Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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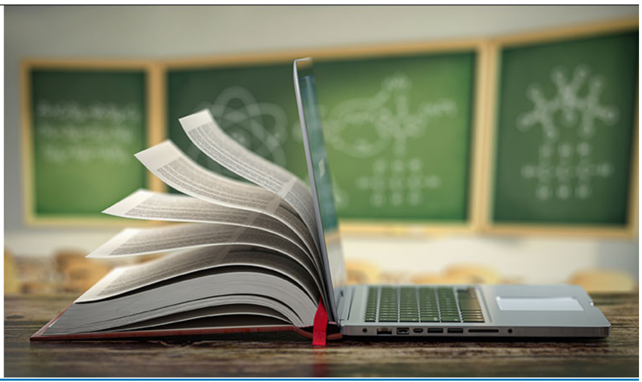
To cite this article: I Korelin and S Porshnev 2020 *J. Phys.: Conf. Ser.* **1679** 032038



Computational approach for researching visitor flow dynamics at public venues and mass gathering events

I Korelin[1] and S Porshnev[1,2]

[1] The Institute of Radioelectronics and Information Technologies, Ural Federal University, 32 Mira st., Yekaterinburg, 620002, Russia
[2] N N Krasovskii Institute of Mathematics and Mechanics of the Ural Branch of the Russian Academy of Sciences

E-mail: korelin.ivan@gmail.com

Abstract. Visitor flow dynamics at public venues has been studied by using mathematical models of the non-stationary queuing system and discrete-event modelling. Computational approach for research visitor flows quantitative characteristics is described. The dependence of input rate from time in non-stationary queuing system model is like the dependencies of rate of visitors to football matches. Quantitative characteristics are waiting line length and waiting time (time spend in queue) from time for different parameters of the input rate and the service rate device. It is proven that the maximum values of the studied characteristics and the corresponding time values are described by deterministic functions that depend on the maximum intensity of visitor flow and the average service speed. The form of these functions is well described.

1. Introduction

The modern facilities for public events (stadiums, concert halls, meetings venues, airports, stations, etc.) are equipped with technical systems to pass the visitors flow to the event. These systems consist of territorially distributed sets of automated turnstiles, inspection frames, scanning devices baggage screening systems at airports, railway stations, etc. The developer's responsibility level in such system is very high. Development and operation experience analysis of such systems shows that in most cases empirical approaches use. This approach is based on the previously collected information about the features of the functioning of access control systems in non-peak workload. Another issue is peak workload on the access control systems. For example, when there is a need for urgent evacuation of venue visitors due to riot on the stadium or a threat of terrorist attack. Emergency situations like this may arise at any time. And in a most cases it had happened.

Characteristics of the access control devices should be calculated and selected based on proven technical solutions. The number of a selection access control devices and their distribution along the perimeter of the mass event facility need to be insured too. This issue is critical because of increased risk of terrorist threats and increasing requirements for law-enforcement officers providing security and countering terrorism. That is why methods to predict dynamics of quantity characteristics of visitor flows are necessary to study.

Queue systems features research is based on statistical information of visitor flow to football matches collected at the stadiums of St. Petersburg, Ekaterinburg in context of served visitors number was made in [1]. Analogies between access control device (ACD) used at the objects of mass events and non-stationary queuing systems (NQS) were justified. Input rate of clients dependency from time like function $\lambda = \lambda(t)$ was also studied in [1]. Experimental information about moments of time when each visitor reaches the turnstile (in terms of the QS theory this moment is the beginning of the service) and the corresponding times of passthrough from turnstile (in terms of QS it is the end of service) was used to create a simulation model of ACD. Benefit of using NQS simulation model is in significant practical interest because it allows to study the dynamics visitor flows for arbitrary laws $\lambda = \lambda(t)$. Typically, the dependencies of input rate $\lambda = \lambda(t)$ in the peak and non-peak workload of ACD for public event facilities will essentially differ from each other. The results of the NQS study using this simulation model are presented in this article. Computational approach for research visitors flows dynamics and describing the quantitative characteristics of visitors flows in the form of appropriate analytical dependencies from the maximum input rate $\max(\lambda)$ and the average service rate $\bar{\mu}$ are shown below.

