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ANALYSIS OF THE IMPACT OF PASSENGER PREPARATION ON THE THROUGHPUT OF SECURITY SCREENING AT AIRPORT CHECKPOINTS

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Abstract. Efficient passenger screening is a critical component of airport security operations, directly influencing both safety standards and the overall passenger experience. As global air traffic continues to grow, optimizing the throughput of security checkpoints while maintaining regulatory compliance has become a major operational challenge. This study investigates one often overlooked factor affecting checkpoint performance – the level of passenger preparation prior to screening. The research combines experimental and simulation-based analyses to assess how improper passenger preparation contributes to the frequency of alarms at walk-through metal detectors (WTMDs). The study focuses on a security lane operating under a free passenger flow configuration equipped with a WTMD. The results demonstrate that better passenger preparation significantly improves checkpoint throughput and overall lane capacity. This microscopic analysis, which quantifies the operational impact of passenger behavior on system performance, addresses a gap not previously covered in the literature. The findings provide practical insights for airport security managers and system designers, emphasizing the importance of targeted passenger guidance and education in enhancing checkpoint efficiency.

Keywords: airport, terminal operations, passenger handling, security screening, simulation model, throughput analysis.

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1. Introduction

Security in air transport has for decades remained an issue of fundamental importance to airport operators, international organizations, air carriers, and public safety institutions alike. The significance of this area increased markedly following a series of terrorist attacks at the beginning of the 21st century, which exposed the fragility of critical infrastructure when confronted with asymmetric threats. Passenger and baggage security screening has become not only an operational component of the passenger handling process but also a key element of a broader preventive strategy against acts of unlawful interference.

In response to these challenges, the International Civil Aviation Organization [ICAO] (2020) established, in Annex 17 to the Chicago Convention, a comprehensive set of standards and recommended practices pertaining to the safeguarding of civil aviation. Member States are obliged to implement national civil aviation security programmes to ensure an appropriate level of protection in airports, air transport operations, and personnel and passenger screening procedures. Following ICAO's guidance, regional regulations such as Regulation (EC) No. 300/2008 of the European Parliament and of the Council established common rules for the safeguarding of civil aviation within the European Union (EUR-Lex, 2008).

With the proliferation of air travel and the intensification of passenger traffic, however, security screening has come to generate serious organizational, operational, and technological challenges. The academic literature increasingly highlights the paradoxical relationship between the effectiveness of security measures and the throughput of passenger processing (Gkritza et al., 2006). On the one hand, airports are obligated to ensure a very high level of security, which entails complex screening structures ranging from manual search procedures and CT scanners to biometric technologies and automated threat detection systems. On the other hand, each additional procedure naturally extends the handling time per passenger, which given a large number of operations – results in cumulative delays and overloading of infrastructure throughput.

The psychological aspect of queue waiting time is also of considerable importance. Studies by Kim et al. (2020) demonstrate the influence of perceived waiting time on passengers' emotional responses and their overall perception of the airport. The results show that prolonged waiting can lead to negative emotions and reduced acceptance of security procedures, which, in turn, affects the airport's image (Maliwat, 2018). Research by Marshall et al. (2022) indicates that the average waiting time for passengers in security screening queues at high-traffic airports is around 20 minutes, although under peak conditions it may extend to an hour. The magnitude of this issue requires extensive infrastructure and sufficient human resources to support operations, which represents a substantial maintenance cost. For example, the annual cost of employing security screening operators at Aéroport de Paris is estimated at around USD 120 million (Brun et al., 2025).

The above-mentioned challenges have prompted extensive research into the functioning and potential optimization of security screening systems. A significant finding is that the quantity of clothing worn by a passenger directly influences queuing time (Bullock et al., 2010). This issue pertains to passenger preparation for the security screening process. However, this aspect has not yet been sufficiently examined in scientific studies. Not only the quantity of clothing but also the number of items carried by the passenger and their general awareness of the screening procedures may cause disturbances and slowdowns in the process. This article provides a detailed analysis of the impact of proper passenger preparation for security screening on system throughput. This topic has not yet been the subject of previous research, and the obtained results provide a basis for significant process improvement.

The subsequent sections of this paper include a review of the current state of knowledge regarding the phenomena studied in the security screening process, identifying the research gap (Section 2). Section 3 presents the problem background based on empirical studies conducted at a real airport. Section 4 introduces the research methodology based on computer simulation and then presents the results and discussion, while Section 5 provides the conclusions.

2. State of the art

One of the areas investigating phenomena occurring during passenger and baggage security screening concerns the effectiveness of detecting prohibited items. Latscha et al. (2024) discovered that the time required for baggage screening strongly depends on the number of items contained within. The more items are present, the longer the operator must spend on the inspection. Simultaneously, detection effectiveness decreases as the number of items in baggage increases. To improve detection rates, various operator-assistance systems are applied. An example is the Explosives Detection Systems for Cabin Baggage (EDSCB), which suggests to the operator specific regions of interest that deserve closer examination. However, Huegli et al. (2025) demonstrated that this approach is flawed, as it distracts operators from other areas, thereby reducing overall detection performance.

