Automation in Construction 47 (2014) 37–49

Contents lists available at ScienceDirect

Automation in Construction

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

# Evaluation of queuing systems for knowledge-based simulation of construction processes

Reza Akhavian [1], Amir H. Behzadan *

*Department of Civil, Environmental, and Construction Engineering, University of Central Florida, 4000 Central Florida Blvd, Orlando, FL 32816-2450, USA*

ARTICLE INFO

*Article history:*
Received 28 January 2014
Received in revised form 11 June 2014
Accepted 17 July 2014
Available online 6 August 2014

*Keywords:*
Construction
Infrastructure
Simulation
Discrete event simulation
Queue
Queue discipline
Wireless data collection
Data mining
Knowledge
Ultra wideband

ABSTRACT

During the course of a construction project, there are many situations in which formation of waiting lines or queues is inevitable. The effect of resource delays in queues on the overall project completion time and cost has motivated researchers to employ simulation for analysis of queuing systems in order to identify the best operational strategies to reduce the time wasted in queues. Providing proper and timely input data with high spatial and temporal accuracy for queuing systems simulation enhances the reliability of decisions made based upon the simulation output. Hence, the presented paper describes a methodology for collecting and mining of spatio-temporal data corresponding to the interactions of queue entities to extract computer interpretable knowledge for simulation input modeling. The developed framework was validated using empirical datasets collected from a series of experiments. The extracted relevant knowledge from the queuing system entities was used to update corresponding simulation models.



## 1. Introduction

Waiting lines or queues exist in almost all industrial and manufacturing processes. In all such queuing systems, there are entities that need to be repetitively processed by other entity(s). The entity waiting in a line to receive service is called a *client* and the entity that processes clients is called a *server*. Similar to queuing systems in manufacturing settings, in many construction systems, clients (or resources) can be delayed in waiting lines when a server (or processor) is already captured by a previously arrived client and thus is busy.

A classic example of a construction queuing system is the arrival of dump trucks in a loading area where excavators or front end loaders load them with soil. As shown in Fig. 1, cyclic activities of an earthmoving operation consist of load, haul, dump, and return processes. A part of this cycle that embraces the waiting line and server is considered as the queuing system. Therefore, it is clear that the boundaries of the system are not necessarily spatially fixed and can dynamically change depending on the length of the queue and the efficiency of the server.

As soon as a client arrives inside the boundaries of the system, depending on the state of the server (i.e. idle or busy), it either waits in the queue or proceeds to be served immediately. Once the service is completed, the client leaves the system and its state, attributes, and other properties will no longer affect the conditions and properties of the queuing system. That is why in queuing systems terminology, the arrival of a client in the system is also referred to as the client's *birth* and its departure from the system is called the client's *death*, which imply that only the time that a client spends inside the queuing system is of interest to queuing analysis [1]. A final note on Fig. 1 is that although it shows a construction operation cycle, a queuing system may not be necessarily part of a cyclic operation; that is, the clients that enter the system may not return and the characteristics of the queuing system do not depend on the clients' identifications.

A construction manager who deals with an operation that involves queues is most often interested in knowing the waiting time during which a resource is delayed in a queue, the service time or how long it takes for the server to finish processing a specific client, and the logistics of the queue (i.e. number of delayed resources in a queue, or the queue length). Such knowledge is of critical importance to allocating the optimal number/type of resources, configuring the site layout, estimating the productivity, and determining the durations of individual operations as well as the entire project. Towards this goal, simulation models have been widely used in modeling queuing systems and to obtain valuable insight into the characteristics of the queues and their impacts on the overall project [2]. As previously stated, this is mainly due to the fact that the processing of clients by a server is a repetitive task and

* Corresponding author. Tel.: +1 407 823 2480; fax: +1 407 823 3315.
*E-mail addresses:* reza@knights.ucf.edu (R. Akhavian), amir.behzadan@ucf.edu (A.H. Behzadan).
[1] Tel.: +1 407 823 2480; fax: +1 407 823 3315.

