

Capacity assessment of the airport cargo screening system under disruptions

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Abstract: Cargo shipments are a growing part of the transport carried out by many air carriers. One of the critical elements in this area of activity is shipment security inspection, which is a mandatory part of the transportation process. This article aimed to study the inspection system's capacity under disruption conditions and determine its dependence on possible technical and organizational improvements. For this purpose, simulation modeling was applied using a microscale model of the cargo security inspection process realized in a colored, timed, stochastic Petri net. Bayesian networks representing the actual process were used to validate the model. As a result of the research, experiments showed that for Katowice Airport in Pyrzowice, more advanced technical solutions can increase capacity by up to 50%. On the other hand, introducing modifications to the procedure, involving at least two checks using specialized assistive devices, can reduce it by up to 40%. Relatively small changes in capacity are expected with changes in the training and experience of screening operators. Based on these results, it can be recommended that airport managers consider using technical solutions with the parameters analyzed in the article. In addition, it is necessary to maintain the level of training at least at the current level. At the same time, any changes in control procedures should be made prudently, only when necessary, due to the need to strengthen the effectiveness of controls during periods of increased terrorist threat.

Keywords: air cargo, security screening, airport capacity, Petri nets, simulation analysis

1. Introduction

1.1. Cargo shipments and the role of the security screening system

Until recently, the air cargo market in Poland accounted for a small share of all air operations at Polish airports. Airports assessed their development mainly by the number of passengers served. With the dynamic development of civil aviation and increased transport accessibility to new markets, the demand for goods delivered by air was also growing.



At the same time, diversification has proven to be the best way to strengthen the resilience of airports to all kinds of fluctuations generated by social or economic events. An example

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of this is the COVID-19 pandemic, which caused a drastic reduction in passenger traffic at airports, which negatively affected their financial condition and hampered the possibility of further development for an extended time. During this period, air cargo was the only area of aviation activity that did not suffer but developed. An example of this is Katowice Airport in Pyrzowice (ICAO code EPKT), where there is a significant increase in cargo traffic when passenger traffic practically dies down. Interestingly, the upward trend in cargo transportation continues. The public, already accustomed to the new form of freight exchange, is generating demand for e-commerce services on a massive scale. In this segment, air cargo transport plays a unique role.

Due to the international impact of air transport, EU and national regulations stipulate many rigorous requirements for ensuring the safety of air operations. They concern the equipment used for security checks and the qualifications of the people authorized to carry out these tasks. The required actions affect cargo operational capabilities. They are mainly related to the capacity of the cargo terminal, which is heavily influenced by screening technology and its organization.

Capacity problems are usually addressed with investment-like measures. However, they are not always correlated with quantitative assessment of expected results. Lack of knowledge in this area causes terminal or equipment infrastructure development difficulties. The variety of cargo transported by air, how it is packed, and its dimensions make the equipment used for inspection vital in cargo clearance. This paper aims to systematize knowledge of cargo clearance technology in air transport and propose measures that consider the type of equipment used or inspection procedure. This research, consequently, will allow quantitative assessment of the capacity of the cargo security checkpoint (CSC) and planning of investment or organizational measures.

1.2. Challenges ahead for airport manager

The trend mentioned above of e-commerce development enforces measures to reduce the delivery time of an ordered shipment. Global shipping and sales companies are choosing to implement increasingly new logistics models based on storage systems for goods located in different, even the most remote countries. Airport managers and cargo operators must reconcile the growth of the cargo segment with the security of air operations. Thus, new technologies based on artificial intelligence are increasingly being implemented to support screening operators on the one hand and on the other to increase the capacity of the security checkpoint and the entire cargo terminal, improving its operational capabilities.

In the development of technology and automation of the process, airport managers see an opportunity to reconcile the growing demand for cargo with the ability to meet stringent and time-consuming security requirements. The increase in cargo air operations increases the risk of their use by criminals and terrorists. Under current regulations, assembled explosives and incendiary devices are prohibited for carriage in cargo. However, with the development of new technologies, the catalog of potential threats is also changing, to which both those involved in cargo clearance and legislators must adapt regulations and work technology.

The air cargo market is expected to grow rapidly regardless of external factors. The area, so far, is characterized by a high degree of resilience to geopolitical or pandemic changes. This implies the need to take a deeper look at the processes involved in cargo clearance, with

particular emphasis on maintaining the expected capacity of the cargo terminal and ensuring the required level of security of air operations.

1.3. Vulnerability of the cargo screening system

The vulnerability of a technical system is a critical aspect that highlights its susceptibility to various interferences and disruptions that can significantly decrease its capacity and functionality. These vulnerabilities can stem from many sources, and their impact can range from minor inconveniences to severe system failures.

External interferences, such as cyberattacks, can compromise the integrity and availability of a technical system, leading to data breaches, service interruptions, and financial losses. Internal factors, including software bugs, hardware malfunctions, and human errors, can pose significant vulnerabilities. These internal interferences can lead to system crashes, downtime, and compromised data integrity, diminishing the system's overall capacity to perform its intended functions. Moreover, changes in environmental conditions, like temperature or power fluctuations, can negatively impact system components and decrease efficiency, further highlighting the system's vulnerability.

Recognizing and mitigating these vulnerabilities is paramount to maintaining and enhancing the capacity and resilience of technical systems. Several strategies can be employed to minimize exposures and ensure that technical systems can operate at total capacity despite potential interferences.

Cargo screening systems (CSS) must be resilient to various interferences, including human errors. They can introduce vulnerabilities and compromise the effectiveness of the screening process. Ensuring resilience to these errors is crucial for maintaining the integrity and security of cargo screening operations.

Resilient cargo screening systems incorporate features and processes that minimize the likelihood of human errors. This can involve user-friendly interfaces, standard operating procedures, and training programs emphasizing error prevention. Even with preventive measures in place, mistakes can still occur. Resilient systems have error-detection mechanisms that identify anomalies or deviations from standard procedures. These mechanisms can include automated checks, alarms, or supervisor oversight. When human errors occur, resilient cargo screening systems have built-in recovery mechanisms. These mechanisms can include the ability to backtrack, re-screen cargo, or rectify errors without causing significant disruptions to the overall screening process.

Resilience to human errors is also achieved through comprehensive training and ongoing competency assessments for personnel operating the screening systems. Well-trained and competent operators are less likely to make errors and can respond when mistakes happen. Cargo screening systems often log and analyze data to identify patterns of human errors over time. This data-driven approach allows continuous improvement by addressing recurring issues and refining procedures. In critical cargo screening operations, redundancy can be employed to reduce the impact of human errors. Redundant systems or operators can cross-check each other's work, enhancing overall reliability.

In summary, resilience to human errors is fundamental to cargo screening systems. By focusing on error prevention, detection, recovery, training, and procedural safeguards, these systems can minimize vulnerabilities introduced by human actions, ensuring the security and effectiveness of cargo screening operations.