Other studies focus on developing fully automated systems capable of identifying prohibited items. Convolutional neural networks have been used to detect certain dangerous objects such as knives (Erarslan et al., 2022), sharp items (Aydin et al., 2018), and firearms hidden in baggage (Akçay et al., 2016). Hättenschwiler et al. (2018), in their study on automating explosives detection systems for cabin baggage, found that human–machine systems with automated decision-making outperformed diagnostic-assistance automation. Schwaninger et al. (2004) demonstrated that the issue may also be related to the level of operator training, indicating that operator training systems require significant improvement. However, the studies cited above primarily focus on ensuring an adequate level of security rather than addressing aspects related to passenger processing throughput.

Another research area focuses on process analysis from the perspective of maintaining a satisfactory level of security. Zeballos et al. (2023) conducted studies confirming the benefits of introducing an element of unpredictability in the screening process. In practice, this means that a randomly selected portion of passengers undergoes screening using more than one method. This significantly enhances overall security levels. Buser et al. (2023) investigated the impact of operator working time on screening performance and confirmed that systematic staff rotation is essential. They also found that the rotation interval can be extended by about ten minutes beyond what regulations mandate.

In other studies, such as Nikolaev et al. (2012), the focus was on developing heuristic methods for assigning passengers to different security classes. Depending on the assigned class, different screening techniques were applied to achieve high security levels without compromising throughput. Similarly, Yildiz et al. (2008) proposed a new configuration of the security checkpoint to improve performance while maintaining a high level of protection. The primary goal of these studies is ensuring security, while passenger throughput remains a secondary concern. As research in other areas of aviation (Karpenko, 2022; Kierzkowski et al., 2024) also indicates, safety is a key aspect. However, a common ground must be found to ensure both safety and performance of the process.

The final group of research studies, which will be indicated in this paragraph, examines process analysis with a focus on passenger throughput performance. This type of analysis requires the development of microscopic models that allow for system sensitivity studies. Li et al. (2018) presented the use of computer simulation to compare six different passenger queuing structures before the security checkpoint. De Lange et al. (2013) proposed assigning passengers specific time slots to arrive at the checkpoint in order to reduce direct waiting times. Olapiriyakul and Das (2007) developed a mathematical model comparing the performance of conventional double-parallel lanes with a serial two-stage control system. Hsu et al. (2012) applied computer simulation to identify resource-minimization methods while maintaining target system throughput. Bruno and Govense (2010) identified the potential for improvement through dynamic management of the system. Kierzkowski and Kisiel (2015a) modelled passenger flow to compare single and double security lane configurations. Subsequently, Kierzkowski and Kisiel (2015b) applied a simulation model to analyse the sensitivity of passenger preparation and baggage reclaim areas on the throughput of a double-lane checkpoint.

Only a few studies found in the literature relate closely to the research presented in this paper. Leone (2002) analysed various scenarios to determine the effect of baggage-triggered alarms and manual baggage inspection procedures on process performance. Van Boekhold et al. (2014) investigated how the number of random alarms set on WTMD devices affects checkpoint throughput. However, random alarms differ in nature from alarms caused by actual screening events. Three primary alarm rates – 10%, 15%, and 20% – were examined. Skorupski and Uchronski (2016) studied how WTMD sensitivity settings influence the number of alarms and their impact on process throughput.

A review of the literature clearly indicates that the number of alarms during passenger screening necessitates additional screening procedures, which directly affects process throughput. Some alarms are triggered randomly, as required by security regulations, while others are caused by improper passenger preparation. The scale of this problem, however, has not yet been quantified. This study addresses that research gap. The aim of this study is to quantitatively assess the impact of improper passenger preparation for security screening on the operational throughput of airport security checkpoints by combining experimental observations and simulation-based analysis.

Section 3 presents empirical research conducted on a real-world system, followed by a sensitivity analysis that shows how varying the number of alarms influences process throughput – a topic not previously explored in detail.

3. Problem background

Passenger security screening is carried out in accordance with applicable legal requirements. The airport where the research was conducted must comply with the provisions of Regulation (EUR-Lex, 2015). At least one of the following methods must be used: manual screening, walk-through metal detector (WTMD), explosive detection dog, explosive trace detection device (ETD), non-ionizing body scanner (BS), or ETD combined with a handheld metal detector (HHMD). When an operator cannot confirm whether a passenger is carrying prohibited items, a combination of methods must be applied until the operator is satisfied that the requirements are met.

