Reliability Engineering and System Safety 94 (2009) 618–627

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Designing airport checked-baggage-screening strategies considering system capability and reliability

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ARTICLE INFO

Article history:
Received 31 October 2007
Received in revised form
26 June 2008
Accepted 29 June 2008
Available online 2 July 2008

Keywords:
Airport baggage screening
Risk analysis
Threshold values
System capability and reliability
Switching probability

ABSTRACT

Emerging image-based technologies are critical components of airport security for screening checked baggage. Since these new technologies differ widely in cost and accuracy, a comprehensive mathematical framework should be developed for selecting technology or combination of technologies for efficient 100% baggage screening. This paper addresses the problem of setting threshold values of these screening technologies and determining the optimal combination of technologies in a two-level screening system by considering system capability and human reliability. Probability and optimization techniques are used to quantify and evaluate the cost- and risk-effectiveness of various deployment configurations, which is captured by using a system life-cycle cost model that incorporates the deployment cost, operating cost, and costs associated with system decisions. Two system decision rules are studied for a two-level screening system. For each decision rule, two different optimization approaches are formulated and investigated from practitioner's perspective. Numerical examples for different decision rules, optimization approaches and system arrangements are demonstrated.

1. Introduction

In the wake of terrorism against air transportation, there have been significant changes in both policy and operational environments of aviation security activities that include passenger and baggage screening systems. In accordance with the requirements exposited in the Aviation and Transportation Security Act (ATSA) of 2001, the Transportation Security Administration (TSA) is charged to deploy 100% screening of all checked baggage for explosives by either explosive detection systems (EDS) or explosive trace detection (ETD) machines [1,2]. To meet the requirement of 100% screening, TSA procured and installed about 1600 EDS and 7200 ETD machines at over 400 airports through June 2006 [3]. Nevertheless, the significant economic and operational concerns regarding these currently used technologies, such as the prohibitory costs, high error rates, and low processing rates, have led TSA to plan improvements in the design of the baggage screening systems and also consider new technologies that offer the opportunity for higher performance and lower cost [4].

To enhance national and even international security, it is critical to design effective baggage screening strategies for maximizing system security under limited resources. Especially for checked-baggage-screening (CBS) systems, the concern of the potential risk associated with error rates of baggage screening systems, namely false alarm and false clear rates, is extremely important. Airport CBS strategies are complex and sensitive in nature due to political, social, and economic consequences of a potential terrorist attack. Hence, all relevant risks, costs and benefits to baggage screening systems and strategies must be appraised in a multi-objective framework [5]. Pertinent metrics should be developed to evaluate the cost, effectiveness, maturity, and efficiency of devices to ensure that they achieve the maximum payoff in improving security for funds spent.

Design and analysis of inspection policies for aviation security systems have been studied in literature. Kobza and Jacobson [6] and Jacobson et al. [7] assessed risk and cost-effectiveness of aviation security systems by considering the false alarm and false clear rates as performance measures. To optimally deploy baggage screening security devices at airports, Virta et al. [8] studied the impact of transferring passengers on the outgoing selectee rate by introducing a method for calculating the outgoing selectee rates. The model developed by Virta et al. [9] focused on modeling tradeoffs between screening only the selectee checked baggage and screening both selectee and non-selectee checked baggage for a single EDS device, where a cost model was also used to measure the cost and benefit associated with various security configurations. Jacobson et al. [10] extended this work to 100% screening,

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doi:10.1016/j.ress.2008.06.015

where tradeoffs between using single-device and two-device systems were studied by utilizing the expected direct cost model. Candalino et al. [11] determined the best selection of technology and optimal number of baggage screening security devices that minimize the expected total cost of the baggage screening strategy by using a cost model including both the direct costs and the indirect costs associated with system errors. In addition to previous studies on risk and cost–benefit analysis, the concern of setting threshold values for continuous security responses were addressed in [12,13] for both single-level screening systems as well as two-level screening systems. A comprehensive total cost function was introduced that includes costs associated, not only with purchasing and operating the baggage screening security devices, but also with system decisions, namely false alarms and false clears.

The existing study on evaluating the baggage screening systems appears to concentrate exclusively on system capability, without considering system reliability issues associated with specific deployment options. This paper incorporates the influence of human reliability on the deployment strategies, since it affects both the system life-cycle cost and the system false alarm and false clear rates. With the consideration of human reliability, this paper aims to select the optimal baggage screening strategy by assessing the risk and cost-effectiveness of various baggage screening technologies and the combination of these technologies. The optimal threshold values to classify threat and non-threat items are determined for the continuous security responses. The proposed methodology, which is previously applied in manufacturing areas for quality improvement [14,15], combines optimization and statistical techniques for designing effective baggage screening systems. *System life-cycle cost*, instead of *system annual cost* [12,13], is developed, which provides a long-term assessment of the cost-effectiveness of a project or a system [16]. For a two-level screening system, two system decision rules are studied, based on which the bags can takes different paths through the system. For each decision rule, two different optimization approaches are formulated and investigated from practitioner's perspective. The first model aims to minimize the life-cycle cost under the constraint of pre-specified false clear rate. The second model minimizes the false clear rate subject to budget constraint on the tangible life-cycle cost of the system.

