Automation in Construction 60 (2015) 1–11

Contents lists available at ScienceDirect

Automation in Construction

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

Queue performance measures in construction simulation models containing subjective uncertainty

N. Sadeghi, A. Robinson Fayek *, N. Gerami Seresht

Department of Civil and Environmental Engineering, University of Alberta, 7-226 Donadeo Innovation Centre for Engineering, Edmonton, AB, Canada, T6G 1H9

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form 26 June 2015
Accepted 28 July 2015
Available online 15 September 2015

Keywords:
Discrete event simulation
Fuzzy
Construction management
Queueing

ABSTRACT

In recent decades, discrete event simulation (DES) has been widely used for analyzing construction projects. Recently, fuzzy discrete event simulation (FDES), which is an integration of fuzzy set theory with DES, has been proposed for simulating construction projects. FDES provides a framework to consider subjective uncertainty (uncertainty due to vagueness, subjectivity, and linguistic expression of knowledge) in construction simulation models. Current FDES frameworks only calculate simulation time (e.g., project completion time) as the simulation output. However, queue performance measures (e.g., average queue length and waiting time)—though important simulation model outputs for decision making, finding bottlenecks, and optimizing construction resources—are not analyzed in current FDES methodologies. Using fuzzy logic to consider the subjective uncertainty of service time and the inter-arrival time of systems' queues may improve such simulation models by more realistically representing their results. This paper provides a novel methodology to consider subjective uncertainty in analyzing the fuzzy queues in construction FDES models. Incorporating fuzzy queuing theory with FDES methodology as proposed in this paper enhances the applicability of FDES in construction projects. The proposed methodology is validated through mathematically solved queueing examples, and its practical aspects are illustrated using an example of an asphalt paving operation.

1. Introduction

Discrete event simulation (DES) has been widely used to analyze and ask what-if questions regarding different management policies or scheduling methodologies of construction processes [1]. Getting accurate and reliable outputs from the simulation models depends on accurate estimation of simulation inputs. However, accurate estimation of simulation inputs has been one of the most challenging aspects of developing simulation models for construction projects. The quality of input parameters and simulation logic determines the quality of the simulation results [31]. Incorrect inputs to a simulation model result in incorrect and misleading outputs [1,2,14,59].

Queue performance measures, such as waiting time and queue length, are one of the most important simulation outputs in construction management for analyzing the balance between different resources. Activity durations directly impact the service time and inter-arrival time of the queues in construction simulation models and affect the analysis of the queue performance measures. Thus, appropriate modeling of activity durations is essential for reliable estimation of important simulation outputs such as queue performance measures. However, activity durations are among the most uncertain inputs to simulation models of construction processes [1]. Two schools of thought exist in modeling activity durations in DES of construction projects [2]:

1. A probability distribution is estimated for the duration of each activity. This probability distribution aggregates the uncertainty associated with numerous factors impacting the duration of that activity.
2. The impacts of different factors on the duration of the activity are explicitly modeled. In this case, the activity duration can be estimated as a probability distribution based on the specific conditions surrounding (e.g., weather) and characteristics of (e.g., skill level of laborers, activity complexity) the activity.

The uncertainty of activity durations in both schools of thought above are represented with probability distributions in traditional DES. Generally, developing reliable probability distributions requires sample data of real project activities. However, in many construction projects, developing probability distributions of construction projects is not possible or feasible due to lack of such data [59]. Recent studies have been carried out in construction management that aim to provide more realistic activity durations using field data collection, such as in [5,6,52,60]. However, collecting sufficient historical data is time-consuming for many construction projects, which makes a probabilistic approach impractical when simulation analysis needs to be carried out

---

* Corresponding author.
E-mail address: aminah.robinson@ualberta.ca (A. Robinson Fayek).

http://dx.doi.org/10.1016/j.autcon.2015.07.023
0926-5805/

within a certain time limit. Additionally, collecting enough historical data may be impossible in some cases due to the uniqueness of the activities or the conditions surrounding them.

Activity durations are estimated by experienced engineers or experts when data are unavailable or it is not feasible to collect such data. Due to the use of expert judgment, an uncertainty is encountered that is due to subjectivity and linguistic expression of knowledge rather than randomness. Furthermore, construction activities are often affected by some factors that are expressed qualitatively rather than quantitatively. For example, a commonly acceptable and standard numerical value cannot be attached to weather conditions. On the other hand, weather conditions can be often described as good or poor. Other subjective factors such as skill level of laborers and complexity of the activity are common in construction projects. Furthermore, in the case of lack of data, the impact of factors on the activity durations are often expressed linguistically by experts. For example, an expert may provide a statement that when the weather conditions are poor, the duration of an activity is very large [4].

Due to the inevitable use of expert judgment in estimating activity durations of many construction projects, subjectivity and linguistic expression of knowledge is often encountered, resulting in subjective uncertainty. Subjective uncertainty is different from stochastic uncertainty: stochastic uncertainty is a system property and represents the uncertainty associated with actual variation of a variable; on the other hand, subjective uncertainty represents the lack of knowledge of the system modeler regarding the actual value of a variable [7]. For example, the linguistic expression of temperature as “hot” provides some information regarding the temperature, but the actual value of the temperature is not known; in this case, temperature contains subjective uncertainty. With regard to the activity durations, stochastic uncertainty corresponds to variability due to the random (stochastic) characteristics of the activities such as environment and materials variations. On the other hand, subjective uncertainty results from limited knowledge due to the lack of data about the activity durations and the use of expert judgment to estimate those durations. Probability distributions are used to model stochastic uncertainty. Fuzzy set theory [55] provides a methodology for mathematical modeling of subjective uncertainty [3,11,16,22,24,51,56,58].