Airports typically perform security screening using WTMD or BS as the primary methods, with some passengers randomly selected for ETD screening. When the WTMD or BS generates an alarm, the cause must be identified. WTMD and BS alarms are most often triggered when passengers are not properly prepared for screening – that is, when they fail to remove all items for separate inspection and carry objects that cause a signal. Once an alarm occurs, the operator must resolve its cause, which may require the passenger to return to the preparation area for re-screening or to undergo manual screening. These additional actions significantly reduce throughput, as demonstrated later in the paper.

Apart from alarms, passengers must also return if they fail to remove outer garments such as coats, jackets, or blazers for separate screening. This results in similar performance impacts as those described above.

To preliminarily assess the scale of the issue, field studies were conducted on a real security lane system. A total of 60 hours of operation were analysed (Figure 1). The lane was equipped with a WTMD for passenger screening. During the study, the number of alarms per hour was recorded. The preparation and item collection areas each accommodated an average of five passengers. Passenger movement through the security lane followed a free-flow pattern, meaning that there were no individual preparation booths – passengers used a shared conveyor belt. The study was conducted under full workload conditions, with a continuous flow of passengers and no interruptions.

During the study period, the proportion of passengers triggering alarms at the WTMD ranged from 7% to 30%, with an average value of 15%. These results exclude randomly generated alarms, which are determined deterministically under classified regulatory parameters for security reasons. Only alarms caused by improper passenger preparation were considered. The measured throughput of the security lane varied between a minimum of 115 pax/h and a maximum of 140 pax/h, with an average value $\bar{x}$ of 123.77 pax/h. Detailed hourly results are shown in Figures 2 and 3.

The results indicate that the proportion of passengers requiring additional screening actions is significant. A clear correlation can be observed between the number of alarms and the throughput of the security lane. Figure 4 shows the relationship between throughput and the number of alarms recorded.

For the analysed dataset, the Pearson correlation coefficient (Equation (1)) indicated a strong negative cor-

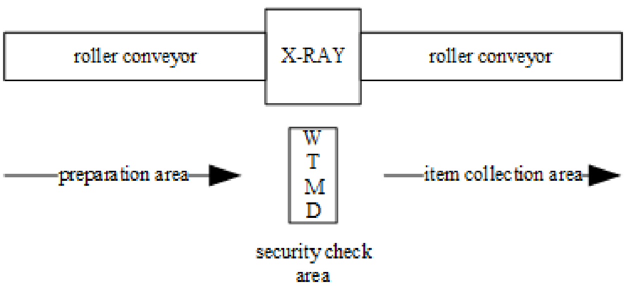

Figure 1. Structure of the analysed security lane

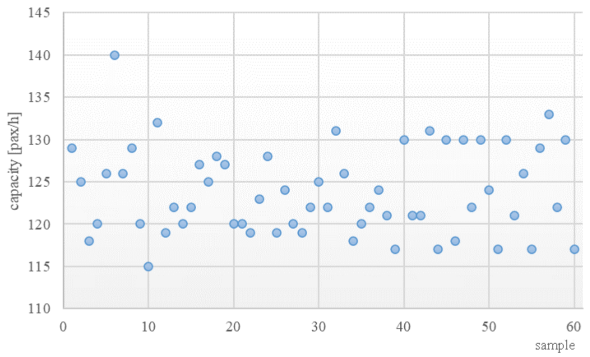

Figure 2. Throughput of the security lane system across 60 measurement samples

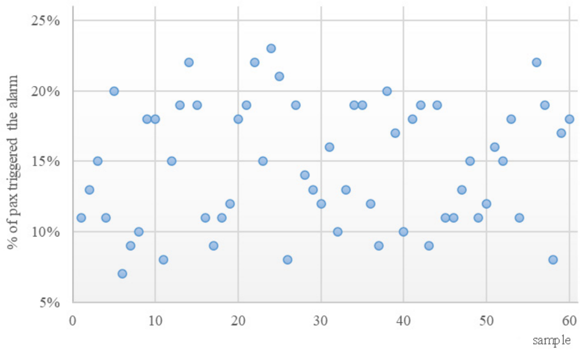

Figure 3. Number of alarms caused by improper passenger preparation across n = 60 samples

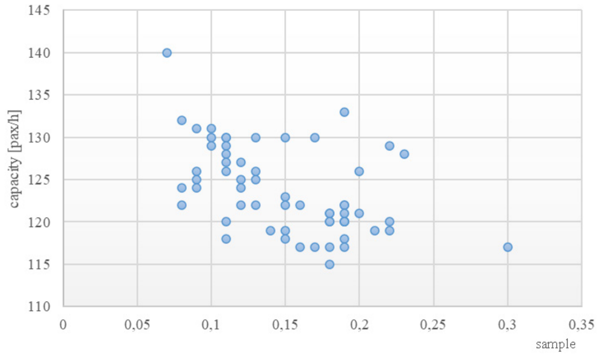

Figure 4. Relationship between throughput and number of alarms

relation. This finding highlights the need for deeper investigation and provides grounds for efforts to improve the process by reducing the number of alarms at security checkpoints:

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} = -0.59, \quad (1)$$

where: x_i is i^{th} result from the test sample for the number of alarms y_i is y^{th} result from the research sample for efficiency $\bar{x}$ is average number of alarms from the sample $\bar{y}$ is average throughput from the sample.

