Engineering Applications of Artificial Intelligence 24 (2011) 840–849

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

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

An inexact fuzzy-queue programming model for environmental systems planning

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ARTICLE INFO

Article history:
Received 22 November 2010
Received in revised form
17 March 2011
Accepted 30 March 2011
Available online 14 April 2011

Keywords:
Decision making
Environment
Fuzzy queue
Interval
Optimization
Uncertainty

ABSTRACT

In this study, an inexact fuzzy-queue programming (IFQP) model is developed for municipal solid waste (MSW) management under uncertainty, where fuzzy queue (FQ) model is introduced into the interval-fuzzy linear programming (IFLP) framework. The proposed IFQP model can not only handle uncertainties that are presented in terms of fuzzy sets and discrete intervals, but also reflect the influence of FQ in decision-making problems. Moreover, it can help quantify the satisfaction degrees of the system cost and constraints under uncertainty. It improves upon the existing optimization model with advantages in data availability, uncertainty reflection and result analysis. In its solution process, the model is transformed into two deterministic submodels based on an interactive algorithm. Interval solutions which are stable in the decision space can be obtained by solving the two submodels sequentially. The developed model is applied to a case of long-term planning of MSW management systems to demonstrate its applicability. It can effectively reflect dynamic, interactive, and uncertain characteristics of municipal waste management systems. The decision variable solutions provide optimal schemes for waste flow allocation corresponding to lower and upper bounds of system cost. The results indicate that reasonable solutions have been generated. They are helpful for supporting: (i) decision making or justification of waste-allocation patterns of MSW management system, and (ii) in-depth analysis of tradeoffs among system cost, satisfaction degree, and environmental constraint under uncertainty.

1. Introduction

Queuing theory is a useful tool for studying the behavior of dynamic and stochastic service systems. It has been extensively applied to service organizations as well as manufacturing firms, where various types of customers are serviced by various types of servers according to specific queue disciplines (Gross and Harris, 1998). Over the past decades, several research efforts on the queuing models were conducted (Gray et al., 1992; Artalejo, 2001; Falin, 2010). For example, Gray et al. (1992) developed a $M/G/1$-type queuing model with service times depending on queue length, in which customers receive different services under different queue lengths. Artalejo (2001) dealt with the $M/G/1$ queue with D-policy, where the server was turned off at the end of a busy period and turned on when the cumulative amount of work firstly exceeded some fixed value D. Falin (2010) developed a single-server batch arrival queue model with returning customers. Although the above queuing models are effective for handling various queuing phenomena with crisp parameters such as arrival rate, service rate and traffic intensity, interarrival times and service time are assumed to follow certain distributions, namely, the arrival rate and the service rate have certain values.

However, in many realistic situations, the arrival and service patterns are more suitably described by fuzzy or stochastic terms. The arrival rate and the service rate describing in the form of possibility are more practical than those in the form of precise. Thus, it is necessary to introduce fuzzy sets theory into the queuing theory to deal with uncertain parameters. A number of studies regarding fuzzy queuing models have been investigated in recent years. Li and Lee (1989) derived analytical results for two fuzzy queuing systems based on Zadeh's extension principle (Zadeh, 1978; Yager, 1981), the possibility concept and fuzzy Markov chains (Stanford, 1982). Negi and Lee (1992) proposed a procedure using two-variable simulation (Chanas and Nowakowski, 1988) and the concept of α-cut sets to analyze fuzzy queues (FQs). Kao et al. (1999) investigated four typical fuzzy queues, namely, $M/F/1$, $F/M/1$, $F/F/1$, and $FM/FM/1$, where F denoted fuzzy time and FM denoted fuzzified exponential time, and constructed their membership functions of the performance measures. Chen (2006) developed a nonlinear programming

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doi:10.1016/j.engappai.2011.03.010

approach to derive the membership functions of the steady-state performance measures in bulk arrival queuing systems with varying batch sizes, in which the arrival rate and service rate were expressed as fuzzy numbers. Kalayanaraman et al. (2010) studied a queueing system with breakdowns and retrials in fuzzy environment and obtained some system characteristics such as mean normal queue size, mean orbit size and mean system size. Generally speaking, the FQ method can deal with imprecision or vagueness (expressed by membership functions) in queuing problems.

Unfortunately, few previous studies focused on FQ models for municipal solid waste (MSW) management planning. In fact, complex queue phenomenons commonly exist in MSW management systems. For example, when waste-transport vehicles waited for the waste treatment of the landfill, incinerator and composting facilities, a queuing phenomenon might occur due to the current demand for a service exceeded the current capacity to provide that service caused by the high waste generation rate. The excessive waiting time of waste-transport vehicles and excessive serving time may cause a number of vehicles to leave because they were costly in the queuing system. Thus, the queuing theory can be introduced into the MSW management system to reflect such complexities. Moreover, in MSW management, uncertainties may exist in many system components (e.g. random waste generation rates, fluctuating disposal capacities) and their complex interactions, and thus affect the relevant decision (Liu et al., 2009). Such uncertainties could bring significant difficulties to the formulation of waste-management models and generation of effective solutions (Huang et al., 1993; Xu et al., 2009; Sun and Huang, 2010).

Therefore, a systematic approach for analyzing waste management is needed to support decisions of regarding short-term waste-management operation and long-term strategic planning (Xi et al., 2010). The objective of this study is to propose an inexact fuzzy-queue programming (IFQP) model for municipal solid waste management, where a $FM/F/1$ FQ model will be introduced into the interval-fuzzy linear programming (IFLP) framework. The developed IFQP model can not only deal with uncertainties expressed as fuzzy sets and interval values, but also reflect the influence of queuing problems. Moreover, it can help quantify the relationships between system cost and degree of satisfaction. This model improves upon the existing optimization model with advantages in data availability, uncertainty reflection and result analysis. A case study of MSW management will then be studied for demonstrating applicability of the developed method. It effectively reflects dynamic, interactive and uncertain characteristics of municipal waste management systems. The results obtained from the IFQP model can help decision makers obtain optimal waste-allocation patterns as well as gain in-depth insights into the tradeoffs between the satisfaction degree and the system cost.

