A method of hold baggage security screening system throughput analysis with an application for a medium-sized airport

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Abstract. The hold baggage security screening (HBSS) is one of the essential steps in a pre-flight operation process. With the continuous increase in the overall air traffic volume, the development of security screening (and control) technologies, and the changes in applicable regulations of law, the structure and equipment of HBSS systems require frequent upgrades. In order to make good, effective decisions about the upgrades, airport management requires tools for quantitative determination of their results. The aim of this work is to analyse the HBSS system throughput. The analysis can serve as an aid in airport management in on-the-go solving of operating issues and making decisions about HBSS upgrades. A mathematical model was established for the analysis in the form of a coloured timed Petri net, and implemented in a computer-aided solution. It was a microscale simulation model, in which every piece of hold baggage is localised in time and with a resolution of a single belt conveyor. The computer-simulated experiments completed with the model helped (i) determine the actual throughput of the HBSS system operated at the Katowice International Airport, (ii) determine the effects of disturbances on the HBSS system operation, (iii) evaluate the impact of the time windows available to SSO (security screening operators), the SSO’s work organisation and the efficiency of automatic security screening on the HBSS system throughput, and (iv) determine the throughput for specific alternative variants of the HBSS organisation, including doubled automatic security screening. These results allow a conclusion, that a four-level HBSS system, which includes automatic security screening, two SSO screening levels based on X-ray imaging, and manual control is an HBSS solution adequate for a regional medium-sized airport. It was also found that, given the growth of airport facility complexity and area, an increase of HBSS throughput is viable rather not by improving the capacity of specific HBSS components, but by deploying them in parallel processing lines. The highest throughput growth potential lies in parallel deployment of automatic security screening lines.

1 Introduction

The hold baggage security screening (HBSS) is one of the essential steps in a pre-flight operation process. The hold baggage is the passengers' luggage that enters the luggage hold of passenger aircraft. The passengers cannot access their hold baggage during flight, irrespective of the flight route (direct or transit). This allows carriage of objects required by passengers for daily use and which cannot be carried in the passenger cabin due to the concerns of their potential use in acts of unlawful interference (ICAO, 2010). A specific regulation exists (European Commission, 2015) that establishes the categories of objects prohibited in both hand and hold baggage. It is against the law to keep explosives, flammables and incendiary materials or devices in hold baggage; however, the final qualification of questionable hold baggage contents as prohibited or not is at the discretion of the SSO (security screening operators). This assignment of discretion is justified as far as the sole technological progress of late enables building improvised explosive devices that had not been foreseen by lawmakers at the time of publishing applicable security regulations. Even if passenger is not able to access the contents of their hold baggage in flight, any failure to detect prohibited objects during a pre-flight security screening can be disastrous.

1.1 Hold baggage security screening (HBSS)

Depending on its configuration, infrastructure or airport performance requirements, the HBSS can vary and its performance can entail various technological solutions. Pursuant to applicable international regulatory guidelines, hold baggage can be inspected by:

- X-ray imaging machines (X-ray screeners);
- explosives detection systems (EDS);
- security manual control;
- explosives trace detectors (ETD);
- „sniffer dogs” for detection of explosive materials.

The essential type of HBSS equipment is an X-ray (radiographic imaging) machine with an EDS. Henceforth, it is referred to as an „EDS screener”. Regulations exist which establish the requirements for HBSS applications of EDS screeners (European Commission, 2015). However, the regulatory requirements have been seeing dynamic changes to adapt them to the reality of new security threats which emerge as technology is developed. Three standards for the requirements have been defined.

1. Dual-energy single-source EDS screeners, which were legal by 2008 (Standard I).
2. Dual-energy multi-source EDS screeners, which are legal by 2020 (Standard II).
3. CTX (computer tomography X-ray) EDS screeners, which will be enforced from 2020 (Standard III).

The three security screening technologies vary in prohibited object detection performance and the screening time. The continuous growth in passenger air traffic requires airport management organisations to adopt engineering and organisational solutions that reduce the security screening time while retaining minimum regulatory security standards.

Hence it is a decision-making problem to choose an HBSS method that maintains a high detection rate without inhibiting airport performance, or even better – to increase the latter. No HBSS solution exists that is explicitly most advantageous; what is more, all solutions are encumbered with high capital expenditure costs and a long deployment time. Hence, some airports operate redundant HBSS solutions that exceed their actual security screening demand; at other airports, the operated HBSS solutions are the performance bottleneck of passenger processing. This problem becomes crucial to the airports that compete for passengers on a free market by striving to apply the highest service standards.

1.2 Literature review

A review of literature on passenger and baggage handling and processing completed under this work provided several pertinent areas of investigation. This section presents some of these areas which are directly related to this paper and explains the extension proposed herein in short.

Security screening as a component of ground handling

Passenger and baggage security screening is a critical component of the overall aircraft ground handling and has been the subject of many research works. The research is mainly focused on the opportunities for improvement of security screening effectiveness, security system throughput, and security assurance cost optimisation (Kirschchenbaum, 2013; Gillen & Morrison, 2015). The suggested measures to achieve these objectives include optimised security screening hardware allocation (Sewell et al., 2013), security screening operator training (McCarley et al., 2004; Schwaninger, 2005), passenger profiling and grouping (Wong & Brooks, 2015; Nie et al., 2009; Lazar Babu et al., 2006), better planning of airport passenger terminals (de Barros & Tomber, 2007), and application of high-reliability security screening equipment (Siergiejczyk et al., 2017).

An HBSS system is usually integrated with a baggage handling system (BHS). The design engineering aspects thereof were studied by (Yu & Xu, 2010). Wu & Xie (2017) investigated the impact of load-balancing policies on the system performance, by assuming an BHS organised as a multichannel queuing system with the specific handling channels endowed with identical characteristics. They proposed to use a join-shortest-queue (JSQ) policy in the airport screening process.

The HBSS effectiveness and investigation into HBSS system configurations with the highest prohibited object detection probability are prominent topics of the refer-
ence sources on the subject considered herein. The authors hereof analysed these problems in the past (Skorupski & Uchroński, 2015a,b; 2016). Testing of security screening effectiveness becomes a different problem from the above ones whenever automatic EDS screeners are required to handle 100% of screening. Nie (2011) presents a probabilistic analysis that enables selection of security screening levels in relation to risk classes assigned to baggage by the baggage risk characteristics. The work considers automatic security only as handled by various screening equipment types and focuses on the cost-effectiveness relationship. A similar approach was applied by Feng et al. (2009) and Blejcharova et al. (2012) to analyse the determination of the optimal combination of technologies in a two-level screening system by considering system capability, human reliability, and total expected cost of screening errors. Butler & Poole (2002) also provided multi-faceted analysis and comparison of existing HBSS technologies. These works point out the necessity of adopting a hybrid HBSS solution that entails automatic security screening equipment with SSO's evaluation of X-ray baggage indications, and security manual control. Our paper contains a systemic analysis of such hybrid HBSS system. The authors considered the actual interdependences between various security screening levels (including automatic and man-operated screening), which have been often disregarded in literature.

Security screening system throughput

The throughput of the passenger and baggage security screening system is a key performance indicator of an airport terminal. It is also a significant factor of passenger's subjective perception of comfort (Gkritza et al., 2006; Alards-Tomalin et al., 2014). Lee & Jacobson (2011) and Wang & Zhuang (2011) suggested the need of finding a certain balance between the security screening system throughput and the screening detail level. Song & Zhuang (2015) analysed an imperfect two-stage screening system with potential screening errors at each stage, and Song & Zhuang (2017) extended the analysis to an N-stage system. In general, the results of the research in this area point to a fact which is quite obvious: the higher the desired efficiency of screening, the lower passenger comfort and satisfaction will be. This applies especially to passenger and hand baggage screening. Passengers most often do not perceive any effect of HBSS solutions on their subjective sense of comfort. The only exception is HBSS system bottlenecks, which may cause departure delays or, in extreme cases, departure of passengers without their hold baggage on board.

The check-in line is the beginning of the handling process in passenger and baggage security screening. A proper organisation of the check-in line has a significant and favourable impact on the throughput of the passenger and baggage security screening system. Kierzkowski & Kiel (2017b) presented a model of dynamic management of the check-in desk system at an airport to keep the variability of passengers reporting to the security checkpoint as low as possible. Bruno & Genovese (2010) proposed a method to manage the check-in system to balance the operation costs and the time of waiting in a queue. Our paper considered these problems in relation to hold baggage by analysing the maximum security screening system throughput and its practical level (which considers a high variability of passengers reporting at the security checkpoints).
Sterchi & Schwaninger (2015) studied the phenomenon of an increase in false alarm rates, which could reduce throughput of the cabin baggage screening. This effect is mainly due to the time needed to resolve an alarm with an ETD system. The false alarm rates of the X-ray screeners were also found to be very important. A similar approach was applied by Dorton (2011) and Dorton & Liu (2016) who investigated the relationship between the security screening throughput, the false alarm rate, and the output volume of the hand baggage screening desk. A queuing system network model was used. Leone & Liu (2005) developed an analytical model that determined the optimal number of explosives detection system devices based on the passenger demand levels and security protocols. The reality of cabin baggage security screening is somewhat different from HBSS. The alarm indications during cabin baggage security screening are verified with other methods. In an HBSS system, rejection of a piece of baggage by automatic security screening does not return a security alarm; it only prompts further baggage analysis. This paper expands the research into the subject hereof to date with a detailed analysis of an HBSS system throughput, a rare topic of similar research, with a specific focus on HBSS interference, internal structure modifications, and the importance of the human factor.

