



Volume 130

2026

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: <https://doi.org/10.20858/sjsutst.2026.130.7>

Journal homepage: <http://sjsutst.polsl.pl>



Article citation information:

Jašek, M., Olivková, I. Simulation of a queuing model for passenger handling at an airport terminal. *Scientific Journal of Silesian University of Technology. Series Transport*. 2026, **130**, 111-124. ISSN: 0209-3324. DOI: <https://doi.org/10.20858/sjsutst.2026.130.7>

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SIMULATION OF A QUEUING MODEL FOR PASSENGER HANDLING AT AN AIRPORT TERMINAL

Summary. This study focuses on simulating a queuing model aimed at optimizing the passenger processing at an airport. The objective is to minimize waiting times and reduce operational costs. The model employs Markov processes to simulate two main phases: passport and security screening. The simulation aims to keep waiting times for passport control under 8 minutes and for security screening under 2 minutes for priority passengers. Software tools Witness were used, and simulations were conducted at intervals of 60 and 75 minutes. The results indicate that longer intervals lead to increased average waiting times and higher costs per passenger. The study also includes an analysis of the operational characteristics of Václav Havel Airport in Prague, with a focus on the capacity and efficiency of the processing counters. The outputs from this simulation provide valuable insights for improving airport management and planning, aiming to enhance efficiency and passenger satisfaction.

Keywords: queuing model, airport operations simulation, Markov processes, passenger processing, operational efficiency

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1. INTRODUCTION

Passenger processing is one of the key components that shape the overall airport experience and influence how travelers perceive the quality of airline services. Because the passenger check-in process significantly shapes how travelers perceive the quality of airline services, this study focuses on analyzing this part of airport operations. [1]

The decisive factor is not only the speed of security and passport control, but above all, the ability to process all passengers within the required time window. The main goal was to create a mathematical simulation of a generally applicable model for airports of various sizes, with the basic setup of the model corresponding to Václav Havel Airport in Prague.

The topic of mathematical models applicable at airports has been addressed by both mathematicians on the European continent [2] and Asian researchers [3].

2. BASIC DESCRIPTION OF A QUEUEING MODEL FOR PASSENGER CHECK-IN

This chapter provides an overview of the queuing model, including its structure, assumptions, and the operational parameters used to represent the check-in process.

This is a Markov queuing model with parallel lane ordering, where passport control (average service time 15 s per passenger) and security screening (average service time 18 s per passenger) are performed independently in each lane. The service times were modelled as deterministic values, as they were derived from direct observations of real operations.

Validation of the service times was conducted at two levels.

The first level consisted of logical validation (face validity), which verified that the model behaves realistically under different passenger arrival intensities and that the throughput of individual lanes corresponds to theoretical expectations based on the specified service times.

The second level of validation was empirical. The service times used in the model were obtained from instructional videos of real airport operations (Istanbul Airport) and subsequently compared with independent measurements carried out in real operation at a Czech regional airport. The measured values were consistent with the parameters used in the model, confirming that the selected service times realistically represent actual processing speeds.

The queue capacity in the system is unlimited (no passengers are rejected), and the order of service follows the FIFO principle. [4] Passenger arrivals were modelled using a Poisson distribution, which is commonly used to represent random arrival processes in airport operations and queuing systems. Service times at security screening and passport control were modelled using an exponential distribution, reflecting the assumption of memoryless processing and allowing the model to capture natural variability in service duration. These assumptions are standard in queuing theory and provide a reasonable approximation of real operational conditions. The hourly arrival rate varies depending on the aircraft scheduled for departure, assuming full occupancy. The objective was to keep the maximum waiting time below 8 minutes for standard passengers and below 2 minutes for priority passengers. Operational costs were also incorporated into the model.

In addition to the standard processing system, a separate subsystem was created for priority passengers. Priority passengers were routed into dedicated security lanes and dedicated passport control counters, operating fully independently from the standard passenger flow. No shared queues or pre-emption rules were used. Both subsystems employed identical service-time parameters, but the priority subsystem was dimensioned to ensure that the maximum waiting

time did not exceed 2 minutes. The proportion of priority passengers was fixed at 20% of the total hourly passenger volume, and these passengers were directed to the priority subsystem immediately upon arrival.

3. CONDUCTING SIMULATION AND DETERMINING OPERATIONAL CHARACTERISTICS

Here, the simulation procedure is described in detail, together with the configuration of model components and the method used to evaluate system performance.

