TRANSPORT PROBLEMS 2024 Volume 19 Issue 2
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2023.19.2.01

Keywords: airport management; security screening; Petri nets

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IMPACT OF THE BODY SCANNER APPLICATION ON PASSENGER SCREENING THROUGHPUT

Summary. The development of airport security screening systems requires the use of increasingly sophisticated and effective equipment to detect prohibited or hazardous items and substances. However, this can lead to a reduction in the throughput of the security checkpoint (SCP). This paper addresses the operationally important problem of the dilemma between screening effectiveness and screening checkpoint throughput, which is important to the real operational capabilities of an airport. In this paper, a comparison of traditional walk-through metal detectors (WTMD) gates and newer technology body scanners (BSs) was carried out in terms of SCP throughput as an element determining the operational capabilities of the airport. For this purpose, a simulation model was developed to study throughput based on a colored timed Petri net. The analysis showed that, depending on the characteristics of the available staff, the level of terrorist and epidemic threat, as well as the time of year, it is advantageous to use different strategies to vary the size of the stream of passengers directed for screening by the WTMD gate and BS.

1. INTRODUCTION

Airport security screening is one of the fundamental processes of passenger handling. The geopolitical situation in the world, combined with technological developments, makes it necessary to use increasingly sophisticated equipment for the detection of prohibited or dangerous objects and substances. Tasks carried out using such equipment must fully comply with legal regulations (EC 2015/1998) [1] and ensure the required effectiveness of control. On the other hand, it should not be a capacity constraint for the whole airport. However, the implementation of new, more effective, technical solutions and procedures for the screening of persons sometimes leads to a reduction in the capacity of the security checkpoint (SCP).

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Given the possible contradiction of the two objectives, a reasonable compromise must be sought. For such a compromise to be achieved, it is important to be able to quantify both the practical throughput and the effectiveness of the screening device used at the security checkpoint. In this work, we focus only on the throughput of screening. The issue of its effectiveness is the subject of ongoing research already conducted by the authors. Additionally, in this paper, we also present a method that allows us to perform experiments related to planned changes in the organization of a security checkpoint or changes in the SCP environment.

The process of preparing passengers for screening is similar regardless of the type of device used, so the analyses consider the throughput of screening devices only: specifically, WTMD and BS.

2. RESEARCH METHODS IN MODELING THE AIRPORT SECURITY SCREENING PROCESS

Due to its nature, in most cases, a security screening system is tested with the use of models because experimenting with an operating system is practically impossible. Sheldon et al. [18] suggested using discrete optimization models to solve for optimal airport baggage screening security device deployments. The papers [3, 7, 21] use colored Petri nets and simulation modeling to evaluate the baggage screening system throughput. A similar simulation approach was applied in AlKheder et al.'s study [2]. A baggage handling system was also tested using simulation modeling by Cavada et al. [5]. In our previous papers, we have successfully used fuzzy inference systems to assess the effectiveness of a passenger screening system as a whole [19], as well as WTMD for passenger screening [20].

A different approach to this issue was presented in [14, 23]. Yoo and Choi's paper [24] concerns the use of an analytic hierarchy process method to study the relative importance of the means to improve passenger security checks at the airport. Concho and Ramirez-Marquez suggested multiple objective optimization models for optimizing passenger inspection security, inspection cost, and processing time [6]. They used an evolutionary approach to solve the model. Li et al. suggested a network-based queuing model for simulating passenger throughput at an airport security checkpoint [15]. Models based on data analysis and game theory have also been used in the analysis of security systems at an airport [11, 12]. Human factors in security screening were analyzed in [4, 10, 16, 17], while automation was found to influence the effectiveness and costs of screening in [8, 9, 22].

Taking into account the conclusions of the literature review, our own experience, and previous research, it was assumed that the study of practical SSC throughput would be carried out using a microscale model of the screening process built using color-coded, time-domain, stochastic Petri nets. In turn, fuzzy inference systems were used to evaluate screening efficiency. This article is a continuation of an article [21] in which we used a model in the form of a colored Petri net to evaluate the throughput of an airport baggage screening system. The research has been extended by applying this approach to the evaluation of WTMDs and BSs, taking into account the variability of the sequence of inspection activities performed and, thus, the dynamic variability of the implemented definition of the inspection process.

This is also a continuation of the article [20], in which we evaluated the effectiveness of the WTMD. Here we will also evaluate the effectiveness of the BS using a fuzzy inference system and compare the two devices. An important extension of the approach used is how the factors affecting the effectiveness of the controls are taken into account, making it possible to compare the devices despite the different operating technologies. Another important extension is the inclusion of additional procedures, both qualitatively (e.g., inspection for traces of explosives) and quantitatively (e.g., the frequency of various types of manual inspections). In turn, the proposed modeling methodology, based on a microscale model in the form of a colored Petri net, allows the observation and modification of the system under study during operation, which facilitates the study of short- and long-term effects of operational changes.

3. PASSENGER SECURITY SCREENING CHECKPOINTS AT AIRPORTS

3.1. Security screening checkpoint organization

For most passengers, the screening process at a station equipped with WTMD is very simple and short. The passenger passes through a detector that is not triggered and does not generate an alarm, manual control is not used, and the passenger leaves the station. However, for some passengers who do not raise the alarm, a random preventive manual check is carried out.

