to multiple locations from a single source	Distribution to a single location from multiple sources
Stable product quality	Unstable product quality
Stable product packaging	Unstable product packaging
Stable product structure	Unstable product structure
Route of distribution is known/determined	Route of distribution is unknown/undetermined
Known main characteristics	Unknown main characteristics
More or less stable pricing	Pricing is effected by various factors/less stable
Speed is important	Speed is not a factor
Easily visualized cost factors	Hard to determine the cost
Stable inventory management	Unstable inventory management
Manageable product life cycle	More complicated product life cycle
Well known marketing techniques	Marketing techniques involve more complicated factors
Clearly observed processes	Less visible processes