Due to the limited size of the empirical dataset and the inability to test the full alarm probability range on a live system, Section 4 presents simulation-based experiments to compute precise dependencies. These results demonstrate how variations in alarm frequency affect passenger throughput at airports, offering valuable insights for airport management to assess whether improvements in throughput are achievable.

4. Analysis of the impact of the number of triggered alarms on passenger throughput

4.1. Description of the simulation model and simulations

To accurately estimate the impact of the number of generated alarms on passenger throughput at a security checkpoint, a simulation experiment was conducted. A simulation model was developed to represent the procedures applied using WTMD (Walk-Through Metal Detector) equipment. The algorithm is presented in Figure 5.

The performance modeling assumes a constant passenger inflow to the security lane. At any given moment t, when the number of passengers in the preparation area $\sum_{p_i(t)\in P} p_i$ is less than five, a new passenger p_i is generated and placed in the preparation zone P. The passenger begins the preparation process for security screening according to the service time assigned from the probability density function (Equation (2)). Then, the algorithm checks whether the passenger is first in the queue and whether

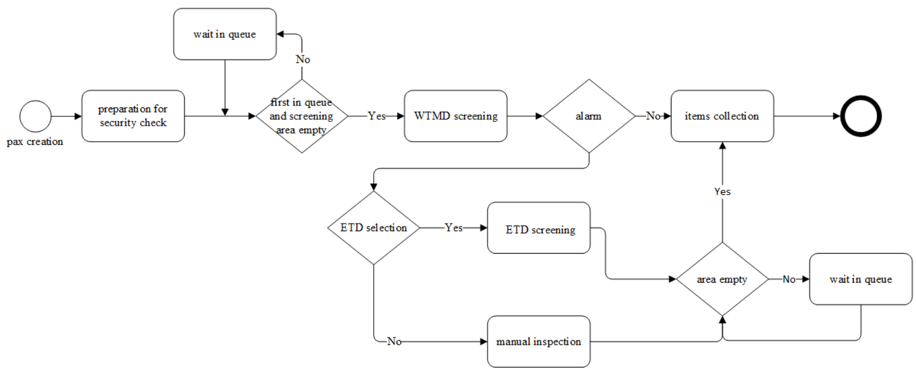

Figure 5. Algorithm of the simulation model

the number of passengers $\sum_{p_i(t)\in C} p_i$ in the control area C equals zero. If not, this condition is checked in a loop until it is satisfied. When the condition is met, the passenger proceeds through the WTMD, with the screening time being deterministic t_{WTMD} = 2 s and corresponding to the average passage time through the WTMD.

The next step verifies whether an alarm is triggered. Alarms can be generated for two reasons. The first is a constant probability P_{Aetd} associated with the detection of trace amounts of explosive materials (ETD). This probability, due to security considerations, remains classified. The second cause of an alarm is improper passenger preparation, requiring manual screening to resolve the issue. Because the occurrence of such events is random and depends on varying intervals between passengers, this variable is generated by the probability density function (Equation (3)), defining the number of passengers between successive alarms. The simulation model counts the number of passengers, and after a given number of correct passages through the WTMD, it meets the condition for alarm occurrence and directs the passenger to manual screening.

If the passenger is subject to ETD screening, the duration of this process is determined by a value drawn from the probability density function (Equation (4)). In cases of manual screening, the duration is generated based on function (Equation (5)). After the screening is completed – or if no screening was required – the algorithm checks whether the passenger can proceed to the baggage reclaim area. The total number of passengers $\sum_{p_i(t)\in IC} p_i$ in the reclaim zone must be less than five. If movement is not possible, the algorithm repeatedly checks for availability in a loop. The passenger then retrieves their belongings within a time interval drawn from the probability density function (Equation (6)) and exits the system:

$$f\left(t_{pr}\right) = 0.33\cdot\frac{t_{pr}-1.38}{12.84}^{3.27} exp\left(-\frac{t_{pr}-1.38}{12.84}^{3.27}\right); \qquad (2)$$

$$f\left(p_{na}\right) = 0.31\cdot\frac{p_{na}}{6.14}^{0.92} exp\left(-\frac{p_{na}}{6.14}^{1.92}\right); \qquad (3)$$

$$f\left(t_{etd}\right) = \frac{\left(t_{etd}-49.27\right)^{-0.96}}{\beta^{0.06}\Gamma\left(0.06\right)} exp\left(-\frac{t_{etd}-49.27}{0.29}\right); \qquad (4)$$

$$f\left(t_{m}\right) = \frac{\left(t_{m}-2.0\right)^{11.08}}{\beta^{12.08}\Gamma\left(12.08\right)} exp\left(-\frac{t_{m}-2.0}{11.11}\right); \qquad (5)$$

$$f\left(t_{ic}\right) = 0.1\cdot\frac{t_{ic}-2.17}{84.29}^{8.19} exp\left(-\frac{t_{ic}-2.17}{84.29}^{9.19}\right). \qquad (6)$$

