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Waiting time computation for blood collection sites

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ABSTRACT

As blood donations are provided on a voluntary non-remunerated basis, blood donors should be treated as user-friendly as possible. Delays and waiting times within blood collection sites (donor centers) should thus be kept at acceptable levels. Waiting times are not incorporated directly other than by practical experience. A more rigorous approach is required.

An analytic waiting time computation is therefore investigated to compute waiting times as a function of production. An analytic so-called product form solution for joint queue lengths is concluded. This product form leads to:

- an exact expression for the marginal waiting time percentiles at each separate phase
- a more formal justification for approximate computation of the total mean waiting time for the non-exponential case.

A computational algorithm is provided to numerically approximate the total delay time distribution, an algorithm that has not been presented before.

The results are tested for and applied to a real life test case of a Dutch representative blood collection site. These results illustrate the practical usefulness for Sanquin, but also the applicability of the models in general.

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1. Introduction

1.1. Motivation

Sanquin, the organization responsible for blood collection in the Netherlands, currently operates over 50 fixed blood collection sites as well as over 100 locations that are operated by mobile blood collection sites. These sites yearly process close to 500,000 (half a million) whole blood donations.

These blood donations follow WHO (World Health Organization) standards: at a voluntary basis and non-remunerated. Donors should thus be handled as user-friendly as possible. Clearly, unnecessary delays and waiting times should be kept to a minimum or at the very least to acceptable levels.

At the same time, for cost reasons, staff capacity at collection sites has to be kept to a minimum. Currently, staff capacity at collection sites is based on production targets. Waiting times are not dealt with systematically and just a few collection sites schedule extra staff based on previous experiences. As a result, waiting times vary greatly across collection sites in the Netherlands. In the worst cases donors might spend an entire evening going through a process that can be done in less than 30 min.

Sanquin strives for a good balance between these – sometimes conflicting – goals. Hence, it is important to be able to compute the waiting times and how some interventions might affect these waiting times. To this end, Sanquin seeks reliable and replicable methods to compute waiting times. These methods should also be usable to determine the necessary staffing level before an intake session starts.

Although our model is inspired by blood collection sites, it can be regarded as generic and the methods can be used in many more situations. In most processes that can be modeled as a Jackson network – a network of queues with probabilistic routing – the models presented in this paper can be applied. The model can be applied within a healthcare setting, like within an emergency

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department or an organ donation system, or even more general production and service systems.

First, we will introduce the process of a blood collection site and discuss the literature (Section 1). We will then introduce the model in more technical detail (Section 2). Next, we will argue the application of some methods described in literature. We will then show that a product form expression applies (Sections 3.1 and 3.2). This will lead to a waiting time distribution for each of the separate phases of the intake process (Section 3.3). We will then illustrate that the total delay remains intriguing. A numerical method to compute the total delay time distribution will therefore be developed (Section 4). Finally, the analytic results and numerical method will be applied to a real life test case with different scenarios and evaluated (Sections 5 and 6).

1.2. Process description

There are two major types of donations: whole blood and plasma donations. In this paper we only consider one type: whole blood donations. To regulate the number of whole blood donations, donors receive invitations to come in for a blood donation. A donor can be invited for a donation several times a year: up to five times for male and up to three times for female donors.

The invitation specifies a collection site and a date after which the donor is asked to donate. Upon arrival at the collection site, the donor will check in at a registration desk. After identifying himself/herself, the donor is handed a questionnaire containing questions regarding his/her health and other factors that could influence the quality of the blood. When the questionnaire is completed, the donor will wait until he/she is picked up by a staff member to be taken to an interview room. Here the questionnaire will be discussed and additional clarifying questions may be asked. If eligible for donation, the hemoglobin (Hb-level), heart rate and blood pressure will be assessed. When results of these tests are within certain preset ranges, the donor will be transferred to the bleeding room and will wait for a staff member to start the actual collection procedure. When the collection procedure is finished the donor is offered some refreshments before leaving the site.