2. Computational approach

Simulation of automated checkpoint system based on statistical information gathered in football matches was described previously in [1]. Also, there was described input flow and service time simulations based on random variables generation. The chosen distribution density is described by two parameters: the scattering and the expected value $E[\xi]$. As a result, the service rate is defined as inverse service duration. Generated service time is measured in seconds, to convert this into a service rate (clients per minute) it must be multiply by 60. To define service rate like number we use not a random service time itself, but its expected value.

$$\bar{\mu} = \frac{1}{E[\xi]} \cdot 60 \tag{1}$$

The algorithm used for statistical simulation is particularly described in [2]. At each interval of the step approximation, the arrival times of the clients t_A with the exponential distribution law [3] are generating. The service time τ_s are generating like random ξ, with expected value $E[\xi]$. For each client waiting for a service moment of entering the service t_E are calculating by alternately viewing all the clients that came during this interval:

$$t_{E_i} = \begin{cases} t_{A_i}, \text{ then } t_{A_i} > t_{E_{i-1}} + \tau_{S_{i-1}} \\ t_{A_i} + (t_{E_{i-1}} + \tau_{S_{i-1}} - t_{A_i}), \text{ then } t_{A_i} < t_{E_{i-1}} + \tau_{S_{i-1}} \end{cases} \tag{2}$$

The first client time of entering service are equal to arrive time $t_{E_1} = t_{A_1}$.

Parameter $T_2 = 30$ min was fixed and parameters T_1, λ_{max} varied. Main goal of this variation to study different input flows with the total number of clients (visitors) N equal to constant (1700) in Monte-Carlo simulations. It is enough to adjust only one of these parameters, for example T_1, because for fixed N and T_2 parameters T_1, λ_{max} are dependent from each other:

$$\lambda_{\max} = 2 \cdot N / (T_1 + T_2), \tag{3}$$

T_1 was varied in the range $[-310; -87]$ minutes and the value λ_{max} varied in the range of $[10, 29]$ people/min. Analysis of the characteristics used for describing the features of the operation of studied NQS was made [3] . Quantitative description of NQS dynamics is the dependence of the visitor queues length (in terms of QS it is client's queues length) from time:

$$L(\lambda_{max}, \bar{\mu}, t_k) = L\left(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k\right) + \sum_{r=1}^{N_j} q^E(t_k) - \sum_{r=1}^{N_j} q^S(t_k), \tag{4}$$

where $q^S(t_k)$ and $q^E(t_k)$ are number of served and number of new clients in a queue during t_k interval respectively. The average visitor waiting duration (in terms of the QS it is client waiting duration) from the time can be used too:

$$\tau^w = \tau^w\left(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k\right) = \frac{\sum_{i=1}^{N_j}(t_i^E - t_i^A)}{q^S(t_k)}, \quad (5)$$

then $t_k = T_1 + \frac{T_2 - T_1}{K}(k-1), k = \overline{1, K},$ K – identity of intervals of step approximation $\lambda(t)$.

The values of quantitative characteristics NQS were taken to be their mean values in the ensemble of independent realizations, because simulation used Monte Carlo method:

$$\bar{\Phi}\left(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k\right) = \frac{\sum_{j=1}^{m}\Phi_j\left(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k\right)}{m}, \quad (6)$$

then m is the number of independent trials in the Monte-Carlo method, Φ is the element of set $\{L, \tau_w\}$.

3. Analysis of the experimental results

The average dependencies of “instant” queue length from time $\bar{L}\left(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k\right)$ are shown below. During simulation quantity of intervals of the step approximation of input rate $\lambda(t)$ K was choose to 680. The quantity m of independent realizations was 1000. Dependencies $\bar{L} = \bar{L}(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k)$ for $\lambda_{max} \in [10, 29]$ people/min, $T_1 \in [-310; -87]$ min, $T_2 = 30$ min., $\bar{\mu} \in \{10; 12; 15; 20\}$ people/min shown in figure 1.

Figure 1 shows:

- in the selected range of NQS parameters, the average queue length increases like monotonic function to the maximum value, after which it decreases monotonically;
- the maximum queue length $\bar{L}_{\max}$ depends on the server performance;
- the time value $t_{L\max}$ corresponding to the maximum length of the queue $\bar{L}_{\max}$ depends server performance;
- the length of the queue once new clients stops queuing up, decreases linearly, while the rate of decrease depends on server performance.

Dependencies of waiting in queue duration on NQS parameters from time $\overline{\tau^w} = \overline{\tau^w}(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k)$ for $\lambda_{max} \in [10, 29]$ person/min, $T_1 \in [-310; -87]$ min, $T_2 = 30$ min, $\bar{\mu} \in \{10; 12; 15; 20\}$ person/min was calculated. They are presented in figure 2.

