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A fuzzy system for evaluation of baggage screening devices at an airport

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ABSTRACT: An airport is a complex engineering system; it is composed of many elements interconnected with numerous internal relations with a strongly pronounced role of the human factor. One of the specific tasks carried out by the Airport Managing Entity (AME) is to configure the Airport Security System (ApSS) so that to attain the expected level of confidence in the airport safety and security. This task consists in selection of infrastructure, technical equipment, allocation of personnel and financial means that are necessary to perform all functions of the ApSS. One of the aspects of the configuration of the ApSS is the allocation of available x-ray baggage screening devices searching for items prohibited for transportation. To make this allocation, we need to know how effective these devices are (in terms of detecting prohibited items). This assessment is dependent on several factors which are treated as linguistic variables and are input to fuzzy inference system: the ability to detect explosives (linguistic variable *Detectability*), the number of detection lines (linguistic variable *Number of detection lines*), the effectiveness of the TIP (Threat Image Projection) system (linguistic variable *TIP evaluation*) and the age of the machine (linguistic variable *Device age*). Some of these elements are difficult to objective assessment, as they are heavily dependent on the human factor or the information is uncertain and incomplete. So fuzzy ApSS analysis is proposed. The output from the fuzzy inference system is linguistic variable *Device evaluation*. The meaning of this variable is the ability to protect the aircraft against prohibited items. The proposed new method of assessing the airport baggage screening system involves the construction of a hierarchical fuzzy inference system. Such a system has been built with the use of the compositional fuzzy inference rule. The usefulness of the method is exemplified for Katowice-Pyrzowice international airport, for which an assessment of devices has been performed. The results show that not only allocation of specific devices for specific control points is important for the security of passengers. Also important are the locally accepted principles of their work, which so far are not specified by international regulations. This applies for instance to the selection of the number (frequency) of TIP images. Preliminary analyzes show that the proposed approach can be effective as part of an expert system for supporting the airport operator in configuring ApSS.

1 INTRODUCTION

An airport consists of numerous elements which are linked with various internal relations with a strong impact of the human factor. It is therefore a complicated socio-technical system. The correct operation of an airport requires providing the appropriate level of security by the Airport Managing Entity (AME). One of the aspects involved in providing security is protection against the acts of unlawful interference (ICAO 2010). The research related to providing the continuity of operation of an airport conducted so far focused mainly on the problem of operational availability i.e. the reliability of various technical components of the airport system considered together with their structural reliability as well as the external factors e.g. weather conditions (Kozłowski 2004). Among papers that are strictly related to the problems of airport security it is worth to note the work of (Gkritza et al. 2006), which indicates the need to provide the proper security level at an airport but at the same time minimize the nuisance caused by the security control process to the passengers. The new way of meeting the requirements for security control were suggested in (de Lange et al. 2013), where considerable savings were found by using the “virtual queues”.

Airport Managing Entity (AME) is responsible for keeping the airport in operation availability. One of the specific tasks performed by the AME is configuring the Airport Security System (ApSS) so that the required level of trustworthiness regarding its safety is reached (Kirschenbaum et al. 2012). This task requires the selection of infrastructure, technical equipment and personnel allocation (Soukour et al. 2013) and assigning the financial means required for the implementation of all ApSS functions. Configuring the ApSS in a rational manner requires the knowledge on how the different elements of the complicated structure affect the final security level of an airport (Gerstenfeld & Berger 2011).

Review of literature indicates that there are no effective methods for the evaluation of airport security. With this in mind, we suggest a mathematical model based on the theory of fuzzy reasoning whose output would be an evaluation of the airport security system as a factor for providing the continuity of operation of an airport. This evaluation will be expressed as linguistic variable value and the method used to obtain it will involve all the required factors related to airport security: screening baggage, control of passengers, perimeter security and security culture. It will also include the impact of the environment in the form of the organisational and operational characteristics.

In this work we present the idea of evaluation the entire ApSS, however, we will concentrate on more detailed description of the local model for evaluating of the x-ray equipment used for scanning of the checked and hand luggage. The developed model, together with its computerised implementation in the SciLab environment may be treated as an expert system supporting the decision making process for persons who are in practice responsible for selecting infrastructure components, technical equipment and personnel required by the airport security system.