The simulation was conducted in intervals of 60 and 75 minutes using the Witness software. Components such as 'Passenger' and 'Luggage' were created, along with machines such as 'Splitter' (splitting one 'Passenger' component into two 'Luggage' and 'Passenger' components), 'Security' (baggage check), 'Scanner' (passenger screening), and 'Passport' (passport control and reuniting the split components). For the 'Passport' machine, it was also necessary to ensure that each passenger took their own luggage, which was achieved by creating an attribute and the 'MATCH' rule. Lastly, a buffer 'Queue,' a variable 'Passenger_Order,' and an attribute 'Order' (both used to match passengers with their luggage) was created. After completing the entire security screening, passengers with their luggage were sent to the gate (not part of the model), which was achieved with the output rule 'PUSH TO SHIP.' The number of active security lanes and passport control counters was not determined using a formal optimization algorithm. Instead, an iterative heuristic approach was applied, in which individual system configurations were tested in progressively refined steps. At the end of each simulation run, the operational characteristics of the 'Passenger' component were determined by opening the 'Statistics' window, where average and maximum waiting times were observed. For each hourly load, the simulation was run once and repeated twice to verify consistency. Witness generates deterministically identical results due to its fixed random seed (default value used), ensuring full reproducibility without multiple replications. It should be noted that after some simulation runs (after the set time interval – 60 or 75 min.), some passengers and their luggage remained in the system and had not been fully processed. Therefore, it was necessary to create the variable 'Processed,' which displayed the total number of passengers and luggage that had been fully processed. The condition was that at the end of the simulation run, no one remained in the queue. [5]

In the following section, there is a Fig. 1 depicting the layout of elements in the system within the Witness simulation software. It shows the system state after 45 minutes, including some in-progress requests (passengers and luggage separately) and passengers waiting in the queue. The Fig. 1 also displays the processed passenger counts and the pairing of passengers with their luggage at the passport control counters.

Weekly traffic at Václav Havel Airport Prague was monitored. The Tab. 1 below shows the number of departing passengers. These numbers were determined based on the aircraft assigned to specific flights. There is a time shift for each hour, meaning that for Wednesday, 406 passengers are scheduled for check-in from 00:00 a.m. to 01:00 a.m., with their departure planned between 01:00 a.m. and 02:00 a.m. These were flights to Hurghada (Boeing 737-900 OK-TSM) and Marsa Alam (Boeing 737 MAX 8 OK-SWA).

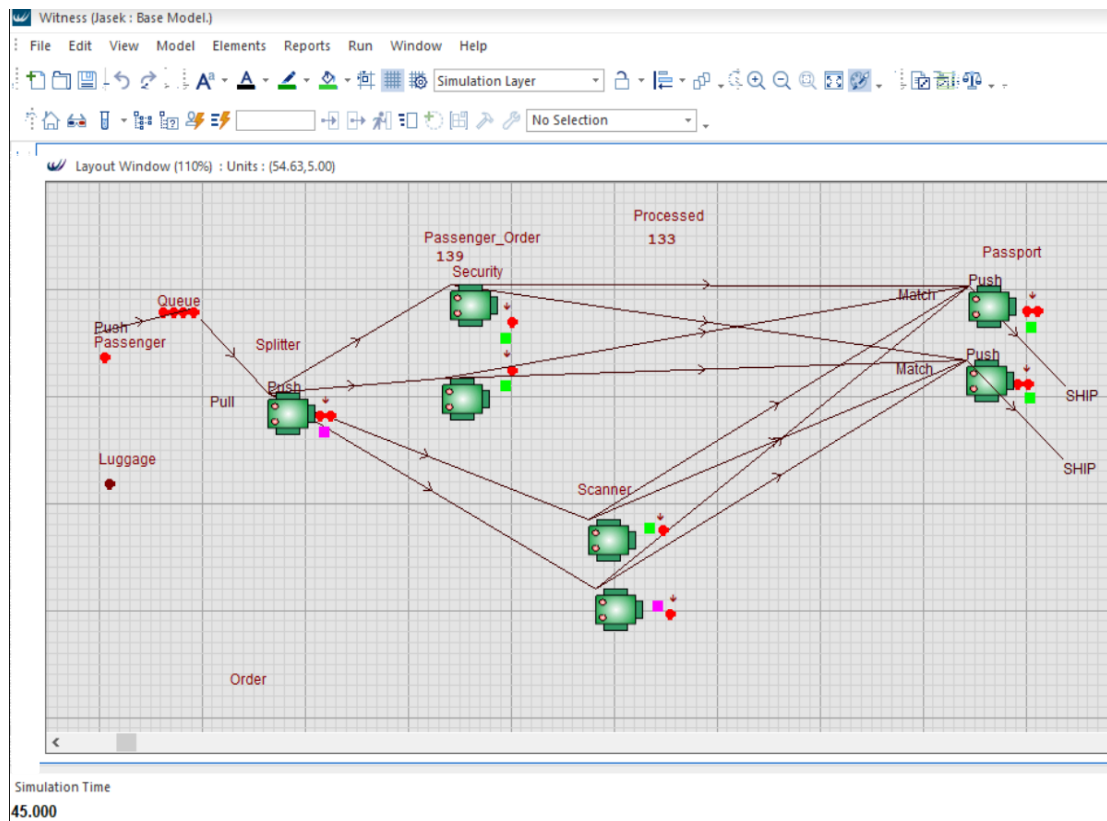


Fig. 1. Sample of the current simulation environment (Witness)