Methods of analysis

Simulation is an important method of analysis applied to passenger and baggage handling systems. Johnstone et al. (2015) applied simulation to analyse the physical design of a BHS and investigated the merging of baggage streams in conveyor-based baggage handling systems with a merging control algorithm, and the impact of the merge’s physical layout. Le et al. (2007) applied simulation to study the feasibility of assuring that check-in stations are not overloaded with bags, which would adversely affect the passenger and baggage handling system, resulting cascade stops and blockages. The works (Sterchi & Schwaninger, 2015; Dorton, 2011; Dorton & Liu, 2016; Kierzkowski & Kisiel, 2017a) also feature discrete event simulation methods to analyse various components of security screening systems.

Microscale modelling has found use in multiple aspects of passenger and baggage handling system performance. Fonseca i Casas et al. (2014) presented a microscale approach to reflect the passenger flow in a hub airport. Passengers were described in relation to their age, gender, mobility, amount of baggage, travelling in a group or alone, the time spent in commercial areas, the purpose of travel and the travel class. Van Boekhold et al. (2014) developed a microscale model to assess the operational efficiency of the passenger processing system with a sole emphasis on the screening of passengers and their carry-on baggage. They concluded that significant improvements occur as the portion of passengers that are positively profiled increases, and lever the pressure on secondary screening. Cavada et al. (2017) proposed microscale simulation to model the movement of baggage along a conveyor using the software originally designed to simulate urban vehicle traffic.

The existing research based on microscale simulation models is focused on the security screening of passengers and their cabin carry-on baggage. The work herein expands these analytical methods by adopting a Petri net model to study the issue of HBSS. A Petri net facilitates analysing multiple parallel process of an HBSS system.
1.3 The concept of work

The organisation of a security screening system often fails to meet the demand defined by the passenger traffic volume. This applies to all security screening stages, including HBSS. Redundant HBSS solutions are often used and justified by the systematic growth in the passenger air traffic volume. However, redundant systems usually have high operating costs. What is more, it usually takes several years from implementing a system to reach target capacity, and a risk grows that by the target capacity is achieved, the security screening equipment becomes obsolete and requires a high-cost replacement. On the other hand, an HBSS system may suffer from an insufficient throughput. These systems require expansion. A separate problem of airports is the need to retrofit or upgrade the HBSS hardware due to the relative high frequency of changes in laws.

The right decision to upgrade an HBSS system requires a good insight into the strengths and weaknesses of specific system components. This insight can only be gained with a detailed microscale model of the HBSS system in question. This kind of models can also be used for an analysis of interference to real-life HBSS systems. HBSS interferences include significant variations in the check-in baggage output, all types of baggage jams or pile-ups in various baggage handling conveyor zones, baggage handling personnel inattention, and faults of baggage tracking systems. In all cases of HBSS interference, a sufficient microscale HBSS system model can help determine proper corrective measures.

Note that HBSS include multiple parallel processes. Although each HBSS system is based on baggage handling belt conveyors which transfer bags sequentially, HBSS is a multithreaded process handled by many operators and devices at the same time (in parallel). Time is treated as continuous and system states as discrete. Hence the adopted development concept for an HBSS system model has based on a coloured timed Petri net which is an adequate tool in such cases. The use of the so-called “fused places” allows for easy modeling of the hierarchical structure of the real system. The HBSS model considered the random nature of events related to the incoming bags and the security screening process, where the latter is in turn strictly related to the contents of bags and the efficiency of SSO’s work. The type of Petri net used allows for easy implementation of stochastic effects and continuous quantities. Furthermore, over classical node-link network models, it is possible to have interactive simulations with results drawn directly and in real time on the Petri net diagram, and it is possible to act during these simulations by, for example, introducing new and modifying existing tokens and even modifying the network structure. The model was used to test the throughput in several variants of HBSS system organisation. Potential interferences were sought and their effect on the system throughput was tested. Various hardware solutions and the effect of the SSO staffing on the HBSS system throughput were also considered. An important part of the analysis presented herein was an assessment of automatic screening on the total HBSS system throughput.

The rest of this paper is organised as follows. Section 2 presents the HBSS system model, detailing its security screening levels and the Petri net applied to describe them and perform their simulation modelling. Section 3 describes the model imple-
mentation with the example of the Katowice International Airport. The detailed structure of the model components is presented with the form of the input data (provided by measurements), the computer-aided implementation in CPN Tools package, and the validation of the HBSS system model and the purpose-developed, dedicated software tool. Section 4 shows the course and results of the simulation experiments done with the use of this tool. The results included: (i) determination of the actual throughput of the HBSS system operated at the Katowice International Airport; (ii) determination of the effects of disturbances on the system operation; (iii) evaluation of the impact of the time windows available to SSOs, the SSO’s work organisation and the efficiency of automatic security screening on the HBSS system throughput; and (iv) determination of the throughput for specific alternative variants of the HBSS organisation, including doubled automatic security screener. Section 5 shows an analysis of the simulation experiments results, whereas Section 6 provides a summary thereof with final conclusions.

2 The HBSS system model

This section discusses the model of a HBSS system with the security screening components integrated into a BHS (baggage handling system). The security screening components mean both technical equipment and human SSOs who examine the X-ray baggage images and handle the manual control. The scheme of HBSS system functioning is described in this section as broadly as possible and is typical for most medium size airports. The presented approach to the HBSS system modeling is applicable to a significant majority of airports of similar size.

The baggage enters the HBSS system from the check-in line (desks) via belt conveyors. The belt conveyor layout of the check-in line is outside this analysis. The input baggage stream coming to the HBSS system has the successive bags randomly spaced and sized. These parameters are critical to the feasibility of using the full throughput of the HBSS system which is the subject of this paper.

A set of bags are screened:

\[ B = \{b_i\}, i = 1, ..., I \]  

(1)

The following function:

\[ p:B \rightarrow NR \times STAT \times CNV \times TIME \]  

(2)

describes the status and location of each bag within the HBSS system, and each bag is described with the following quadruple:

\[ (nr, st, j, tm) \in NR \times STAT \times CNV \times TIME \]  

(3)

where:

\( NR \) - the set of bag numbers, \( NR \subseteq \mathbb{N} \), where \( nr \) is the sequential number of the bag coming from the check-in system;
STAT - the set of statuses assigned to each bag to define their security level. \( STAT = \{ Y, C, N, S, T, D, A \} \), where the status \( Y \) denotes a safe bag cleared for boarding, whereas the statuses \( C, N, S, T, D \) and \( A \) denote the bags not cleared for boarding. The specific status definitions are explained further in this paper.

CNV - the set of belt conveyor numbers, \( CNV \subset \mathbb{N} \), where \( j \) is the sequential number of a belt conveyor;

TIME - the set of time points, \( TIME \subset \mathbb{R} \), where \( tm \) is the time point of a specific belt conveyor occupancy.

It was assumed that each bag has the status "Not Checked" (\( C \)) at the time of reporting in the HBSS system. To be cleared for boarding, each bag has to be accepted by one of the security screening components by granting the status "Secure" (\( Y \)). This may happen at any level of control. Sometimes, however, baggage gets another status. A general scheme of the sequence of changes in baggage status at each screening level is shown in the following relation

\[
\begin{align*}
\{ C \} \xrightarrow{\text{automatic}} \{ Y, A \} & \xrightarrow{\text{standard}} \{ N, D \} & \xrightarrow{\text{special}} \{ S, T \} & \xrightarrow{\text{manual}} \{ Y, A \} & \xrightarrow{\text{to the beginning}} \{ Y, A, S \} & \xrightarrow{\text{to the beginning}} \{ C \}
\end{align*}
\]

Detailed rules for granting status are provided in Sections 2.1-2.4.

The number of security screening levels at specific airports varies with the HBSS configuration; they are triggered as required to assess the baggage as secure for flight. The effect of the detailed HBSS configuration on the screening effectiveness was discussed in (Skorupski & Uchorński, 2015a). This paper features an experiment in testing the detailed HBSS configuration on the system throughput.

### 2.1 Automatic security screening level

The first level of a typical HBSS system consists in an automatic analysis of the baggage contents being X-rayed. The analysis is processed by dedicated algorithms implemented in the X-ray screener. This level features no involvement of any SSO. The first level is automated to reduce the security screening time per bag. Here, and given the security considerations, the X-ray screener software is designed to issue the status "Secure" (\( Y \)) to the screened bag only when its security is unquestionable.

The security screening analysis on this level can result in one of the following:

- a bag is cleared as "Secure" (\( Y \)) only when no suspicious objects or substances were detected; this allows for moving a bag to the target roller tables for pickup and transfer directly to the aircraft. The acceptance level at this security screening level depends on the imaging analysis algorithm, the screener's technical solution, etc. It is designated with \( \alpha_a \).
— a bag is not cleared and receives the status "Not OK" ($N$). This means that it was not possible to explicitly determine that the bag contains no prohibited objects or substances;
— a bag is not cleared and receives the status "Dark" ($D$). This means that the bag contains objects of extreme density that prevent a correct X-ray image analysis due to insufficient penetration by X-rays. If the status is $N$ or $D$, the screened bag image is relayed to an SSO workstation for resolving on the standard screening level.
— a bag is not cleared and receives the status "Alarm" ($A$). This raises an alarm due to an explicit bomb threat. The bag is transferred directly to a staging site for pickup and disposal. The HBSS system also generates a suitable visual and sound alarm to alert the SSO and airport staff.