The organization of this paper is as follows. Section 2 presents the principles underlying the model formulation of the problem, followed by the two-level system architecture in Section 3. In Section 4, the life-cycle cost model is formulated. Section 5 introduces two optimization models based on different motivations. In Section 6, numerical examples for 16 possible arrangements of devices are studied, and analyses are presented for two optimization models. Section 7 concludes the paper providing additional discussions.

2. Problem formulation

The currently used technologies at most US airports for baggage screening are EDS and ETD. However, the constraints on operational efficiency and security levels have prompted TSA to consider alternative technologies based on applications in Europe and Israel, which were also discussed at the Aviation Security Technology Conference in Atlantic City in 2001 [4]. These alternative technologies that utilize automated X-ray imaging include backscatter X-ray (BX), coherent scattering (CS), dual-energy X-ray (DX), and multiview tomography (MVT), among others. The differences of these technologies, such as purchasing cost, operating cost, processing rate, and accuracy, should be taken into account when deciding which technology or combination of technologies to deploy. For four image-based screening technologies, i.e., EDS, BX, DX, and MVT, this paper studies the deployment of two-level screening strategies. Continuous responses provided as an output at each level are combined into the system response function. A probability utility function is developed to represent purchasing cost, operating cost, processing rate, and system decision costs associated with risks for evaluating different combinations of these technologies.

2.1. Continuous responses

Image-based screening devices usually provide continuous security responses, such as the matching ratio between the screened item and the image of a known threat item [12,13]. Let X represent the continuous security response from a screening device, and X takes values in [0, 1], where a response close to 0 and 1 suggests a non-threat item and a threat item, respectively [7]. Other values of continuous responses can be rescaled such that $0\leqslant X\leqslant 1$ [12].

The conditional probability density functions, given a threat or a non-threat item, must be estimated in order to set the screening threshold value that classifies threat items from non-threat ones. A binary variable Z is used to denote the actual status of an item with $Z=0$ indicating a non-threat item and $Z=1$ indicating a threat item. Let $f_{X|Z=1}(x)$ and $f_{X|Z=0}(x)$ represent the conditional probability density functions, given a threat item and a non-threat item, respectively. $f_{X|Z=1}(x)$ exhibits a non-decreasing shape and $f_{X|Z=0}(x)$ shows a non-increasing shape for $0\leqslant X\leqslant 1$. These conditional probability density functions can be estimated using sampling procedures over various threat or non-threat items, such as the static grid estimation procedure [7]. In this paper, a family of β-distributions is utilized to model the security responses, since it exhibits many forms including decreasing, unimodal right-skewed, symmetric, uniform, U-shaped, unimodal left-skewed, and increasing shapes [17]. The probability density function of a β-distribution with parameters ρ and τ, $\beta(\rho,\tau)$, is given by

$$f(x|\rho,\tau)=\frac{\Gamma(\rho+\tau)}{\Gamma(\rho)\Gamma(\tau)}x^{\rho-1}(1-x)^{\tau-1}$$
$$\text{for}\quad 0\leqslant x\leqslant 1,\quad \rho>0,\quad \tau>0, \tag{1}$$

where $\Gamma(\cdot)$ is a gamma function. The parameters of β-distribution can be estimated using classical statistical approach on sampling data or utilizing Bayesian inferential method based on both sampling data and prior information.

2.2. Two types of errors

Like in any other inspection processes, two types of errors can occur in a baggage screening system. The system can allow either a *false clear*, when a threat item to pass through undetected, or a *false alarm*, when a non-threat item is not allowed to gain access. Both false alarm and false clear rates impact airport operations negatively. False alarms lead to additional steps being taken, which ultimately affect the cost-effectiveness of the system, whereas false clears have catastrophic social and economic consequences. Ideally, the false clear rate of a baggage screening system should be very close to 0. Additionally, the system can return correct responses, in the form of a *true clear* by correctly determining that an item does not pose a threat or a *true alarm* by correctly detecting a threat item.

False alarm and false clear rates are determined to a large extend by the upper specification limit or the threshold value, u, on continuous security responses. Bearing a greater security response than the threshold value, an item is specified as a threat item, and the response variable is transformed into an alarm. The