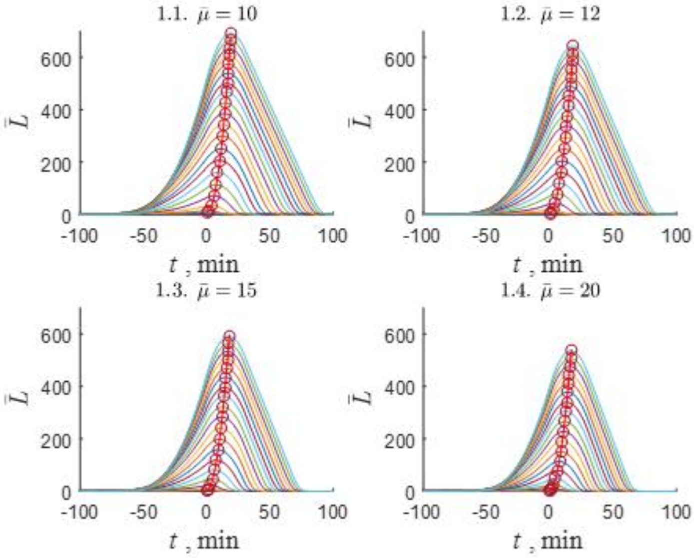


Figure 1. Dependencies $\bar{L}(\lambda_{max}, \bar{\mu}, t)$ (the beginning of the match, $t = 0$) for different values of parameters $\lambda_{max}, \bar{\mu}$.

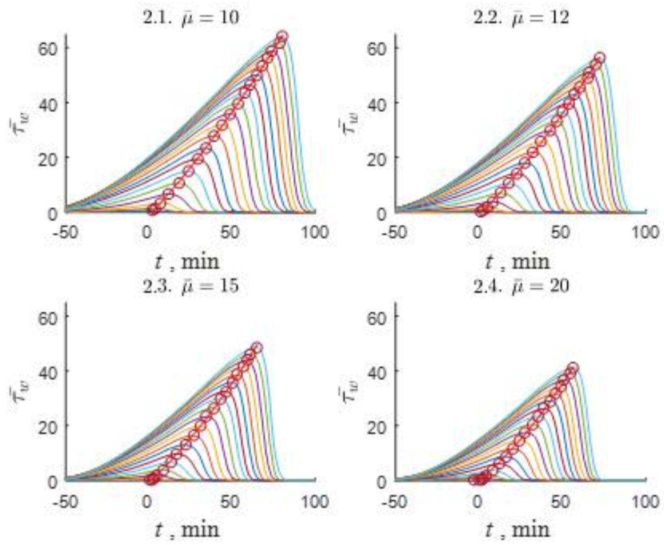


Figure 2. Dependencies $\overline{\tau^w}(\lambda_{max}, \bar{\mu}, t)$ (the beginning of the match, $t = 0$) for different values of parameters $\lambda_{max}, \bar{\mu}$.

Considering figure 2:

- in the selected range of system parameters, the average waiting duration increases like monotonic function to a certain maximum value, after which it decreases monotonically;
- the maximum waiting duration $\overline{\tau^w_{\max}} = \max(\overline{\tau^w})$ depends on the input rate of clients and the server performance;

 1679 (2020) 032038 doi:10.1088/1742-6596/1679/3/032038

- the maximum waiting duration $\overline{\tau^w_{\max}}$ is reached at various points in time $t_{\overline{\tau^w_{\max}}}$, depending on the input rate of clients and the performance of the service device.

Note that presented results of NQS simulation are consistent with physical representations. In fact increasing input rate with a fixed service time should lead to increased length of the queue and, accordingly, increased waiting time for clients in the queue once new clients stops queuing up. Service time reduction with a fixed input rate will lead to reduced length of the queue and time for servicing the clients once new clients stops queuing up.

Analysis of the dependences, $\bar{L} = \bar{L}\left(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k\right)$, $\overline{\tau^w} = \overline{\tau^w}(T_1, T_2, \lambda_{max}, \bar{\mu}, t_k)$ shows that the dependences, $L_{\max}(\lambda_{max}, \bar{\mu})$, $t_{L\max}(\lambda_{max}, \bar{\mu})$, $\overline{\tau^w_{\max}} = \overline{\tau^w_{\max}}(\lambda_{max}, \bar{\mu})$ $t_{\overline{\tau^w_{\max}}}(\lambda_{max}, \bar{\mu})$ and can be approximated by a function of two variables of the form:

$$\bar{F}\left(\lambda_{\max}, \bar{\mu}\right) = a_0 + a_1\lambda_{max} + a_2\bar{\mu} + a_5\lambda^2_{max} + a_4\lambda_{max}\bar{\mu} + a_3\bar{\mu}^2 + a_6\lambda^3_{max} + a_7\lambda^2_{max}\bar{\mu} + a_8\lambda_{max}\bar{\mu}^2 \quad (10)$$

Corresponding coefficient values a_i, $i = \overline{0,8}$, are calculated using the method of least squares. Coefficient values are presented in table 1. And approximating surfaces are shown in figure 3.