The HBSS system may not properly recognise a bag which has been mislabelled on the check-in line or the identification labelling barcode is illegible or damaged. A mislabelled bag is subject to the same process as all other not cleared bags – a full security screening cycle. If verified as cleared (accepted) and "Secure", the mislabelled bag is sent to a separate roller table for identification and then to the aircraft.

The important aspects of an HBSS system throughput is the rate of baggage reported to the automatic screener, and the rate of processing to be handled by the automatic screener. At the maximum traffic volume, both rates are determined by the belt conveyor speed upstream of the automatic screener, inside the automatic screener, and downstream the automatic screener. They are designated as $v_R$ and $v_a$, respectively. Another parameter of significance is the layout (distribution) of baggage across the conveyor belts, defined by so called "the window". This value is the minimum spacing between each two successive pieces of baggage. The window was designated $w_0$. Several methods exist for physically forcing the separation of bags at a spacing of $w_0$ minimum. One of them is to differentiate the speed values of individual belt conveyors in a belt conveyor line. However, this method is not always sufficient. Hence, specific belt conveyors are controlled with photocells installed on them. The logic of the control method is to assure that the next bag can only enter the belt conveyor once the previous bag has left it.

Hence, the maximum input rate of baggage is expressed with the relation:

$$\lambda_0 = \frac{v_R}{w_0}$$  \hspace{1cm} (5)

and the maximum rate of automatic security screening processing is:

$$\mu_a = \frac{v_a}{w_0}$$  \hspace{1cm} (6)

Both values were applied to determine the maximum throughput of the automatic security screening station. When studying the actual usage ratio of the maximum automatic security screening throughput, the actual random process of reporting the baggage coming in from the check-in line must be considered by e.g. testing a random variable distribution which defines the spacing (or time intervals) between the successive bags.
2.2 Standard screening level

Each bag that was not assigned the status $Y$ during the automatic security screening is inspected by an SSO in a standard screening mode. The standard screening is to analyse the X-ray image of the bag contents passed to an SSO's workstation by the EDS device operated on the automatic security screening level. The SSO's standard analysis of the X-ray image of the bag can result in one of the following:

- to issue the status $Y$, just like on the automatic security screening level;
- to issue the status "Suspicious" ($S$). This means that the SSO questioned the studied X-ray image of the bag contents and decided to pass it to further scrutiny;
- to raise a bomb alarm (the status $A$).

The standard screening is processed by one or more SSO, and the number of SSO depends on the actual passenger traffic and number of bags to be inspected. Each SSO has a workstation to which the X-ray images from the automatic level are passed whenever an EDS screener failed to verify positively the baggage contents.

During the standard screening, the bag moves from the EDS screener output to a sorter (usually a vertisorter) at which the SSO decides to either divert the bag to the baggage sorting facility (if the status issued was $Y$), or for the next screening level (if the status issued was $S$). The SSO changes the bag status with a respective control button on their workstation desk. If the SSO fails to decide within an allotted standard time, the bag status automatically changes to "Timeout" ($T$); the bag is still considered dangerous and directed to the next level of control.

An important factor is the standard screening time. Generally, an SSO is granted a limited maximum time for their standard screening (it was designated as $d_{st}^{max}$). The standard screening time may be longer than the bag's time of transfer from the EDS screener to the vertisorter. If the SSO does not decide to change the status of the bag within the standard screening time, the bag is held upstream of the vertisorter and block its belt conveyor. The layout of the belt conveyor group upstream of the vertisorter stops only the belt conveyor with the questionable bag on hold. The next piece of baggage may approach the stopped belt conveyor but has to wait for it to be released. The first belt conveyor put on hold is released after the timeout of $d_{st}^{max}$ or by the SSO's decision about further processing of the held bag, irrespective of that decision's effect, i.e. the status being changed to $Y$ or $S$. The number of the belt conveyors operating separately between the EDS output to the vertisorter and the related time $d_{st}^{max}$ depend on the actual HBSS solution of the airport terminal being investigated.

Note that the time $d_{st}^{max}$ for each bag with the status $N$ or $D$ is measured from the time of leaving the automatic screening EDS channel, even if the bag's image is not relayed to an SSO's workstation because that SSO is still analysing the image of a previous bag. This can make the standard screening time of the next bag much shorter than the time $d_{st}^{max}$. Under extreme circumstances, e.g. at a high rate of bags, each leaving the automatic screening with the status $N$ or $D$, and when the SSO uses most of the available time $d_{st}^{max}$, the actual standard screening time available to the SSO is close to zero. Naturally, this poses a serious problem with the HBSS system throughput and the security screening accuracy and effectiveness, where the latter two be-
come insufficient. A practical solution to the problem is to deploy several SSO workstations for the standard screening level. Each next bag image that requires a standard screening (i.e. each with the status $N$ or $D$) is then sent to the first available SSO workstation. This solution can be effectively deployed at airports with constrained free floor of the BHS (and specifically, the HBSS system). An alternative solution is to extend the standard screening level section in length.

2.3 Special screening level

The standard screening level is intended for bags the assessment of which is easy to the SSO. Hence, a relatively short time frame of $d_{st}^{max}$ is assigned to it. However, a bag may require more time to be screened, under certain circumstances. These include bags containing high-density objects, electronic components, a contents layout hardly penetrable to EDS screeners, and any other conditions that prevent a fast assessment.

The special screening level consists in a re-screening imaging of the questionable bag with an X-ray machine integrated with the BHS. This may provide an image angle different than produced in the previous stages. The special screening level has much more time — $d_{sp}^{max}$ — available for the SSO to examine the bag contents with due care. This is especially important if previous HBSS stages failed to change the status to $Y$; it is then reasonable to assume that the special screening level has a higher probability of confirming the presence of a prohibited or dangerous object.

The special screening level is also used to process a certain percentage (designated as $rc$) of bags which are assigned the status $Y$ on the automatic or the standard screening levels. This reduces the HBSS throughput, however, it is a type of a repeated spot check that can greatly improve the flight security level by increasing the odds of detecting a bag with the status $Y$ assigned in error or by sabotage.

The special screening level is processed sequentially. The individual baggage belt conveyors are equipped with photocells for proper queuing of all bags awaiting the SSO decision on status qualification. Not unlike on the standard screening level, the decision result can be as follows: to change the status to $Y$ and divert the bag to the target roller table; to keep the status $S$ and divert the bag to the manual control level; to divert a confirmed dangerous bag (with the status $A$) for disposal.

Despite the special screening time $d_{sp}^{max}$, which is significantly longer than the available standard screening time, an SSO is not always able to make the decision before the timeout. Once the special screening time is out, the screened bag is assigned the status "Timeout" ($T$), followed by the status "Not Checked" ($C$), and diverted for recycling through the entire HBSS. The same applies whenever an SSO misses a bag assigned to them and fails to act and make a status qualification decision. The practical experience in the airport security industry has proven that an SSO workstation may fail to display the image of a bag directed to the special screening level. This may happen when a bag is misaligned on a belt conveyor and its identification fails (the ID label barcode is not scanned). Whenever this happens, the bag is also assigned the status $T$ and diverted for full HBSS recycling. This improves the protection against clearing unscreened baggage for flight.
2.4 Manual control level

The last baggage screening level in an HBSS is the verification of baggage contents by physical search, which an SSO handles in a designated manual control zone. Each bag is physically searched in witness of the passenger who owns it and the SSO interrogates them to determine the risk of an act of unlawful interference. The screening on this level comprises a search by hand and a visual inspection. Whenever SSO’s suspicions are justified, they may use other tools to verify the questionable baggage contents, including ETD, or sniffer dogs trained in detection of explosives and narcotics. The security manual control room has a facility to display the X-ray image of the bag being processed. The X-ray image is imported from upstream HBSS screeners the bag passed by scanning the ID label barcode; this method also displays all the data regarding the bag and its status as stored in the airport systems. The SSO’s decision on status during the security manual control may result in one of the following:

- assigning the status Y to the bag. Next, an SSO moves the bag to the output belt conveyor of the manual control room and scans the ID label with a portable barcode reader. The bag is returned to the input of the HBSS system and then moved to the baggage sorting facility and the target aircraft.
- keeping the status S and holding the bag for further processing with a notice for law enforcement services of proper jurisdiction. This happens when a security manual control reveals objects or substances otherwise than dangerous to flight operations but possession or carriage of which by air is prohibited if unlicensed. These substances and objects include various narcotics and intoxicants or all goods subject to strict regulatory export controls.
- issuing the status A with a bomb alarm. This happens when an explosive device is found.