Tab. 1

Some departures from October 4, 2023 [6]

| Scheduled departure time | Flight number | Destination | Airline | Aircraft |
|--------------------------|---------------|-------------|----------------|---------------|
| 0:50 | QS1240 | Hurghada | Smartwings | B739 (OK-TSM) |
| 0:55 | QS2568 | Marsa Alam | Smartwings | B38M (OK-SWD) |
| 1:00 | QS2558 | Hurghada | Smartwings | B739 (OK-TSM) |
| 1:10 | QS1222 | Marsa Alam | Smartwings | B38M (OK-SWA) |
| 4:05 | QS1108 | Larnaca | Smartwings | B738 (OK-TST) |
| 4:45 | QS1146 | Rhodes | Czech Airlines | A320 (OK-IOO) |

4. AIRCRAFT CAPACITIES AND CHECK-IN CAPACITIES NEEDED

This part summarizes the aircraft types operating at the airport and uses their seating capacities to estimate hourly passenger volumes.

To determine the exact number of passengers that need to be processed for departure, it was necessary to estimate the approximate number of passengers for each individual type of aircraft and then sum up the aircraft capacities for each hour. This is mentioned in Tab. 2.

Tab. 2

An overview of aircraft types and their configurations that appeared at the airport during the given week [7][8]

| Aircraft type | Number of seats | Aircraft type | Number of seats |
|--------------------|-----------------|---------------------|-----------------|
| Airbus A220-133 | 133 | Bombardier CRJ 1000 | 100 |
| Airbus A380 | 550 | Embraer E170 | 72 |
| ATR 72-500 | 68 | Embraer E175 | 88 |
| ATR 72-600 | 78 | Embraer E190 | 114 |
| Bombardier CRJ 900 | 90 | Embraer E195 | 116 |
| Airbus A318 | 132 | Fokker 100 | 122 |
| Airbus A319 | 160 | Boeing 737-300 | 149 |
| Airbus A320 | 190 | Boeing 737-400 | 147 |
| Airbus A321 | 230 | Boeing 737-700 | 149 |
| Airbus A330-200 | 260 | Boeing 737-800 | 189 |
| Airbus A350 | 350 | Boeing 737-900 | 217 |
| Boeing 777-300 | 396 | Bombardier CRJ 1000 | 100 |

The first level represented logical validation (face validity), which verified that the model exhibits realistic behavior under various intensities of incoming passengers and that the throughput of individual lanes corresponds to theoretical assumptions derived from service times.

The second level of validation was empirical and focused on verifying the service times used in the model. These values were obtained from instructional videos of real operations (e.g., Istanbul Airport) and subsequently compared with independent measurements conducted during actual operations at a Czech regional airport. The measured values differed only minimally from the parameters used, confirming that the selected service times realistically correspond to actual operations.

The following Tab. 3 a Tab. 4 contains the number of passengers per hour and day that need to be processed. There are no passengers for the time 1:00 a.m. - 3:00 a.m. All data are from the year 2023.

Tab. 3

Number of passengers needed to be processed during the selected week (morning)

| Time | | Wed 04/10 | Thu 5/10 | Fri 6/10 | Sat 7/10 | Sun 8/10 | Mon 9/10 | Tue 10/10 |
|------|---------------|--------------|-------------|-------------|-------------|-------------|-------------|--------------|
| a.m. | 0:00 – 1:00 | 406 | | | | 378 | | |
| | 3:00 – 4:00 | 1,704 | | | | 1,490 | 406 | |
| | 4:00 – 5:00 | | | | | 190 | 189 | |
| | 5:00 – 6:00 | 1,705 | 1,784 | 190 | | 798 | 2,341 | |
| | 6:00 – 7:00 | 727 | 655 | 756 | | 654 | 580 | |
| | 7:00 – 8:00 | 1,416 | 1,431 | 2,203 | 799 | 1,715 | 1,662 | 438 |
| | 8:00 – 9:00 | 1,387 | 2,486 | 1,692 | 1,962 | 1,436 | 1,704 | 2,062 |
| | 9:00 – 10:00 | 2,589 | 1,543 | 2,393 | 1,325 | 2,025 | 2,296 | 1,297 |
| | 10:00 – 11:00 | 2,866 | 2,232 | 1,942 | 1,923 | 2,436 | 3,220 | 2,448 |
| | 11:00 – 12:00 | 2,614 | 2,144 | 2,914 | 2,333 | 2,146 | 1,357 | 801 |

