Journal of Air Transport Management 66 (2018) 13–24

Contents lists available at ScienceDirect

Journal of Air Transport Management

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

Network-based queuing model for simulating passenger throughput at an airport security checkpoint

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ARTICLE INFO

Keywords:
Airport security checkpoint
Network structure
Queuing network
Passenger strategies
Simulation analysis

ABSTRACT

This paper models different passenger strategies, shows potential network structures, and compares different performance cases for queuing at airport security checkpoints. Our findings show that different network structures require different passenger strategies to achieve optimal performance. The open network structure performs significantly better than the restrictive one, and the allocation of more security staff for baggage checking improves performance under the precondition that the total number of security staff remains constant. We also find that the combination of *n* M/M/1 systems will perform almost the same or even better than the M/M/*n* system when the passengers' strategies and feelings are considered. Based on these findings, some practical insights are provided on how to improve airport security checkpoints.

1. Introduction

Since the terrorist attacks on Sept. 11, security screening has been significantly enhanced at airport security checkpoints throughout the world. However, many passengers are increasingly complaining about the inconvenience and long waiting time (Podemska-Mikluch and Wagner, 2017). Thus, there is a tension between the desire to minimize the waiting time of passengers and the need to maintain the expected level of security screening. This paper aims to explore an efficient queuing structure (or network structure, essentially) for airport security checkpoints without any decrease in the safety.

Generally, passengers' ID cards and passports, their carry-on baggage and their bodies are screened for explosives and other dangerous items at an airport security checkpoint. Although the screened items are nearly identical in different airports, the queuing structures and the screening processes can be quite different (Janic, 2007). For example, passengers are asked to queue in a line before entering the checkpoint in some airports in Canada, whereas passengers can freely choose in which queue to wait in most airports in China. In fact, different queuing structures will cause different efficiencies in most cases; therefore, we want to explore the optimal queuing structures under different conditions. Hence, **the first motivation** of this paper is to determine which kind of queuing structure is efficient under certain conditions.

It is well known that people often have their own strategies that shape their rules of behaviour, especially when they come from different nations. As a result, these strategies will also affect the efficiency of the checkpoint even if the same queuing structure is used (Schwartz, 1974). For example, facing the same situation, people with different strategies might choose different queues to wait in; therefore, the whole waiting time of this system is likely to be different. Based on the above phenomenon, this paper aims to explore the relationship between the strategies of passengers and the efficiencies of different queuing structures. Thus, **the second motivation** of this paper is to determine how to design a proper queuing structure that can accommodate these different passenger strategies.

Apart from the various strategies mentioned above, passengers also have different attributes, such as gender, age, and number of pieces of carry-on baggage. Numerous previous studies, such as those of Hainen et al. (2013), Wu et al. (2014) and Pitchforth et al. (2015), have found that these attributes can significantly impact the efficiency or even the design of an airport security checkpoint. Following these publications, this paper further explores how to improve the efficiency of checkpoints by utilizing these available attributes of passengers. Therefore, **the third motivation** of this paper is to introduce the attributes of passengers into the design of the queuing structure.

Actuated by the above three motivations, this paper will adopt the technique of simulation analysis to cope with these problems, since it is difficult to describe the human behavioural characteristics and intuitively reflect the design of queuing structures with pure mathematical analysis. In addition, the abovementioned queuing structure is

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http://dx.doi.org/10.1016/j.jairtraman.2017.09.013
Received 27 March 2017; Received in revised form 24 September 2017; Accepted 26 September 2017

essentially a network structure, and simulation analysis is often adopted to uncover the functions or outputs of certain network structures (Li et al., 2015). On the other hand, simulation analysis also has limitations. One of them, in our opinion, is the inability to cover all the cases, and another is the possibility of inaccurately representing real scenes. To overcome these shortcomings, a series of numerical experiments are elaborately designed to mimic typical scenes in the real world, and the initial parameter values are estimated from the real data. Similar to experiments conducted in the natural sciences, all the comparisons will be conducted under the same initial conditions to achieve sound results.

The main contributions of this paper are summarized as follows: (1) This paper considers the different strategies of passengers and constructs mathematical models to depict them. (2) Different network queuing structures are designed for airport security checkpoints. (3) A series of numerical experiments are conducted to compare the performances of different network queuing structures with different strategies and attributes of passengers. (4) Based on the reported simulation results, this paper provides several new findings about how to establish an efficient, satisfying and robust network queuing structure for an airport security checkpoint. (5) This paper also presents a new finding that the combination of n M/M/1 systems will perform almost the same or even better than an M/M/n system when the passengers' strategies and feelings are considered, which contradicts the traditional theoretical result in the field of queuing theory.