2.5 Petri net for modelling the HBSS process

The HBSS system model was developed as a coloured, timed, hierarchical, prioritised and stochastic Petri net. Petri nets were originally developed to describe concurrent computer systems. However, a Petri net is a mathematical formalism which can also be used effectively in other fields, also to model processes in the air transport (Werther et al., 2007; Oberheide & Sofker, 2008; Skorupski, 2012; 2015a; Florowski & Skorupski, 2016; Vidosavljevic & Tosic, 2010; Kovacs et al., 2005; Smieszek & Karl, 2013). Additionally, the use of the CPN Tools 4.0 package (Ratzer et al., 2003), which features a convenient simulation mechanism that allows observation of the dynamics of a process, enables performing of a large number of experiments, some of which are discussed in Section 4.

A Petri net is a net consisting of two disjoint sets of vertices that are called places (and are depicted as circles) and transitions (which are depicted as rectangles). Vertices are connected by arcs which describe the relations between them. The most important feature of Petri nets, which differentiates them from other graph structures, is that they allow defining the so-called tokens which are assigned to places but which can also move around a net through transitions. In this way, the dynamics of the mod-
elled system is represented. The movement of tokens depends on the transition activity. It occurs when all of 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. Because of firing, tokens from the input places are transferred to the output places (connected by an arc directed from the transition to the place).

So-called coloured Petri nets can be used to analyse baggage movements within the security control checkpoint; these nets can be written in the following form:

\[ S_Q = \{P, T, A, M_0, X, \Gamma, C, G, E, B\} \tag{7} \]

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 which defines the initial state of the system that is being modelled;
- \( X: T \times P \rightarrow \mathbb{R}_+ \) – random time of carrying out an activity (event) \( t \);
- \( \Gamma \) – finite set of colours which correspond to the possible properties of tokens;
- \( C \) – function determining what kinds of tokens can be stored in a given place;
- \( G \) – so-called “guard” function which determines the conditions that must be fulfilled for a given event to occur;
- \( E \) – function describing so-called 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 there are several events that can occur simultaneously.

The idea of a colour is treated very widely in the tool used (CPN Tools 4.0). Each colour belonging to \( \Gamma \) can be a complex data structure. Its elements correspond to real objects. In this paper, the set \( \Gamma \) consists of six main subsets: G, STAT, BAG, SCR, LOC, and DL.

The colour designated as \( G \) corresponds to integer numbers with timestamps and represents the individual belt conveyors that can be occupied and relieved independent of each other. The timestamps designate the time point at which the belt conveyors will be relieved and ready to accept the next bags in the sequence.

The colour designated as \( STAT \) describes the number of bags with individual statuses that leave the successive security screening levels. The elements of the colour \( STAT \) are listed as part of the description of the formula (3).

The colour designated as \( BAG \) defines the status and transfer of successive bags. Its structure corresponds to the description shown by formula (3), and in the programming language used, it is written as:

\[ \text{colset } BAG = \text{product } \text{INT*STAT*INT timed}; \tag{8} \]

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

\[ 1 \cdot (2, D, 7)@16.3+++ \tag{9} \]
where elements of the structure \((nr, st, f)@tm\) have the following meanings:

- \(nr = 2\) is the number of bag;
- \(st = D\) defines the status of the bag ("Dark");
- \(j = 7\) is the number of the successively occupied belt conveyor;
- \(tm = 16.3\) is the foreseen belt conveyor occupancy time.

The colour designated by SCR describes the activity of an SSO and is defined as:

\[
\text{colset SCR} = \text{product INT*STAT timed};
\]  

(10)

The following notation represents the activities of a single SSO:

\[1`(2,Y)@17.7\]

(11)

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

- \(nr = 2\) is the number of the bag the image of which is currently assessed by the SSO;
- \(st = Y\) describes the screening result; the SSO qualifies the bag as "Secure" for flight;
- \(tm = 17.7\) is the time of screening completion and screening status qualification decision.

The colour designated by LOC describes the actual position of the bag in the HBSS and the total time to make the decision about clearing it for the flight, and is defined as:

\[
\text{colset LOC} = \text{product INT*STAT*INT*REAL};
\]  

(12)

The following notation represents a single bag:

\[1`(2,D,6,36.5)\]

(13)

where elements of the structure \((nr, st, j, tm)\) have the following meanings:

- \(nr = 2\) is the number of bag;
- \(st = D\) defines the status of the bag ("Dark");
- \(j = 6\) is the number of the currently occupied belt conveyor;
- \(tm = 36.5\) defines the time for the screening status qualification decision; if this time is out, the bag status will change to \(T\) ("Timeout") and the bag will be routed to the next screening level.

The colour designated by DL describes the list of bags qualified for screening. It is assigned when there is more than one bag with the status other than \(Y\) on a single screening level.

3 Implementation of the HBSS system model for the Katowice International Airport

This Section shows the specific values of the HBSS system model implemented for the Katowice International Airport (henceforth "KTW"). KTW is a classic representative of Category A0 airports as proposed by Dobruszkes et al. (2017). They divided airports into five categories; Category A includes all airports located in metropolitan areas with over 2 million citizens. When only one airport exists in the area of that
size, it is qualified as Category A0. This airport category is critical in all analyses of the growth trends in air transport. It is a natural destination of traditional air carriers; however, low-cost air carriers have been increasingly eager to use this airport category in the recent years. This suggests good prospects of growth (Dobruszkes et al., 2017).

3.1 HBSS system model for KTW

The HBSS system model for KTW included all four security screening levels described in Section 2.1 to 2.4 in the following order: automatic security screening, standard screening, special screening, and security manual control.

The duration of automatic security screening strictly depends on the belt conveyor speed in the EDS channel and the bag sizes. The belt conveyor speed should be fixed at 0.5 m/s per manufacturer specifications. The measurements show that given the principle that the next bag can enter a belt conveyor only when it has been completely cleared by the last bag, the time interval between the successive images of screened bags is at least 4.7 s. It should be considered as a random variable due to the differences in bag dimensions. This random variable was measured in July 2016. Cumulative distribution functions were used to generate random variables during simulation. Therefore, they were also used to describe the nature of random variables. The cumulative distribution of the automatic security screening time at KTW is shown in Fig. 1a.

![Cumulative distribution functions](image)

**Fig. 1.** Empirical cumulative distribution function of a) automatic, b) standard, c) special, security screening time at KTW

The rate of individual status issue during on the automatic security screening was also analysed. The data were derived from an EDS system software. In the measurement period from the 1st to the 30th of June 2016, a total of 49708 bags were recorded with the following statuses assigned on the automatic security screening level: $Y$ (51.6%), $D$ (10.3%), $N$ (38.1%). The acceptance level $ar_a$ assumed at 0.561 was one the most critical data of the HBSS system model.
The belt conveyor group between an EDS screener and the vertisorter is relatively short in length and includes 8 individual belts: BF 1.30.2.1 (2.8 m long), BF 1.30.3 (1.3 m), and BF 1.32.1 to 6 (1.3 m) (Fig. 2).

Fig. 2. Diagram of the standard screening level at KTW

The X-ray EDS belt conveyor (BF 1.30.2.1) and the belt conveyor directly downstream of it (BF 1.30.3) move at an equal speed; the next belt conveyor (BF 1.32.1) moves 1.25 times faster than the X-ray EDS belt, and all further belt conveyors move 2 times faster. The total belt conveyor travel time through the standard screening zone is ca. 12 s. It is often too short for the SSO to finish a standard screening, the allotted time for which is 29 seconds. The random values of the bag contents assessment time were measured. The related cumulative distribution function is shown in Fig. 1b.

The rate of individual status issue during on the standard screening level was also analysed. In the same measurement period (1 to 30 June 2016), the following statuses were assigned on the standard screening level: Y (95.1%), and S (2.1%). In 2.8% of all standard screenings, the SSO made no decision, which resulted in the status "Timeout" (T).

Two SSO workstations are provided on the standard screening level. At a higher rate of incoming baggage, both SSO workstations are manned and alternately receive the baggage images for standard screening. If the workload is lower, only one SSO workstation is manned.

The part of the baggage handling belt conveyor assigned for the special screening level includes 8 sections: BF 1.34.2 (1.3 m long), BF 1.34.4 (1.3 m), BF 1.48.1 (1.6 m), BF 1.50.1 (1.3 m), BF 1.50.2.1 (2.8 m), BF 1.50.3 (1.3 m), BF 1.52.1 (1.9 m), and BF 1.54.1 (1.3 m). The EDS screener is located in the middle of the special screening level part of the belt conveyor (Fig. 3).

The special screening level has a single screening workstation staffed by an SSO who has a maximum of 180 seconds to assess the contents of each bag received. The random values of the bag contents assessment time were measured. The related cumulative distribution function is shown in Fig. 1c.

The rate of individual status issue during the special screening level was also analysed. In the measurement period (1 to 31 October 2016), the following statuses were assigned on the special screening level: Y (97.2%), and S (2.1%). In 0.7% of all special screenings, the SSO made no decision, which resulted in the status "Timeout", T.
As mentioned before, the special screening level receives a percentage of the bag-
gage accepted for flight on upstream screening levels (and assigned "Secure" status, Y). The completed measurements showed that the re-screening ratio \( r_c \) equals 4% of
the baggage status \( Y \) assigned on the automatic security screening level or the stan-
dard screening level.

Security manual control is rarely done. At KTW, only ca. 0.4% of all screened
baggage was received in the security manual control level. Hence, the statistical fre-
cquency values for status assignment and manual control time had a poor credi-
ability. However, by reference to expert knowledge, the authors assumed that the probability
of assigning the status \( S \) is equal to \( 10^{-5} \); in all other instances, the status \( Y \) is
assigned. The average security manual control time measured at KTW is 7 minutes.