Based on these parameters, the simulation model was verified. A total of 100 simulation repetitions were conducted, each with a 60-minute duration. A parametric two-sample significance test was performed, adopting the null hypothesis that the mean throughput of the real system equals that of the simulation model. The u statistic was calculated according to Equation (7), where $\bar{x}_1, \bar{x}_2$ the means and s_1^2, s_2^2 variances correspond to those of the real and simulated systems, and n_1, n_2 represents sample sizes:

$$u = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = -2{,}78\,. \qquad (7)$$

For a significance level of α = 0.05, the critical value of the test is u_α = 2.81. Since the condition $|u| \geq u_\alpha$ was not met, there is no basis for rejecting the null hypothesis. Therefore, the simulation model can be considered consistent with the real system:

$$f\left(p_{na}\right) = 0.31\cdot\frac{p_{na}+loc}{6.14}^{0.92} exp\left(-\frac{p_{na}+loc}{6.14}^{1.92}\right). \qquad (8)$$

4.2. Results of the simulations and analysis

Based on validated model (Section 4.1.), a sensitivity analysis was performed in which the location parameter (loc) of the probability density function (Equation (8)) was varied from −12 to 20, enabling assessment of system behavior across the full range of average alarm probabilities *Pa* caused by improper passenger preparation. The results are shown in Figure 6.

A large-sample Monte Carlo simulation with 2,000 repetitions enabled the identification of the key influence of passenger preparation on security screening throughput. It was observed that, in a scenario where all passengers require manual screening, the throughput of a security lane may drop to 92 pax/h. In contrast, under optimal conditions – when all passengers are perfectly prepared – the throughput can reach up to 152 pax/h. The difference between the maximum and minimum values is 60 pax/h, which is highly significant, considering that airports typically operate several to a dozen or more security lanes in parallel.

Thus, the effectiveness of passenger preparation can either constrain or enhance an airport's capacity to process

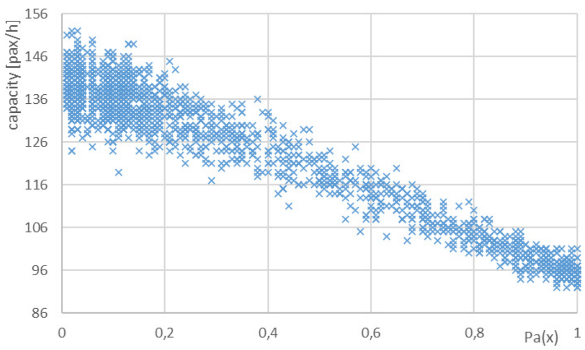

Figure 6. Impact of the average alarm probability on the throughput of a security lane

several aircraft per hour, particularly in hub airports. Figure 6 demonstrates the linear nature of throughput variation as a function of alarm probability. Consequently, the Pearson correlation coefficient was recalculated for the entire simulated population (Equation (9)):

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} = -0.98. \quad (9)$$

The resulting linear correlation coefficient indicates a strong linear relationship between the number of manually screened alarms and the achieved system throughput. This dependence can be expressed by Equation (10):

$$y = -45.29x + 140.95. \quad (10)$$

The derived relationship serves as a reliable indicator of the linear dependency between these variables. However, it must be emphasized that this is not the only factor influencing overall system performance. Another key aspect is the human factor – specifically, the time required for individual actions by both passengers (e.g., preparation, retrieving belongings) and operators (e.g., manual or ETD screening time). This effect is visible in the presented results (Figure 6). Even under optimal conditions, when the number of manual screening alarms is minimal (0–1%), the achievable throughput ranges between 134 and 152 passengers per hour. In Figure 6, it can be observed that a high number of alarms becomes the dominant factor determining system performance and reduces the randomness of the process. It becomes easier to predict how many passengers will be processed. For example, when 90% of alarms are generated, the variance of the average throughput is 10.96, whereas for 10% of generated alarms, this value equals 20.07. Therefore, by reducing the number of alarms through better passenger preparation, other random factors must also be addressed. This is important because the lack of predictability in system performance can lead to poor planning of the number of workstations required to handle the process. To optimize the process, further research should investigate other factors contributing to process randomness and performance degradation. Another possible solution may involve maintaining a higher capacity reserve by opening additional screening lanes. In this case, a pessimistic scenario is assumed, in which the system does not reach its average throughput level. Proper management and optimization of the security checkpoint should therefore take into account all contributing factors. This provides a foundation for extending the research presented in this paper.

