Computers and Electronics in Agriculture 151 (2018) 441–452

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Analyzing an emergency maintenance system in the agriculture stage of a Brazilian sugarcane mill using an approximate hypercube method

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ARTICLE INFO

Keywords:
Emergency maintenance service
Approximate hypercube queuing method
Extensions of the hypercube model
Sugarcane industry

ABSTRACT

In this paper, we present and apply an approximate hypercube queuing method to analyze an emergency maintenance system within the agricultural stage of Brazil's sugarcane industry. We incorporate differentiated service rates in the approximate hypercube method to deal with significant travel times as well as partial backup and priority in queue to mimic the dispatch policies of the system. We then applied this method using data from a case study conducted in an existing sugar and alcohol mill. We also investigated an alternative scenario for this system, as proposed by the company‘s managers, whereby the number of servers increases. The results showed that the method is an efficient way to investigate the original configuration as well as an alternative scenario for the case study. Furthermore, the method might be useful in larger applications and/or similar agro-industries.

1. Introduction

The sugarcane industry is a leading agribusiness in Brazil and, according to Triana (2011), Brazil is the most experienced country in the production of sugarcane and ethanol. Not surprisingly, Brazil is one of the largest producer of sugar and ethanol in the world (Crago et al., 2010; Gauder et al., 2011; Triana, 2011; Filoso et al., 2015) and, according to the Brazilian Supply Company (CONAB, 2016), it is also the largest producer of sugarcane in the world, with a planted area of 9 million hectares and a production of 665 million tons of sugarcane in 2015/2016. Moreover, Brazil is recognized worldwide for producing sugarcane in a most cost efficient manner (Almeida et al., 2007). In doing so, it relies on a very flexible industrial structure, in which most units are allowed to produce both sugar and ethanol.

The production process underlying the sugarcane industry must take into account the seasonality of sugarcane, which can be described as a sequence of farming (agricultural stage) and industrial (industrial stage) operations. In the former, all the harvesting and transportation of sugarcane to the mills occurs during the harvest season. The industrial stage, on the other hand, uses the raw materials and a complex system of industrial processes to generate its final products. These may be sugar, ethanol, energy, drinks, cosmetics, plastics, paper, animal feed, and a range of other products. The product mix of choice depends on the capacity and flexibility of each company, and the market/demand for each product.

In the agricultural stage, mechanization has been increasingly used due to its ability to generate high levels of productivity compared to manual harvesting (Capaz et al., 2013). Sugarcane burning is also used to increase the productivity of the manual harvest and, according to Braunbeck et al. (1999) and Capaz et al. (2013), causes an increase in pollution levels (CO and selected particulates), which impacts the population's health, and contributes to the loss of sucrose in sugarcane.

Moreover, it is important to recognize the perishability of sugarcane. According to Silva et al. (2011), sugarcane deteriorates as the time between harvesting and milling rises, causing a loss of quality and compromising industrial efficiency. The sugarcane should be quickly processed by establishing a satisfactory period of between 24 and 36 h to do so. Van den Wall Bake et al. (2009) also state that any delay prior to processing and burning may lead to significant loss of sucrose in the amount of 6–10 kg per ton of sugarcane in the first 72 h.

On the other hand, the time interval between cutting and processing is 3–5 days in most mills, resulting in huge losses of sucrose (Verma et al., 2012). As a result, the mills have sought to reduce the amount of stored sugarcane (Silva et al., 2011; Grunow et al., 2007). The obvious

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https://doi.org/10.1016/j.compag.2018.06.023
Received 20 March 2017; Received in revised form 17 April 2018; Accepted 10 June 2018

objective is to reduce the high costs due to the lack of sugarcane supply in the industrial stage, as well as the possibility of disrupting mill activities (Silva et al., 2011). It is therefore essential that there be reliability and agility in sugarcane cutting, as well as loading and transportation operations, since several disruptions generally occur between cultivation planning and harvest. According to Grunow et al. (2007), these disruptions are caused by unexpected weather conditions, equipment failures, plant diseases, and illegal crop fires.

As a result of mechanization and its high investment costs in the agricultural stage, it is important to minimize equipment downtimes. At the same time, key equipment categories, such as harvesters, planters and trucks, regularly require mechanical and electrical maintenance in the field. This triggers a crucial need for teams of repairmen, who move to call locations in repair trucks, perform the necessary service, and subsequently return to their bases (e.g., repair shops, or planting and cutting fronts).

Concerns in the agricultural stage thus include the possibility of mill activity disruption due to an insufficient level of sugarcane supply, and/or the loss of sugarcane's sucrose. Hence, teams must respond as quickly as possible to field calls, thereby minimizing the time that key equipment is not producing, or, working at less effective levels.

In this way, the number, location, and dispatch policy of servers (here, repair teams and their trucks, as well as the positioning of repair bases), all influence call response times and, in turn, the percentage of time teams remain busy. Thus, by analyzing the emergency maintenance services of the agricultural stage, it appears that the average response time to calls can likely be reduced by increasing the number of servers, as well as the number of employees within the teams, and by enhancing the quality of their training. However, such systemic improvements and investments will likely incur significant additional operational costs. There is thus a trade-off between the choice of service level being offered and the investment and operational costs required in a given system.