### 3.2 Computer implementation of the HBSS system model

The HBSS system model considered herein was implemented in the CPN Tools 4.0
package. CPN Tools helps defining and simulating a model based on a high-level
Petri net. In our model Petri net characteristics are as follows:

- places represent system states, and transitions represent activities (events) leading
to state changes;
- the Petri net is coloured with tokens assigned to the colours defined in Section 2.5;
- the Petri net is also timed, where time is related to the tokens as follows: a token
can be active only when its timestamp value is lower or equal to the actual simula-
tion time;
- the Petri net is also stochastic, which meant that the transitions related e.g. to the
decisions made by the SSO, the automatic security screening result, the qualific-
tion of a bag for a re-screening are described with random variables;
the Petri net is also prioritised, each transition has a priority that defines the order of firing if more than one transition is active;

the Petri net is also hierarchical and so-called “fused places” are used as a synchronisation mechanism. This means that all places marked with the same label (bottom left of the circle representing the place) belong to the same fusion set, which is equivalent to the fact that the places are identical.

The HBSS system model's hierarchical structure comprised three levels: Automatic standard, Special, and Manual, each corresponding to the specific security screening stage. The automatic security screening was implemented jointly with the standard screening due to the common use of the same screening image generated by the EDS screener. The number of places and transitions, their list and types of transitions for all models are presented in Table 1. Abbreviations for types of transition were used: P - priority, T - timed, I - immediate, G - with guard function.

<table>
<thead>
<tr>
<th>Model</th>
<th>Places</th>
<th>Transitions</th>
<th>Transition type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic standard</td>
<td>Sort, Cptcy, Fix, TF, L1stat, LOC2=LOC2a, L2, Q, TQ, Not ok, In ctrl, OKB1, OKB1T, VS, L2stat, Q1</td>
<td>Level1, T2, C Calc, CLEAR, Niist, Qin, EXIT</td>
<td>P, T, G</td>
</tr>
<tr>
<td>Special</td>
<td>VS, TQ=TQa, TF, L3, LOC3=LOC3a, L3stat, M, Sort, OKB3, OKB3T, Not ok, Q1</td>
<td>Level3, In-3, S,T3 CLEAR3, Ni list, EXIT P, Q i-o</td>
<td>P, T, G</td>
</tr>
</tbody>
</table>

The Automatic standard level (Fig. 4) shows the situation after ca. 722 seconds from the simulation beginning. The place Fix represents a successive bag coming into the HBSS system. This is the bag number 96 with the status "Not Checked" (C), and ready for entry to the EDS screener in the 720th second.

The place LOC2 describes the actual occupancy of the belt conveyors. In this example, the bag no. 94 occupies the belt conveyor no. 7. A maximum time was defined for the security screening status decision in the standard screening for this bag. The decision had to be made by the 743rd second at the latest. The bag’s status is Y, which means that it was already cleared as secure for flight. The bag no. 95 occupies the belt conveyor no. 1 and has the status N. This means that at the automatic security screening it was not possible to state the bag is secure; hence, an SSO was referred to verify the bag’s screening image. This is confirmed by the token in the place In Ctrl. It defines the queue of bags awaiting the security screening status decision. The queue has only one bag – number 95. At the same time, the place OKB1T is occupied by a token that describes the security screening status decision of the SSO concerning the bag no. 95 as foreseen by the HBSS system model and the time that decision will be made. The decision time equals the maximum time for the security screening status decision,
which represents that the decision will not be made at all. Hence, the bag no. 95 will receive the status "Timeout" ($T$).

Fig. 4. The part of the model representing automatic and standard screening

The place $TF$ has 15 tokens which contain the information about the releasing of individual belt conveyors. For example, the belt conveyor no. 7, occupied by the bag no. 94, will be released in the 724th second. If the release time value recorded at the place $TF$ is lower than the actual HBSS system time, as it is for the belt conveyor no. 12, the respective belt conveyor is released and empty. The place $L2$ has the information about the occupancy times of subsequent belt conveyors. Example: the belt conveyor no. 2 will be occupied by the bag no. 95 in the 724th second.

The place $L1\text{stat}$ has the information about the results of completed automatic security screenings. 49 bags were assigned the status $Y$, 37 bags were assigned the status $N$, and 9 bags were diagnosed as containing high-density objects (status $D$). By analogy, the place $L2\text{stat}$ contains the information about the baggage status after the standard screening.

The place $SORT$ specifies that 93 bags passed the entire HBSS and left for the baggage sorting facility. The places $TQ$ and $Q$ and the transition $Q$ in reduce the number of bags in the standard screening zone; due to the required smooth flow of bag movement, the belt conveyors in the EDS screener area and directly downstream of it must be empty, even if the HBSS system is locked out e.g. by a security status decision timeout for a bag.
The Special level (Fig. 5) shows the situation in the special screening zone after ca. 1311 seconds from the simulation start.

Now, the special screening zone has three bags numbered 168, 169, and 170, which occupy the belt conveyor no. 16, 14 and 11, respectively (the place \textit{LOC3}). All these three bags have the status \textit{N}, which means that their screening is in progress. The SSO does a special screening of the bag no. 168 (the place \textit{OKB3T}); the modelled result of this activity is the issue of the status \textit{I} in the 1326th second. The bag no. 169 is waiting in the queue (the place \textit{Not ok}) until the SSO is available. The bag no. 170 is still upstream of the X-ray screener and not yet included in the screening image analysis process. The place \textit{L3stat} shows the results of the completed special screening.

The Manual level (Fig. 6) shows the situation after ca. 6387 seconds from the simulation start. The bag number 900 is in the manual control zone, since an SSO decided so on the special screening level. The bag status \textit{S} proves it. The place \textit{L4stat} shows that one manual control took place so far and cleared a bag for flight (the status \textit{Y}). The transition \textit{BACK} represents a bag that went to the security manual control zone due to a timeout. The bag is removed from the HBSS system without increasing the processed bag counter, represented by the place \textit{Sort}. 

\textbf{Fig. 5.} The part of the model representing special screening
3.3 Throughput calculation

The use of the model to determine the throughput is based on simulation. The model incorporates a number of random variables such as screening times and the probability of assigning individual statuses at subsequent screening levels. We simulate the continuous operation of the system during screening 10^5 pieces of baggage and record the time necessary to carry out these actions. During the simulation, all random events occur according to parameters of random variables that describe them. This allows us to determine the number of bags handled within one hour. When calculating the maximum throughput, we assume that bags flow continuously, separated from each other by the minimum distance specified by "the window". When determining the practical capacity we assume that the bags flow characteristics are as observed in real system, only the intensity of the inputs varies.

3.4 Model validation

The primary method of verifying the adopted solution and validating the tool was to compare the outcomes from the model with the performance of the actual system for the same input. At first, the results for moderate passenger traffic were compared. Fig. 7 shows an empirical cumulative distribution function of the time interval between successive bags reported for HBSS. The sample included 768 bags, and the measurement took 9 measurement sessions in July 2016. This data is typical for KTW Terminal B with three check-in desks open.

In moderate traffic, the security screening of 768 bags took approximately 257 minutes, which gave ca. 179 bags processed per hour. The HBSS system model results for the same characteristics of bag reporting for security screening deviated by no more than 4%, totalling 174 bags screened per hour.

Another model validation method was applied as a comparison of the actual measurement results to the HBSS system model results under the maximum workload of the system. The maximum workload may occur over short time intervals and largely whenever a bag is temporarily blocked or jammed on a belt conveyor in the HBSS
zone. This gives a pile-up of the baggage coming in from the check-in line. Once the block's or the jam's cause is cleared, the HBSS system operates for a limited time with a constant flow of incoming checked-in bags. This condition was witnessed and measured in June 2017, when a backpack shoulder strap caught a belt conveyor housing. The HBSS system operation was halted (with the bags coming in from the check-in line) for 2 minutes and 10 seconds. Once the jam was cleared, the piled-up bags gave a short-term maximum workload condition. The next 30 bags were processed in 151 seconds. This gave a maximum theoretical HBSS throughput of 715 bags per hour. This is an indicative value only, because the measurement interval was relatively very short, and no special screening or manual controls were carried out in that time. Modelling these conditions over a longer period (the authors assumed 200 hours) and with all security screening levels applied, gave a maximum HBSS throughput of 646 bags per hour (which was approximately 9.7% less than the measurement result). This value should be considered as the maximum throughput of the HBSS system at KTW. The minimum observed security handling of 10 bags under a high HBSS load was 55 seconds, i.e. 655 bags per hour.

![Graph](image)

**Fig. 7.** Empirical cumulative distribution function of the time interval between successive bags reported for HBSS (measured in July 2016)

To obtain homogeneous operating conditions of the HBSS system, it was necessary to select relatively short measurement sessions. The same operating conditions were simulated in the software. No formal quantitative criteria defining the threshold for acceptance (or rejection) of the result were defined, because in these short measurement sessions not all events provided in the model occurred. However, in our opinion, the comparison of the measurement results and the HBSS system model results both for moderate and maximum loads validates its feasibility for simulation experiments.