The screening process is slightly more complex when a walk-through detector is triggered, and an alarm is generated. In this case, an operator can immediately perform a manual check or ask a passenger to pass through the detector again. In this case, numerous passengers re-check whether they have any metal objects, and once they are found, they put them on the conveyor and pass through the detector again. Therefore, in some cases, when the passenger passes through the detector a second time, the alarm is not generated again. In such a case, a security screening operator (SSO) may terminate the screening process or perform a manual check. If the alarm is activated during the second passage through the WTMD, a manual check is obligatory.

See Fig. 1 for a diagram of the standard passenger flow at a screening station equipped with the WTMD. The numbers on this chart indicate the empirical probabilities of a process taking a given path. They were determined from measurements as the ratio of the number of occurrences of a given event to all instances.

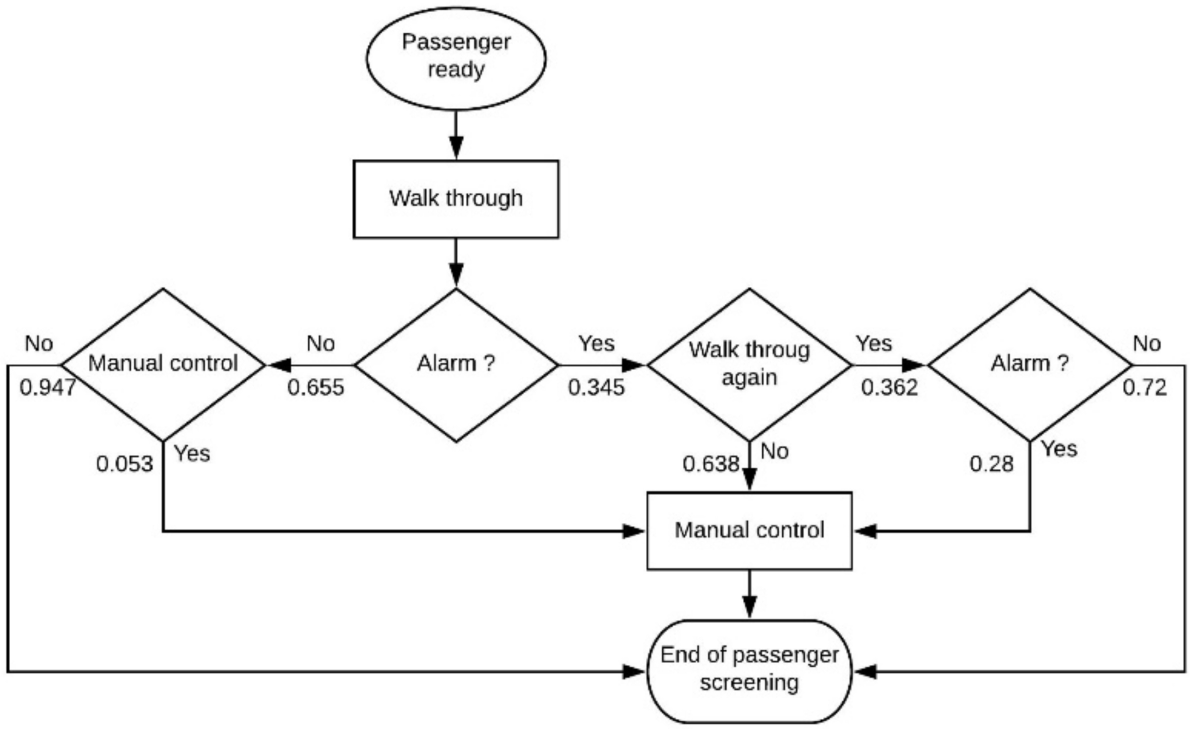

Fig. 1. Standard passenger flow at a station equipped with a WTMD

As already mentioned, the throughput declared by a manufacturer is significantly higher than the throughput that can be achieved in reality, depending on the station configuration, available space, passenger behavior, etc. The characteristics of the SSO are also an important factor influencing the inspection process. This influence manifests itself both in the efficiency of task performance and concerning the duration of the inspection. The most important of these factors include the operator's training, experience (expressed as years of service on the job), fatigue, and their individual approach to the job. In July and August 2019, measurements were taken in passenger terminal B of the KTW airport in order to determine the screening station throughput in real-life conditions. See Table 1 for a fragment of the measurement data from 200 passengers.

Based on the measurements performed, empirical distribution functions of random variables for the check duration at a station equipped with WTMDs were determined. These distribution functions are determined independently for each possible combination of events occurring during the check. As can be seen in Fig. 1, in each case where a process branches, it is possible to move to one of two states. Thus, we are dealing with discrete random variables that can take on only two values, creating a two-point probability distribution. See Fig. 1 for the empirical probability of a particular state's occurrence and Table 2 for values of expected screening times for various combinations of events.