1.4. Literature review

Previous research has created several models to study the capacity of the screening system for passengers and checked and cabin baggage (Skorupski et al., 2018; AlKheder et al., 2019; Li et al., 2018; Mota et al., 2021). A separate group of works dealt with the analysis of the effectiveness of such inspections (Skorupski and Uchroński, 2018), including taking into account the human factor (Knol et al., 2019; Skorupski and Uchroński, 2015; Michel et al., 2014) and also the relationship between throughput and effectiveness (Lee and Sheldon, 2011). In addition to these two criteria, some researchers proposed costs for evaluating security control systems (Kirschenbaum, 2013; da Cunha et al., 2017; Gillen and Morrison, 2015). The extent of automation in airport security screening and the impact of technical equipment on its effectiveness is also present in the literature (Leone and Liu, 2005; Huegli et al., 2020; Skorupski and Uchroński, 2020).

As already mentioned, air cargo security screening is governed by numerous international regulations. Domingues et al. (2014) and Price and Forrest (2016) analyzed policies in this regard. The risk-based security screening concept was studied by Wong and Brooks (2015)

The cargo screening system model was created as a colored, timed, hierarchical, and stochastic Petri net. Petri nets were initially developed to describe concurrent computer systems. However, a Petri net is a mathematical formalism that can also be used effectively in other fields, also to model processes in air transport (Werther et al., 2007; Oberheid & Sofker, 2008; Skorupski, 2011; 2015; Florowski & Skorupski, 2016; Davidrajuh & Lin, 2011; Vidosavljevic & Tomic, 2010; Kovacs et al., 2005; Smieszek & Karl, 2013). Additionally, the use of the CPN Tools 4.0 package (Ratzer et al., 2003), which is equipped with a convenient simulation mechanism that allows one to observe the dynamics of the process, makes it possible to perform a large number of experiments, some of which will be presented in Section 4.

1.5. Research concept

The organization of the cargo screening system is often inadequate to meet the demand determined by the volume of freight handled. This issue applies to all stages of screening. Often, redundant solutions are used, which are justified by the constant increase in the volume of air traffic. However, there are then high costs of operating the system. In addition, it usually takes several years to reach the target traffic level, in which case the equipment may become obsolete and require expensive replacement.

On the other hand, there is often a situation where the capacity of the cargo screening system is insufficient. Then, it is necessary to expand the inspection system. In addition, this state of affairs is also influenced by the systematic increase in freight, which undoubtedly reflects the public's demand for this type of service.

Making the right modernization decision depends on understanding the strengths and weaknesses of the individual elements of the cargo security control system under consideration. This is only possible if a detailed microscopic model of the system is available. Such a model is even more critical when analyzing disturbances in a real system. They can include significant fluctuations in the inflow of cargo, all kinds of downtime, and accumulation of freight at different times of the day, but also inattentiveness of employees

or the failure of baggage checking equipment. In each of these cases, having a suitable microscopic model can establish the appropriate countermeasures.

It is worth noting that there are many concurrent processes in the cargo inspection system. Although the whole organization of the system is based on the delivery of cargo to a single inspection point, the inspection process is carried out in multiple ways by many people and devices simultaneously. Therefore, creating a model of the cargo security inspection system using a colored, timed Petri net, an adequate tool in such cases, was adopted. The model considers the random nature of the events involved in the inspection process, which is closely dependent on the type of cargo, its weight and density, and the efficiency of the screening operators. Using this model, we will investigate the throughput of the inspection system. We will identify possible disruptions and examine their impact on throughput at the cargo inspection point. We will also consider alternative solutions and their impact on throughput.

The remainder of the article is organized as follows. Section 2 presents the cargo screening system's organization, the process's flow, and the factors affecting the system's capacity. The importance of CSC throughput in air transportation organizations is also explained. Section 3 discusses the details of the model created to conduct the research - the technology used, the assumptions, the implementation, the input data, and how the interference is mapped. Section 4 presents the research experiments conducted using the model. In particular, the validation of the model on actual data is discussed, the impact of interference is analyzed, and the possibility of increasing system throughput through hardware, organizational, or personnel training changes. Section 5 deals with the analysis and discussion of the results obtained. In Section 6, we include a summary and conclusions.

2. Cargo security screening system

2.1. System organization

Carriage of cargo by air is characterized by a rather complicated process related to the acceptance of goods for transport and their proper preparation for carriage on board an aircraft. Following the current legal regulations (European Commission, 2015), these tasks are performed by a registered agent, who is also responsible for implementing cargo security checks. This control is carried out by qualified personnel - security control operators (SCO). They have obtained an SCO certificate issued by the Civil Aviation Authority (CAA) after a series of lengthy training courses and successful completion of a state exam.

The selection of screening equipment is strictly regulated. Inspection methods, in turn, should be adapted to the nature of the cargo. Freight and mail shall be screened using at least one of the following inspection methods:

- manual,
- with an X-ray machine (Fig. 1),
- with an explosives detection system (EDS) device,
- using explosives detection dogs (EDD),
- with explosives trace detector (ETD) equipment,
- visual,
- using metal detection equipment (MDE).

Depending on the type of cargo and its complexity, one of the available inspection methods can be used to ensure that the contents of the scanned goods do not raise any objections to the safety of the air operation. In practice, however, only two of the abovementioned devices are usually used in a cargo warehouse. These are the X-ray viewer and the explosive trace device (ETD). These devices must meet the stringent technical requirements described in classified documents and have the appropriate certification confirming their suitability for cargo and mail screening tasks. Of course, several suppliers of these devices are on the market, offering products that differ in operating technology, handling, and technical parameters.



Fig. 1. Example of an X-ray device for screening cargo shipments (Smiths Detection, 2021)

Depending on the choice of equipment and the way of work organization, determining the operational readiness of the cargo warehouse also changes. As a rule, cargo is controlled with an X-ray device. This inspection form is often sufficient if the cargo density is not too high or the X-ray device is equipped with a sufficiently powerful X-ray generator. Otherwise, such a cargo must be inspected with a device for detecting trace amounts of explosives. This activity is time-consuming and requires, to be effective, the decomposition of the shipment or even the opening of individual parcels that make up one batch of cargo. Depending on the type of cargo, its inspection can also take the form of manual or visual inspection. They are used both as a supplement to the previously described methods and as a primary one - especially in the case of cargoes that are too large to be decomposed in such a way as to be screened with an X-ray machine.

2.2. Inspection process

The technological process in a cargo warehouse involves a series of technical, organizational, and personnel activities. As mentioned, its course depends on the choice of equipment (e.g., cargo handling and security control equipment) and the skills of SCO operators. In practice, the disruptions that occur are also a significant influence. In this paper, we focus on analyzing the impact of the equipment used and the selection of personnel on the throughput of the warehouse. We will also examine the effect of disruptions on capacity. Cargo received at the warehouse is usually stored on standard cargo pallets (120x80cm euro pallets). Suppose the size of the inspection tunnel of the X-ray machine does not allow for inspecting all the cargo placed on the pallet. In that case, it is necessary to depalletize the load and deliver it individually to the X-ray machine's conveyor belt. At the same time, sometimes the shipments are small, and picking them to fill the entire pallet is necessary.