2. Model development

Consider a waste-management system wherein n nearby cities ship their wastes to m facilities including landfill, waste-to-energy (WTE) facility, and recycling facility. An effective option for MSW treatment is to transport the waste to WTE facility because the waste-treatment costs can be offset by selling energy on market; however, waste-transport vehicles have to wait in queue because of its limited daily treatment capacity. If the waiting time is excessive, this may lead to a number of vehicles to leave the WTE facility to the landfill to pursue a minimum system cost. In addition, in real-world MSW management problems, the quality of available information is generally poor, being often presented as vague values and/or discrete intervals. For example, the uncertainties in waste transportation costs, facility operation costs and revenues, and waste-generation rates may be described as intervals; at the same time, the lower and upper bounds of these interval parameters may also be fuzzy in nature, leading to dual uncertainties (Li et al., 2008). Therefore, an inexact fuzzy-queue programming (IFQP) model is desired for tackling such complexities and uncertainties. The IFQP will incorporate the fuzzy queue (FQ) theory within an IFLP framework.

2.1. Fuzzy queuing model

Consider a general queuing system in which customers arrive at a facility with one server. The mean fuzzy arrival rate $\tilde{\lambda}$ and mean fuzzy service rate $\tilde{\mu}$ are approximately known and are represented by the following fuzzy sets (Kao et al., 1999):

$$\tilde{\lambda} = \{(x, \mu_{\tilde{\lambda}}(x)) | x \in X\}, \tag{1a}$$

$$\tilde{\mu} = \{(y, \mu_{\tilde{\mu}}(y)) | y \in Y\}, \tag{1b}$$

where X and Y are the crisp universal sets of the arrival rate and service rate, and $\mu_{\tilde{\lambda}}(x)$ and $\mu_{\tilde{\mu}}(y)$ are the corresponding membership functions. The α-cut sets of $\tilde{\lambda}$ and $\tilde{\mu}$ are:

$$\lambda_\alpha = \{x \in X | \mu_{\tilde{\lambda}}(x) \geq \alpha\}, \tag{2a}$$

$$\mu_\alpha = \{y \in Y | \mu_{\tilde{\mu}}(y) \geq \alpha\}, \tag{2b}$$

where λ_α and μ_α are crisp sets. Based on the α-cut technique, the arrival rate and service rate can be represented by different levels of confidence intervals (Zimmermann, 1995). Then, a fuzzy queueing model can be reduced to a family of crisp queues. The two sets represent sets of movable boundaries, and they form nested structures for expressing the relationship between ordinary sets and fuzzy sets (Kaufmann, 1975).

Let $\tilde{\lambda}$ and $\tilde{\mu}$ are fuzzy numbers. Their confidence intervals can be denoted as $[l_{\lambda_\alpha}, u_{\lambda_\alpha}]$ and $[l_{\mu_\alpha}, u_{\mu_\alpha}]$. The idea is to assume a uniform distribution in the interval of confidence and derive different possibility level α (Negi and Lee, 1992). Numerical simulation is applied to complicated queuing systems instead of analytical derivation. In this study, parametric programming is employed to formulate the problem. Then the membership functions of interests can be constructed through the solution. In the following, two models will be discussed, one for the case of one fuzzy variable and the other for that of two fuzzy variables.

Suppose the arrival rate is a fuzzy number and the service rate follows a crisp value. The α-cut of $\tilde{\lambda}$ defined in Eq. (2a) is a crisp interval which can be expressed in the form of $[\min_{x \in X}\{x | \mu_{\tilde{\lambda}}(x) \geq \alpha\}, \max_{x \in X}\{x | \mu_{\tilde{\lambda}}(x) \geq \alpha\}]$. The interval indicates where the constant arrival rate lies at possibility degree of α. According to the convexity of a fuzzy number, the bounds of the interval are functions of α and can be derived from $l_{\lambda_\alpha} = \min \mu_{\tilde{\lambda}}^{-1}(\alpha)$ and $u_{\lambda_\alpha} = \max \mu_{\tilde{\lambda}}^{-1}(\alpha)$, respectively. Let $p(x,y)$ denote the system performance measure of interest. The $p(\tilde{\lambda},y)$is a fuzzy number when $\tilde{\lambda}$ is fuzzy. According to Zadeh's extension principle, the membership function of $p(\tilde{\lambda},y)$ can be expressed as follows:

$$\mu_{p(\tilde{\lambda},y)}(z) = \sup_{x \in X}\{\mu_{\tilde{\lambda}}(x) | z = p(x,y)\}, \tag{3}$$

where the interval for x varies with the different α-cut levels. Consequently, we can construct its membership function based on its α-cut definition. Concretely, to find the intervals for $p(\tilde{\lambda},y)$ at possibility level α, two mathematical programs for the lower and upper bounds of it based on the different α-cut levels can be formulated:

$$l_{p_\alpha} = \min p(x,y) \ \text{ subject to : } l_{\lambda_\alpha} \leq x \leq u_{\lambda_\alpha}, \tag{4a}$$

$$u_{p_\alpha} = \max p(x,y) \ \text{ subject to : } l_{\lambda_\alpha} \leq x \leq u_{\lambda_\alpha}. \tag{4b}$$