Table 1

Measurement data for a station equipped with a WTMD (31.07.2019)

No	Alarm	Manual control	Walk through again	Screening time [s]
1	No	No	No	4
2	No	No	No	3
3	Yes	Yes	No	12
4	Yes	Yes	No	24
5	Yes	No	Yes	27
6	Yes	Yes	No	22
7	No	No	No	3
8	No	No	No	3
9	No	No	No	2
10	No	No	No	3
11	No	No	No	3
12	Yes	Yes	No	19
13	No	No	No	3

Table 2

Expected screening times for different series of events

Series of events	Expected screening time [s]
Alarm → Manual check	21.7
Alarm → Walk through repeated → Manual check	33.3
Alarm → Walk through repeated → No check	24.2
No alarm → Manual check	19.3
No alarm → No check	2.9
All	10.6

Considerations in the field of the psychology of SSO' work go beyond the scope of this paper; however, the results presented in Table 2 enable us to observe two interesting phenomena:

1. A manual check performed after passing through a detector without triggering an alarm takes a little less time than in a situation when an alarm is activated.
2. A manual check is even shorter in the case of repeated walkthroughs and two alarm triggers.

3.2. Passenger flow – BS

In the case of standard passenger traffic through a station equipped with a BS, the first step for a passenger is to enter the device. In most cases, it is similar to a small cabin, though it may have a different structure. A passenger must position themself in a specific place, with their body in a correct position. This task is facilitated by graphic signs showing where to stand and how to hold one's hands: sometimes above the head, sometimes along the body, but slightly inclined. After the passenger takes the correct body position, the screening process takes place. In the case when the passenger does not have any prohibited objects, they leave the BS cabin and the entire station.

If the device detects a suspicious object, a manual check is carried out, where an SSO receives detailed visual information on the objects' locations. Depending on the number of objects detected, this process is followed by either a directional or full check.

From the point of view of the security screening checkpoint throughput, one must take into consideration a situation when the body position adopted by a passenger is incorrect. In this case, the device does not commence the screening process (the check is not performed). In this case, SSO must intervene, providing guidance regarding the correct body position.

See Fig. 2 for a diagram of the standard passenger flow at a screening station equipped with a BS. The numbers on this chart indicate the empirical probabilities of a process taking a given path. They were determined from measurements as the ratio of the number of occurrences of a given event to all instances.

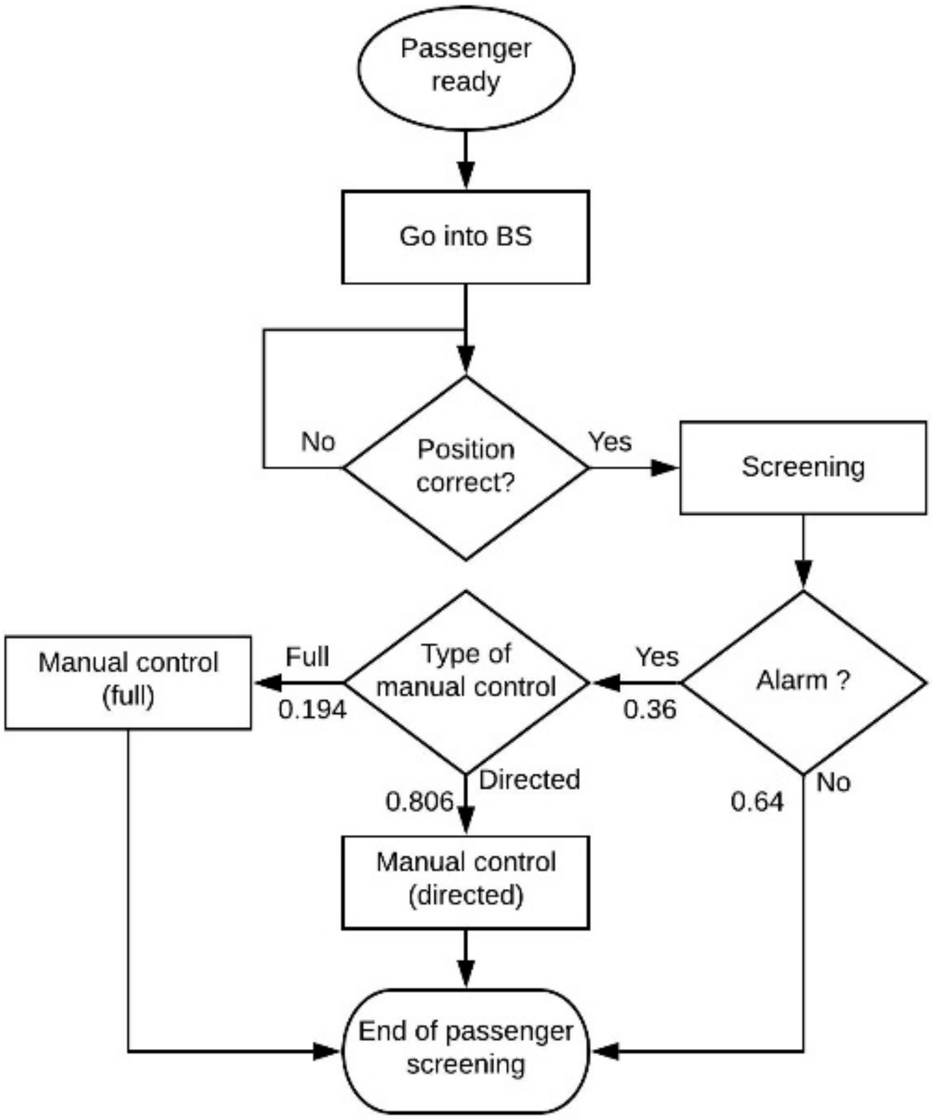

Fig. 2. Standard passenger flow at a station equipped with a BS

Similar to the previous case, in July and August 2019, measurements were performed in terminal B of the KTW airport in order to determine the screening station throughput in real-life conditions. See Table 3 for a fragment of measurement data from 200 passengers.