After all these procedures, scanning with the X-ray device is carried out, and the contents are evaluated. If the SCO is convinced that the shipment does not contain a prohibited item, it finishes the inspection.

The screening process can also be more complex, consisting of several stages. Depending on the nature of the cargo and its density, it may be necessary to perform an additional check to confirm the security status of the shipment. It is caused, as a rule, by the so-called black alerts, i.e., dark areas on the screen of the X-ray machine's monitor that could potentially hide a dangerous object or substance. The power of the X-ray machine's generator largely determines the number of black alarms that appear. The selection of the device and the nature of the loads, therefore, have a significant impact on the timing of the security screening performed.

The additional inspection can be done in several ways. One is to re-screen with an X-ray machine, for example, placing the load at a different angle. Alternatively, it can be done with an ETD (explosive trace device). The screening operator can also verify the cargo's contents by manual inspection, which is time-consuming due to the need to break down the load into individual pieces. Also distinguished from manual is visual inspection, which is carried out in conjunction with other inspection methods. However, a visual inspection can only be used when the nature of the cargo, its composition, and its construction allow for that.

2.3. Capacity of cargo security checkpoint

The throughput of the cargo inspection system will be understood in our work as the maximum number of shipments that can be checked in a given time interval, usually within an hour. Based on the throughput, the cargo expected to be transported, and cargo preparation technology, it is possible to estimate when the inspection should begin. Starting the check at the wrong time can lead to delays in delivery or organizational problems at the airport, for example, storage-related issues. Some guidance is provided by the available information on the shipment's contents. However, it is general and does not allow for a precise determination of both the type of inspection needed and the time required.

The rapid growth of the air cargo market, noticeable especially after the COVID-19 pandemic, caused the existing infrastructure not always to be sufficient to clear cargo within a strictly set time frame. CSC throughput is a fundamental issue from an operational point of view, measurably affecting the company's financial stability. The ergonomics of SCO operation and the time involved in preparing for inspection are beyond the scope of our research, but a more precise knowledge of the inspection time using the available equipment determines, to a large extent, the performance of other areas related to cargo handling. For this reason, the topic addressed in the work is also essential from the economic point of view.

In addition, it should be remembered that air operations are carried out under a strict time regime, which can also impose time pressure on security personnel, compounded by cargo volume and the expected financial consequences from contractual penalties. The epidemic threat mentioned above has also demonstrated globally the importance of cargo traffic to the financial condition of international airports. Diversification of airline operations, which, in addition to carrying passengers, also have cargo business opportunities, proved to be the only way for many airports to maintain their cash flow during the epidemic. With the above in mind, the studies indicate possible solutions for maintaining a balance between the operational needs of the entity and the scope of planned investments. Proper planning of the

cargo screening process is also vital for detecting prohibited items effectively, as demonstrated in previous research.

The throughput of the entire cargo warehouse, in addition to the inspection process itself, is influenced by other technical and administrative activities that result from regulations, procedures, or the nature of the freight forwarding company's business and its policies (e.g., regarding the time of delivery of the shipment for transport). These include the identification of cargo, its acceptance, and appropriate safeguarding for transportation. A comprehensive analysis will be the subject of our subsequent research. In this study, we wish to identify and dimension the essential activities of cargo security control.

2.4. Factors affecting inspection time

Many technical, infrastructural, and organizational factors influence the level of security and the throughput at the CSC. During cargo clearance, the X-ray equipment used for inspection is essential. Leaving aside possible equipment failures, it is worth noting that the choice of X-ray machine itself directly affects the time and manner of the inspection and the work of all cargo screening operators.

Among the various possible X-ray devices, we highlight the following as typical:

1. X-ray device with a small inspection tunnel (100x100cm), with a 160 kV generator, with an average energy consumption of 1.3 kVA, which penetrates the cargo to a depth of 35mm as standard. This solution implies the frequent need for the so-called depalletization of goods already accumulated on a cargo pallet, which, due to their size, cannot be screened in their entirety. The additional tasks of depalletizing and preparing the cargo for security inspection and then re-building the shipment for transport have a measurable impact on the cost of cargo handling. Such a solution should be used for handling cargo of relatively small size or a small volume. The advantage of using this type of device is its small size and limited need for electricity consumption.
2. An X-ray device with an increased size of the inspection tunnel (145x180cm), with a 160 kV generator, with an average power consumption of about 2.2 kVA, penetrating the cargo to a depth of 35 mm. With the help of this device, the warehouse operator can screen whole-pallet cargo without having to adjust the cargo size to the size of the inspection tunnel. Such a solution positively influences the time of air operations and the throughput of the cargo warehouse. An additional advantage is the energy savings resulting from the shorter operation time and the lower demand for the workforce. However, there is a risk of using additional inspection methods due to more frequent black alarms.
3. X-ray device with maximum size of inspection tunnel (180x180cm), with 300 kV generator, with average power consumption of 4.5 kVA, having the ability of standard penetration of the load to a depth of 70 mm. In this case, we are dealing with an X-ray device with the maximum available size of the inspection tunnel. With the help of this device, it is also possible to x-ray whole-pallet cargoes, but twice the penetration depth allows for a clearer image of the load. This has a measurable effect on reducing the number of black alarms, reducing the need to perform time-consuming manual inspections or inspect with an explosive trace device (ETD).

Another important factor determining inspection time is the level of training of screening operators. They must have unique skills and knowledge of techniques for concealing

prohibited or dangerous items in seemingly harmless ones. In this context, the SCO's experience is significant, which can be directly translated into correctly assessing the scanned cargo's analyzed image.

Given the nature of the goods, the role of the SCO is to select the appropriate inspection methods for the load. This skill makes it possible to reduce the time required to inspect cargo properly. Experienced operators, having the cargo specifications at their disposal, can eliminate methods that will be ineffective and select the appropriate ones for the case. Thus, they avoid additional, time-generating steps.

It should also be emphasized that as SCOs become more skilled and experienced, their confidence in their actions and conviction in their decisions also increases. Beginners SCOs will need more time to decide how to perform inspections. They may also use methods that are not entirely effective. Of course, such action significantly impacts the throughput of the cargo inspection point and the throughput of the entire warehouse.

Mention should also be made of proper organization at the security checkpoint. In addition to the SCO's experience and skills, the number of employees at the checkpoint is equally important, which allows (if reasonable) to perform inspection tasks in parallel using different methods. Such a solution has its economic consequences but provides for a significant increase in the capacity of the CSC and can be an alternative to other, much more costly measures of an investment nature.