2 AIRPORT SECURITY SYSTEM

An Airport Security System (ApSS) is used to prevent acts of unlawful interference. This notion is defined in (ICAO 2010) as an unlawful and purposeful act involving e.g.:

- destruction of an aircraft or causing damage to it,
- placing objects, devices or substances on-board an aircraft which may cause the destruction of the aircraft,
- hijacking an aircraft,
- destruction of ground or on board equipment or causing interference in their operation,
- providing false information which causes hazard for people and their belongings in aviation communication,
- destruction or severely damaging devices at an airport.

A practical method of achieving the goals of the ApSS is to perform a security control of the persons and their baggage before they are boarded on an aircraft. On the other hand it also involves the so called perimeter security i.e. the prevention of unlawful access to the airport area.

There are numerous structures related to security control which are discussed in detail in (Uchroński 2011). The security control is performed at the Security Control Points (SCP) and is a complex process that involves numerous devices whose effectiveness and pace of operation has a big impact on the ability of the ApSS to perform its functions (Hainen et al. 2013). The following devices are used:

- metal detector gates,
- manual metal detectors,
- x-ray baggage screening equipment used for detecting explosives and other prohibited items (Wetter 2013),
- radioactive material detectors.

This paper analyses the effectiveness of equipment (x-ray devices) used to detect prohibited items in registered and hand baggage.

3 MODEL OF THE AIRPORT SECURITY SYSTEM

Four basic factors which influence the airport security level may be defined. These are: the baggage screening system, the passenger control system, external security and security culture. A general schematic of relations between these factors is presented in Figure 1.

Each of the elements (rectangles) presented in Figure 1 is a complex structure. The internal relations are highly dependent on the human factor and other factors which are not subject to precise description. As a result, they will be treated as representations of fuzzy hierarchical local models with numerous inputs. Establishing the values of linguistic variables *Baggage Screening*, *Person Control*, *External Security* and *Security Culture* requires a further development of the diagram. Due to the limited volume of the paper it is impossible to present the entire diagram structure. In order to illustrate the essence of the method, Section 5 discusses a local model used for the evaluation of devices used for registered and hand baggage screening.

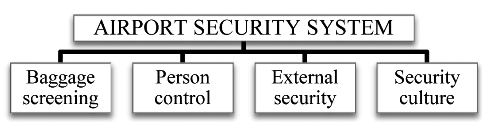

Figure 1. Diagram of a fuzzy model of main factors influencing the security level at an airport.

4 CONCEPT FOR THE EVALUATION OF AN AIRPORT SECURITY SYSTEM

This paper suggests an evaluation of an airport security system based on a hierarchical model of fuzzy reasoning. This approach results from the fact that the tested system is heavily influenced by the human factor and other elements, which are not subject to unequivocal and precise description. It is impossible to detect the functional relationships between the various factors which influence the effectiveness of the security system and an evaluation of the security level. In such cases it is required to use expert opinions. As we have to deal with expert opinions, it is a known fact that very often they are formulated in a descriptive and an imprecise way. We must therefore view the decision making problem in context of uncertainty related to decision making (Dubois & Prade 1992). All this locates the decision making problem in an area described by e.g. the theory of fuzzy sets or rough sets (Greco et al. 2001).

This paper focuses on fuzzy reasoning. A similar approach, although related to the evaluation of an aircrew status, was presented in the work by (Skorupski & Wiktorowski 2013). This paper is a follow up to the work by (Skorupski & Uchroński 2014), where the general structure of interaction model in the airport security model is discussed in detail.

A fuzzy set A will denote a set of

$$A = \{(x, \mu_A(x)) : x \in X, \mu_A(x) \in [0,1]\} \tag{1}$$

where μ_A is the membership function of this set and X is a set of considerations.

A linguistic variable is a variable whose values are words or sentences in a natural or artificial language. These words or sentences will be called the linguistic values of a linguistic variable.