Based on the measurements, empirical distribution functions of random variables for the check duration at a station equipped with BS were determined. These distribution functions were determined independently for each possible combination of events occurring during the check. As can be seen in

Fig. 2, in each case where a process branches, it is possible to move to one of two states. Thus, here we are dealing with discrete random variables that can take on only two values, meaning there is a two-point probability distribution. See Fig. 2 for the empirical probability of a particular state's occurrence and Table 4 for values of expected screening times for various combinations of events.

Table 3

Measurement data at a station equipped with a BS (16.07.2019)

No	Alarm	Manual control (full)	Manual control (directed)	Screening time [s]
1	No	No	No	11
2	Yes	Yes	No	29
3	No	No	No	13
4	No	No	No	14
5	Yes	No	Yes	45
6	No	No	No	10
7	No	No	No	9
8	No	No	No	16
9	No	No	No	14
10	Yes	No	Yes	25
11	Yes	No	Yes	17
12	No	No	No	8
13	No	No	No	12

Table 4

Expected screening times for different series of events

Series of events	Expected screening time [s]
Alarm → Manual check (full)	36.1
Alarm → Manual check (directional)	21.5
No alarm → No check	8.9
All	14.6

3.3. Effect of the number of alarms on SCP throughput and inspection time

See Fig. 3 for a general comparison of the number of alarms and the number of manual checks for both types of devices based on the measurements performed.

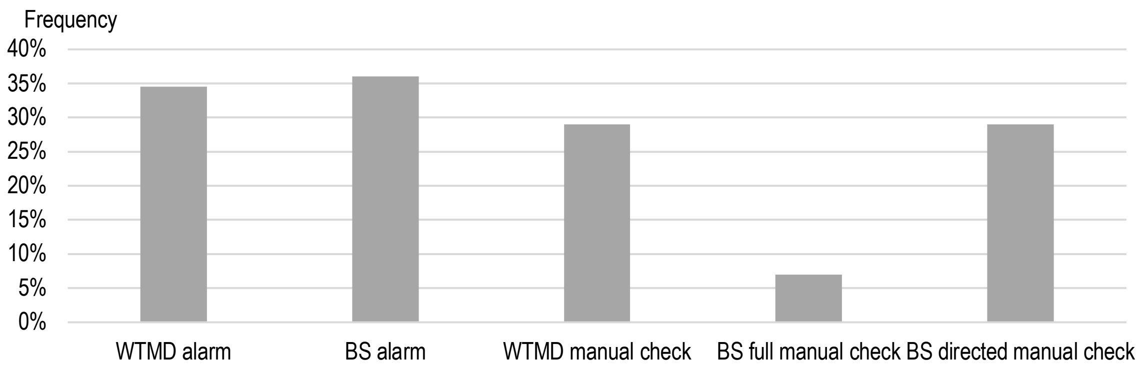

Fig. 3. Empirical frequency of alarms and manual checks

At first sight, it can be seen that the frequency of alarms for WTMDs and BSs is very similar. This goes against common intuition that suggests that, in the BS, the number of alarms (and, therefore, the number of detected prohibited objects) should be higher, as non-metallic objects are also detected.

However, it should be borne in mind that the total number of alarms generated by WTMDs also includes alarms during a repeated passage through the detector.

According to the analyzed procedure, each BS alarm results in a (full or directional) manual check. In our sample, it concerned 36% of passengers. In the case of WTMDs, some alarms do not require a manual check if the alarm does not repeat when a passenger passes the detector again (after removing forgotten metal objects). However, some passengers who did not trigger an alarm are subject to random checks. In total, manual checks after passing through a WTMD in our sample were performed for 29% of passengers.

It is also interesting to compare the times of different types of checks performed with the use of both devices. The graph from our measurement sample is shown in Fig. 4.