Table 1. The values of the coefficients of the functional dependences, $L_{\max}(\lambda_{max}, \bar{\mu})$, $t_{L\max}(\lambda_{max}, \bar{\mu})$, $\overline{\tau^w_{\max}}(\lambda_{max}, \bar{\mu})$ **and** $t_{\overline{\tau^w_{\max}}}(\lambda_{max}, \bar{\mu})$.

	$L_{\max}(\lambda_{max}, \bar{\mu})$	$t_{L\max}(\lambda_{max}, \bar{\mu})$	$\overline{\tau^w_{\max}}(\lambda_{max}, \bar{\mu})$	$t_{\overline{\tau^w_{\max}}}(\lambda_{max}, \bar{\mu})$
a_0	970±160	–32±(–3.3)	99±13	–72±12
a_1	–167±16	2.4±0.18	15.5±1.3	3.4±0.7
a_2	–54±17	1.1±0.37	–6.4±1.4	3.3±1.3
a_3	7.8±0.7	–0.04±(–0.01)	0.66±0.06	–0.025±0.015
a_4	7±1	0.004±(–0.005)	0.7±0.08	0.1±0.021
a_5	0.66±0.54	–0.025±(–0.011)	0.099±0.045	–0.12±0.04
a_6	–0.1±0.11	0	–0.0092±0.0009	0
a_7	–0.09±0.015	0	–0.0075±0.0012	0
a_8	–0.078±0.027	0	–0.0095±0.0022	0

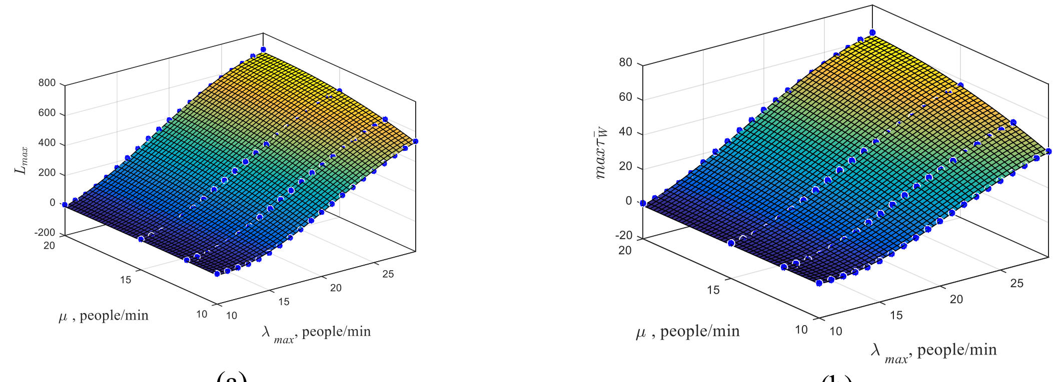


Figure 3. Dependencies (a) $L_{\max}(\lambda_{max}, \bar{\mu})$ and (b) $\overline{\tau^w_{\max}}(\lambda_{max}, \bar{\mu})$ for different values of parameters $\lambda_{max}, \bar{\mu}$.

Thus, the results, which were obtained by the NQS simulation, were consistent with the physical representations of its functioning features. This allow to confirm the adequacy of the used mathematical model of NQS and the efficiency of the corresponding software implementation.

4. Conclusions

The results of this research allow us to conclude that it is possible to describe for given law $\lambda = \lambda(t)$ NQS characteristics (not just the maximum average queue length $\overline{L}_{\max}$ and the time to reach the maximum average queue length $t_{L_{\max}}$, but also its other characteristics) using a polynomial depending on two "macroscopic" characteristics of NQS: maximum clients input rate $\lambda_{\max}$ and the average service rate $\overline{\mu}$.

Found dependencies can be used during ACD system design phase for objects of public events when analyzing technical characteristics of the access control system (ACS) turnstiles to mee safety requirements for mass gathering events.

The proposed approach makes it possible to study the characteristics of NQS in various modes of operation, including normal workload as well as handling emergency situations.

Acknowledgments
The work was supported by Act 211 Government of the Russian Federation, contract № 02.A03.21.0006

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