Our models will most often assume that the membership functions of linguistic variable values have a trapezoidal shape and that a typical membership function with the parameters (a,b,c,d) is as follows:

$$\mu_i(x;a,b,c,d) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a < x \le b \\ 1, & b < x \le c \\ \dfrac{d-x}{d-c}, & c < x \le d \\ 0, & x > d \end{cases} \tag{2}$$

Within the scope of the reasoning process we will use the input value fuzzification block, reasoning block using a number of rules and the defuzzification block. The rule sets will be created using experts' opinions, in particular those presented by persons responsible for organising a Security Management Systems (SeMS) at airports. Such set may contain classic non-fuzzy implications as well as fuzzy implications. In the second case we will use the so called compositional method of reasoning introduced by Zadeh (1973) which uses a generalised "modus ponens" fuzzy reasoning rule. This results in the following reasoning scheme (Kacprzyk 1986), where P, P', Q, Q', S are fuzzy relations.

$$\begin{aligned} & I : P \Rightarrow Q \\ & P : P' \\ & C : P' \circ (P \Rightarrow Q) \end{aligned} \tag{3}$$

where I denotes implication, P—premise, C—conclusion, while "°" is a max-min composition, defined on the sets X, Y, Z, whose result for fuzzy relations $A \subset X \times Y$ and $B \subset Y \times Z$ is a fuzzy relation $A \circ B \subset X \times Z$ with a membership function:

$$\mu_{A \circ B}(x,z) = \vee_{y \in Y}(\mu_A(x,y) \wedge \mu_B(y,z)), \quad \forall x \in X, \forall z \in Z \tag{4}$$

Relations P and P' are often constructed on the basis of the AND operator, as in Tables 1 and 2. We will use implications in the form of fuzzy conditional sentences (rules) i.e.

$$IF\ P\ THEN\ Q\ ELSE\ S \tag{5}$$

The conditional sentence is equal to a certain fuzzy relation $R \subset X \times Y$; we will use the max-min rule that was selected from the numerous definitions of such fuzzy relations found in the literature

$$R = (P \times Q) + (\sim P \times S) \tag{6}$$

which is expressed in the form of the following membership function

$$\mu_R(x,z) = (\mu_P(x) \wedge \mu_Q(y)) \vee ((1 - \mu_P(x)) \wedge \mu_S(y)), \quad \forall x \in X, \forall y \in Y \tag{7}$$

If we write down the reasoning scheme (3) in the form of a fuzzy reasoning system we will reach the following form

$$\begin{aligned} & I : IF\ P\ THEN\ Q \\ & P : x\ IS\ P' \\ & C : y\ IS\ Q' \end{aligned} \tag{8}$$

where $P, P' \subset X$, $Q, Q' \subset Y$

Table 1. Fuzzy reasoning rules for the *TIP Evaluation* local model.

Rule	Premise	Conclusion
R1	TIP_Number IS very_low AND TIP_Frequency IS very_high	TIP_Evaluation IS very_low
R2	TIP_Number IS low AND TIP_Frequency IS high	TIP_Evaluation IS low
R3	TIP_Number IS medium AND TIP_Frequency IS medium	TIP_Evaluation IS medium
R4	TIP_Number IS high AND TIP_Frequency IS low	TIP_Evaluation IS high
R5	TIP_Number IS very_high AND TIP_Frequency IS very_low	TIP_Evaluation IS very_high

Table 2. Fuzzy reasoning rules for the *Device evaluation* local model.

Rule	Premise	Conclusion
R1	Detectability IS very_low	Device_evaluation IS very_low
R32	Detectability IS low AND TIP_Evaluation IS medium AND Number_of_detection_lines IS low AND Device_age IS very_low	Device_evaluation IS low
R102	Detectability IS medium AND TIP_Evaluation IS low AND Number_of_detection_lines IS high AND Device_age IS very_low	Device_evaluation IS medium
R193	Detectability IS high AND TIP_Evaluation IS medium AND Number_of_detection_lines IS high AND Device_age IS low	Device_evaluation IS high
R292	Detectability IS very_high AND TIP_Evaluation IS very_high AND Number_of_detection_lines IS medium AND Device_age IS very_low	Device_evaluation IS high

