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Time value of delays in unreliable production systems with mixed uncertainties of fuzziness and randomness

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ABSTRACT

This paper proposes a parametric programming approach to address the notion of the time value of delays in the presence of mixed (random and fuzzy) uncertainties that result from unreliable systems. To consider different types of delay time values, the system states are appropriately and carefully identified and defined, and a cost-based fuzzy decision model that incorporates several unreliability factors is constructed. Then, the proposed model is transformed into a pair of nonlinear programs parameterized by the possibility level α to identify the lower and upper bounds on the minimal total cost per unit time at α and thus construct the membership function. To provide analytical expressions, a special case with analytical results is also presented. In contrast to existing studies, the results derived from the proposed solution procedure conserve the fuzziness of the input information, representing a significant difference from the crisp results obtained using approaches based on probability theory. The results indicate that the proposed approach can provide more precise information to managers and improve decision-making in practical system design.

1. Introduction

The time value of delays, which we define as the substantial loss incurred as a result of delays in state-dependent operation, is particularly significant in the food and high-technology industries because of the practical importance of on-time delivery and high-quality products (Govindan, Jafarian, Khodaverdi, & Devika, 2014; Krajewski & Ritzman, 2005). However, operations in manufacturing and service processes are often imperfect. For example, an unreliable machine is typically subject to unpredictable breakdowns. When such an event occurs, operation will be interrupted until the breakdown is repaired. Moreover, the output of an unreliable machine may contain defective items that must be scrapped, reworked, or sold at a discounted price. In all cases, substantial costs are incurred, and thus, the time value of delays in unreliable systems should be carefully investigated. In fact, the time value of delays is important to the design of manufacturing and service systems, such as patient examination service systems, job-shop-type production systems, flow lines, flexible manufacturing systems (FMSs), field service support systems, and telecommunication systems (Berman & Larson, 2004; Dobson, Lee, Sainathan, & Tilson, 2012; Govil & Fu, 1999; Gross & Harris, 1998; Koyanagi & Kawai, 2003; Liu et al., 2010; Margavio & Chin, 1993; Margavio & Chin, 2008; Papadopoulos & Heavey, 1996; Taha, 2003; Waller, 1996).

Queueing models have widespread applications in both service organizations and manufacturing firms in the sense that time-dependent system performance measures are of primary concern. Therefore, this paper employs queueing theory (Gross & Harris, 1998; Papadopoulos & Heavey, 1996) to address the notion of the time value of delays. In fact, many unreliability factors exist in practical systems. In this paper, the term “unreliability” is defined as the condition of being undependable or untrustworthy, and an unreliability factor is defined as an operation that can malfunction with the result of placing the system in an undependable state, including untrustworthy services (e.g., careless inspections, service interruptions or breakdowns, ineffective repairs and reworking) and undependable outcomes (e.g., unqualified products or services). Many studies on unreliable queues have been published, and research on this subject can be traced back to the 1950s. Early and fundamental articles regarding service interruptions include those by Avi-Itzhak and Naor (1963), Gaver (1962), Keilsen (1962), Mitrani and Avi-Itzhak (1968), Thiruvengadam (1963), White and Christie (1958), and Federgruen and Green (1986). Thereafter, many studies considered various types of queues subject to certain unreliability factors, but not all of the possible unreliability factors were considered. For example, Gopalan and Kannan (1995) proposed a two-stage queueing network model considering inspection and reworking; however, they did not consider the unreliability factor of breakdowns. Wang, Chiang, and Ke (2003) investigated an unloader queueing system; however, they considered only the unreliability factor of breakdowns.

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Bowling, Khasawneh, Kaewkuekool, and Cho (2004) proposed a Markovian approach to determining optimum process target levels for a multistage serial production line in which the product quality was considered. However, they did not consider the unreliability factor of breakdowns. In addition, Sherman and Kharoufeh (2006) investigated an M/M/1 retrial queue with an unreliable server and infinite orbit capacity. Wang (2006) proposed an M/M/1 unreliable queue with finite capacity. Economou and Kapodistria (2010) studied an M/M/1 unreliable queue with customers performing synchronized abandonments. Wu et al. (2014) studied a multi-server queueing system with unreliable servers. Moreover, several articles have also discussed unreliable M/G/1 retail queues, for example, Atencia, Fortes, Moreno, and Sanchez (2006), Choudhury and Deka (2008), Choudhury and Ke (2014), Ke and Chang (2009), Kim and Lee (2014), Wang et al. (2001), Wu et al. (2014) and Mytalas and Zazanis (2015). However, most did not consider unreliable outcomes. Few studies, even among the most recent, have considered both unreliable service and unreliable outcomes in queueing systems. Indeed, it is challenging to consider all of these unreliability factors simultaneously.