3. Model of cargo security screening system

3.1. Petri nets

A Petri net consists of two disjoint sets of vertices called places (and are depicted as circles) and transitions (shown as rectangles). Vertices are connected by arcs, which describe the relations between them. The most crucial feature of Petri nets, which makes them different from other graph structures, is that they make it possible to define the so-called tokens assigned to places but which can also move around a net through transitions. In this way, the dynamics of the modeled system is represented. The movement of tokens is dependent on the activity of transition. It occurs when all the places that are input into the transition (places connected by an arc directed from the place to the transition) contain an adequate number of tokens. An active transition can be fired. As a result of firing, tokens from the input places are transferred to the output places (connected by an arc from the transition to the place).

So-called colored Petri nets can be used to analyze shipment movements within the security control checkpoint; these nets can be written in the following form:

$$S_c = \{P, T, A, M_0, X, \Gamma, C, G, E, B\} \quad (1)$$

where:

P – set of places;

T – set of transitions $T \cap P = \emptyset$;

$A \subseteq (T \times P) \cup (P \times T)$ – set of arcs;

$M_0: P \rightarrow \mathbb{Z}_+ \times \Gamma$ – marking defining the initial state of the system that is being modeled;

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

Γ – finite set of colors which correspond to the possible properties of tokens;
 C – function determining what kinds of tokens can be stored in a given place: $C: P \rightarrow \Gamma$,
 G – so-called "guard" function which determines the conditions that must be fulfilled for a given event to occur;
 E – function describing weights of arcs, i.e., the properties of tokens that are processed;
 $B: T \rightarrow \mathbb{R}_+$ – function determining the priority of a given event, i.e., controlling the net's dynamics when several events can co-occur.

The idea of color is treated very widely in the tool used (CPN Tools 4.0). Each color belonging to Γ can be a complex data structure. Its elements correspond to real objects. In this paper, the set Γ consists of two subsets: STAT and BAG.

The color designated as STAT describes the loads with individual statuses that leave the successive security screening levels. The color designated as BAG defines the status and transfer of successive bags. Its structure corresponds to the description shown by formula (2), and in the programming language used, it is written as:

$$\text{colset BAG} = \text{product INT*STAT timed}; \quad (2)$$

Example: the following notation represents a single bag in the CSS system:

$$1 \text{ ` } (1, N) @ 280++ \quad (3)$$

where elements of the structure $(nr, st)@tm$ have the following meanings:

$nr = 1$ is the number of the bag;

$st = N$ defines the status of the bag ("Black alert");

$tm = 280$ is the foreseen time when the screening of the bag may begin.

The proposed approach to determining the practical throughput of a cargo control point will allow the precise determination of the effects of decisions, thus providing significant support for them. It is worth noting that the method can be applied both to the current conditions of operation of the cargo warehouse and for the conditions expected in the future, but also under the conditions of disruptions resulting from emergencies.

3.2. Schematic of the inspection process

In air transport, various types of cargo may be transported, the structure, composition, density, or number of which determine the choice of inspection method. During the research carried out at EPKT airport, ten different schemes were identified among the available control methods, the use of which depended on the nature of the cargo. After a more detailed analysis, it was possible to aggregate some of the schemes due to similarity in frequency and timing of inspections. Finally, the following control patterns were adopted in the model:

- XRY - a single X-ray screening with an X-ray device, as a result of which the operator was able to determine whether the cargo could be allowed to be transported,
- XRY+XRY - double screening, used when the density or nature of the load prevents a proper assessment of its contents (so-called black alert), and it is necessary to perform an inspection from another angle or after the shipment has been decomposed,
- ETD, VCK, or PHS - a single inspection using an explosive trace detection device (ETD), visual inspection (VCK), or manual inspection (PHS) - typically used when the load is too large to be placed in an X-ray machine,

- XRY+ETD - two-stage inspection, used after a black alert, consisting of X-ray screening in an X-ray machine followed by a check by detecting trace amounts of explosives; alternatively, XRY+PHS or XRY+VCK were used,
- a combination of ETD, VCK, and PHS methods.

In general, the aggregate cargo control scheme at EPKT Airport is shown in Fig. 2.

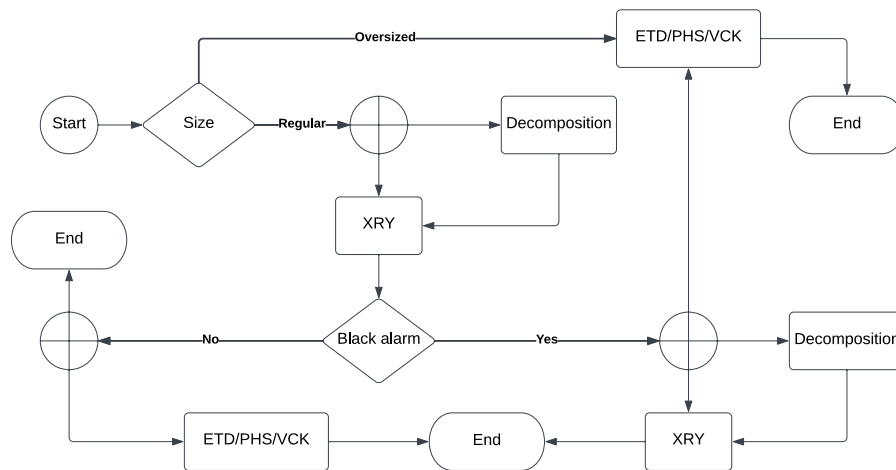


Fig. 2. Aggregate cargo screening scheme at the airport

3.3. Process model

Based on the observations made, after considering the simplifications that resulted in the process scheme adopted for modeling (Fig. 2), a process model was created using colored, timed Petri nets. In this model, the subsequent decisions made by the SSO to declare the baggage safe or to continue the inspection using the same or a different method were mapped. These decisions are generally represented by transitions (rectangles), while places (ellipses) represent the states resulting from the decisions. The general scheme of the Petri net mapping of the studied control scheme is shown in Figure 3.

Given the purpose of the modeling - to determine the capacity of the cargo security checkpoint, the probabilities of individual SSO decisions and the times required for checks play a critical role. Due to the nature of the phenomena, they are treated as random variables. The measurements and their statistical analysis showed a very high variance of these random variables. Thus, reliable parameterization of the model proved difficult. A Bayesian networks approach (Skorupski & Uchroński, 2023) was used to solve this problem. More details are presented in Section 3.6.

3.4. Implementation of the model

A model of the cargo inspection process at the airport was computer-implemented in the CPN Tools package. It is a powerful software package used for modeling and analyzing Petri nets. CPN Tools stands for "Colored Petri Net Tools" and provides comprehensive Petri net modeling and analysis features.