## 4 Simulation experiments

All simulation experiments emulated the process of handling $10^5$ bags that corresponded to approximately 200 hours of continuous operation of the HBSS system. The reference variant (Section 4.1) assumed that the standard screening area was
staffed by one SSO at a time and no HBSS system interference occurred. The actual throughput was determined for the HBSS system in KTW Terminal B. This was adopted as the reference value. Section 4.2 distinguishes five specific groups of interference in the HBSS system performance and the impact of which on the HBSS system throughput was evaluated. Section 4.3 describes an experiment carried out to analyse the impact of reducing the SSO's screening time of a single bag on the HBSS system throughput. Section 4.4 describes an analysis of the effects of deploying EDS screeners with a different rate of baggage acceptance for flight. Section 4.5 shows the simulated effects of changes to the SSO's work organisation during standard and special screening. Section 4.6 shows the potential of applying the HBSS system model to determine the HBSS system throughput with a different organisation i.e. a different number of security screening levels. Section 4.7 discusses an HBSS system with two EDS screeners operated on the automatic security screening level.

4.1 Determination of the HBSS system throughput at KTW

The general operating principles of the HBSS system in KTW Terminal B are discussed in Section 3.1. The most significant aspects that seem to be crucial to the HBSS system throughput are:

- the automatic, standard, special and manual control security screening levels are processed sequentially, and the status "Secure" (Y) assigned to any bag in the HBSS interrupts the sequence;
- the bags that passed the automatic security screening level are not diverted directly to the aircraft awaiting departure; they pass a group of belt conveyors over which the standard screening is handled;
- the time for standard and special security screening is limited, and the time spent on analysing one image automatically reduces the time to analyse the next image in order;
- a part of the bags which passed a positive verification (had the status Y) on the automatic and standard screening levels are rescreened;
- the bags which have no security status decision made on the special screening level are handled back to the belt conveyor start and have the full HBSS repeated.

The analysis of the HBSS system throughput in the reference variant assumed that the form (the shape) of the distribution function, that defined the time interval between the successive bags reported for security screening, was fixed with variable distribution parameters. The cumulative distribution function shown in Fig. 7 had the average baggage interval of 19.8 seconds. Approximately 179 bags per hour could be processed at this ratio of baggage reported for security screening. The theoretical maximum throughput calculated in Section 3.4 is 715 bags per hour. This is 4 times more than observed in the measurement period. A simulation was performed to test the actual HBSS system throughput with the distribution function form unchanged. In this simulation, all random time intervals between the successive bags reported for security screening were generated for the distribution function shown in Fig. 7 and reduced four times.
The experiment for reference variant gave a HBSS system throughput of 508 bags per hour. Henceforth, this will be called the practical throughput of HBSS system. The throughput determined for the constant flow of baggage to be processed is 646 bags per hour, this will be called the maximum throughput of HBSS system.

4.2 Assessment of the HBSS system throughput with interference

The presented processing technology of the HBSS system and its available throughput are adequate for the standard passenger/baggage traffic volume and conditions. Problems with the HBSS system throughput occur in periods of a significant traffic increase and especially during interference, e.g. hardware failures, human errors, non-standard bags, or understaffing. Generally speaking, the causes of stoppage at KTW Terminal B can be divided into five groups:

1. HBSS system-specific stoppages (belt conveyor alignment and bends): Here, the recurring errors include snagging of bag straps by a belt conveyor housing, jamming of large bags when rotated by 90 degrees before entering the next belt conveyor, and jamming of bags at the roller tables in the baggage sorting facility.
2. Check-in line errors: Here the problems are caused by bags standing upright; the HBSS system may stop when an excessive bag height is detected or when castors of a bag became stuck between the belt conveyor joints. Other problems include bags that are too light and which should have been checked in on trays, and bags that are too long that should have been checked in at a designated check-in desk for oversize baggage.
3. Delayed collection of bags by baggage room staff.
4. SSO-related stoppages, e.g. due to a SSO missing from their workstation or an SSO’s failure to make a security screening status decision.
5. X-ray screener and belt conveyor failures.

The practical observations of the KTW HBSS system operating conditions indicated that the first and second group usually halted the system, which often required a full HBSS system restart. This is not a very lengthy operation, it takes about 120 seconds. The third, the fourth, and the fifth group might also cause this, although rarely.

To perform the simulation experiments the frequency of specific interferences and their effects (with a specific focus on the HBSS system stoppages) were analysed in May and June of 2017. The real-world observation results are listed in Table 2.

### Table 2. Stoppages of the HBSS system at KTW

<table>
<thead>
<tr>
<th>Interference Group</th>
<th>No. of stoppages</th>
<th>Stoppage probability of occurrence per hour</th>
<th>Total stoppage duration [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>0.061</td>
<td>2646</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>0.02</td>
<td>678</td>
</tr>
<tr>
<td>3</td>
<td>42</td>
<td>0.142</td>
<td>6342</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.003</td>
<td>240</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.00078</td>
<td>&gt;3600 (for one case)</td>
</tr>
</tbody>
</table>
The observations took 14 days, totalling at 294 hours. No interferences in the fifth group were found during the observation period; hence, their probability of occurrence was estimated in an analysis of such events over a period of one year.

The simulation of interferences in the first group included snagging of a loose bag part by the housing of a randomly selected belt conveyor on the standard screening level. The result for the process of handling $10^5$ bags gave an HBSS system throughput of 505 bags per hour, which was only slightly below its reference value. The authors understand that the effects of transient baggage pile-ups were neutralised by the uninterrupted HBSS performance at all other times. However, the same analysis ran for a single hour in which a stoppage occurred revealed that the HBSS system throughput was ca. 488 bags per hour, which was a drop by about 4%.

The stoppages caused by the interferences in the second group are like those caused by the first group; the difference is the location at which the HBSS system was blocked. The jams and blocks occur near the EDS screener. The HBSS system throughput with these interferences amounted to ca. 506 bags per hour in the analysis of $10^5$ bags, and 492 bags per a single hour of interference. These events are less frequent than those from the first group and characterised with a shorter stoppage time. Hence, the jamming of a belt conveyor upstream of the EDS screener or within its work zone results in more severe consequences that jamming of a belt conveyor anywhere closer to the vertisorter.

Table 2 indicates that the stoppages caused by the third group were most frequent. The third group interferences block the belt conveyors nearest to the vertisorter. The simulation experiment with the HBSS system model revealed that the average system throughput over a long simulation run time (10^5 of bags) was 503 bags per hour and 490 bags per a single hour of interference in the third group.

The fourth group of interference causes refers to rather general and extensive issues of SSO work organisation and discipline. It is studied in more detail in Section 4.5, where the summary of all results is discussed for the HBSS system performance exposed to interferences.

The HBSS system operating interferences caused by hardware failures (the fifth group) were rare, yet extremely annoying, since each lasted couple of hours. A single event for the fifth group of interference causes was modelled as observed in real world conditions in 2017. The event featured failure of a single generator of the EDS screener on the automatic security screening level. Emergency procedures were implemented to remove the failed EDS screener from the screening line. Hence, the SSO had no access to screened baggage images, which disabled the standard screening level. All bags were then routed to the special screening level following the standard screening level "Timeout" ($T$). The simulation of this event on the HBSS system model gave an HBSS system throughput of 164 bags per hour.

### 4.3 Analysis of the effects of the standard and special screening time windows

As said before herein, the time windows for the standard and special screening of baggage are limited; in KTW, the respective time windows are 29 seconds ($d_{st}^{max}$) and 180 seconds ($d_{sp}^{max}$). As explained in Section 2.2, a single bag screening image analy-
sis which is close to the screening time window assigned to an SSO will reduce the time for this operation on the next bags. Hence, a domino effect can occur by which many bags are continuously moved to the next level of security screening. A similar situation can occur on the special screening level. The simulation experiment described in this section concerns an analysis of the effect of changing the baggage security screening time window assigned to the SSO on the HBSS system throughput.

Two series of simulation tests were run on the input data, same as in the reference variant (Section 4.1), with the maximum screening time window changed accordingly on the standard and special screening levels. Fig. 8 shows the results.

![Fig. 8. Effects of changing the maximum bag screening time window on the HBSS system throughput](image)

The maximum standard screening time window, both on the standard screening level ($d_{st}^{\text{max}}$) and the special screening level ($d_{sp}^{\text{max}}$), affects the HBSS system throughput, albeit only when those times are short. The values assumed at KTW ($d_{st}^{\text{max}} = 29$ s and $d_{sp}^{\text{max}} = 180$ s, respectively) are high enough to prevent obstructions; however, they also prevent any growth in the HBSS system throughput. On the other hand, assuming short time windows, especially for both screening levels simultaneously, can have a major impact on the HBSS system performance. For example, the maximum time windows equal to the actual mean value of 7.7 seconds on the standard screening level and 20.3 seconds on the special screening level reduce the HBSS system throughput by ca. 10%, to 458 bags per hour.

### 4.4 Analysis of the effects of the automatic screening effectiveness

The knowledge in image analysis has been continuously expanded recently. Hence, further development of automatic HBSS algorithms should be expected. This section shows an analysis of the effects of the automatic screening effectiveness on the HBSS system throughput.
In terms of the HBSS performance, automatic security screening requires analysing specific distinct features (or indications) on the screening image of the bag to decide if the bag qualifies for the status "Secure". Given the context of our experiment discussed herein, image analysis algorithms should be developed that enable automatic approval of larger numbers of bags. Hence, the research plan hereof was to analyse the HBSS system throughput in relation to the rate of issuing the status "Secure" on the automatic security screening level. Fig. 9 shows the results.