Tab. 4

Number of passengers needed to be processed during the selected week (afternoon)

| | Time | Wed 04/10 | Thu 5/10 | Fri 6/10 | Sat 7/10 | Sun 8/10 | Mon 9/10 | Tue 10/10 |
|---------------|--------------|----------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------------|
| p.m. | 12:00 – 1:00 | 1,199 | 1,198 | 1,169 | 917 | 818 | 946 | 818 |
| | 1:00 – 2:00 | 1,678 | 2,141 | 1,757 | 1,281 | 2,548 | 2,171 | 1,080 |
| | 2:00 – 3:00 | 1,858 | 1,876 | 1,266 | 1,354 | 1,819 | 1,497 | 1,458 |
| | 3:00 – 4:00 | 1,063 | 804 | 1,981 | 1,254 | 1,414 | 2,070 | 874 |
| | 4:00 – 5:00 | 2,015 | 595 | 878 | 717 | 1,296 | 915 | 997 |
| | 5:00 – 6:00 | 1,912 | 2,163 | 2,876 | 2,606 | 2,173 | 2,463 | 1,568 |
| | 6:00 – 7:00 | 2,199 | 1,334 | 1,769 | 1,917 | 1,747 | 1,221 | 917 |
| | 7:00 – 8:00 | 1,215 | 1,536 | 1,067 | 538 | 1,335 | 1,844 | 994 |
| | 8:00 – 9:00 | 1,236 | 1,867 | 1,836 | 1,096 | 1,108 | 1,267 | 1,079 |
| | 9:00 – 10:00 | 1,028 | 379 | 986 | | 230 | 1,257 | 636 |
| 10:00 – 11:00 | 189 | 217 | 217 | 946 | 217 | 189 | 189 | |

Operational characteristics were analyzed separately for 60-minute and 75-minute intervals. To ensure that no passengers were turned away, in other words, to ensure that all passengers were processed before the aircraft's departure (within the given time interval), it was necessary to configure the system (number of counters) so that no passengers were left waiting at the end of the selected time interval. [9]

5. SYSTEM WITH A 60-MINUTE INTERVAL AND A MAXIMUM WAITING TIME OF 8 MINUTES

The following section presents the results for the standard service scenario and examines how different system configurations affect waiting times and costs.

The number of counters was adjusted in this case to ensure that all passengers were processed within 60 minutes and to avoid exceeding the maximum waiting time of 8 minutes.

Tab. 5 below shows that increasing the number of security lanes and passport control counters leads to a systematic reduction in maximum waiting times. At low passenger volumes (e.g., 91 passengers per hour), the system operates with minimal infrastructure, but the waiting times remain relatively high due to the limited number of active counters. As the hourly passenger load increases, additional counters are activated, which stabilizes both the average and maximum waiting times despite the higher demand.

The unit cost per passenger decreases as the number of processed passengers grows. This trend reflects the fixed-cost nature of the system: once additional counters are activated, their operational cost is distributed across a larger number of passengers, resulting in lower per-passenger costs. On the other hand, at very high passenger volumes (above 2,000 passengers per hour), the system reaches almost the same costs as in the case of lower passenger volumes.

As the Tab. 5 and Fig. 2 show, increasing the number of counters significantly reduces the maximum waiting time. As the number of processed passengers grows, the unit costs are initially high but gradually decrease and remain at approximately the same level.

Tab. 5

Operational characteristics for different numbers of passengers processed per hour

| Number of passengers processed | Number of lanes set (1 security + 1 scanner) | Number of passport counters | Costs per passenger [EUR] | Waiting time [s] | |
|--------------------------------|--|-----------------------------|---------------------------|------------------|---------|
| | | | | Average | Maximum |
| 91 | 1 | 1 | 0.425 | 106.2 | 307.2 |
| 329 | 3 | 3 | 0.385 | 124.2 | 360.6 |
| 606 | 5 | 5 | 0.383 | 141 | 289.2 |
| 852 | 7 | 7 | 0.385 | 153 | 298.2 |
| 1,089 | 9 | 9 | 0.377 | 145.2 | 289.2 |
| 1,359 | 11 | 11 | 0.373 | 127.8 | 233.4 |
| 1,627 | 13 | 13 | 0.374 | 144 | 256.8 |
| 1,869 | 15 | 15 | 0.369 | 112.8 | 216.6 |
| 2,145 | 17 | 17 | 0.370 | 132.6 | 247.2 |
| 2,392 | 19 | 19 | 0.373 | 126 | 232.2 |
| 2,501 | 20 | 20 | 0.425 | 117.6 | 223.8 |

