A Mathematical Framework for Sequential Passenger and Baggage Screening to Enhance Aviation Security

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Abstract

To enhance security at both national and global levels, airport security screening systems must be designed with high efficiency and effectiveness, which are affected by both screening technologies and operational procedures for utilizing those technologies. The operational efficiency and aviation security can be enhanced if an effective passenger prescreening system is integrated into the baggage screening system. In this paper, passenger information is incorporated into a two-level checked-baggage screening system to determine the screening strategy for different subsets of passengers. By deploying a passenger prescreening system, this paper considers selectively applying baggage screening procedures for 100% screening. Since new image-based screening technologies differ widely in cost and accuracy, a comprehensive mathematical framework is developed in this paper for selecting technology or combination of technologies for efficient 100% baggage screening. The objective is to determine the optimal combination of technologies and the setting of threshold values for these screening technologies as well. Probability and optimization techniques are used to quantify and evaluate the risk and cost-effectiveness of various device deployment configurations, which are captured by using a system life-cycle cost model. Numerical analysis for all possible system arrangements is demonstrated.

Keywords

Aviation security risk analysis; Passenger prescreening; Checked baggage screening; Selective screening; System life-cycle cost; Threshold values

1. Introduction

The terrorist attacks on September 11, 2001 prompted significant policy and operational changes in aviation security systems. One of the important changes is involved in the passenger and baggage screening processes prior to boarding an aircraft. Different screening approaches implemented for passenger and baggage screening procedures can be classified into two basic approaches: uniform screening and selective screening (McLay et al., 2007). 100% uniform screening is mandated by current law in accordance with the requirements specified in the Aviation and Transportation Security Act of 2001 (ATSA), in which every passenger and their corresponding baggage are subject to identical screening procedures. Transportation Security Administration (TSA) is required to perform 100% screening on checked baggage at all commercial airports using Explosive Detection Systems (EDS), Explosive Trace Detection Systems (ETD) or alternative technologies (effective as of December 31, 2002) (TSA, 2006; GAO, 2006; Butler and Poole, 2002).

Different from uniform screening, selective screening classifies passengers into different subsets that are screened by separate screening regulations or procedures, which was implemented at the nation's commercial airports prior to the 100% screening mandate. Selective screening requires a passenger prescreening system to perform a computer-derived risk assessment on the information collected for each passenger, such as the Computer-Aided Passenger Prescreening System (CAPPS) developed by Federal Aviation Administration (FAA), Northwest Airlines and the Department of Justice (Virta et al., 2003). The checked baggage of selectee passengers (i.e., those who are not cleared by CAPPS) were screened by EDS systems, and those of non-selectee passengers received no further security attentions (Nikolaev et al., 2007).

Uniform screening used for the 100% checked-baggage screening eliminates the distinction between selectee and non-selectee passengers, due to the assumption that every passenger can pose a risk. However, recent research suggests that the 100% checked-baggage screening is not cost-effective (Butler and Poole, 2002). The screening technologies deployed for 100% baggage screening have caused significant economic and operational concerns, such as the prohibitory costs, low processing rates, and high error rates of the EDS and ETD technologies (Butler and Poole, 2002). TSA is encouraged to improve the design of the baggage screening system and consider new technologies that may offer the opportunity for higher performance at a lower cost.

Existing literatures addressed the cost and risk analyses for both uniform and selective screening systems. McLay et al. (2007) utilized passenger prescreening information to develop screening strategies that maximize system security subject to system capability, as well as evaluating the effectiveness of passenger prescreening. Virta et al. (2003) presented a cost model including false alarm and false clear costs to assess the trade-off between screening only selectee baggage and screening both selectee and non-selectee baggage for a single EDS machine. For various security configurations involving EDS, ETD, X-ray and Backscatter (BX) machines for both single-device and two-device systems, Jacobson et al. (2006) used the expected direct cost to study the cost and benefit for 100% screening. Kobza and Jacobson (1997) and Jacobson et al. (2001) studied assessed risk and cost-effectiveness of aviation security systems by considering the false alarm and false clear rates as performance measures for single-device and multiple-device systems. Candalino et al. (2004) determined the best selection of technology and optimal number of baggage screening security devices that minimize the expected total cost of the 100% 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 of 100% baggage screening, the concern of setting threshold values for continuous security responses were addressed in Feng (2007) and Feng and Sahin (2007) for both single-level screening systems as well as two-level screening systems. A comprehensive system life-cycle cost function was introduced that includes costs associated not only with the purchasing and operating the baggage screening security devices, but also with system decisions, namely false alarm and false clear.