Fuzzy set theory has been used in many applications in the domain of civil engineering and construction management [8,12,13,18,23,26,28,37,42,45,48,50,54]. Recently, fuzzy discrete event simulation framework (FDES) has been proposed for construction management as an integration of fuzzy set theory and DES [13,46,47,49,59]. For example, Cheng and Wu [13] presented a methodology for incorporating fuzzy numbers in discrete event simulation that is based on advancing the simulation time by comparing fuzzy events that are defuzzified into crisp values; they did not, however, explore different methods of ranking fuzzy numbers nor did they address queue performance measures. FDES enables the consideration of subjective uncertainty in construction simulation, which is only capable of dealing with probability distributions (modeling stochastic uncertainty).

FDES studies have mainly focused on the ranking of events for advancing the simulation time and calculating the project duration [13,41,59]. However, methodologies for calculating the fuzzy queue performance measures, such as average queue length and waiting time, have not been developed yet. The queue analysis in DES methodologies is based on the queuing theory, as discussed extensively by Saaty [46]. Saaty [46] introduces the queuing theory as a model for predicting the behavior of a system that provides a service for an arising demand. When integrated with queuing theory, a DES framework calculates the inter-arrival time between arising demands based on the simulation of the system (i.e., deterministic or probabilistic simulation). Queue performance measures, such as average queue length and waiting time, are important for finding bottlenecks and optimizing the number of resources for construction projects [20]. Many applications of construction projects analyze average waiting time as an important output of the simulation model [30,32,52,53]. Despite there being several applications of queue analysis in DES models, as of yet there are no instances where fuzzy queue analysis methodology has been incorporated with the current FDES frameworks.

Fuzzy queuing theory was introduced by Prade [43] as an extension to crisp queueing theory. In crisp queuing theory, service time and inter-arrival between arising demands are expressed by crisp numbers while in fuzzy queuing theory, the two values (i.e., service time and inter-arrival time) are expressed by fuzzy numbers. Li and Lee [29] analyzed a fuzzy queuing system using Zadeh's extension principle. Kao et al. [25] proposed a general approach for calculating the fuzzy queues performance measures (i.e., fuzzy queue length and fuzzy waiting time) based on alpha-cuts and interval calculations. There are also some applications of fuzzy queuing theory in construction literature, such as in Zeng et al. [58], where queueing networks with fuzzy data for concrete transportation systems are analyzed. While the subjective uncertainty of activity durations in FDES models may introduce subjectivity to queue inter-arrival time and/or service time, fuzzy queuing theories are required to analyze the fuzzy queue performance measures in FDES models. However, no existing FDES frameworks incorporate fuzzy queuing theories to analyze model fuzzy queues through simulation. This lack of a methodology for analyzing fuzzy queues confines the practicality of FDES in many construction projects.

The calculation of average queue length and waiting time in FDES is challenging because the event times in FDES are fuzzy numbers, and fuzzy arithmetic is required to calculate average queue length and waiting time. At the same time, these fuzzy event times are correlated and their correlations have to be considered when performing fuzzy arithmetic. The objective of this paper is to provide an extension to FDES that provides the average queue length and waiting time as the output of the simulation model using fuzzy arithmetic. The proposed extension to FDES will allow the consideration of subjective uncertainty in the analysis of queues in event-based simulation models, for the first time, which broadens the opportunity for simulation-based analysis of construction projects when facing subjective uncertainty, for example due to the use of expert judgment in estimating activity durations.

The paper is organized as follows: In Section 2, a brief background about representing activity durations using fuzzy numbers is provided; Section 3 explains how DES and FDES work. In Section 4, the proposed approach for calculating the average fuzzy queue length and waiting time in FDES is provided. In Section 5, the results of the developed approach are validated through analytically solved examples of simple fuzzy queueing systems. In Section 6, the practicality of the developed approach is illustrated through an example of an asphalt paving operation. Finally, the conclusions and future directions are discussed in Section 7.

2. Fuzzy numbers for representing activity durations

Zadeh [55] developed a formal mathematical system referred as fuzzy set theory that enables representing subjective uncertainty. One of the primary goals of fuzzy set theory is to quantify linguistic and vague terms, often referred to as linguistic variables. Some examples of linguistic terms are good market conditions, very complex project, or very large duration [40]. A fuzzy set is a generalized form of a crisp set. In a crisp set, each value in the domain is either a member or non-member of the set. On the other hand, in a fuzzy set, each value in the domain has a membership degree between 0 and 1. Thus, a membership function, $\mu A(x)$, can be defined for a fuzzy set A, where $\mu A(x)$ is the membership degree of x in A.

A fuzzy number is a fuzzy set if its membership function is defined on real numbers; is piecewise, continuous, and convex; and has at least one element with full membership (maximum membership degree of one) [40]. Fuzzy numbers have been used to represent activity durations when subjective judgment of experts is used in estimating activity durations. An uncertain activity duration, D, can be described by a