CPN Tools offers an intuitive graphical interface where users can create and visualize Petri net models. It extends traditional Petri nets by introducing the concept of color, which

the screening and (ii) the time required to analyze the image of the screened shipment. In the first of these cases, we will modify the time of performing the preliminary actions, which in the model is implemented in the transitions *Gen*. In turn, the time of image analysis by the SCO is represented by the transitions *XRY1* and *XRY2* and, more specifically, by the associated function $f_{xry}()$.

Another way to represent the level of SCO training in the model is to modify the probabilities of performing each type of control. In the case of less experienced SCOs, as an experiment, we will increase the probabilities of ETD, VCK, and PHS type controls, as we observe in reality. In the model, this corresponds to parameter modifications on numerous arcs implemented by the $pr()$ function.

A separate experiment will study the impact of using a different X-ray device. In this case, we will vary the probability of black alarm ($pr()$ function on the arc connecting the transition *XRY1* to the place *Black*) and the likelihood of oversized load ($pr()$ function on the arc connecting the transition *Gen* to the place *Size*) in the model.

As part of an experiment on modifying the inspection procedure, we will study the impact of introducing a rule that each shipment must be inspected using ETD equipment. It will require changing the model's structure so that each inspection consists of at least two steps - an inspection with an X-ray device and an ETD device.

3.6. Input data

The actual process of controlling cargo shipments at Katowice International Airport in Pyrzowice was measured to parameterize the model. The measurements were made in two series. The first - in April 2021, the HI-SCAN 145180-2is baggage screening device was in use at the time (with a smaller inspection tunnel diameter and less penetration depth, described in Section 2.4 as device No. 2). The second - in October 2021, when the HI-SCAN 180180-2is pro device (described in Section 2.4 as device No. 3) was in use.

Additional surveys were conducted in January and February 2023 to verify and refine the previous ones and prepare a suitable sample for model validation using a machine learning method or, more specifically, a naive Bayes classifier. We recorded the duration of the inspection, the number of loads comprising one shipment, the weight of the shipment, and the detailed inspection procedure.

All inspection times were determined based on measurements. For the inspection time of an oversized shipment, a constant value was taken equal to the average time of this type of inspection obtained from the sample. For the other inspection types, two approaches were taken. The first, for inspection types performed relatively infrequently (PHS, VCK), was to use a random variable with a uniform distribution, with the average obtained from the sample. The second, for types of inspections performed frequently (XRY, ETD), consisted of using a random variable with a distribution obtained from the sample.

For example, an empirical distribution obtained from measurements determined the time required to inspect a shipment with an X-ray machine. Such inspection is the most commonly used, so the number of measurements was large enough to determine the distribution reliably. The mean value of this time was 139 s, and the median was 25 s. The form of the distribution is shown in Figure 4.

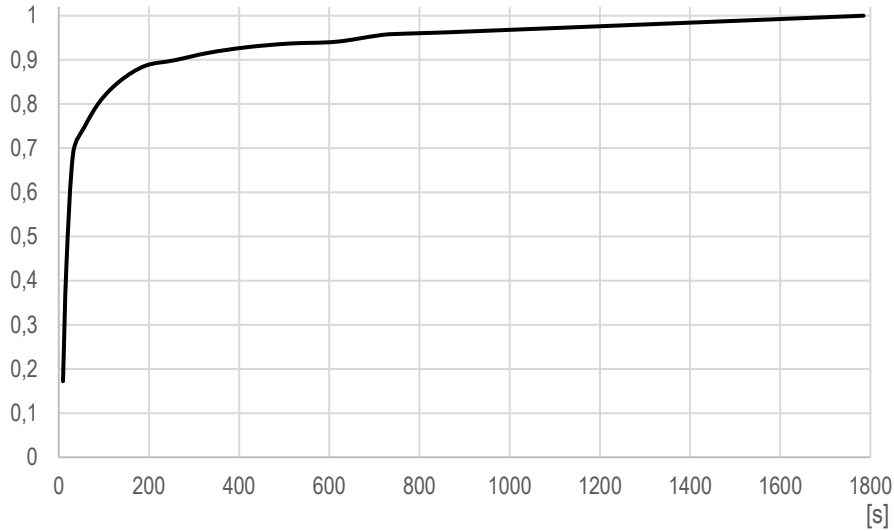


Fig. 4. Empirical distribution of XRY (X-ray inspection) operation time

As mentioned, a model based on a Bayesian Network (BN) was developed to examine the probability of performing particular types of inspections depending on the weight and number of pieces comprising a single cargo unit (Skorupski & Uchroński, 2023). A schema of this model is shown in Fig. 5. The Size node represents the check to see if there is an oversized load. The CTRL1, CTRL2, and CTRL3 nodes represent the subsequent inspection steps. The Black alert node represents the situation when the cargo cannot be classified as safe after the first inspection with the X-ray machine. The Ovs_C node represents the inspection procedure implemented for oversized freight. The monitors shown in Fig. 5 beside the nodes illustrate the apriori conditional probabilities of specific control steps occurring, determined from measurements.

The probabilities used in the model (seen in Figure 3) are conditional, assuming that specific actions were performed earlier or certain events occurred earlier. They were obtained from the analysis of the BN model, but the details of this process will be omitted as less important.

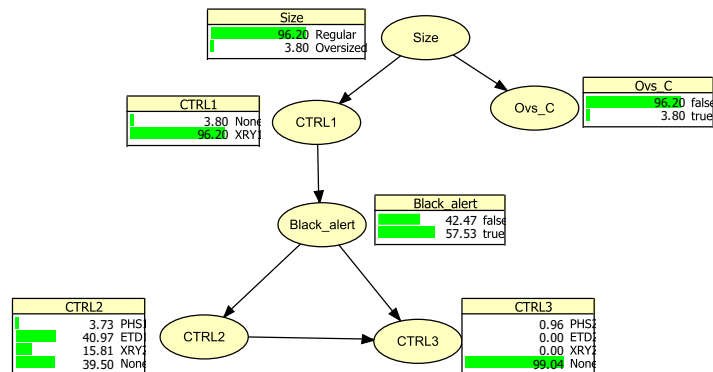


Fig. 5. Schematic of cargo security screening model using Bayesian network

The diagram shown in Fig. 5 corresponds to measurements made using an older generation device with a smaller inspection tunnel diameter and less capacity to penetrate

deep into the cargo (device No. 2 described in Section 2.4). Analogous measurements taken when using other X-ray equipment (with a larger inspection tunnel diameter and better cargo penetration capability) will show different probabilities of both needing to decompose the cargo and performing particular types of inspections.