The result of reasoning Q' is specified according to the compositional rule of inference as

$$\mu_{Q'}(y) = \bigvee_{x\in X} \left(\mu_{P'}(x) \wedge \mu_R(x,y)\right), \forall y \in Y \tag{9}$$

where $R \subset X \times Y$ is a fuzzy relation specified by the formulas (6–7). In such cases the membership function of the result has the final form of

$$\mu_{Q'}(y) = \bigvee_{x\in X} \left(\mu_{P'}(x) \wedge \left(\mu_P(x) \wedge \mu_Q(y)\right) \vee \left(1-\mu_P(x)\right)\right), \quad \forall y \in Y \tag{10}$$

A fuzzy reasoning system implemented in the SciLab package and applied in Section 5 uses the above inference reasoning method specified in formulas (8–10).

5 A FUZZY MODEL FOR THE EVALUATION OF X-RAY BAGGAGE SCREENING DEVICES AT AN AIRPORT

5.1 *General structure of the fuzzy model "Device evaluation"*

Figure 1 presents a general diagram of interactions in the *Airport Security System* model. As mentioned before it is a complex hierarchical structure. One of its elements is the *Screening baggage* local model. It consists of two local sub-models: *Hand baggage* and *Registered baggage*. Each of these is further composed of three sub-models: *Device evaluation*, *Personnel evaluation* and *Control procedure*.

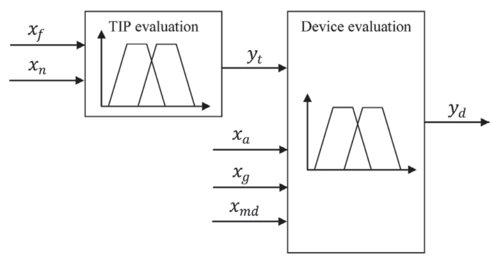

Figure 2. Diagram of the *Device evaluation* fuzzy model.

The subject of analysis in this section is the *Device evaluation* fuzzy model. Its diagram is presented in Figure 2. The output of the fuzzy reasoning system (y_d) associated with this fuzzy model is dependent on four input variables: *Detectability*(x_{md}), *TIP evaluation* (y_t), *Number of detection lines* (x_g), *Device age* (x_a).

5.1.1 *"Detectability" input variable*

The *Detectability* linguistic variable characterises the technical parameters of the x-ray devices which determine the effectiveness of the entire security control process. This category encompasses the conventional RTG devices and EDS (Explosive Detection System) devices. The latter are more advanced as they are able to detect explosives on their own. In case of conventional RTG devices the effectiveness of security control rests in the most part on the abilities of the Security Screener (SS). EDS devices, apart from the parameters of conventional equipment, also allow:

– detecting explosive materials located in the baggage or other parcels irrespective of their shape, location and position and signalling their presence using an alarm,
– sending an alarm signal in case of: detecting an object that is used to prevent the detection of explosive materials, contents of the baggage or parcel are too dense to perform an control.

The values assumed by the *Detectability* linguistic variable are: *very small*, *small*, *medium*, *big* and *very big*. It is assumed that the membership functions of given fuzzy sets will have a trapezoidal shape. To establish them we will use a standard procedure for the evaluation of the device that is performed during every start-up. This calls for using a standard test sample that help verify if the device meets the minimum values related to set requirements (European Commission 2010):

1. resolution of a single wire,
2. useable penetration,
3. spatial resolution,
4. singular penetration (thin material),
5. singular penetration (dense material),
6. differentiating materials,
7. detection of explosive material and signalling,
8. signalling the detection of an item preventing the detection of explosive materials,
9. signalling if the contents of the baggage or parcel are too dense to perform an control,
10. indicating the location of the item that triggered the alarm.

The end result of the test is a filled record form which specifies the number of requirements being met. For a standard, fully functional RTG device this number is 6 (requirements 1–6) and for an EDS class device—10 (additional requirements 7–10). Other values are possible for devices which are partially damaged during operation which is not noticed by the technical personnel. The representation of the *Detectability* linguistic variable is shown in Figure 3.

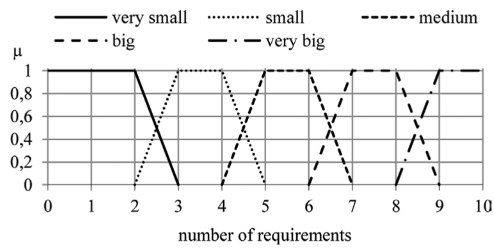

Figure 3. Membership functions of the *Detectability* linguistic variable values.