4.3. Results discussion

The results obtained clearly highlight the dominant influence of passenger preparation on the operational efficiency of airport security screening. However, several aspects merit further interpretation and discussion.

Firstly, while the strong linear correlation (r = –0.98) demonstrates a consistent relationship between alarm frequency and throughput, real-world checkpoint performance is rarely governed by a single variable. The model assumes uniform passenger behavior and operator response times, which simplifies the actual operational dynamics. In practice, throughput is influenced by multiple stochastic factors such as variability in passenger flow, communication delays, equipment readiness, and human fatigue. These aspects can introduce nonlinear effects that slightly deviate from the idealized linear dependency observed in simulations. Therefore, extended field validation using real checkpoint data is recommended to confirm the general applicability of the results.

Secondly, the relationship between alarm rates and overall process stability reveals an operational trade-off. While lower alarm rates enhance throughput, they also increase the stochasticity of the process. The system becomes more sensitive to random individual delays, especially when passenger preparation time or operator availability fluctuates. This indicates that system optimization should not focus solely on maximizing throughput but also on maintaining predictability and resilience under varying operating conditions.

Thirdly, the results point to the broader implications of human factors. Passenger behavior, situational awareness, and adherence to preparation guidelines significantly affect system efficiency. Similarly, operator workload distribution and response patterns play a crucial role in sustaining throughput. These findings suggest that improvements in human–system interaction, such as better staff training, ergonomic workstation design, and intelligent queue management, could yield efficiency gains comparable to those achieved by technological upgrades.

Moreover, the study underscores the potential of passenger education and communication strategies. Providing clear guidance through digital tools (e.g., mobile applications, automated signage, or video instructions) can meaningfully reduce the share of alarms triggered by improper preparation. However, the real impact of such measures may depend on cultural factors, passenger demographics, and airport layout, all of which should be investigated in future research.

Finally, this analysis opens a path for further exploration of systemic resilience. Introducing predictive modeling and adaptive lane allocation – using data-driven or AI-supported decision systems – could help dynamically adjust resources to real-time conditions. Such developments would not only enhance operational performance but also reduce the uncertainty associated with fluctuating passenger behavior and random process disturbances.

5. Conclusions

The outcomes of conducted study confirm the crucial role of passenger preparation in determining the overall efficiency of the security screening process. The Monte Carlo simulation results clearly demonstrate that the number of alarms requiring manual screening has a significant and strongly negative impact on lane throughput. This implies that even a small improvement in passenger preparation effectiveness and a reduction in the number of alarms can lead to a noticeable increase in operational efficiency. The relationship between alarm frequency and throughput is linear, allowing for the prediction of performance changes based on specific operational parameters. Nevertheless, it should be noted that other factors – particularly those related to human performance, such as reaction time, work pace, and cooperation between passengers and operators – also affect process efficiency.

The findings not only confirm the quantitative impact of alarm frequency but also reveal the broader qualitative dimensions of system performance. A high alarm rate increases the predictability of the system by reducing random variations, while a low alarm rate, although improving throughput, introduces greater stochastic variability in passenger processing times. This duality suggests that optimizing security checkpoint operations should aim not only to maximize throughput but also to maintain system stability and predictability under varying traffic conditions.

Moreover, the results underscore the importance of integrating human and organizational factors into performance modeling. The influence of operator workload, passenger compliance, and interaction dynamics within the screening lane plays a substantial role in determining actual efficiency. In this context, the concept of passenger education becomes a practical and measurable intervention. Enhanced communication through digital channels (e.g., airline mobile applications, pre-departure notifications, interactive signage) and proactive staff guidance can significantly reduce the number of alarms triggered by improper preparation. Such measures would not only streamline the screening process but also improve the passenger experience by minimizing delays and uncertainty.

From an operational management perspective, the study highlights the need for adaptive resource planning at airport checkpoints. In real-world conditions, unpredictable fluctuations in alarm frequency or passenger behavior may require flexible staffing and the dynamic allocation of screening lanes. Incorporating predictive analytics and data-driven decision support systems could allow security managers to anticipate performance deviations and deploy resources more efficiently.

Finally, the presented research establishes a foundation for future investigations. Subsequent studies should focus on validating the proposed relationships in real operational environments and extending the simulation model to include additional stochastic parameters, such as variability in passenger flow patterns, equipment reliability, and operator fatigue. Furthermore, future work could explore the integration of behavioral modeling and machine learning methods to predict passenger compliance and optimize queue management strategies.

In summary, improving passenger preparation is not only a procedural enhancement but a strategic opportunity to balance efficiency, predictability, and passenger satisfaction within the broader framework of airport security operations.