Moreover, in practice, manufacturing and service systems are often likely to be burdened by mixed uncertainties of both randomness and fuzziness. Events occur randomly in such systems, and precise output data are not always available (Faraz & Shapiro, 2010; Luhandjula, 2015; Luhandjula & Joubert, 2010). For example, the system lifetime can be reasonably assumed to be represented by a certain random variable, but the associated parameters are often unknown because they are difficult to estimate from incomplete or unreliable data. In this case, an expert's opinion, described in linguistic terms, such as "the expected lifetime is considerably larger than 10 hours" or "the expected lifetime is approximately 12 hours," is often employed to estimate these parameters instead. Such a variable is typically called a fuzzy random variable (Puri & Ralescu, 1986) or is referred to as a generalization of a random variable, and this type of variable can be used to represent the inexactness that results from both randomness and fuzziness simultaneously (Gong & Wang, 2007; Kwakernaak, 1978, 1979). In fact, there are many practical applications of fuzzy random variables; recent examples include control charts (Faraz & Shapiro, 2010) and life annuity pricing (de Andrés-Sánchez, González-Vila Puchades, 2012).

In addition, Taha (2003) noted that the primary barrier to the implementation of cost-based queueing decision models is the difficulty of obtaining a reliable estimate of the unit cost of waiting, particularly when human behavior affects the operation or conditions of the system (Chen, 2007). Specifically, in many practical applications, the input data may be obtained subjectively, e.g., the arrival and service patterns or the values of the random variables that they distribute may be more suitably described in linguistic terms, such as "fast," "moderate," or "slow," rather than through the use of probability distributions. Moreover, the costs of facility operation and waiting may be fuzzy because of certain uncontrollable factors. Clearly, fuzzy input information of this type will undermine the quality of decisions made using conventional (crisp) decision models. Thus, decision problems in which the time value of delays is measured with random and fuzzy uncertainties deserve further investigation.

This study was motivated by phenomena observed in many manufacturing and service systems, such as an automated car wash operation with a machine that is of a new design but is unreliable (e.g., Diamantidis & Papadopoulos, 2009; Liu, Yang, Wu, & Hu, 2012; Tan & Yeralan, 1997). In a real-world manufacturing or service firm, the management will wish to set the processing rate to minimize the total cost per unit time, where the time value of delays is the primary concern. Therefore, the research questions of this paper are to determine how to effectively address the notion of the time value of delays in unreliable systems with several unreliability factors and mixed (random and fuzzy) uncertainties and to determine the optimal processing rate to minimize the total cost per unit time. Few articles have been published on this topic. Based on queueing theory and fuzzy theory, this paper proposes a parametric programming approach to solve this problem. First, we construct a cost-based fuzzy queueing decision model that incorporates the notion of the time value of delays. Notably, we consider several unreliability factors, including a server that is subject to breakdowns and repairs, the output of which could include defective items that must be reworked. To the best of our knowledge, the existing queueing models cannot be applied to this problem. One must carefully and appropriately define the states relevant to the problem. Second, the proposed fuzzy queueing decision model is transformed into a pair of two-level mathematical programs to identify the lower and upper bounds on the total cost per unit time.

According to Zadeh's extension principle in fuzzy set theory, if any input data are fuzzy, then the total cost per unit time is fuzzy as well (Zadeh, 1978; Zimmermann, 2001). An important feature of the proposed method is that the results obtained are fuzzy rather than crisp. By contrast, the results obtained using stochastic methods are typically crisp; therefore, the optimal total cost could be overestimated or underestimated, as could the optimal decision variables. Such over- or underestimation not only causes a loss of information because only point values rather than membership values are obtained but also distorts the results and undermines the quality of decision-making. Accordingly, this study's contributions include the following: (1) the notion of the time value of delays is addressed and embedded in the unreliable system design problem; (2) the developed model is more general than existing approaches because it considers more unreliability factors and mixed fuzzy and random uncertainties, and thus, it can more precisely describe the system behavior; and (3) a solution procedure is proposed that yields results that conserve the fuzziness of the input information concerning the unreliable system.

The remainder of this paper is organized as follows. Section 2 describes the problem of the time value of delays in a system with unreliable data. Section 3 proposes an approach to modeling the time value of delays by carefully identifying and defining the states of the system. Then, a fuzzy queueing decision model is proposed to determine the optimal processing rate to minimize the total cost per unit time. In Section 4, a solution procedure is proposed that conserves the fuzziness of the input information, in which the fuzzy model is transformed into a pair of parametric programs. In Section 5, a special case is presented for which analytical results are derived to demonstrate the validity of the proposed model. Some discussion is also provided. Finally, the conclusions are presented.

2. Problem description

Consider a manufacturing or service system in which jobs are performed by a new but unreliable machine, as illustrated in Fig. 1. For example, consider an automated car wash facility with a machine that is of a new design but is unreliable, operating with only one bay. Reliance on an unreliable machine means that the manufacturing or service process is subject to breakdowns and that the output of the process may include defective items that must be reworked. The system capacity (that is, the maximum number of jobs allowed in the system) is finite and denoted by N. Without loss of generality, in this paper, we consider that each event (e.g., the arrival of a job, the completion of a service, the occurrence of a breakdown, or the completion of a repair) occurs in a completely random manner, where the term "random" means that the event is not influenced by the length of time that has elapsed