A data-driven model of the cargo screening process was developed in the HUGIN Researcher package. This package was also used to create a Naïve Bayes classifier (NBC) and conduct model validation using it (Section 4.2). HUGIN Researcher Software is a tool for building and analyzing Bayesian networks. Using a graph structure, they are a statistical model representing the dependencies between random variables. HUGIN Researcher Software offers a user-friendly graphical interface for constructing, testing, and refining BNs. It supports a variety of probabilistic inference algorithms, including exact inference, approximate inference, and sampling-based methods. In addition, HUGIN Researcher Software provides tools for learning the structure of a BN from data, known as structure learning, and for estimating the parameters of a model, known as parameter learning. HUGIN Researcher Software has applications in various fields, including healthcare, finance, risk assessment, and predictive modeling. Researchers and practitioners widely use it for decision-making, prediction, and diagnosis.

Table 1 summarizes the adopted model parameters for the device No. 2.

Table 1. Parameters of the cargo shipment control model

Parameter	Value
Probability of oversized shipment P_{ovs}	0.038
Inspection time of oversized shipment T_{ovs}	468 [s]
Average XRY inspection time (primary and re-inspection) T_{xry}	139 [s]
The median time of XRY controls	25 [s]
The probability of black alert	0.575
Probability of performing an XRY re-inspection	0.158
Probability of performing ETD checks	0.41
Average ETD inspection time	754 [s]
Probability of performing VCK and PHS checks (except for oversize shipments)	0.037
Average time for VCK and PHS inspections	300 [s]

4. Experiments

As mentioned, the basic parameters that determine throughput are the number of screening stages, the type of screening performed at each stage, and the timing of screening activities. In the nominal variant, we will assume all values according to measurements. As part of the analysis of equipment changes, we will consider another device with better performance characteristics and a larger inspection tunnel. In the experiment on training the screening operator, we will assume different execution times for inspection operations in the model - shorter for better-trained operators and longer for less-trained ones. On the other hand, in an experiment with a different inspection procedure, we will examine how throughput will be affected by the need to perform inspections using an ETD device for each shipment.

4.1. Nominal variant

As mentioned, in the nominal variant, we adopt all the parameters of the model and its structure following the observations of the actual system and the measurements taken. This approach means adopting the structure of the model as in Figure 3 and the data as in Table 1. Five simulation runs were performed, each involving the inspection of 10,000 shipments, corresponding to several weeks of CSC operation at the airport under study. The results obtained are shown in Table 2.

Table 2. Experimental results in the nominal variant

Simulation run	1	2	3	4	5
Total inspection time [s]	4927490	4932146	4891706	4995230	4924091
Hourly throughput [shipments/hour]	7.3	7.3	7.4	7.2	7.3

4.2. Model validation

The Bayesian network mentioned in Section 3.6 was also used to validate the model. An essential part of the research was developing a tool for predicting the inspection time of an entire batch of shipments to be transported on a single flight. For this purpose, a Naive Bayes Classifier was used, which proved effective in the application studied.

The Naive Bayes Classifier is a simple but effective probabilistic classifier based on Bayes' theorem, which states that the probability of a hypothesis or event given some observed evidence is proportional to the likelihood of the evidence given the hypothesis, multiplied by the prior probability of the hypothesis:

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)} \quad (4)$$

where

A, B – events, $P(B) > 0$,

$P(A|B)$ – the probability of occurrence of an event A provided that event B occurs,

$P(B|A)$ – the probability of occurrence of an event B provided that event A occurs.

The created classifier was used to calculate a probability distribution of cargo inspection times for the nominal variant. The average inspection time estimated using the NBC classifier was 468 s, and the probability estimates (after rounding to two decimal places) in each of the adopted ranges are shown in Table 3.

Table 3. Estimating control time using the NBC classifier

Range [s]	7-12	12-15	15-19	19-25	25-33	33-49	49-103	103-281	281-747	747-8597
Probability	0.1	0.07	0.1	0.11	0.08	0.12	0.1	0.12	0.12	0.08

The expected control time for a single load calculated from the Bayesian network created for the nominal variant is 479 seconds, corresponding to an average hourly throughput of 7.51 shipments per hour. The difference from the Petri net model value of 2.83% shows good agreement between the model results and the actual measurements, allowing us to conclude that the model was built correctly and can be used in future experiments.

4.3. Hardware changes variant

Section 2.4 describes the different types of X-ray devices that can be used for cargo screening. In this experiment, we will examine the impact on throughput of using a more modern device that can inspect larger cargo. This issue has a practical dimension, as the Katowice Airport in Pyrzowice, which was analyzed when the study was undertaken, was faced with the decision to purchase the device described in Section 2.4 as device number 3.

Due to the improved load penetration capability, the probability of a black alarm will be reduced once the new equipment is installed. Of course, this probability must be estimated for model tests since it is impossible to make appropriate measurements before installing the device. A comparison of the technical parameters of the two devices led us to assume a black alarm probability of 0.288 (based on penetration depth analysis) and an oversized load probability of 0.021 (based on inspection tunnel dimension analysis).

Simulations analogous to the nominal variant were carried out for the assumed input data. The results obtained are shown in Table 4.

Table 4. Experimental results in the hardware changes variant

Simulation run	1	2	3	4	5
Total inspection time [s]	3387071	3330104	3370877	3372794	3409987
Hourly throughput [shipments/hour]	10.6	10.8	10.7	10.7	10.6

4.4. SCO training variant

The measurements used within the framework of this article were taken during regular traffic, which means that SCOs were not specially selected. So, it can be assumed that they were a mix of very well-trained and especially experienced operators and people with less work experience. So, in this experiment, we will examine the effect on CSC capacity of the level of CSO training.

For this research experiment, we distinguish two cases: SCOs with less experience than the nominal variant and SCOs with more experience than the nominal variant. Following the principles outlined in Section 3.5, the following changes in model parameters were adopted.

A. Variant with SCOs with less experience:

- an additional 20 s for initial load analysis and inspection method selection,
- 20% more time to analyze the image obtained from the X-ray device,
- probability of performing a verification inspection using ETD, VCK, and PHS methods at 0.1 when no black alarm occurred and at 0.6 in the case of black alarm and manual inspection.

B. Variant with SCOs with more experience:

- 20% shorter analysis time of the image obtained from the X-ray device,
- a probability of performing a verification inspection using ETD, VCK, and PHS methods of 0.01 when no black alarm occurred and 0.15 in the case of black alarm and manual inspection.

Simulations analogous to the nominal variant were carried out for the assumed input data. The results obtained are shown in Table 5.

Table 5. Experimental results for different SCO training variant

Simulation run	1	2	3	4	5
Total inspection time [s] (variant A)	5767738	5778788	5895115	5747315	5845499
Hourly throughput [shipments/hour]	6.2	6.2	6.1	6.3	6.2
Total inspection time [s] (variant B)	4669188	4577966	4606576	4662687	4574582
Hourly throughput [shipments/hour]	7.7	7.9	7.8	7.7	7.9

4.5. Modification of the control procedure variant

Currently, the existing control procedure is quite complicated, and at the same time, it is not formalized; that is, the SCO has a lot of freedom in choosing it. As part of this experiment, we analyzed the CSC's throughput after modifying it by introducing a rule that each shipment must be inspected using ETD equipment. To do this, we changed the structure of the model so that each inspection consists of at least two steps - an inspection with an X-ray device and an ETD device.