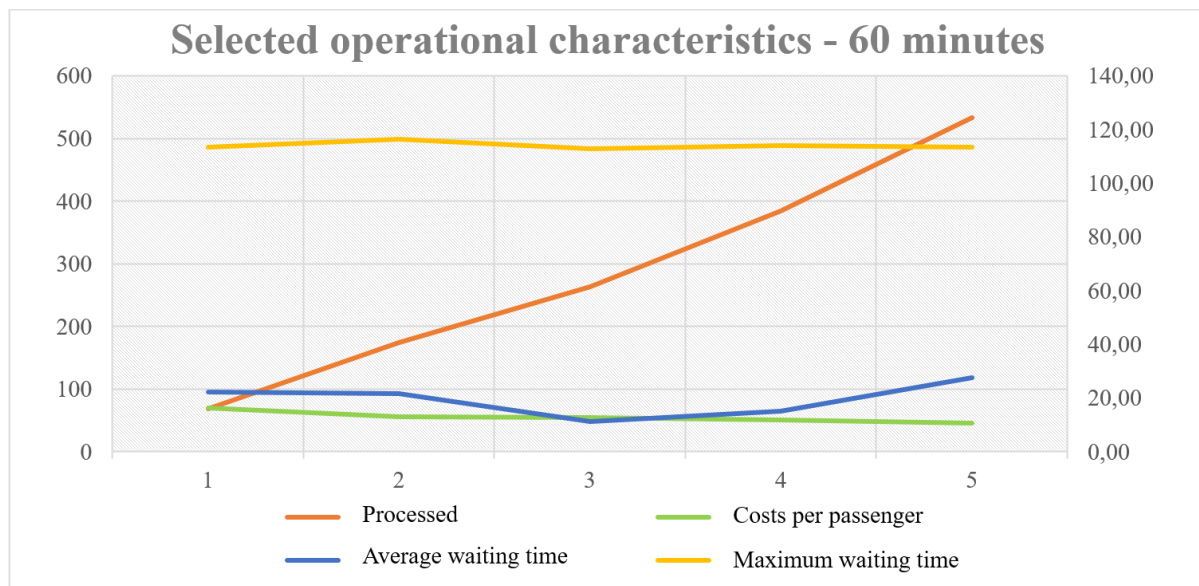


Fig. 2. Variation of selected operational characteristics for the hourly interval

6. SYSTEM WITH A 60-MINUTE INTERVAL AND A MAXIMUM WAITING TIME OF 2 MINUTES

This chapter focuses on the priority processing scenario, analyzing the infrastructure required to maintain significantly shorter waiting times.

In addition to ensuring that no passengers are left in the queue at the end of the required time interval, it was also necessary to reduce the maximum waiting time to 2 minutes. Therefore, compared to the previous configurations, a greater number of lanes had to be added.

The number of lanes was adjusted in this case to ensure that all passengers were processed and that the maximum waiting time of 2 minutes was not exceeded.

Tab. 6 shows that meeting the stricter requirement of a maximum 2-minute waiting time requires a disproportionately higher number of processing lanes, even at relatively low passenger volumes. The system must therefore operate with several dedicated priority lanes to maintain the required service level.

Tab. 6

Operational characteristics for different numbers of passengers processed per hour

| Number of passengers processed | Number of lanes set (1 security + 1 scanner) | Number of passport counters | Costs per passenger [EUR] | Waiting time [s] | |
|--------------------------------|--|-----------------------------|---------------------------|------------------|---------|
| | | | | Average | Maximum |
| 69 | 1 | 1 | 0.676 | 22.2 | 113.4 |
| 174 | 2 | 2 | 0.535 | 21.6 | 116.4 |
| 263 | 3 | 3 | 0.532 | 11.4 | 112.8 |
| 384 | 4 | 4 | 0.485 | 15 | 114 |
| 534 | 5 | 5 | 0.437 | 27.6 | 113.4 |

The maximum waiting time stays close to the 2-minute limit across all configurations, confirming that the system is correctly dimensioned. However, the unit cost per passenger is higher than in the standard model because priority processing requires more infrastructure per traveler. This illustrates the fundamental trade-off: very short waiting times can be achieved, but only at the expense of higher operational costs. The variation of selected operational characteristics is shown in Fig. 3.