The measurements made at KTW showed that the actual baggage percentage that received the status "Secure" (\( Y \)) was approximately 52%. An analysis of the simulation experiment results revealed that increase in the automatic security screening effectiveness has no effect on the practical HBSS system throughput. This was somewhat different in the determination of the maximum HBSS system throughput, for which a steady and uninterrupted inflow of baggage to the HBSS system exists. Here, assuming the automatic security screening effectiveness (acceptance rate) is zero (which is equivalent to an HBSS system organisation without any automatic security screening), the maximum HBSS system throughput is 413 bags per hour; assuming the full effectiveness of the automatic security screening, the maximum HBSS system throughput is 665 bags per hour — a difference of +60%. Figure 9 shows that if a high volume of baggage would come into the HBSS system, deployment of EDS screeners with more effective image analysis algorithms that provide a better acceptance rate could improve the HBSS system throughput approximately by only 2.9%, i.e. from 646 bags for the 52% of baggage that was positively verified to 665 bags for the 70% of baggage that was positively verified, both on the automatic security screening level.
4.5 Analysis of the effects of the SSO work organisation

As already highlighted in the introduction, two SSO workstations are installed on the standard screening level. The reference values (Section 4.1) were determined for a case with only one SSO workstation manned by SSO personnel. The simulation test for both SSO workstations manned gives a practical HBSS system throughput at 510 bags per hour and a maximum HBSS system throughput of 663 bags per hour. It is evident that the opportunity for increasing the HBSS system throughput with a real-life checked-in baggage input volume is very limited (at 0.4%). If the checked-in baggage inflow for security screening would be continuous, manning both SSO workstations would provide a very small benefit (the HBSS system throughput would grow by 2.7%).

The HBSS system operating procedures assume that the SSO should screen each bag at their workstation for a maximum of 20 minutes (with a continuous duty), followed by 10 minutes of rest. An automatic SSO logout function was implemented to relieve the SSO from having to always check their work time. If the SSO staffing was insufficient, certain interference could occur in the HBSS performance, simply due to the need of calling another SSO to take post at an SSO workstation. In extreme cases, the time to staff the line with next SSO could take up to 90 seconds. During this time the belt conveyors at the EDS screeners are stopped.

A simulation experiment was carried out to determine the effect of these SSO organisational errors on the HBSS system throughput. With a security screening delay of 90 seconds due to an SSO change, the resulting system throughput is 469 bags per hour. That means a throughput reduction by 8% and can be problematic, especially in periods of increased passenger traffic. Whenever this happens, a procedure should apply that each SSO must have a substitute standing by the SSO workstation. A reduction of the logon change time (from logging out one SSO to logging in another SSO) to an average of 10 seconds gives an HBSS system throughput of 504 per hour, which can be deemed satisfactory. Another solution to this problem is to assure that both SSO workstations are staffed on the standard screening level. As demonstrated above, this alone did not warrant a marked increase in the HBSS system throughput. However, it can prevent the problem defined in this simulation experiment.

Table 3 shows a summary of the analyses of the HBSS system performance at KTW Terminal B with all interference groups, separately for the maximum and the practical throughput, for a simulation cycle of $10^5$ of bags, and for a single hour of interference. The long simulation cycle analysis was abandoned for the fifth group of interruptions, since their probability of occurrence was very low. The results in the Table 3 summarize the analysis presented in Sections 4.1, 4.2 and 4.5.

<table>
<thead>
<tr>
<th>Throughput [bags/h]</th>
<th>Interference Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Practical (long simulation cycle)</td>
<td>508</td>
</tr>
<tr>
<td>Practical (1 hour with an interference)</td>
<td>508</td>
</tr>
<tr>
<td>Maximum (long simulation cycle)</td>
<td>646</td>
</tr>
<tr>
<td>Maximum (1 hour with an interference)</td>
<td>646</td>
</tr>
</tbody>
</table>
The drop of the maximum HBSS system throughput (with a continuous inflow of checked-in baggage) is very like the drop of the practical HBSS system throughput (with the actual baggage inflow characteristics) in each interference group, and by a minimum ratio (of less than 1%) in the long simulation cycle (10^5 bags), and by a slightly higher ratio (of ca. 4%) in the single hour in which an HBSS system stoppage event occurred. The drop of the HBSS system throughput (both maximum and practical) is slightly larger – ca. 8% – for the HBSS systems stoppages caused by the SSO's temporary absence due to the SSO logon change. All HBSS system stoppages caused by hardware failures give a very pronounced reduction of the HBSS system throughput, down to a point that precluded any normal operation of the system. It can only work in an emergency mode until the failure is remedied.

4.6 HBSS system throughput for other organisational variants

The four levels of HBSS studied herein is a solution widely practised at many airports around the world. However, other potential solutions for the HBSS system organisation exist. This section considers the throughput of an HBSS system which featured only three security screening levels: automatic, standard, and manual control. A simulation analysis ran on the developed HBSS system model demonstrated that the system was not stable with only one SSO handling the manual control. This would mean that the SSO who manned the security manual control workstation was not capable of screening all incoming bags, and the baggage queue approached infinity. This condition would naturally be unacceptable given the HBSS operating concerns.

Limiting the baggage queue to 10 bags, for example, with blocking the entire HBSS system when this limit is reached, helped stabilised the system, although on a very poor throughput level of 135 bags per hour. This solution can only be acceptable at very small airports with relatively low passenger traffic volumes. In this HBSS system organisational variant, approximately 9% of all handled bags were subject to manual control; in reality, this share would be somewhat problematic, since the bag's owner would have to assist in the search.

One of the investigated opportunities for improving throughput of the analysed HBSS system organisation consisted in increasing the SSO staff at the security manual control desks. This solution, however, would require expanding the HBSS infrastructures, especially by adding more belt conveyors and rooms or booths. The authors also analysed the effects of increasing the time for analysis of the bag screening image, resigning from re-screening of the part of the baggage with the status Y, and increasing the automatic security screening level effectiveness. The results are listed in Table 4.

Table 4. HBSS system throughput with three security screening levels (automatic, standard, and manual control)

<table>
<thead>
<tr>
<th>Extra activities to improve throughput</th>
<th>SSO count at the manual control workstation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>


The maximum HBSS system throughput attainable without applying additional activities to improve it is 494 bags per hour, which is ca. 3% less than in the reference variant. Increasing the single bag standard screening time window by ca. 50% helps reduce the number of bags leaving the standard screening level with the status $Y$; this somewhat improves the HBSS system throughput. However, this increase is only slight. A better solution is to deploy an EDS screener with a high automatic screening effectiveness. Increasing the automatic screening effectiveness by 20% helps boost the HBSS system throughput by ten-odd percent. An even better way tested to improve the HBSS system throughput is to reduce the number or rescreening of the bags with the status $Y$. Note, however, that this solution reduces the HBSS effectiveness, and the overall security performance.

### Analysis of an HBSS system with twin automatic security screeners

The research into the alternative variants of the HBSS system organisation included the effect of doubling the EDS screener on the automatic security screening level on the system throughput. A variant was then assumed where two EDS screeners were connected to a tandem of four downstream belt conveyors. The two baggage flows from the EDS screeners were merged on the fifth downstream belt conveyor and carried together to the vertisorter. The SSO operating on the standard screening level were analysing the screened bag images from both baggage flows (without assigning SSOs to separate baggage flows). The special screening and security manual control levels were organised just like in the reference variant.

Table 5 lists the results of this simulation experiment for a varying number of SSO on the standard screening level and separately for the practical and maximum HBSS system throughput levels.

<table>
<thead>
<tr>
<th>Throughput [bags/h]</th>
<th>SSO count at the standard screening workstation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Practical</td>
<td>633</td>
</tr>
<tr>
<td>Maximum</td>
<td>812</td>
</tr>
</tbody>
</table>

It is evident that applying the double automatic security screening markedly increased the HBSS system throughput: by ca. 25% (practical) and ca. 27% (maximum). Given the doubled number of the belt conveyors in this alternative variant for
the bags to await the standard screening, the number of the SSO in this HBSS system organisation is critical – especially to the maximum throughput. Staffing both SSO workstations helps increase the practical throughput by ca. 30% and the maximum throughput by ca. 75% when compared to the reference variant.

5 Analysis of the results

KTW (Katowice International Airport) processes about 30 thousand flight operations and over 3 million flight passengers per annum. The local HBSS system structure has four security screening levels, typical of the airports of KTW’s size category. The HBSS system includes X-ray screeners and baggage belt conveyors supplied by global vendors and available on the commercial market. Note that the details of the engineering solutions between the HBSS systems at various airports may vary in e.g. the number of baggage belt conveyors in specific belt conveyor groups, the type and location of the X-ray screeners, the strategy of baggage flow through the individual security screening levels, or the applied HBSS automation and control systems. However, the general conclusions derived from the simulation experiments will be largely applicable to most similarly-sized airports or even universal for all airport types which operate HBSS systems integrated with their BHS solutions.