Author contributions

Conceptualization – T. K. and A. K.; methodology – T. K.; software – T. K. validation – J. R.; formal analysis – A. K.; investigation – T. K.; data curation – T. K.; writing – original draft preparation – T. K. and A. K.; visualization – J. R.; review – D. V.; supervision – D. V.

References

Akçay, S., Kundegorski, M. E., Devereux, M., & Breckon, T. P. (2016, 25–28 September). Transfer learning using convolutional neural networks for object classification within x-ray baggage security imagery. In *Proceedings of the 2016 IEEE International Conference on Image Processing* (*ICIP*) (pp. 1057–1061), Phoenix, AZ, USA. IEEE. https://doi.org/10.1109/ICIP.2016.7532519

Aydin, I., Karakose, M., & Akin, E. (2018, 28–30 September). A new approach for baggage inspection by using deep convolutional neural networks. In *Proceedings of the 2018 International Conference on Artificial Intelligence and Data Processing* (*IDAP*) (pp. 1–6), Malatya, Turkey. IEEE. https://doi.org/10.1109/IDAP.2018.8620749

Brun, A., Feron, E., Alam, S., & Delahaye, D. (2025). Schedule optimization and staff allocation for airport security checkpoints using guided simulated annealing and integer linear programming. *Journal of Air Transport Management*, *124*, Article 102746. https://doi.org/10.1016/j.jairtraman.2025.102746

Bruno, G., & Genovese, A. (2010). A mathematical model for the optimization of the airport check-in service problem. *Electronic Notes in Discrete Mathematics*, *36*, 703–710. https://doi.org/10.1016/j.endm.2010.05.089

Bullock, D. M., Haseman R., Wasson, J. S., & Spitler, R. (2010). Automated measurement of wait times at airport security: Deployment at Indianapolis International Airport, Indiana. *Transportation Research Record*: *Journal of the Transportation Research Board*, *2177*(1), 60–68. https://doi.org/10.3141/2177-08

Buser, D., Schwaninger, A., Sauer, J., & Sterchi, Y. (2023). Time on task and task load in visual inspection: A four-month field study with X-ray baggage screeners. *Applied Ergonomics*, *111*, Article 103995. https://doi.org/10.1016/j.apergo.2023.103995

De Lange, R., Samoilovitch, I., & van der Rhee, B. (2013). Virtual queuing at airport security lanes. *European Journal of Operational Research*, *225*(1), 153–165. https://doi.org/10.1016/j.ejor.2012.09.025

Erarslan Altindag, E., & Yuksel, S. E. (2022, 3 June). Threat detection in x-ray baggage security imagery using convolutional neural networks. In *Proceedings of the Anomaly Detection and Imaging with X-rays* (*ADIX*) *VII*, 121040H, Orlando, FL, USA. SPIE Digital Library. https://doi.org/10.1117/12.2622373

EUR-Lex. (2008). *Regulation* (*EC*) *No 300/2008 of the European Parliament and of the Council of 11 March 2008 on common rules in the field of civil aviation security and repealing Regulation* (*EC*) *No 2320/2002*. https://eur-lex.europa.eu/eli/reg/2008/300/oj/eng

EUR-Lex. (2015). *Regulation* (*EU*) (*2015*) *No 2015/1998 of 5 November 2015 laying down detailed measures for the imple-*

mentation of the common basic standards on aviation security. https://eur-lex.europa.eu/eli/reg_impl/2015/1998/oj/eng

Gkritza, K., Niemeier, D., & Mannering, F. (2006). Airport security screening and changing passenger satisfaction: An exploratory assessment. *Journal of Air Transport Management*, *12*(5), 213–219. https://doi.org/10.1016/j.jairtraman.2006.03.001

Hättenschwiler, N., Sterchi, Y., Mendes, M., & Schwaninger, A. (2018). Automation in airport security x-ray screening of cabin baggage: Examining benefits and possible implementations of automated explosives detection. *Applied Ergonomics*, *72*, 58–68. https://doi.org/10.1016/j.apergo.2018.05.003

Hsu, C.-I., Chao, Ch.-Ch., & Shih, K.-Y. (2012). Dynamic allocation of check-in facilities and dynamic assignment of passengers at air terminals. *Computers & Industrial Engineering*, *63*(2), 410–417. https://doi.org/10.1016/j.cie.2012.04.003

Huegli, D., Chavaillaz, A., Sauer, J., & Schwaninger, A. (2025). Effects of false alarms and miscues of decision support systems on human–machine system performance: A study with airport security screeners. *Ergonomics*, *68*(12), 2088–2103. https://doi.org/10.1080/00140139.2025.2453546

International Civil Aviation Organization. (2020). *Annex 17 to the Convention on International Civil Aviation*: *Security – Safeguarding International Civil Aviation Against Acts of Unlawful Interference*. ICAO.