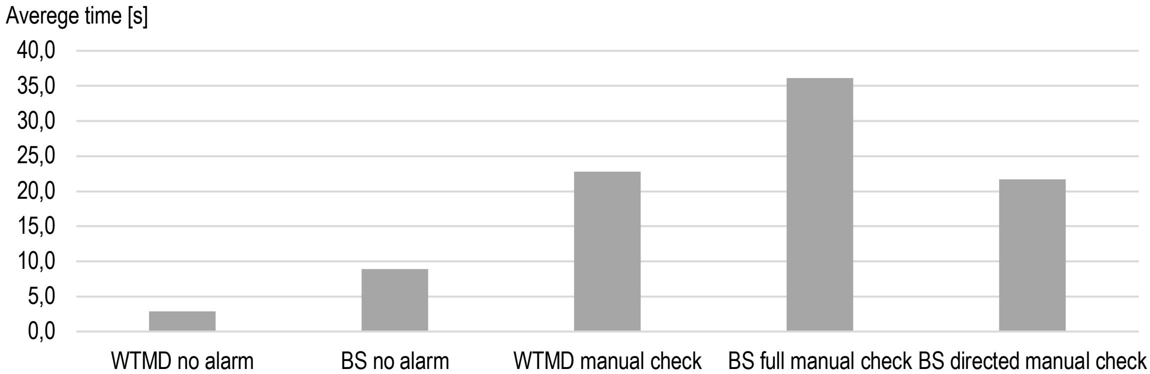

Fig. 4. Screening times in various operational situations

It is clear that, in the case of disciplined passengers, the screening time is much longer when using a BS than when utilizing a WTMD. This is, of course, due to the way the device works. When using a WTMD, a passenger freely passes through the detector, and when using a BS, they must perform additional actions. This is very important, as this group of passengers constitutes the largest percentage of passengers handled.

The frequency of full manual checks using BSs gives us a certain estimate of the number of passengers that we call "potentially dangerous." It can be assumed that if a passenger has four or more objects with him or her, which triggered the BS alarm, it is not incidental but rather an intentional action. Of course, it is usually not about the willingness to act unlawfully but about the willingness to check the screening personnel's behavior. Interestingly, for these persons, the time of a full manual check is longer than the time of a full manual check with the use of a WTMD. This is slightly surprising, taking into account the fact that, basically, the scope of both checks does not differ. This can be explained in two ways.

1. After using a BS, a SSO is aware that they may be dealing with a dangerous passenger, so they try to perform a search even more carefully than usual. Alternatively, an SSO manually checking a random passenger who did not trigger the WTMD alarm is aware that they are likely to be dealing with a disciplined passenger giving them no reason to suspect them of carrying prohibited objects, so the manual check may be carried out slightly faster.
2. A BS indicates all areas to be thoroughly checked. In such a case, the SSO is obliged to reveal all objects that caused the alarm. As regards small objects or objects that are a doubtful cause of an alarm, the process of searching for and explaining the cause of the alarm may take a little longer.

Thus, the third group (i.e., undisciplined passengers) remains. If a WTMD is used, it is a group that triggers an alarm while walking through the detector twice, so these are passengers subjected to manual checks. If using a BS, it is a group to which directional checks apply. As can be seen from our measurement data, this group is quite large (approx. 30%), and the duration of a manual check is similar regardless of the detector type used.

4. IMPLEMENTATION OF THE MODEL AS A COLORED PETRI NET

4.1. Petri nets

A model reflecting the screening processes at a station equipped with a WTMD and BS has been implemented in the form of a colored, timed, stochastic Petri net. These processes are dynamic and can be considered continuous in time and discrete in terms of states. We will test them using the discrete simulation, which makes Petri nets a suitable tool for their implementation. Petri nets were originally used to analyze concurrent processes taking place in computer systems, but today they have had many more applications in various areas, as well as in the study of air transport operations.

Colored Petri nets offer several advantages when modeling dynamic systems that exhibit both continuous and discrete characteristics, especially in concurrent processes. They include flexibility by allowing for the modeling of systems with both discrete and continuous behaviors. Convenient modeling of systems with time-dependent behavior is also valuable, as we are dealing with processes where time plays a significant role. Colored Petri nets use colored tokens that carry additional information. This is especially useful in our case as we need to represent different screening system condition attributes. The colored tokens can represent those characteristics of system entities. Colored Petri nets also support formal methods, enabling rigorous verification and validation of system properties. This is important for ensuring that the modeled system behaves as intended, and it helps identify potential issues early in the design phase. In summary, colored Petri nets are advantageous for modeling dynamic systems that exhibit both continuous and discrete characteristics, especially when concurrency is involved. Their flexibility, expressiveness, support for time representation, and compatibility with formal methods make them a powerful modeling tool for capturing the complexity of dynamic, concurrent processes.

The screening station model was built based on the following colored Petri net:

$$S_{SD} = \{P, T, A, M_0, \tau, X, \Gamma, C, G, E, R, r_0\} \tag{1}$$

where:

P – set of places, representing the different states of the control process,

T – set of transitions $T \cap P = \emptyset$, representing events (actions) in the passenger screening process,

$A \subseteq (T \times P) \cup (P \times T)$ – set of arcs, showing the relationships between events and states in the control process,

$M_0: P \to \mathbb{Z}_+ \times R$ – marking which defines the initial state of the system,

$\tau: T \times P \to \mathbb{R}_+$ – function determining the static delay of activity (event) *t*,

$X: T \times P \to \mathbb{R}_+$ – random time of carrying out an activity (event) *t*,

Γ – finite set of colors corresponding to the possible properties of tokens,

C – function determining what kinds of tokens can be stored in a place: $C: P \to \Gamma$,

G – function which determines the conditions for a given event to occur,

E – function describing properties of tokens that are processed,

R – set of timestamps (also called time points) $R \subseteq \mathbb{R}$,

r_0 – initial time, $r_0 \in R$.

CPN Tools 4.0 package was selected for creating and researching the colored Petri nets model. It is very convenient for this type of analysis, largely due to the transparency and coherence of the model and, in particular, the possibility to analyze the screening process course for each passenger separately. This enables the model to include various individual passenger properties and behaviors, and it allows the changes taking place in the system to be observed along with applicable organizational or operational changes [13].