A series of simulations analogous to the nominal variant were carried out for the input data assumed. The results obtained are shown in Table 6.

Table 6. Experimental results in the control procedure change variant

Simulation run	1	2	3	4	5
Total inspection time [s]	7913826	7967003	7860875	7879789	7881533
Hourly throughput [shipments/hour]	4.5	4.5	4.6	4.6	4.6

5. Analysis of results

The capacity in the nominal variant, i.e., the one that existed at Katowice Pyrzowice Airport when the study was undertaken, averages 7.3 shipments per hour. Of course, it must be borne in mind here that the term "shipment" includes a wide variety of goods in terms of their type and the number of items that comprise it. In practice, this number of pieces varies from 1 to as many as 400, so there are large fluctuations in the inspection time of a single shipment. This approach is correct because the SCO treats such a shipment as a whole, allowing it to be transported or forbidden to be transported in its entirety. Even if, for technical and organizational reasons, it inspects each of its components individually.

The validation analysis showed that our research model in the colored Petri net technique was built correctly. A Bayesian network based on actual data was used to map the existing relationships in the measurement sample for validation. Of course, the applicability of this tool is broader, as presented in the article (Skorupski and Uchroński, 2023), but here it was used only for validation purposes.

Based on the created model, we conducted simulation experiments to determine the capacity's dependence on various factors that can affect it. A summary of all experimental results is shown in Table 7.

In Experiment 1, we studied the dependence of capacity on hardware changes. The change was using an X-ray device with much better cargo penetration capability, which results in the ability to interpret the image of the contents for much larger and more complex

shipments. At the same time, the device analyzed has a larger inspection tunnel, which reduces the need to inspect oversized cargo without X-ray technology, which is fundamental to this type of inspection.

Table 7. Summary of experimental results

Variant	Average CSC Capacity [shipments/hour]
0. Nominal	7.3
1. Hardware change	10.7
2a. SCO training A	6.2
2b. SCO training B	7.8
3. Procedure change	4.6

As can be seen from the results, introducing the new type of device will give a significant increase in throughput of up to 50%. This change can be crucial in traffic congestion situations and allow the realization of transport without delays, even in operationally difficult situations. So, in our opinion, the airport manager should consider the possibility of purchasing and putting into operation equipment with similar technical parameters.

In Experiment 2, we investigated how the level of training and experience of SCOs affects cargo checkpoint capacity. The results show that any benefits in additional training or other efforts to hire better-qualified operators are unlikely to yield significant gains in capacity. Simulations (variant 2b) show the possibility of increasing capacity by about 7%, which is not impressive. Perhaps this is because the SCOs currently employed are people with high professional competence, and there is limited room for improvement. At the same time, if the composition of the staff performing the inspections deteriorates (option 2a), a sizable drop in capacity is possible by about 15%. So it is essential here to take care to maintain at least the existing level of training. In doing so, it should be noted that our research only addressed the issue of CSC capacity and did not address the effectiveness of SCO in detecting prohibited items. Such studies are planned for the future.

In Experiment 3, we analyzed changing the inspection procedure by introducing at least a two-step inspection using specialized equipment (XRY-XRY or XRY-ETD). Such measures could be considered to standardize the approach and reduce the subjectivity of SCOs in their actions. Another case where such an approach seems appropriate is in a situation of increased terrorist threat. However, as the results of our experiment show, this type of idea should be approached with caution, as it can cause a significant drop in capacity by about 40%. Under normal conditions, this could make it impossible to handle cargo efficiently and on time.

6. Summary and conclusions

The conducted research and experiments using the created model based on actual measurement data allowed for capturing some relationships between CSC throughput and disturbances. They also made it possible to analyze the impact of potential changes in the organization of the control process on throughput. The effect is quite evident qualitatively, but the experiments conducted allowed us to learn about this impact quantitatively.

Both the disruptions studied and the organizational changes are, to some extent, subject to the decisions of the airport manager. Additional funds can be allocated for supplemental staff training, the purchase of more modern and versatile equipment, or the implementation of changes in control procedures. However, knowing how much SCS capacity will increase in each case is essential. And this is the question that our research brings an answer to.

The experiments have shown a high possibility, about 50%, of improving the capacity of the cargo security checkpoint by using more modern equipment with greater cargo penetration capacity and a larger inspection tunnel. In contrast, the introduction of mandatory inspections using ETD equipment to inspect trace amounts of explosives is risky in terms of capacity, as it is expected to be reduced by up to 40%. Relatively small changes in capacity are expected due to changes in the training and experience of screening operators. This conclusion, however, should be treated with caution, as it may be due to the specific nature of the personnel employed at the airport that was analyzed.

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References

1. AlKheder, S., A. Alomair and B. Aladwani (2019). Hold baggage security screening system in Kuwait International Airport using Arena software. *Ain Shams Engineering Journal*, 11(3), 687-696.
2. da Cunha, D., R. Macário and V. Reis (2017). Keeping cargo security costs down: A risk-based approach to air cargo airport security in small and medium airports. *Journal of Air Transport Management*, 61, 115-122.
3. Davidrajuh, R. and Lin, B., 2011. Exploring airport traffic capability using Petri net based model. *Expert Systems with Applications*, 38 (9), 10923–10931.
4. Domingues, S., R. Macário, T. Pauwels, E. van de Voorde, T.y Vanelslander and J. Vieira (2014). An assessment of the regulation of air cargo security in Europe: A Belgian case study. *Journal of Air Transport Management*, 34, 131-139.
5. European Commission, 2015. Commission Implementing Regulation (EU) 2015/1998 of 5 November 2015 laying down detailed measures for the implementation of the common basic standards on aviation security, *Official Journal of the European Union*, 58, L 299.
6. Florowski, A. and Skorupski, J., 2016. Method for evaluating the landing aircraft sequence under disturbed conditions with the use of Petri nets. *The Aeronautical Journal*, 120 (1227), 819–844.
7. Gillen, D. and W. Morrison (2015). Aviation security: Costing, pricing, finance and performance. *Journal of Air Transport Management*, 48, 1-12.
8. Huegli, D., S. Merks and A. Schwaninger (2020). Automation reliability, human-machine system performance, and operator compliance: A study with airport security screeners supported by automated explosives detection systems for cabin baggage screening. *Applied Ergonomics*, 86, 103094.
9. Kirschenbaum, A. (2013). The cost of airport security: The passenger dilemma. *Journal of Air Transport Management*, 30, 39-45.
10. Kovács, A., Németh, E., and Hangos, K.M., 2005. Modeling and Optimization of Runway Traffic Flow Using Coloured Petri Nets. *International Conference on Control and Automation (ICCA)*, 881–886.
11. Knol, A., A. Sharpanskykh and S. Janssen (2019). Analyzing airport security checkpoint performance using cognitive agent models. *Journal of Air Transport Management*, 75, 39-50.
12. Lee, A.J. and H.J. Sheldon (2011). The impact of aviation checkpoint queues on optimizing security screening effectiveness. *Reliability Engineering & System Safety*, 96(8), 900-911.
13. Leone, K. and R. Liu (2005). The key design parameters of checked baggage security screening systems in airports. *Journal of Air Transport Management*, 11(2), 69-78.