5.1.2 *"TIP Evaluation" local model*

The second input variable in the device evaluation model is the variable specifying the TIP (Threat Image Projection) system effectiveness. In reality this variable is an output of another local model with *TIP number* (x_n) and *TIP frequency* (x_f) being the fuzzy input variables. The TIP system used for projection of virtual threat images is one of the tools which allow for constant improvement of the operator's skill. Its idea is to project a virtual prohibited item on the image of the piece of baggage being screened. The task of the operator is to detect the virtual object in the image and confirm this fact by pressing the button on the RTG device. This increases the awareness of screening personnel who are forced to search for prohibited items in the baggage image more often than is the case when the TIP system is not used. The effectiveness of the TIP system depends on two parameters:

– number of dedicated TIP images (number of TIPs), which must be numerous enough to prevent memorising their configuration, shape, type etc.; the greater the number of virtual images available in the device the more effective it is at screening baggage,
– frequency at which the TIP images are projected on the real screen image (TIP frequency); in this case, too high frequency of the TIP images in relation to the number of baggage items being screened may cause automatic indications of suspect baggage without an in-depth analysis of the reviewed baggage image.

TIP frequency is established based on individual practice at every airport and this value is kept secret. The *TIP number* and *TIP frequency* input variables assumed for this model are shown in Figures 4–5.

The output variable of the local fuzzy reasoning model for TIP evaluation is presented in Figure 6. This variable is at the same time the input variable for the device evaluation model. The example assumed fuzzy reasoning rules are shown in Table 1.

5.1.3 *"Number of detection lines" input variable*

The x-ray devices differ with the number of generators creating the image. Each generator creates one detection line which allows for creating an image seen from one set direction (angle). In a multiple generator variant, the screened baggage (as it passes through the device's tunnel) is inspected

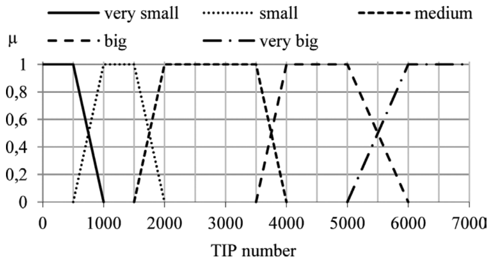

Figure 4. Membership functions of the *TIP Number* linguistic variable.

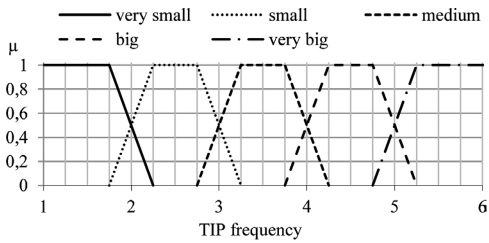

Figure 5. Membership functions of the *TIP Frequency* linguistic variable.

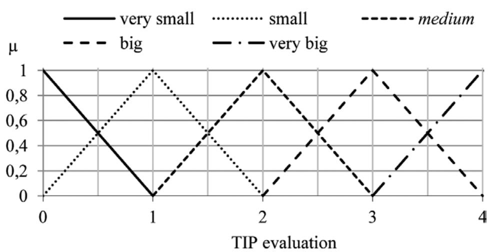

Figure 6. Membership functions of the *TIP Evaluation* linguistic variable.

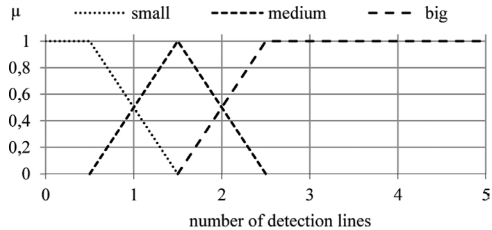

Figure 7. Membership functions for the *Number of detection lines* linguistic variable.