4.2. Model of a station with a WTMD

See Fig. 5 for a fragment of the model representing the screening process utilizing a WTMD.

The set of places will be defined as follows:

$$P = \{InW, W1, W2, Dec1, Dec2, Out, ETD, ExW\} \tag{2}$$

Place InW corresponds to the situation when a passenger is prepared for a check performed using a $WTMD$. It corresponds to the “Passenger ready” situation in Fig. 1 (marked with an oval). Places $W1$ and $W2$ show the situation after passing through the detector, which applies to each passenger, and the second passage through the detector, which may take place if the first check generates the $WTMD$ alarm. They correspond to the “Alarm ?” situations in Fig. 1 (marked with rhombuses). Places $Dec1$ and $Dec2$ represent the decision-making situations for a SSO, respectively, after the WTMD has generated the alarm and if the passage through the detector has not triggered the alarm. Thus, $Dec1$ corresponds to the "Manual control" situation, while $Dec2$ corresponds to the "Walk through again" situation in Fig. 1 (also marked with rhombuses). Place Out corresponds to the passenger's exit from the screening station (i.e., the detector). It corresponds to the "End of passenger screening" situation in Fig. 1. Place ETD represents the screening performed with an ETD device. On the other hand, place ExW shows that a passenger has fully left the security screening station.

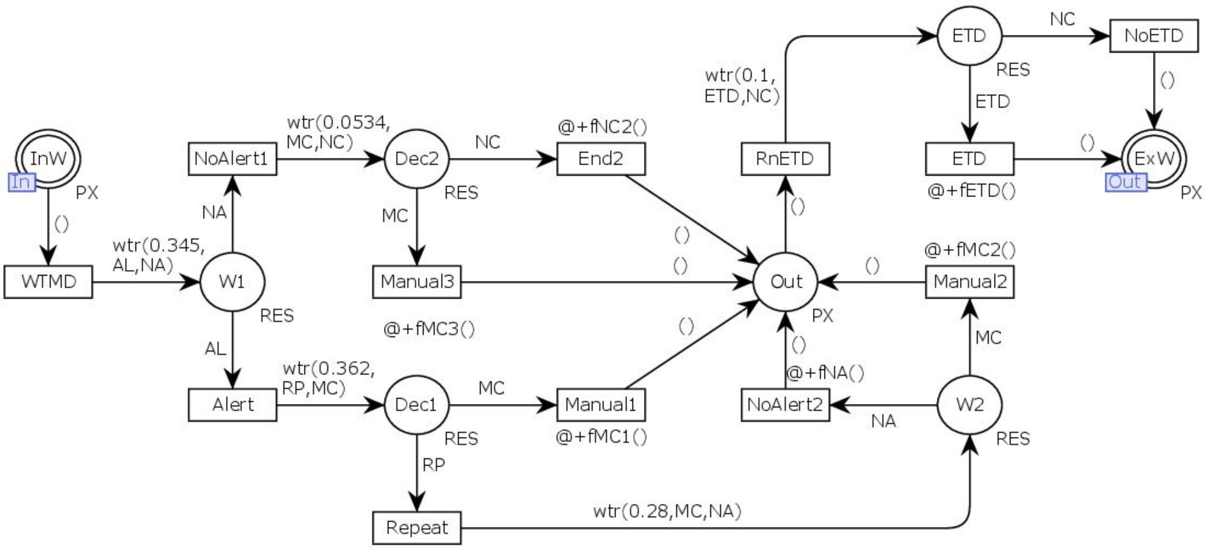

Fig. 5. Model of the screening process utilizing a WTMD

The set of transitions is as follows:

$$T = \left\{ \begin{matrix} WTMD, Alert, NoAlert1, NoAlert2, Manual1, \\ Manual2, Manual3, Repeat, End2, RnETD, ETD, NoETD \end{matrix} \right\} . \tag{3}$$

Transition $WTMD$ represents the passenger’s passage through the $WTMD$. It corresponds to the "Walk through" situation in Fig. 1 (marked with a rectangle). Transition $Alert$ corresponds to $WTMD$ screening when a passenger carries objects that cause an alarm. Transitions $NoAlert1$ and $NoAlert2$ represent a situation when the passenger's passage does not cause a $WTMD$ alarm when they walk through the detector for the first and second time, respectively. Transitions $Manual1$, $Manual2$, and $Manual3$ are related to manual checks, respectively: after a passenger walks through the detector for the first and second time, triggering an alarm, and when, despite the lack of an alarm at the first passage through the detector, the SSO qualifies the passenger for a random manual check. They correspond to the "Manual control" situation in Figure 1 (marked with a rectangle). Transition $Repeat$ represents the situation in which a passenger walks again through the $WTMD$. Transition $End2$ relates to passenger screening completion without a manual check. Transition $RnETD$ relates to a random selection of a passenger to be checked using an ETD.

Depending on the result of this selection, transition ETD or $NoETD$ is implemented. Most of the transitions described in this section are responsible for generating random variables according to the two-point distributions defined in Fig. 1. The functions described below are used for this purpose.