Given these considerations, we look at the hypercube queuing model (Larson and Odoni, 2007). This is a well-known and important tool for the analysis and planning of spatially distributed services. In the current scenario of interest, this model would allow for both the calculation of several important system performance measures, as well as the use of queuing theory within probabilistic location models.

The current paper therefore applies a hypercube queuing method to assist in the analysis, planning and optimization of emergency maintenance services in the agricultural stage of the Brazilian sugarcane industry. In an effort to do so, an extension of the hypercube model to deal with the issues of partial backup, multiple priority classes of customers and differentiated service rates, was developed. The potential for partial backup is employed due to the large distances between farms, i.e., servers are not allowed to travel to all regions (here called atoms) due to the likelihood of extensive travel times. The priority in queue is used to avoid disruptions in mill activities, the possibly unavailability of other harvesters to replace those who are in maintenance, and finally, the flexibility inherent in some forms of equipment.

The differentiated service rates is employed to model travel times in the maintenance system by incorporating the possibility of a server traveling from where it ended the service to the location of the next call while there are calls waiting in queue. Our approximate hypercube method also assumed non-homogeneous servers. It seems reasonable looking at the application under consideration in which servers are spatially distributed. Therefore, in order to confirm this assumption, we performed statistical tests on sample data. The results showed up that servers' service time were statistically different from each other, confirming the former assumption of non-homogeneous server.

It is worth noting that our extension of the hypercube model assume exponentially distributed service times and that statistical tests on sample data supported this assumption. This assumption is clearly a limitation of our extended method. However, we believe that deviations from this assumption do not compromise the accuracy of the extension developed, as shown by Larson and Odoni (2007) for the classic hypercube model. In an effort to further validate the proposed approach, we compared a plethora of results with the results from a companion simulation model.

Importantly, these models can be used to support decisions at both the tactical and strategic levels during any given project, while helping to better configure a system's emergency services (Swersey, 1994; Galvão and Morabito, 2008).

In supporting use of an extended hypercube method in the current study, we note earlier contributions of quantitative methods within the sugarcane industry (see, for instance, Jiao et al., 2005; Milan et al., 2006; Kawamura et al., 2006; Iannoni and Morabito, 2006; Paiva and Morabito, 2009; Silva et al., 2011; Neungmatcha et al., 2013; Lamsal et al., 2016; Masoud et al., 2016; Sethanan and Neungmatcha, 2016). Further, in regards to analyzing emergency systems in the sugarcane industry, we note mention Rodrigues et al. (2016) which addresses tire repair systems using hypercube queuing and simulation models. At the same time, to the best of our knowledge, there are no earlier studies in the literature analyzing emergency maintenance systems in an existing sugar and alcohol mill.

The current paper is organized as follows: Section 2 describes extensions of the hypercube model, and the proposed approximate method with differentiated service rates. Section 3 briefly describes the emergency maintenance system faced by a typical Brazilian sugarcane company, while Section 4 discusses the application of the approximate method for such a system. Section 5 presents a companion simulation model designed to crosscheck the hypercube method. Section 6 compares performance measures obtained by the approximate method and the simulation model when each is applied to the current system configuration, as well as under an alternative scenario involving adding an additional server, as suggested by company managers. Finally, Section 7 presents a series of concluding remarks, and some perspectives for future research.

2. Hypercube queuing model

2.1. Brief literature review

Some queuing systems do not adhere to the classical structure of queue with fixed servers in which users (customers) must travel to the servers' locations (Larson and Odoni, 2007). As a result, Larson (1974) first proposed the hypercube queuing model, a specific tool for planning and evaluation of service systems that have spatially distributed random demand.

The name 'hypercube' derives from the availability of servers through a given state space. The basic idea of the hypercube model is thus to expand the state space queues, so that each server can be treated individually while incorporating the complexities inherent in dispatching policies (Larson and Odoni, 2007). In a classic hypercube model, each server at a certain point in time can be either free (0) or busy (1). Further details on the hypercube model, can be found, for example, in Larson and Odoni (2007) and Chiyoshi et al. (2011).

This model was initially designed to deal with police systems, but, since then, has been applied to a variety of emergency systems, including police systems (Chelst and Barlach, 1981; Larson and McKnew, 1982; Sacks and Grief, 1994), emergency medical systems in urban areas (Brandeau and Larson, 1986; Takeda et al., 2007; Ingolfsson et al., 2008, Rajagopalan and Saydam, 2009; Baptista and Oliveira, 2012; Davoudpour et al., 2014; Souza et al., 2015; Iannoni et al., 2015; Toro-Díaz et al., 2013, 2015), emergency medical systems along highways (Mendonça and Morabito, 2001; Iannoni and Morabito, 2007; Atkinson et al., 2006, 2008; Iannoni et al., 2008, 2009, 2011), firefighting and social service systems (Larson and Odoni, 2007), disruptions in electricity distribution, civil defense, government response to future terrorist attacks and other major emergency situations (Larson, 2004),