To express these items clearly, the rest of this paper is organized as follows: Section 2 briefly reviews the previous studies that contain the classical queuing models, the queuing network model, and the relevant simulation studies; Section 3 presents the basic model, which describes the passengers with different strategies, the security staff with different tasks and the concerned queuing structures; Section 4 provides the numerical experiments and reports the results; Section 5 discusses the basic model and explores the extended model; and Section 6 concludes the paper.

2. Previous studies

2.1. Classical queuing models

At the beginning of the 20th century, Erlang (1909) discovered the call congestion problem and initiated the study on queuing theory. Then, driven by the developing probabilistic methods, queuing theory gradually became a hot field and guided numerous applications in operations research (Zheng et al., 2016), computer science (Vilaplana et al., 2014), traffic engineering (Daganzo and Knoop, 2016) and so forth. Especially in the field studied by this paper, a large number of publications using classical queuing theory can be found. For example, Gilliam (1979) discussed how to use the famous queuing model to explore the improvement of passenger security screening at an airport, and additional studies, such as De Lange et al. (2013) and Okoshi et al. (2015), were performed.

M/M/1 and M/M/n are two classical queuing models where the arrival time interval of passengers and the service time of staff are both assumed to follow the exponential distribution based on numerous discoveries from real data (Kulkarni, 2016). In addition, it has been proven that the M/M/n system is much more efficient than the combination of n M/M/1 systems, which implies that the single-queue strategy will save much more waiting time compared to the multi-queue strategy (Borovkov, 2012). However, the correctness of the above conclusion depends on the precondition that all the passengers should be identical and without any individual strategies for choosing the waiting queue. In fact, many real airports do not adopt the one-queue strategy, as mentioned in the Introduction. Therefore, it will be meaningful to consider the various waiting strategies of passengers when the efficiency of airport security checkpoints is studied. Thus, the second motivation of this paper is to address the two problems described above.

The reviewed classical queuing models lay a solid foundation for our study, especially for the distributional assumption of both random arrival time and random service time. Moreover, the abovementioned conclusion on efficiency also provides some ideas about how to design an efficient security checking system at an airport. More importantly, the reasons many real airports do not adopt the more efficient one-queue strategy are worth uncovering, and the waiting strategies of passengers should be further considered under the multi-queue strategy used in real airports.

2.2. Queuing network model

Starting from the Jackson network (Jackson, 1957), network queuing models have been gradually attracting the attention of researchers (Kunwar et al., 2016). Developed from the classical queuing theory mentioned above, the queuing network model not only inherits the probabilistic analysis from the classical queuing model but also considers the network structure of queuing systems based on the theory of complex networks (Master and Bambos, 2016). Among numerous applications of network queuing theory, an early study can be traced back to McKelvey (1988), where a network queuing model was adopted for representing the structure of the passenger-processing network and for assessing terminal design alternatives.

In particular, the queuing network model can reflect the complex process of airport security queuing and can connect the different stages of the queuing system, which feature complex interactions and interdependencies among one another. Thus, this model has been widely applied in our studied field. For example, Wang et al. (2015) combined the queuing network model and game theory to simulate a multi-stage screening security system at an airport with the aim of determining the optimal screening probabilities in each stage. Coincidentally, Dorton and Liu, 2016 adopted the queuing network model to investigate the effects of baggage volume and alarm rate at the security screening checkpoint of an airport to find the most efficient queuing network structure.

This paper, in parallel to the above studies and many others not mentioned, also focuses on the application of the queuing network model to analyse the efficiency of airport security screening, especially to explore the relationship between the queuing network structure and the efficiency of security screening. Recalling the Introduction, this focus corresponds to the first motivation of this paper.

2.3. Relevant simulation studies

Simulation analysis is widely used in studying operations problems at airports, since simulation in general is an effective tool that allows for the control of extraneous variables while allowing the researcher to generalize the results (Fayez et al., 2008). For example, taking workload balance as the controllable variable, Kim et al. (2017) proposed a reallocation algorithm using a merge configuration to reduce imbalances for airlines sharing a baggage collection conveyor. In another example, Kierzkowski and Kisiel (2017) took the system design as the controlled variable and presented a simulation model of security control system functioning based on the Wroclaw Airport terminal. Following the above two papers, we regard the passenger attributes as the controllable variables; this is related to the third motivation in the Introduction.

The flexibility of simulation allows for various queuing mechanisms or passenger attributes and then compares them in terms of efficiency, safety and satisfaction in the specific problem of simulating passenger throughput at an airport security checkpoint. For example, Van Boekhold et al. (2014) provided a simulation model to assess the operational efficiency of the passenger processing system with a sole emphasis on the screening of passengers and their carry-on baggage, and Chen et al. (2015) developed a fast and simple simulation model that provided insight into the key performance indicators of an airport