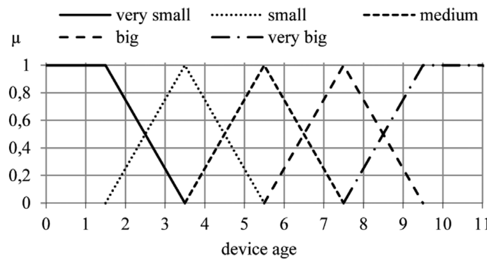

Figure 8. Membership functions of the *Device age* linguistic variable.

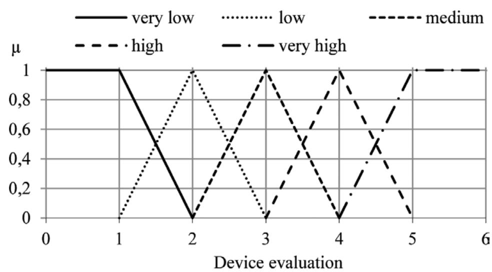

Figure 9. Membership functions of the *Device evaluation* output variable.

by several beams of Roentgen radiation which generates signals in multiple detectors installed in the device at various angles. This allows to obtain images as seen from different directions. Therefore, the probability of detecting a prohibited item hidden in the baggage is much greater if a device with several radiation generators is used during security control. The membership functions for the *Number of detection lines* linguistic variable are shown in Figure 7.

5.1.4 *"Device age" linguistic variable*

The fourth factor taken into account in the analysis is the device age. It influences the probability of failure of the device during operation. Due to frequent reliability checks of the device (at every start-up) the possible time of operation at less the full operational capability is relatively limited. Thus, the age of the device will also be considered a minor factor in the evaluation. The assumed membership functions for different values of the *Device age* linguistic variable are shown in Figure 8.

5.1.5 *Output variable of the "Device evaluation" local model*

The *Device evaluation* local model assumes a five-level scale of linguistic variable values. This is shown in Figure 9.

The fuzzy reasoning system is completed by 301 fuzzy rules defined by expert practitioners; some examples are shown in Table 2.

Table 3. List of baggage x-ray devices at the Katowice-Pyrzowice International Airport.

No.	Manufacturer/model	x_n	x_f [%]	x_{md}	x_g	x_a	y_d
1	Heimann 6040 aTiX	6000	2.8	10	4	6	5.2
2	Heimann 6046 si	6000	2.8	6	1	7–8	2.8–3.1
3	Heimann 6040 i	6000	2.8	6	1	9–10	2.1–2.5
4	Heimann 100100 T	0	0	6	1	7	1.4
5	Smiths 10080 EDX-2is	904	2.8	10	2	8	4.4
6	Smiths 100100 T-2is	599	2.8	6	2	4	3.5
7	Smiths 100100 V-2is	0	0	6	2	3	2.7

5.2 *Example of device evaluation for Katowice-Pyrzowice International Airport*

The Katowice-Pyrzowice International Airport has almost 2.5 million passengers per year with 1.7 million passenger in scheduled traffic and about 0.8 million in charter. In the years 2011–2013 about 30 thousand air operations per year were performed (GTL, 2014a). The Upper Silesian Aviation Group, the entity managing the airport has developed and implemented its own security policy. One of its elements is to perform effective and proactive corrective actions in order to minimise the risk (GTL, 2014b). One of the elements of such actions is the evaluation of x-ray devices presented below.

At the Katowice-Pyrzowice International Airport baggage screening is performed using standard commercially available equipment listed in Table 3. Using the hierarchical fuzzy model described above and a calculation tool created using the SciLab package utilising the max-min compositional inference rule based on relations (8–10) the following results were achieved which are specified in the last column of Table 3. It contains defuzzified values of the *Device evaluation* linguistic variable (see Fig. 9).

Analysis of the results shows that the devices operating in the EDS standard ($x_{md} = 10$) are evaluated as *very high* or *high* (see Fig. 9). The evaluation of the device without the EDS function ($x_{md} = 6$) depends mostly on the number of detection lines. In case of devices with two lines the evaluation results are close to *medium* even though these devices have very few TIP images or do not have such function at all (no 6–7). Devices with a single detection line are rated in the scope from *very low* for a x-ray without TIP image function (no 4), through *low* for older device (no 3), to *medium* for newer devices of this class (no 2).