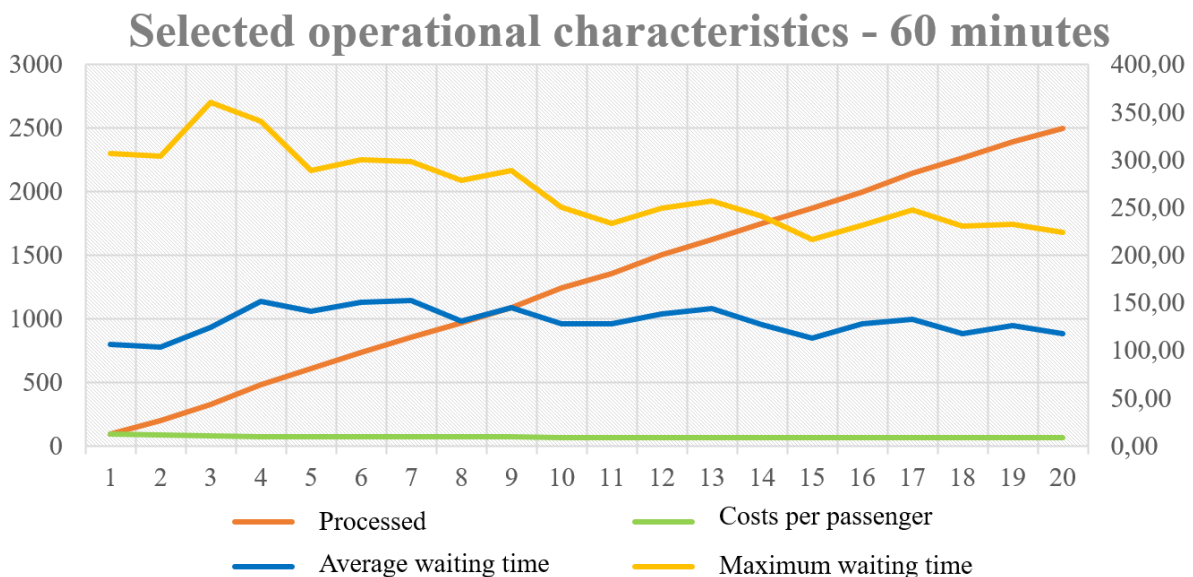


Fig. 3. Variation of selected operational characteristics for the hourly interval with a maximum waiting time of 2 minutes

During the research experiment, changes in system behavior were also tested by extending the interval to 75 minutes. With this change in the check-in interval, both configurations (basic and priority) saw an increase in unit costs, with the priority model's unit costs rising by 19%.

Although the number of passengers processed in the basic model increased by one-tenth, the unit costs also rose by approximately the same margin. This longer interval did not bring any significant benefits, as the number of processed passengers remained relatively low, leading to an undesirable increase in unit costs. While unit costs in the priority model remained stable, the maximum wait time did not change, and the average wait time only decreased slightly. However, in the model with a one-hour interval and an eight-minute maximum wait time, there were large fluctuations in waiting times. Overall, unit costs and average wait times remained relatively stable in both intervals, suggesting that extending the check-in interval may not be efficient given the low number of passengers.

7. THEORETICAL IMPLEMENTATION OF THE MODEL FOR VÁCLAV HAVEL AIRPORT IN PRAGUE

This section discusses how the proposed model could be applied in practice at Václav Havel Airport, taking into account its current layout and operational constraints.

The queuing system was originally intended for the airport in Prague, as shown in Fig. 4. Security screening at Václav Havel Airport takes place at twelve locations according to the map of Terminals 1 and Terminal 2. The number of gates available for use is around fifty.



Fig. 4. Extract from the terminal map of Václav Havel Airport [10]

The security screening could therefore take place at multiple locations at this airport simultaneously. Based on the daily aircraft stand utilization plan, the required number of security screening counters could be activated at each individual gate, depending on which aircraft are scheduled to be stationed there.

8. COST CALCULATION ASSOCIATED WITH SECURITY AND PASSPORT CONTROL

The economic aspect of the model is introduced here, explaining how operational costs are derived and how they relate to system performance.

In addition to analyzing waiting times and system throughput, it is important to assess the economic implications of different configurations of security and passport control counters. The cost calculation provides a quantitative measure of operational efficiency and allows the comparison of alternative setups in terms of their financial impact per processed passenger.

Formula for calculating the costs that each passenger must pay in EUR:

$$nc = \frac{h \cdot 0,247 \cdot (2n_{zr} + np) + h \cdot 9,36 \cdot (2n_{zr} + np)}{pc}, \quad (1)$$

where h is the length of the time interval, nc are the costs that each passenger must pay, n_{zr} is the number of luggage and security scanners in operation, np is the number of passport control counters, pc is the number of passengers processed, 6,19 is the hourly rate for the annual rental of a counter, and 9,36 is the hourly cost associated with paying employee wages.