The set of colors is as follows:

$$\Gamma = \{RES, SCPX\} . \tag{4}$$

Markers describing the screening system condition are represented by color RES, while:

$$RES = \{NA, AL, RP, MC, NC, ETD\} , \tag{5}$$

where: NA – condition after the passenger passes through the $WTMD$ which did not generate an alarm; – AL condition after the passenger passes through the $WTMD$ which generated an alarm, RP – condition after the SSO has decided that a passenger needs to walk through the detector again, MC – condition after the SSO has decided that a manual check is necessary, NC – condition after the SSO has decided that a manual check is unnecessary, ETD – condition after a decision of conducting an ETD check has been made.

Function $wtr()$ also plays an important role in the model, as it is responsible for the execution of random processes per the empirical probability presented in Fig. 1. For example, the $wtr(0.345, \mathrm{AL}, \mathrm{NA}$ function seen in Fig. 5 on the arc connecting the $WTMD$ transition to the $W1$ place is responsible for randomly generating the system's transition to the AL state (alarm raised after a passenger passes through the WTMD gate), with a probability of 0.345, or to the NA state (no alarm), with a probability of 0.655, according to Fig. 1. A similar role concerning the empirical distribution functions of the screening execution time in the sequences listed in Table 2 is played by the following functions: $fMC1(), \dots, fMC3()$ and $fNA(), fETD$ and $fNC2()$. For example, the $fNC2()$ function shown in Fig. 5 above the $End2$ transition is responsible for randomly generating the time needed to pass the security screening checkpoint in a situation were passing the WTMD gate did not cause an alarm and the SSO did not decide to perform a manual check. This time is generated according to the data given in Tab. 2 (the line described by the sequence No alarm → No check)

4.3. Model of a station with a BS

See Fig. 6 for a fragment of the model representing the screening process utilizing a BS. As in Section 4.2, all places and transitions correspond to their respective situations during the inspection process. This case is described in Section 3.2 and illustrated in Fig. 2.

In this case, the set of places is defined as follows:

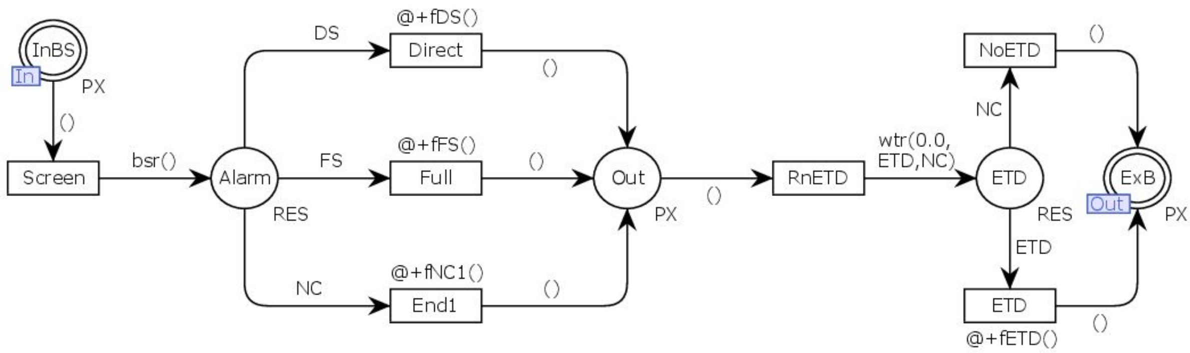

Fig. 6. Model of the screening process utilizing a BS

The set of places is defined as follows:

$$P = \{InBS, Alarm, Out, ETD, ExB\}\ . \quad (6)$$

Place $InBS$ shows a situation when a passenger is inside the BS cabin. They assume the correct body position and are subjected to scanning. Place $Alarm$ represents the decision-making situations for the SSO after the device has been activated. Place Out corresponds to the passenger's exit from the screening station. Places ETD and ExB play the same roles as in the case of the part of the model responsible for screening at a station equipped with a $WTMD$.

The set of transitions is as follows:

$$T = \{Screen, Full, Direct, End1, RnETD, ETD, NoETD\}\ . \quad (7)$$

Transition $Screen$ corresponds to the passenger's scanning process. Transition $Full$ represents a situation in which the number of potential points detected by the detector, where a prohibited object can be hidden, is large enough to justify a full manual check. Transition $Direct$ relates to the manual directional check. Transition $End1$ relates to passenger screening completion without a manual check.

Transitions $RnETD, ETD$, and $NoETD$ play the same roles as in the case of the part of the model responsible for screening at a station equipped with $WTMD$.

The set of colors is the same as in the model of the station equipped with $WTMD$, while color RES storing markers describing the screening system conditions have the following elements:

$$RES = \{NC, FS, DS, ETD\} \ , \tag{8}$$

where: NC – condition after the SSO decides that a check is unnecessary, FS – condition after the SSO decides that a full manual check is necessary, DS – condition after the SSO decides that a directional manual check is necessary, ETD – condition after a decision of conducting an ETD check has been made.

Function $bsr()$ is responsible for the execution of random processes per the empirical probability presented in Fig. 2. Empirical distribution functions for the check execution time in the sequences listed in Table 4 are generated by functions $fDS()$, $fFS()$, $fETD()$, and $fNC1()$.