6 METHOD FOR SELECTING EQUIPMENT AND WORK TECHNOLOGY FOR A X-RAY DEVICES AT AN AIRPORT

It is obvious that the most beneficial solution would involve using only new, modern EDS devices with numerous detection lines and equipped with many TIPs. However, this is a very costly solution, which is often hardly justified by the volume of air traffic.

The presented method for the evaluation of a x-ray devices allows us to present an interesting solution in the field of work technology. This solution is a result of analysis of impact of increasing the frequency of TIPs. A model of relation between the *Device Evaluation* output variable and *TIP Frequency* input variable has been analysed by changing the x_f value in the scope between 0 and 6%. Figure 10 shows the results for an EDS standard device but with a small number of TIPs using the Smiths Detection 10080 EDX-2is as an example.

As we can see the x-ray devices's evaluation result depends on the frequency of TIP images. The borderline values which guarantee the highest evaluation values for the device reaching 4.4, which is the intermediate zone between the *high* and *very high* result, are values 1% and 2.8%. Exceeding those values would result in lowering the effectiveness of the baggage screen system to as low as level 3.1 i.e. *medium* value. The decrease of the result is explained by the low number of TIPs available in the x-ray machine. High frequency of images not only lowers the alertness of the SIO but also allows him to memorise the TIPs, thus decreasing the effectiveness of the control.

In case of a standard RTG device, the selection of the correct TIP frequency may also result in increased work effectiveness (Fig. 11).

As we can see the evaluation result for this device is not affected very much by the TIP display frequency. This is understandable as they are very numerous and the SIO is unable to memorise them. Yet, the remark made in the chapter describing input variables still applies—too high TIP frequency lowers the alertness of the operator. Assuming a work technology which displays more than 3% of TIPs results in an evaluation result of about 3.0, which is equal to the *medium* value. Lowering the TIP frequency to about 1.6–1.8% allows slightly improve the effectiveness of the system (to 3.3).

Taking into consideration the borderline frequencies for device with a low number of TIPs and

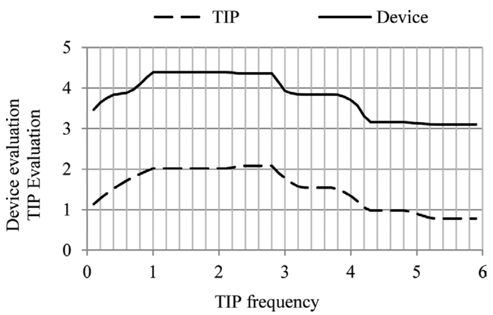

Figure 10. Relation between the *TIP Evaluation* and *Device Evaluation* variables and the *TIP Frequency* variable for the Smiths Detection 10080 EDX-2is.

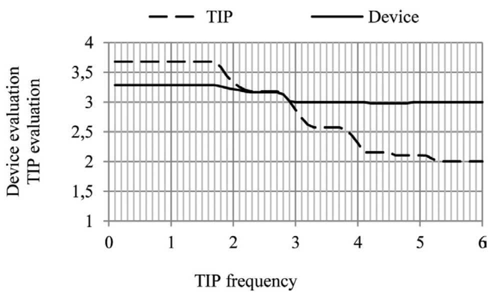

Figure 11. Relation between the *TIP Evaluation* and *Device Evaluation* variables and the *TIP Frequency* variable for the Heimann Smiths 6046 si device.

for devices with a high number of TIP we suggest assuming the *TIP Frequency* parameter value at about 1.8% as a simple and cost-free method of improving the effectiveness of baggage screening system at the airport.

7 SUMMARY AND CONCLUSIONS

The method for the evaluation of effectiveness of x-ray devices at an airport suggested in this paper allows for simple evaluation of individual devices. The developed *Device Evaluation* fuzzy model is part of a bigger model constructed in order to improve the effectiveness of the airport's entire security system.

The evaluation of effectiveness, although important, needs not to be a goal by itself. The suggested approach allows for researching the possible changes in equipment and work technology in order to find solutions that are better than those currently in use. The presented practical example of the Katowice-Pyrzowice International Airport shows that this is not only possible but also does not necessarily require any expenditure.

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