Karpenko, M. (2022). Landing gear failures connected with high-pressure hoses and analysis of trends in aircraft technical problems. *Aviation*, *26*(3), 145–152. https://doi.org/10.3846/aviation.2022.17751

Kierzkowski, A., & Kisiel, T. (2015a). An impact of the operators and passengers' behavior on the airport's security screening reliability. In *Safety and Reliability*: *Methodology and Applications – Proceedings of the European Safety and Reliability Conference* (pp. 2345–2354). Taylor and Francis Group. https://doi.org/10.1201/b17399-322

Kierzkowski, A., & Kisiel, T. (2015b). Concept reliability model of the passenger service at the Wroclaw airport landside area. In *Safety and Reliability of Complex Engineered Systems*: *Proceedings of the 25th European Safety and Reliability Conference, ESREL 2015* (pp. 1599–1606). CRCPress/Balkema. https://doi.org/10.1201/b19094-208

Kierzkowski, A., Kisiel, T., Milewski, M., Török, Á., Stosiak, M., & Wróbel, J. (2024). Computer-aided simulation of unmanned aerial vehicle composite structure dynamics. *Transport*, *39*(4), 302–312. https://doi.org/10.3846/transport.2024.23159

Kim, M. H., Park, J. W., & Choi, Y. J. (2020). A study on the effects of waiting time for airport security screening service on passengers' emotional responses and airport image. *Sustainability*, *12*(24), Article 10634. https://doi.org/10.3390/su122410634

Latscha, M., Schwaninger, A., Sauer, J., & Sterchi, Y. (2024). Performance of X-ray baggage screeners in different work environments: Comparing remote and local cabin baggage screening. *International Journal of Industrial Ergonomics*, *102*, Article 103598. https://doi.org/10.1016/j.ergon.2024.103598

Leone, K. (2002). Security system throughput modeling. In *Proceedings of 36th Annual 2002 International Carnahan Conference on Security Technology* (pp. 144–150), Atlantic City, NJ, USA. IEEE. https://doi.org/10.1109/CCST.2002.1049240

Li, Y., Gao, X., Xu, Z., & Zhou, X. (2018). Network-based queuing model for simulating passenger throughput a tan airport security checkpoint. *Journal of Air Transport Management*, *66*(C), 13–24. https://doi.org/10.1016/j.jairtraman.2017.09.013

Maliwat, J. D. (2018). Five typical emotional reactions to airport security screening: A case study. *Journal of Psychology Research*, *8*(12), 594–602. https://doi.org/10.17265/2159-5542/2018.12.003

Marshall, Z. A., Mott, J. H., Gottwald, A. J., Patrick, C. A., & Dy, L. R. I. (2022). Expediting airport security queues through advanced lane assignment. *Journal of Transportation Security*, *15*, 245–262. https://doi.org/10.1007/s12198-022-00247-9

Nikolaev, A., Lee, A., & Jacobson, S. H. (2012). Optimal aviation security screening strategies with dynamic passenger risk updates. *IEEE Transactions on Intelligent Transportation Systems*, *13*(1), 203–2012. https://doi.org/10.1109/TITS.2011.2167230

Olapiriyakul, S., & Das, S. (2007). Design and analysis of a two-stage security screening and inspection system. *Journal of Air Transport Management*, *13*(2), 67–74. https://doi.org/10.1016/j.jairtraman.2006.11.008

Schwaninger, A., Hardmeier, D., & Hofer, F. (2004, 11–14 October). Measuring visual abilities and visual knowledge of aviation security screeners. In *Proceedings of the 38th Annual 2004 International Carnahan Conference on Security Technology* (pp. 258–264), Albuquerque, NM, USA. IEEE. https://doi.org/10.1109/CCST.2004.1405402

Skorupski, J., & Uchroński, P. (2016). Managing the process of passenger security control at an airport using the fuzzy inference system. *Expert Systems with Applications*, *54*, 284–293. https://doi.org/10.1016/j.eswa.2015.11.014

van Boekhold, J., Faghri, A., & Li, M. (2014). Evaluating security screening checkpoints for domestic flights using a general microscopic simulation model. *Journal of Transportation Security*, *7*(1), 45–67. https://doi.org/10.1007/s12198-013-0129-8

Yildiz, Y., Abraham, D. Q., Panetta, K., & Agaian, S. (2008). A new concept of airport security screening. In *IEEE Conference on Technologies for Homeland Security* (pp. 444–448), Waltham, MA. IEEE. https://doi.org/10.1109/THS.2008.4534493

Zeballos, M., Fumagalli, C. S., Ghelfi, S. M., & Schwaninger, A. (2023). Why and how unpredictability is implemented in aviation security – A first qualitative study. *Heliyon*, *9*(3), Article e13822. https://doi.org/10.1016/j.heliyon.2023.e13822