1.3. Literature

Literature on waiting times for blood collection sites, also known as donation centers, is surprisingly sparse. Especially, if we consider that this is a process that handles around 500,000 whole blood donations just in the Netherlands, with similar systems existing throughout the world. A recent publication by Blake and Shimla [1] describes a method to calculate the number of staff members needed at each station of the donation process in Canada. They propose a flow shop model. Here the minimum number of staff members is adjusted for variations by modeling each station as an $M/M/s$ queue, implicitly assuming independence of the queues. They have not included a formal justification for the separate use of these expressions. In another paper, Testik et al. [2] mainly focus on arrival patterns by using data mining techniques. They then apply approximate methods using coefficients of variation to estimate the expected waiting time, based on modeling the system as a network of queues in series—also called a tandem queue. Bretthauer and Côté [3] provide a blood collection site as an example to demonstrate a general method which uses a combination of Integer Linear Programming (ILP) and basic queueing theory to calculate the minimum staffing of health care systems. Alfonso et al. [4] use data from the French National Blood Service to build a discrete event simulation model to simulate and then analyze various possible improvement scenarios.

In general, analytic results for total waiting or delay times in serial or tandem structures, which is the most realistic approach to model a blood collection site, appear to be rather limited. Even for the "simple" case of just a tandem queue with two queues in series, such results only seem to be available for special situations or under special assumptions, such as identical servers at both stations, single server cases or overtaking-free assumptions and infinite capacities; e.g. see the book by Boxma and Daduna [5] and references therein.

Product form results for queueing networks without finite capacity constraints are well-known in literature since the pioneering work by Jackson [6] for Jacksonian networks. In particular, Gordon and Newell [7] have explicitly presented a product form solution for unlimited serial or tandem structures. Exact product form results for systems with finite capacity constraints, however, are essentially more limited. In Gordon and Newell [8] only closed tandem structures – with a fixed total number of jobs circulating – are studied with finite constraints in specific cases, when these constraints are small or large.

In Jackson [9], an extension of his classical 1957 paper [6], finite capacity constraints are incorporated by either a total number dependent arrival rate or by lower limit service rates for each phase. As a special case in its Section 5, the product form preservation is also argued by either instantaneous triggering of new arrivals or by service deletion. However, a natural upper limit application for just one phase, as in Section 3.2, is not included. In addition, all of these earlier references verify the product form by the global balance or Kolmogorov equations. None of the references explicitly mention more detailed verifications for each phase separately, as shown in Appendix A.

In Kelly [10] and Pittel [11], the inclusion of finite constraints is only justified by a specific routing assumption. The product forms remain valid with finite truncations provided the system has a so-called reversible routing. A tandem or serial system, like the application in this paper, is excluded as its routing structure is strictly not reversible.

Some specific product form applications have been mentioned in a health care setting, e.g. see Xie et al. [12] and Yom-Tov [13]. For blood collection sites, however, no explicit mentioning or justification of product forms has been made.

In addition, in all of these earlier references the product form result is verified by the global balance or Kolmogorov equations. No explicit mentioning is made of the more detailed verifications for each phase separately as argued and shown by straightforward proof presented in this paper (see Appendix A).

As such, the product form result that will be reported, at least from an application point of view, can be regarded as new. To some extent—mainly focusing on finite limitations in a tandem queue, it is also new from a more technical point of view. The exact product form result that will be presented for the unlimited case also leads to marginal waiting time percentiles, in the case of our application for the testing and collection phase.

Given the practical and generic character of serial structures as well as finite capacity constraints in assembly line and production systems, literature has paid considerable attention to approximate methods for infinite and finite serial systems. Work on this topic has been done by, among others, the book on Queueing networks with blocking by Perros [14], the excellent survey on manufacturing flow line systems by Dallery and Gershwin [15], the well-known QNA method by Whitt [16], which is also described below, and the early elegant paper by Buzacott [17] to capture interaction based on Pollaczek–Khinchine's formula. Without exception, these approximate procedures use some form of decomposition by which the service stations or phases are regarded as separate with interaction between the stations incorporated by coefficients of variation. These coefficients link variability in arrival and service times. Some of these procedures also include a number of iterations for adjustments. In Section 3.4

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