http://dx.doi.org/10.1016/j.autcon.2014.07.007
0926-5805/

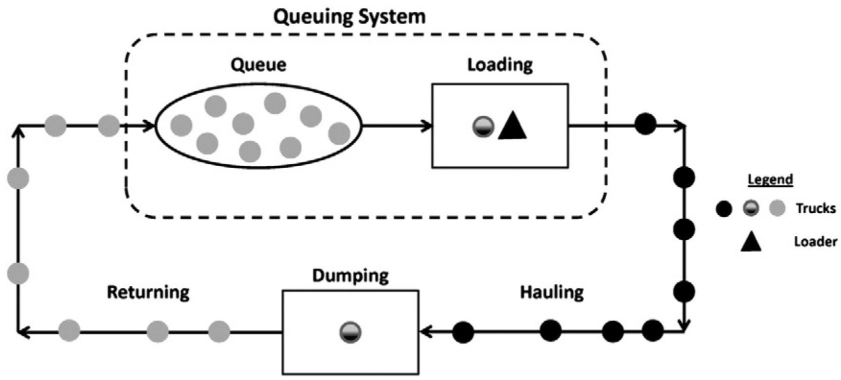


**Fig. 1.** Example of a single server queuing system in construction projects.

simulation models are perfect tools to predict the performance measures of repetitive processes of undeterministic nature. Among others, discrete event simulation (DES) models are particularly employed in construction and infrastructure projects since most often, the entire construction system can be broken down into discrete processes [3–5]. Within the construction and infrastructure domain, proper modeling of queuing systems is not a trivial task due to the stochastic, uncertain, and transient nature of such operations. A good example of such stochasticness that happens frequently and needs to be analyzed in the context of construction management is rework [6,7]. In queuing systems, in order to model the uncertainties in customer arrival times, most mathematical queuing theories suggest the use of specific probability distributions such as the exponential distribution [1,2,8]. However, previous research in construction systems based on real world observations of resource arrivals (e.g. dump trucks waiting in line to receive service from a front end loader or an excavator) indicated that the assumption of exponentially distributed arrival times can be often invalid [8–11]. Moreover, there are other important properties of a queuing system such as the queue discipline that must be accurately modeled when simulating queue operations. In particular, the sequence of queue operations not only can follow any of the well-known disciplines (which will be described in details in this paper), but also can be adjusted occasionally due to spatio-temporal requirements of the jobsite and the real vs. planned work progress [9,12]. Halpin and Riggs [9] indicated "breaks in queue discipline" as the first challenge among several difficulties in filed applications of queuing models. According to Martinez [12], discipline expression in modeling construction queues can be very dynamic and dependent on resource dynamic properties. Therefore, modeling of queuing systems requires accurate input with regard to queue properties that may change over the course of a construction project.

The necessity of providing a simulation model with accurate input data describing queuing systems and client–server interactions under dynamic and uncertain conditions highlights the importance of utilizing adaptive DES models that can be updated and fine-tuned in accordance to operations-level changes occurring in the real system. This requires meticulous data collection and mining processes to enable extracting relevant knowledge necessary to build the simulation model. To this end, this paper describes algorithms designed to extract knowledge pertinent to client–server interactions in queuing systems and to provide computer interpretable input for corresponding simulation models. First, a description of relevant previous studies is provided and identified gaps resulting in the presented research are discussed. Next, major properties that characterize a queuing system are introduced and their significance in designing construction and infrastructure simulation models is explained. Then, the algorithms that were designed and implemented to find and represent queue properties inside simulation models are described and the underlying mathematical background is briefly explained. Finally, the robustness and effectiveness of these algorithms will be examined using empirical data and results will be discussed.

## 2. Research background

Although utilizing operations-level simulation models that help achieve high levels of efficiency in managing construction projects has been explored and widely advocated in academic research [3,9,13,14], there is still much room for investigating their real value and potential applications that can result in their systematic accreditation by the construction industry [3,15]. Recent studies tried to investigate the reasons behind the limited and often, isolated use of simulation models in large scale by the industry. Among others, it was stated that most existing construction simulation systems rely on historical data and expert opinions to create simulation models [16]. Given the dynamics involved in most construction systems, such input data may turn out to be unrealistic (resulting in optimistic or pessimistic output), and are often hard to be independently verified. Therefore, the output of the resulting simulation models can be far from the realities of the operations on the ground. In the absence of methods that facilitate the process of constantly updating these simulation models with factual data from the real construction system, such models will soon be obsolete and of little (if any) value to the decision-making process [3,4,16]. In order to alleviate this problem, it has been previously discussed that collecting factual data as the project makes progress, discovering meaningful knowledge from these data, and feeding the extracted knowledge to corresponding simulation models can be a promising approach [17]. In order to achieve this, the possibility of collecting, fusing, and mining process data has been recently investigated by the authors through developing an integrated framework for construction equipment data-driven simulation models [17–19]. There have also been other sparse studies aimed at addressing this problem in limited scopes [20,21]. Despite these efforts, in almost all previous studies, project resources and entities were considered as single units for data collection and little knowledge was produced from the collected data to describe how individual entities would interact with one another at the process-level over time. AbouRizk et al. [15] indicated that the first requirement of developing a construction simulation model is acquiring knowledge about the logic and sequence of the operation. Knowing the interactions, relationships, and interdependencies between different entities is a crucial step in acquiring knowledge about the logic and sequence of activities, and can reveal potential predominant work patterns dictated by some entities. Therefore, in the context of queuing systems where entities are in constant interaction with one another, acquiring accurate data to generate knowledge pertaining to the client–server relationships is necessary for developing valid simulation models.

A number of researchers studied the implementation of queuing systems in construction simulation modeling. For instance, in one study, the FLEET program, queuing theory, and DES were used for selection of loader-truck fleets in infrastructure projects [10]. Using DES models, Ioannou [22] investigated the formation of queues during the process of rip-rap placement for the construction of a dam embankment. In