An integrated model for both passenger prescreening and baggage screening is not available in the literature. Previous study investigated strategies for either checked-baggage screening (Feng, 2007; Feng and Sahin, 2007) or passenger prescreening (McLay et al*.,* 2007). Although Virta et al. (2003) and Jacobson et al. (2006) analyzed cost-benefit of screening selectee and non-selectee baggage whose volumes are predetermined for the airport under study, the procedure for classifying passengers was not studied. In light of the advantage of implementing selective screening and the mandatory requirement of 100% baggage screening, this paper extends previous work by developing an integrated strategy for *screening passengers and checked-baggage sequentially* in a selective screening setting. With appropriate data, the work in this paper can provide insights into the design of aviation security passenger and baggage screening systems. The specific objectives of this paper are twofold:

a) To utilize the distinctive procedures in selective screening while satisfying the 100% checked-baggage screening requirement as mandated by the federal law, we propose a *100% selective screening* system that classifies passengers and their checked baggage into two subsets (selectee and non-selectee), and then assigns them to two different screening procedures in a multiple-level screening system. In other words, the 100% checked-baggage screening is ensured through distinctive screening procedures implemented for selectee and non-selectee passengers, rather than leaving non-selectee passengers without further security screening as practiced in the CAPPS.

b) To determine the optimal combination of screening devices that minimizes system false clear level subject to budget constraint, we develop a probability utility function to represent *system life-cycle cost* that associates with direct and indirect costs. The threshold value of prescreening system to classify passengers (as selectee or non-selectee) and the threshold values of screening devices to classify baggage (as threat or non-threat) are determined as well. The influences of human reliability are also incorporated to the deployment strategies, since it affects both the system life-cycle cost and the system false alarm and false clear rates (Feng et al., 2009).

The paper is organized as follows. In Section 2, the multiple-level screening with passenger prescreening architecture is introduced. Section 3 presents the principles underlying the problem formulation and the optimization model. In Section 4, numerical analysis of the optimization model is studied and sensitivity analysis is presented. Section 5 concludes the paper providing additional discussions.

2. 100% Selective Screening System Architecture

The proposed *100% selective screening* strategy consists of two key components: *passenger prescreening* and *checked-baggage screening*. The passenger prescreening information is collected and analyzed to determine checked-baggage assignments to two different screening procedures, which are designed using two different system decision rules for *controlled sampling* (Candalino et al., 2004; Kobza and Jacobson, 1996). The advantage of implementing selective screening is that costly but more reliable technologies can be used for screening the high-risk group. Based on the risk assessment and the perceived risk level of passengers, different screening strategies can be developed and implemented that can target potential threats more effectively. In this way, the prohibitive cost can be avoided to screening low-risk passengers with sensitive and expensive technologies and procedures (McLay et al., 2007). Therefore, the cost-effectiveness and the overall security level of baggage screening systems can be enhanced.

Selective screening strategy requires the risk assessment of each passenger to be performed prior to baggage screening. The passenger prescreening system, such as CAPPS, processes computer-derived conclusions about an individual and then provides a numerical risk estimate (McLay et al., 2007). Color-coded threat levels are then utilized to classify passengers into three groups: red, yellow, and green (Barnett, 2004). A *no-fly list* is made up of passengers who pose such high levels of risk that they are not allowed to fly (red-scored). As an extremely small number of passengers are red-scored, we assume that the effect of this small fraction on the system can be ignored. The remaining passengers are classified as either high risk, *selectees* (yellow-scored), or low risk, *non-selectees* (green-scored). Each of these classes is subject to be screened by a pre-assigned screening procedure, where selectees would get the higher level of scrutiny in terms of applied system decision rules.