14. Li, Y., X. Gao, Z. Xu and X. Zhou (2018). Network-based queuing model for simulating passenger throughput at an airport security checkpoint. *Journal of Air Transport Management*, 66, 13-24.
15. Michel, S., M. Mendes, J. de Ruiter, G. Koomen and A. Schwaninger (2014). Increasing X-ray image interpretation competency of cargo security screeners. *International Journal of Industrial Ergonomics*, 44(4), 551-560.
16. Mota, M.M., P. Scala, A. Murrieta-Mendoza, A. Orozco and A. Di Bernardi (2021). Analysis of security lines policies for improving capacity in airports: Mexico City Case, *Case Studies on Transport Policy*, 9(4), 1476-1494.
17. Oberheid, H. and Söffker, D., 2008. Cooperative Arrival Management in Air Traffic Control - A Coloured Petri Net Model of Sequence Planning. In: K. van Hee and R. Valk, eds. *Applications and Theory of Petri Nets*. Springer Berlin / Heidelberg, 348–367.
18. Price, J. and J. Forrest (2016). Air cargo security. In J. Price and J. Forrest (Eds.), *Practical Aviation Security (Third Edition)*, pp. 437-459. Butterworth-Heinemann.
19. Ratzner Wells, L., Lassen, H.M., Laursen, M., Qvortrup, J.F., Stissing, M.S., Westergaard, M., Christensen, S., and Jensen, K., 2003. CPN Tools for Editing, Simulating, and Analysing Coloured Petri Nets. In: *Proc. of 24th International Conference on Applications and Theory of Petri Nets (Petri Nets 2003)*, LNCS 2679. Berlin: Springer-Verlag, 450–462.
20. Skorupski, J., 2011. Method of analysis of the relation between serious incident and accident in air traffic. *Advances in Safety, Reliability and Risk Management*, 2 (11), 2393–2401.
21. Skorupski, J., 2015. The risk of an air accident as a result of a serious incident of the hybrid type. *Reliability Engineering & System Safety*, 140 (140), 37-52.
22. Skorupski, J. and P. Uchroński (2015). A fuzzy model for evaluating airport security screeners' work, *Journal of Air Transport Management*, 48, 42-51.
23. Skorupski, J. and P. Uchroński (2018). Evaluation of the effectiveness of an airport passenger and baggage security screening system. *Journal of Air Transport Management*, 66, 53-64.
24. Skorupski, J. and P. Uchroński (2020). Multi-criteria group decision-making approach to the modernization of hold baggage security screening system at an airport, *Journal of Air Transport Management*, 87, 101841.
25. Skorupski, J. and P. Uchroński (2023). Data-driven analysis of the airport cargo screening process, in *Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)*, Southampton, United Kingdom.
26. Skorupski, J., P. Uchroński and A. Łach (2018). A method of hold baggage security screening system throughput analysis with an application for a medium-sized airport. *Transportation Research Part C: Emerging Technologies*, 88, 52-73.
27. Smieszek, H. and Karl, C., 2013. An approach to cognitive simulation of air traffic controllers based on coloured petri nets. In: D. Soeffker and A. Kluge, eds. *Kognitive Systeme*. Duisburg: DuEPublico, Duisburg-Essen Publication.
28. Smiths Detection (2021). HI-SCAN 145180-2is, Technical Information, Smiths Detection Group, Wiesbaden, Germany.
29. Vidosavljević, A. and Tošić, V., 2010. Modeling of turnaround process using petri nets. In: *Proceedings (CD) of the 14th ATRS World Conference*. Porto, Portugal, 1–13.
30. Werther, N., Moehlenbrink, C., and Rudolph, M., 2007. Colored Petri Net based formal airport control model for simulation and analysis of airport control processes. In: V.G. Duffy, ed. *Proceedings of the 1st international conference on Digital human modeling (ICDHM'07)*. Berlin, Heidelberg: Springer-Verlag, 1027-1036.
31. Wong, S. and N. Brooks (2015). Evolving risk-based security: A review of current issues and emerging trends impacting security screening in the aviation industry. *Journal of Air Transport Management*, 48, 60-64.

Ocena przepustowości systemu kontroli bezpieczeństwa cargo w porcie lotniczym w warunkach zakłóceń

Streszczenie: Przesyłki cargo stanowią coraz większą część przewozów realizowanych przez wielu przewoźników lotniczych. Jednym z kluczowych elementów w tym obszarze działalności jest kontrola bezpieczeństwa przesyłek, która jest obowiązkowym elementem procesu przewozowego. Celem artykułu było zbadanie przepustowości systemu kontroli w warunkach zakłóceń, a także określenie jej zależności od możliwych ulepszeń technicznych i organizacyjnych. W tym celu zastosowano modelowanie symulacyjne z wykorzystaniem mikroskalowego modelu procesu kontroli bezpieczeństwa cargo zrealizowanego w postaci kolorowanej, czasowej, stochastycznej sieci Petriego. Do walidacji modelu wykorzystano sieci Bayesowskie reprezentujące rzeczywisty przebieg procesu. W wyniku przeprowadzonych eksperymentów badawczych wykazano dla lotniska Katowice w Pyrzowicach, że użycie bardziej zaawansowanych rozwiązań technicznych może zwiększyć przepustowość nawet o 50%. Z kolei wprowadzenie modyfikacji procedury, polegające na co najmniej dwukrotnej kontroli z wykorzystaniem specjalizowanych urządzeń wspomagających, może doprowadzić do jej zmniejszenia nawet o 40%. Stosunkowo niewielkie zmiany przepustowości są spodziewane w przypadku zmian w zakresie wyszkolenia i doświadczenia operatorów kontroli bezpieczeństwa. Na podstawie tych wyników można rekomendować, aby zarządzający portem lotniczym rozważyli użycie rozwiązań technicznych o parametrach, które były analizowane w artykule. Dodatkowo, konieczne jest utrzymanie poziomu wyszkolenia na co najmniej dotychczasowym poziomie, zaś wszelkie zmiany procedur kontroli należy wprowadzać rozważnie, tylko wówczas kiedy jest to niezbędne z powodu konieczności wzmocnienia skuteczności kontroli w okresach zwiększonego zagrożenia terrorystycznego.

Słowa kluczowe: cargo lotnicze, kontrola bezpieczeństwa, przepustowość lotniska, sieci Petriego, analiza symulacyjna