Calculation of unit costs for the case of a 75-minute interval, 176 processed passengers, 2 baggage screening counters, 2 security scanners for passenger screening, and 2 passport control counters:

$$nc = \frac{1.25 \cdot 6,19 \cdot (2 \cdot 2 + 2) + 1.25 \cdot 9,36 \cdot (2 \cdot 2 + 2)}{176} = 0,66 \text{ EUR} \quad (2)$$

The cost parameters used in the model are based on the official price list of Václav Havel Airport Prague. nA hourly cost of approximately 6,19 EUR per counter. The labor cost of 9.36 EUR per hour reflects the average hourly wage associated with operating security and passport control positions. These values were selected to represent realistic airport operating expenses and to ensure that the economic component of the model corresponds to actual operational conditions.

A linear cost structure was adopted because both counter rental fees and labor costs increase proportionally with the number of active processing stations. The resulting unit cost per passenger is calculated by dividing the total hourly operational cost by the number of passengers processed within the interval, which enables a direct comparison of different system configurations.

9. EXAMPLE ON A SPECIFIC DAY

This chapter applies the model to real traffic data from a selected day and demonstrates how passenger demand influences the required number of counters and resulting costs.

Let us consider the case where on Wednesday, October 4th, around 31,000 passengers will be processed. These passengers arrive at the security checkpoint one hour before boarding (operating interval of 60 minutes) at varying intensities, calculated based on the deployed aircraft and seat configurations listed in the table above. [8] To ensure that all passengers are processed on time and do not have to wait long in the queue, the corresponding minimum

number of counters must be activated. These numbers were obtained by approximating the calculated states shown in the tables above. Additionally, 20% of these passengers are premium, meaning they have purchased priority processing with reduced waiting times.

Tab. 7 shows how the required number of counters changes throughout the day in response to fluctuating passenger demand. During peak hours, both standard and priority systems require substantially more security lanes and passport counters to process all passengers within the 60-minute interval, while off-peak periods require only minimal infrastructure.

Priority passengers require additional dedicated counters, which raises total costs slightly, but the difference between standard and priority processing remains relatively small, indicating efficient dimensioning of the priority subsystem.

Tab. 7

The cost of the system at different intensities of incoming passengers

| Wed 4/10 | | Number of passengers by fare type | | | | | | | |
|----------|---------------|-----------------------------------|----------|----------|----------|----------|----------|----------------|----------------|
| Time [h] | | <i>a</i> | <i>b</i> | <i>c</i> | <i>d</i> | <i>e</i> | <i>f</i> | <i>g</i> [EUR] | <i>h</i> [EUR] |
| a.m. | 0:00 – 1:00 | 325 | 81 | 4 | 4 | 2 | 2 | 93,32 | 0,69 |
| | 3:00 – 4:00 | 1,363 | 341 | 12 | 12 | 4 | 4 | 186,63 | 0,44 |
| | 5:00 – 6:00 | 1,364 | 341 | 12 | 12 | 4 | 4 | 186,63 | 0,44 |
| | 6:00 – 7:00 | 582 | 145 | 5 | 5 | 2 | 2 | 93,32 | 0,45 |
| | 7:00 – 8:00 | 1,133 | 283 | 10 | 10 | 3 | 3 | 139,98 | 0,43 |
| | 8:00 – 9:00 | 1,110 | 277 | 10 | 10 | 4 | 4 | 186,63 | 0,47 |
| | 9:00 – 10:00 | 2,071 | 518 | 17 | 17 | 6 | 6 | 279,95 | 0,41 |
| | 10:00 – 11:00 | 2,293 | 573 | 19 | 19 | 6 | 6 | 279,95 | 0,41 |
| | 11:00 – 12:00 | 2,091 | 524 | 17 | 17 | 5 | 5 | 233,29 | 0,39 |
| p.m. | 12:00 – 1:00 | 1,342 | 336 | 11 | 11 | 4 | 4 | 186,63 | 0,42 |
| | 1:00 – 2:00 | 1,486 | 372 | 12 | 12 | 4 | 4 | 186,63 | 0,40 |
| | 2:00 – 3:00 | 850 | 213 | 7 | 7 | 3 | 3 | 139,98 | 0,44 |
| | 3:00 – 4:00 | 1,612 | 403 | 13 | 13 | 5 | 5 | 233,29 | 0,42 |
| | 4:00 – 5:00 | 1,530 | 382 | 13 | 13 | 4 | 4 | 186,63 | 0,42 |
| | 5:00 – 6:00 | 1,759 | 440 | 15 | 15 | 5 | 5 | 233,29 | 0,42 |
| | 6:00 – 7:00 | 972 | 243 | 9 | 9 | 3 | 3 | 139,98 | 0,46 |
| | 7:00 – 8:00 | 989 | 247 | 9 | 9 | 3 | 3 | 139,98 | 0,45 |
| | 9:00 – 10:00 | 822 | 206 | 7 | 7 | 3 | 3 | 139,98 | 0,45 |
| | 10:00 – 11:00 | 151 | 38 | 2 | 2 | 1 | 1 | 46,66 | 0,74 |

where:

- a* - number of basic fare passengers,
- b* - number of priority fare passengers,
- c* - number of lanes (security + scanner),
- d* - number of passport counters,
- e* - number of priority lanes (security + scanner),
- f* - number of priority passport counters,
- g* - total costs,
- h* - costs per passenger.

Note: In the column h the costs are higher compared to the previous tables. This is because the number of passengers registered for the flight are intermediate values from the previous tables. To ensure all passengers are processed on time, it was necessary in some cases to increase the number of counters by one compared to the tables, which resulted in an increase in the average unit cost per passenger.

10. CONCLUSIONS

The final section summarizes the key findings, reflects on the model's limitations, and outlines directions for further research and practical application.

The initial intention was to calculate the required number of lanes for entire days, with simulations running in 24-hour cycles. This approach was eventually abandoned due to excessive computational demands and the unrealistic number of lanes required for continuous operation. Instead, simulations were performed for different hourly passenger intensities, allowing the system to activate only the number of lanes needed in each specific hour. This approach proved significantly more efficient: for example, at peak loads exceeding 2,000 passengers per hour, the system required up to 17 security lanes and 17 passport counters, whereas off-peak periods operated with only one or two active stations. The results also showed that the unit cost per passenger decreases as the number of processed passengers increases, stabilizing at approximately 0.37-0.39 EUR per passenger in the standard model. In contrast, the priority model achieved waiting times below 2 minutes but required substantially more infrastructure, resulting in higher unit costs (0.43-0.68 EUR per passenger).

Extending the processing interval from 60 to 75 minutes did not bring operational benefits. Although the number of processed passengers increased slightly, unit costs rose by approximately 10-19%, and waiting times fluctuated more significantly. These findings indicate that shorter processing intervals are more efficient for maintaining stable waiting times and predictable operational costs. Provided that service times at security screening and passport control remain comparable, the model can be applied to airports of various sizes, which represents one of its practical advantages.

The simulation model also has several limitations, particularly in its ability to fully capture qualitative aspects of service delivery. Validation is constrained by the availability and accuracy of operational data, and the model may not fully reflect real peak loads or actual aircraft occupancy. Moreover, the model focuses primarily on time-based indicators such as waiting time, while other factors influencing perceived service quality (such as comfort, cleanliness, or the availability of information) are not included. Passenger perceptions of acceptable waiting times also vary and are not represented in the model. For these reasons, the simulation could be complemented by additional service quality assessment methods and passenger feedback to provide a more comprehensive evaluation. [11] [12]

The findings of this study are consistent with previous research on airport queuing systems. Similar to Zhang et al. (2017) and Chen & Yu (2020), the results confirm that reducing processing intervals and increasing the number of active lanes significantly decreases waiting times, but at the cost of higher staffing requirements. The observed nonlinear increase in required counters at high passenger volumes is consistent with the findings of Dorton (2015), who showed that passenger throughput at security checkpoints is highly sensitive to demand fluctuations and that additional lanes reduce waiting times only up to a certain capacity threshold. Similarly, the results reported by Li, Gao, Xu and Zhou (2018) demonstrate that both queuing-network models and discrete-event simulation reveal diminishing returns when

increasing lane capacity and that maintaining very short waiting times requires disproportionately higher staffing levels. These conclusions align with our results, which also show clear capacity limits and a trade-off between short waiting times and higher operational costs. [13] [14]

From a practical perspective, the model provides several recommendations for airport operators. Airports with fluctuating hourly demand should dynamically activate only the number of lanes required for each specific hour, as this approach minimises operational costs while maintaining acceptable waiting times. Priority processing can be offered as a premium service, but airports should be aware that maintaining a maximum waiting time of 2 minutes requires significantly more infrastructure. Finally, extending the processing interval beyond 60 minutes is not recommended, as it increases operational costs without improving system performance. [15]

Acknowledgements

This work was supported by the project SP2024/095 Research, Development, and Innovation in the Field of Transport and Logistics.

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Received 30.09.2025; accepted in revised form 24.02.2026



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