100% screening on checked baggage is usually performed by deploying one or two levels of screening devices (Jacobson et al., 2006; Kobza and Jacobson, 1996). Two-level screening is implemented in a sequential manner to further improve the accuracy of screening procedures. Previous studies show that two-level screening systems outperform one-level screening systems in terms of security levels, measurement errors, and total system costs (Jacobson et al., 2006;

Feng, 2007; Feng and Sahin, 2007). In this paper, we assume that a two-level baggage screening system is implemented after the initial classification of passengers. To address the concerns about operational efficiency and security level provided by the currently used ETD and EDS technologies, TSA is prompted to consider alternative screening technologies that utilize automated X-ray imaging include Backscatter X-ray (BX), Coherent Scattering (CS), Dual-energy X-ray (DX), and Multiview Tomography (MVT). This paper studies the deployment of two-level baggage screening strategies that deploy one or a combination of the following image-based screening technologies: EDS, BX, DX, and MVT. At each level of baggage screening, only one type of device is deployed, where the number of devices at each level is determined by the device capacity and the volume of bags to be screened.

2.1. Decision Rules for Selectee and Non-Selectee

In a two-level screening system, system decisions must be distinguished from the decisions at each level. All bags are inspected at Level 1, and then *controlled sampling* is used to determine the bags to be inspected at Level 2. In controlled sampling, the decision whether or not to inspect an item at Level 2 may depend on two decision rules, where a system alarm can be defined in two ways (Jacobson et al., 2006; Kobza and Jacobson, 1996, 1997):

- Rule 1: A system alarm is triggered when both devices signal alarms on an item;
- Rule 2: A system alarm is triggered when any one of the two devices signals an alarm on an item.

Rule 1 is currently used for the 100% baggage screening at most U.S. airports (Jacobson et al., 2006). Using this rule, two levels of screening check each other, and therefore, the system false alarm (a non-threat item does not gain access) probability can be reduced to the detriment of the false clear (a threat item passes through undetected) probability. Using Rule 2, any individual alarm in the system triggers the system alarm, and therefore, the system false clear probability decreases indicating the enhanced security level, although the system false alarm probability increases. Previous research involving multi-level screening studied and compared the system performance using Rule 1 and Rule 2 (Jacobson et al., 2006; Feng, 2007; Kobza and Jacobson, 1997).

In this paper, the sequential passenger and baggage screening system is proposed to integrate both rules in the multi-level screening, that is, to apply Rule 1 to non-selectee passengers' baggage and Rule 2 to selectee passengers' baggage after the initial passenger classification. The motivation is to apply tighter screening procedures guarded by Rule 2 (with the lower false clear rate and the higher false alarm rate) to high-risk passengers, and vice versa. For non-selectee passengers' baggage, rather than allowing them to pass without further security screening as practiced in the CAPPS, screening procedures designed based on Rule 1 (with the lower false alarm rate and the higher false clear rate) are implemented for low-risk passengers.