This paper contains an analysis of the HBSS system throughput. The system input is an X-ray screener which makes the first imaging of each bag; the HBSS system final output is the start of the belt conveyor heading to the baggage sorting facility. The bags come from the check-in line to the HBSS system at random. The nature of the probability distribution of the time interval between the successive bags has a major impact on the number of bags possible to process. This aspect is typical to all queuing systems and HBSS belongs to this group (Neufville & Odoni, 2013). This was also proven through the experiment explained in Section 4.1. The practical HBSS system throughput (508 bags/h) that reflected the actual characteristics of the checked-in baggage inflow to HBSS was 21% lower from the maximum HBSS system throughput (646 bags/h) that reflected a continuous, uninterrupted flow of baggage. This points to a high potential for increasing the HBSS system throughput. This potential consists in baggage preparation that would make the baggage flow denser. This could be achieved by altering the work organisation of the check-in line desks or changing the performance characteristics of the belt conveyor line, for instance by lowering “the window” \( w_0 \) (see Section 2.1). Note, however, that a dense packing of the baggage flow might cause problems with bag identification, production of correct baggage images by X-ray screeners, or mechanical overstressing of the belt conveyors. Each of these conditions will reduce the HBSS system throughput; hence, a fair balance must be found. The authors hereof will focus on these issues in future papers.

The current practical HBSS system throughput is sufficient for the present passenger traffic. In 2016, both KTW Terminals handled an average of 420 passengers per hour. Not every passenger checking in for a flight has a hold baggage; this proves that the existing HBSS solution enables a smooth security screening of the checked-in bags. Not only the average performance values are important; instantaneous values
matter too, especially when they apply to peak hours. To determine them, the number of hold bags registered for security screening at Terminal B was measured in 1-hour intervals in June 2017. The highest numbers were recorded in the morning hours (from 4:00 AM to 7:00 AM), when the holiday-season charter flights tended to cumulate, and with a large percentage of passengers travelling with hold baggage. The maximum number of hold baggage reported for security screening was 328 bags per hour. This indicated that even during passenger traffic pile-ups, the existing throughput of the local four-level HBSS system was sufficient.

The fact of its sufficient capacity under normal operating conditions prompts an analysis of the HBSS system throughput under emergency conditions and in the event of a temporary capacity reduction. In reality, these interferences have been witnessed and deemed to be very negative, as they highly obstruct normal airport operations. The simulated operation results of the HBSS system exposed to interferences revealed that total HBSS system blockages were relatively frequent; their empirical probability of occurrence exceeded 0.2. However, proper vigilance of the HBSS system operating staff keeps these stoppages relatively short (at an average of 148 s). Hence, a reduction of the HBSS system throughput in the hour of stoppage is relatively low and amounted to several percent only. This usually does not really interfere with airport operations. In the completed analyses a short reaction time was assumed for the maintenance personnel tasked with the HBSS system recovery. However, an observation of real-world conditions suggests that the reaction time is not always negligible. Two or more interferences can occur in the HBSS system at the same time. This causes stoppage of the HBSS system that affect the operating performance of the airport, including delayed flight departures. A matter critical to airport operations is to have mechanisms, procedures, or equipment that enable quick detection of HBSS stoppages and a short maintenance response. Hardware failure (of belt conveyors or X-ray screeners) is also a major issue. Albeit rare, they can reduce the HBSS system throughput down to 30% of the practical throughput and down to as little as 25% of the maximum throughput. Failures resulting in periodic stoppages are the primary causes of capacity limitations to the system in most airport environments. A solution to these problems is to assure operating continuity with replacement hardware, or to route baggage to a different and fully-operational BHS system section.

The SSO are critical elements of every HBSS system. This personnel analyses the passenger baggage contents as shown on the screening images from the X-ray screeners. As demonstrated before, the standard and special screening by the SSO is restricted in time. Restrictions of the standard and special screening time windows per bag may affect the safety of air transport; it may well happen that the SSO who are pressed for time will make rash judgement about a bag’s status without verifying that it is free of prohibited objects. An analytical simulation ran with the HBSS system model showed that extending the screening time window per bag did not significantly increase the HBSS system throughput. However, reducing the time windows may actually reduce the HBSS system throughput, with a lack of symmetry between the standard screening level and the special screening level. A radical reduction of the standard screening time window could result in a severe loss of the HBSS system throughput by values that may preclude screening of a moderate (average) checked-in
This hazard does not exist on the special screening level. Hence, a certain practical recommendation is formulated as below. Whenever an SSO questions the contents of a bag on the standard screening level, they should not pro-tract their screening operation; instead, the SSO should promptly change the bag's status to "Suspicious" (5) and divert it to the special screening level. This research demonstrates that the time window per bag is sufficient on the special screening level, and the SSO handling it will can examine "Suspicious" bags without reducing the overall HBSS system throughput.

Another important component which largely affects the HBSS system throughput and the safety of air transport are the X-ray screeners applied on the automatic security screening level. As the experiments herein revealed, the EDS screeners with low-quality X-ray imaging or image analysis algorithms that fail to assign the status "Secure" (Y) to many processed bags may significantly reduce the HBSS system throughput. Doubling the number of automatic security screeners can significantly increase the HBSS system throughput, especially when combined with an increased number of the SSO at the standard screening workstations.

An important part of HBSS system management is to choose a proper organisation, or more specifically, the number and types of security screening levels. During the simulation experiments shown herein, two types of HBSS system organisation were tested as alternative to the HBSS system at KTW. The first alternative had three security screening levels: standard, special, and manual control (and no automatic security screening). According to the results presented in (Skorupski & Uchoński, 2015a), this HBSS alternative variant has a moderate effectiveness of detection of prohibited objects. The experimental results herein also prove that the HBSS system throughput in this variant is much lower than in the reference variant. It is then not recommended for most hub airports. The only advantage behind this alternative is to avoid high capital expenditure of purchasing an EDS screener.

The second alternative variant of the HBSS system organisation included these three security screening levels: automatic, standard, and manual control (without special screening). This organisational variant is viable for airports like the Katowice International Airport; however, reaching a sufficient throughput requires many more SSO at the manual control workstations than the reference variant. In practical terms, the security manual control level must be staffed by at least four SSO. Only this number or higher can provide an effective and smooth manual screening of the baggage flow, without blocking the automatic security screening level or the standard screening level. This variant might be appropriate in two scenarios:

1. Whenever an airport has an insufficient number of the SSO trained in X-ray bag image analysis;
2. Whenever a higher baggage screening effectiveness is desired, e.g. due to an elevated threat of terrorism, since, as demonstrated in (Skorupski & Uchoński, 2015a), this variant improves the HBSS effectiveness.
6 Summary and final conclusions

This paper presents a microscale model of an HBSS system in the form of a hierarchical, coloured, timed, and prioritised Petri net. A major characteristic of this research approach was the detailed mapping of functions that allowed to easily trace the location of every bag down to a single conveyor, the bag security status, and the decisions of the screening components that changed the security status. The HBSS system model was implemented in a computer-aided tool and validated with real world data. A tool was developed to analyse the system throughput with the example of the HBSS operated at the Katowice International Airport. Experiments were performed to determine the HBSS system throughput in a reference variant, in variants with interferences, and for the alternatives to the HBSS system and SSO work organisation.

The computer tool works efficiently for medium-sized airport like KTW. However, the application of this approach to larger airports (or a more complex HBSS system) is also possible. Places and transitions mainly model control posts and types of activities performed there, and not individual pieces of baggage, particular SSOs or individual conveyor belts. For example, the more complex HBSS structure described in Section 4.7, which duplicates the automatic control and some of the conveyor belts, does not require additional places or transitions compared to reference variant. This is possible thanks to the type of Petri net used and a complex mechanism for describing the weights of arcs (function E) and guards (function G). For a larger airport, it may be necessary to perform a simulation for more pieces of baggage, which will require a bit longer calculation time. However, for KTW conditions, for \(10^5\) bags (approximately 200 hours of uninterrupted operation of the HBSS system) simulations and calculations take about 75 seconds on a PC with a moderate computing power. Therefore, this does not appear to be a limitation in the applicability of the presented approach to larger airports.

The courses and results of the simulation experiments verify the necessity of applying microscale models to similar analytical work. The Petri net implemented in CPN Tools 4.0 was a convenient measure to reach this objective – largely due to the transparency and coherence of the model, and especially the integrated simulation engine that enabled a precise analysis of the internal processes in investigated HBSS systems.

The results provided herein demonstrate that a four-level HBSS system with the structure as in the investigated case is a correct solution for a regional medium-sized airport. Simple HBSS organisational or engineering solutions do not improve the HBSS throughput in a significant way; at the same time, small faults, failures and interferences do not cause marked drops in the HBSS throughput over a long time horizon. However, the solution poorly resists short-term reductions of the HBSS throughput under likewise conditions. Other system organisations are viable in practice, especially at small airports. Removing the special screening level, however, requires more staff on the security manual control level. An HBSS system without an automatic security screening level is much less efficient than a full, four-level HBSS system.

A very important conclusion from this research is that a HBSS system with the structure investigated herein offers no straightforward means to improve its through-
put. Given the increasing air traffic and the growth of airports, HBSS systems should be expanded and upgraded not by improving the efficiency of their components, but by adding more parallel components. The simulation experiments herein showed that highest throughput growth potential lies in parallel deployment of automatic security screening lines. A different viable method of improving the HBSS system potential is to make the checked baggage flow denser at the HBSS system input by modifying the check-in line system performance. The authors will focus on both these problems in further work.

References