4.4. Model validation

In order to verify the correct model operation, we have performed an analytical determination of the empirical throughput of a device. The obtained values are compared with the throughput values obtained directly from the model in Sections 3.1 and 3.2.

The following symbols are used:

- for a station equipped with a WTMD:

t_s^{WTMD} – average screening time for passengers who did not trigger an alarm and were not subjected to a manual check;

t_{mc}^{WTMD} – average screening time for passengers who triggered an alarm and were subjected to a manual check;

t_r^{WTMD} – average screening time for passengers who walked through the detector again and were not subjected to a manual check;

t_{rmc}^{WTMD} – average screening time for passengers who walked through the detector again and were subjected to a manual check;

t_{etd}^{WTMD} – average screening time using ETD;

P_s^{WTMD} – frequency of situations in which a passenger did not trigger an alarm and was not subjected to a manual check;

P_{mc}^{WTMD} – frequency of situations in which a passenger triggered an alarm and was subjected to a manual check;

P_r^{WTMD} – frequency of situations in which a passenger walked through the detector again and was not subjected to a manual check;

P_{rmc}^{WTMD} – frequency of situations in which a passenger walked through the detector again and was subjected to a manual check;

P_{etd}^{WTMD} – frequency of situations in which a passenger was checked using ETD;

- for a station equipped with a BS:

t_s^{BS} – average screening time for passengers who did not trigger an alarm and were not subjected to a manual check;

t_{fmc}^{BS} – average screening time for passengers who triggered an alarm and were subjected to a full manual check;

t_{dmc}^{BS} – average screening time for passengers who triggered an alarm and were subjected to a directional manual check;

P_s^{BS} – frequency of situations in which a passenger did not trigger an alarm and was not subjected to a manual check;

P_{fms}^{BS} – frequency of situations in which a passenger triggered an alarm and was subjected to a full manual check;

P_{dmc}^{BS} – frequency of situations in which a passenger triggered an alarm and was subjected to a directional manual check.

For the above-mentioned determinations, we obtained equations relating to hourly throughput for a station equipped with a WTMD:

$$T^{WTMD} = \frac{3600}{P_s^{WTMD} \cdot t_s^{WTMD} + P_{mc}^{WTMD} \cdot t_{mc}^{WTMD} + P_r^{WTMD} \cdot t_r^{WTMD} + P_{rmc}^{WTMD} \cdot t_{rmc}^{WTMD} + P_{etd}^{WTMD} \cdot t_{etd}^{WTMD}} \tag{9}$$

The same was done for a station equipped with a BS:

$$T^{BS} = \frac{3600}{P_s^{BS} \cdot t_s^{BS} + P_{fmc}^{BS} \cdot t_{fmc}^{BS} + P_{dmc}^{BS} \cdot t_{dmc}^{BS}} \tag{10}$$

Formulas (9) and (10) provide the numerical values concerning the frequency of events presented in Figs. 1 and 2 and the duration of checks presented in Tables 2 and 4. From these formulas, the analytical throughput values ($T^{WTMD} = 281$ and $T^{BS} = 249$) were obtained. These values were used to verify the correctness of the Petri net model.

For the data set described in Section 3, 10^6 seconds (approx. 280 hours) of uninterrupted station operation was simulated, using the model described in Section 4. Assuming the continuous inflow of passengers ready for security screening, this allows 79,770 passengers to be handled at a station equipped with a WTMD and 69,716 passengers to be handled at a station equipped with a BS. This means that the throughput of a station equipped with a WTMD, under nominal conditions, is 287 passengers per hour. Meanwhile, the throughput of a station equipped with a BS, under nominal conditions, is 251 passengers per hour.

In order to verify the correct operation of the designed tool, we compared the results with the analytical calculations presented in this section. The obtained throughput results equal to 281 passengers per hour (WTMD) and 249 (BS) are very similar to the results obtained from the model (differences of 2% and 1% respectively). Thus, it can be concluded that the built model is correct.

5. CONCLUSIONS

This paper presents a problem that is important from the operational point of view related to the dilemma between security screening effectiveness and security screening checkpoint throughput, which is important for the real operational capabilities of an airport. A comparison of traditional WTMDs and the newer but more expensive BSs was carried out concerning these two criteria. Appropriate simulation models were developed for this purpose.

As regards an airport demonstrating characteristics similar to the analyzed KTW, the use of WTMDs seems to be more favorable in nominal conditions after increasing the SSP personnel such that people of both sexes work simultaneously. In the case of increased terrorist and epidemiological threats, it is more beneficial to use stations equipped with BSs. On the other hand, taking into account the character of passengers' clothes for different seasons of the year, the solution that is the most beneficial from the operational point of view consists of directing a larger stream of passengers to stations equipped with WTMD in the summer and to stations equipped with BSs in the winter.

Obviously, the final decision on the scope in which both types of devices are used is also influenced by available financial resources, infrastructural capabilities, as well as the current and forecast volume of air traffic. The comprehensive multi-criteria analysis exceeded the scope of this study, which focused on SSC throughput and effectiveness. The tools we proposed, which give quantitative results, may, however, facilitate the decision-making process. This above-mentioned multi-criteria analysis will be the subject of our further studies.

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Received 23.11.2022; accepted in revised form 06.06.2024