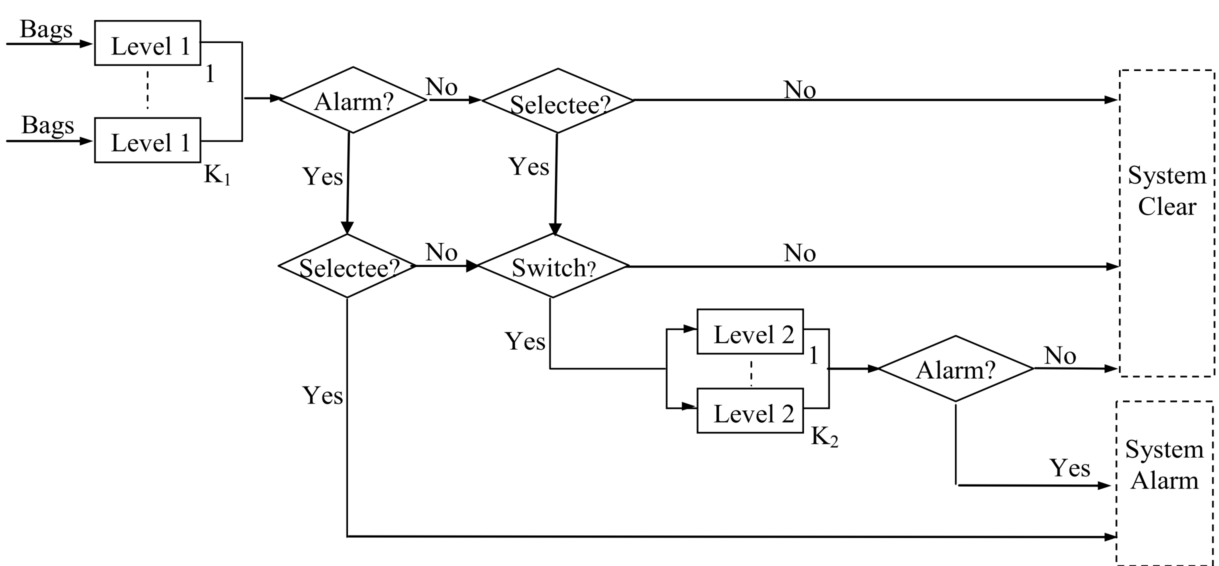

Figure 1: Two-level screening system with passenger prescreening

The implementation procedures are described as follows and shown in Figure 1.

1) Each passenger is assessed by the passenger prescreening system and classified as either *selectees* or *non-selectees* based on a numerical risk estimate.
2) All bags are screened at Level 1, regardless of *selectees* or *non-selectees.*
3) Whether or not a bag is screened at Level 2 is determined based on the passenger's risk group and the result from Level 1 screening:
   - For non-selectee passengers' baggage (Rule 1 applied), only the bags that do trigger an alarm at Level 1 are screened at Level 2, that is, an item not signaling an alarm at Level 1 does not need to be screened at Level 2 and therefore cleared by the system. To trigger the system alarm, a non-selectee passengers' bag should give an alarm at both levels.
   - For selectee passengers' baggage (Rule 2 applied), only the bags that do not trigger an alarm at Level 1 are to be switched for further inspection at Level 2. It means that an item triggering an alarm at Level 1 triggers a system alarm and does not need to be screened at Level 2. A system alarm is triggered when any one of the two levels signals alarm on a selectee passengers' baggage.

2.2. Switching Probability

In a multi-level screening system, an item needs to be transferred by an operator to the subsequent screening device. However, human performance may degrade due to fatigue and decreased vigilance of the operator, which directly influences system availability and accuracy, as well as the performance in terms of system decisions and the overall life-cycle cost. Existing research on evaluating baggage screening systems appears to concentrate exclusively on system capability, without considering system reliability issues associated with both equipment and human (operators) that influence the system performance in significant ways.

This paper incorporates the effects of the human reliability on the system performance that is reflected in a form of the switching probability, P_S, defined as the probability that an item can be successfully switched. The effects of the switching probability on the system performance are shown in Figure 1. For both selectee and non-selectee passengers' baggage, if the items to be screened at Level 2 fail to be conveyed due to switching failure, they will be classified as cleared items by the system.

3. Model Formulation

3.1. Continuous Security Responses and Passenger Risk Estimates

Image-based screening technologies generally provide continuous security responses on screened items, such as the matching ratio between the image of a screened item and of a pre-defined threat item. 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 (Jacobson et al., 2001). Other values of continuous responses can be rescaled such that $0 \le X \le 1$ (Feng, 2007; Feng and Sahin, 2007). To classify threat items from non-threat ones, a screening threshold level must be determined for the continuous security response, which requires the conditional probability density functions of X given a threat or a non-threat item. 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 of X given a threat item and a non-threat item, respectively. Generally, $f_{X|Z=1}(x)$ exhibits a non-decreasing shape and $f_{X|Z=0}(x)$ shows a non-increasing shape for $0 \leq X \leq 1$. 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 (Jacobson et al., 2001). In this paper, a family of beta distributions is used to model the security responses for each technology, as it can express the versatility of conditional probability density functions of X (Martz, 1982). Beta density function with parameters ρ and τ, *Beta* (ρ, τ), is given by

$$f(x \mid \rho, \tau) = \frac{\Gamma(\rho+\tau)}{\Gamma(\rho)\Gamma(\tau)} x^{\rho-1}(1-x)^{\tau-1}, \quad \textit{for} \quad 0 \leq x \leq 1, \ \rho > 0, \ \tau > 0, \tag{1}$$

where $\Gamma(.)$ is the gamma function. The parameters of beta distribution for each technology can be estimated in various ways based upon sampling data, such as the method of moments illustrated in Guenther (1971).

A passenger risk estimate is defined as the security information from a prescreening system about the assessed passenger. Let R indicate the continuous risk estimates from the passenger prescreening system, and R takes values in [0, 1] where a value close to 1 indicates a passenger with high-risk level whose baggage may contain threat items. The conditional probability density function of R given a passenger whose baggage indeed contains a threat item (Z =1), $f_{R \mid Z=1}(x)$, generally shows an increasing shape, and vice versa. Both conditional probability density functions can be estimated by triangular distributions as (Simms, 1997)

$$\begin{aligned} f_{R \mid Z=0}(r) &= 2(1-r) \\ f_{R \mid Z=1}(r) &= 2r. \end{aligned} \tag{2}$$

Based on the continuous risk estimates from the passenger prescreening system, the passengers are classified as selectee and non-selectee passengers using the threshold value, k. If the assessed risk estimate is greater than the threshold value ($R > k$), the passenger is classified as a selectee; otherwise he/she is classified as a non-selectee.

3.2. Two Types of Errors

Like in any other inspection processes, two types of errors may occur in an airport security screening system. The system can experience either a *false alarm* when an item, that does not pose a risk, is not allowed to gain access, or a *false clear* when a non-threat item passes through undetected. False alarms lead to additional security procedures, which ultimately affect the cost-effectiveness of the system, whereas false clears have catastrophic social and economic consequences, and therefore, the ideal false clear rate should be very close to zero. The probabilities of false alarm and false clear depend on both the sensitivity of security devices and the proportion of objects that contain a threat. The sensitivity of a device is controllable through the setting of threshold values on security responses, which affects the false alarm and false clear probabilities to a large extend. The formulations of system false alarm and false clear probabilities are introduced as follows.

System False Alarm Probability

The probability of system false alarm is composed of two parts: false alarm probability of screening selectee baggage (using Rule 2) and false alarm probability of screening non-selectee baggage (using Rule 1). The probability of false alarm for screening selectee baggage, α_s, is given as

$$\begin{aligned}\alpha_S &= \mathrm{P}\left(\text{system alarm when inspecting by Rule 2} \mid \text{selectee, non-threat}\right)\\ &= \mathrm{P}\left(\text{L1 alarm}\mid\text{non-threat}\right)\ \mathrm{P}\left(\text{selectee}\mid\text{non-threat}\right)\\ &\quad + \mathrm{P}\left(\text{L1 no alarm} \cap \text{switch works} \cap \text{L2 alarm}\mid\text{non-threat}\right)\mathrm{P}\left(\text{selectee}\mid\text{non-threat}\right),\end{aligned}$$

where L1 and L2 indicate Level 1 and Level 2 baggage screening, respectively. Similarly, the probability of false alarm for screening non-selectee baggage is given by

$$\begin{aligned}\alpha_{NS} &= \mathrm{P}\left(\text{system alarm when inspecting by Rule 1} \mid \text{non-selectee, non-threat}\right)\\ &= \mathrm{P}\left(\text{L1 alarm} \cap \text{switch works} \cap \text{L2 alarm} \mid \text{non-threat}\right)\ \mathrm{P}\left(\text{non-selectee} \mid \text{non-threat}\right).\end{aligned}$$

The classification of selectee and non-selectee passengers is based on the threshold value on the continuous risk estimate from the passenger prescreening system. If the value of a risk estimate is greater than the threshold value ($R > k$), the passenger will be sorted as selectee. Similarly, the classification of baggage as an alarm or a clear is based on the threshold values on the continuous security responses from two devices, denoted by $\mathbf{u} = (u_1, u_2)^T$. If the value of a security response from the i^{th} level screening is greater than the threshold ($X_i > u_i$, for i = 1, 2), the i^{th} level signals an alarm. The risk estimates from passenger prescreening and security responses from two levels of devices on the same item are assumed to be independent. Hence, the probabilities of false alarm for screening selectee baggage and non-selectee baggage can be calculated respectively as

$$\alpha_S(\mathbf{u},k) = \left(\int_{x_1 > u_1} f_{X_1|Z=0}(x_1)dx_1 + P_S \int_{x_2 > u_2} \int_{x_1 \le u_1} f_{X_1|Z=0}(x_1) f_{X_2|Z=0}(x_2) dx_1\, dx_2 \right) \int_{r > k} f_{R|Z=0}(r)dr, \quad (3)$$

$$\alpha_{NS}(\mathbf{u},k) = \left(P_S \int_{x_2 > u_2} \int_{x_1 > u_1} f_{X_1|Z=0}(x_1) f_{X_2|Z=0}(x_2) dx_1\, dx_2 \right) \int_{r \le k} f_{R|Z=0}(r)dr. \quad (4)$$

By combining Equations (3) and (4), the probability of system false alarm is obtained as

$$\begin{aligned}\alpha(\mathbf{u},k) = &\left(\int_{x_1 > u_1} f_{X_1|Z=0}(x_1)dx_1 + P_S \int_{x_2 > u_2} \int_{x_1 \le u_1} f_{X_1|Z=0}(x_1) f_{X_2|Z=0}(x_2) dx_1\, dx_2 \right) \int_{r > k} f_{R|Z=0}(r)dr \\ &+ \left(P_S \int_{x_2 > u_2} \int_{x_1 > u_1} f_{X_1|Z=0}(x_1) f_{X_2|Z=0}(x_2) dx_1\, dx_2 \right) \int_{r \le k} f_{R|Z=0}(r)dr.\end{aligned} \quad (5)$$

System False Clear Probability

The probability of system false clear can be calculated as 1- P (true alarm). In the similar manner as for system false alarm, the formulation of true alarm probability can be divided into two components. The probability of true alarm for screening selectee bags, $P_{TA,S}$, is given by

$$\begin{aligned} P_{TA,S} &= \mathrm{P}\left(\text{system alarm when inspecting by Rule 2} \mid \text{selectee, threat}\right) \\ &= \mathrm{P}\left(\text{L1 alarm} \mid \text{threat}\right)\ \mathrm{P}\left(\text{selectee} \mid \text{threat}\right) \\ &\quad + \mathrm{P}\left(\text{L1 no alarm} \cap \text{switch works} \cap \text{L2 alarm} \mid \text{threat}\right)\ \mathrm{P}\left(\text{selectee} \mid \text{threat}\right). \end{aligned}$$

The probability of true alarm for screening non-selectee bags, $P_{TA,NS}$, is calculated as

$$\begin{aligned} P_{TA,NS} &= \mathrm{P}\left(\text{alarm when inspecting by Rule 1} \mid \text{non-selectee, threat}\right) \\ &= \mathrm{P}\left(\text{L1 alarm} \cap \text{switch works} \cap \text{L2 alarm} \mid \text{threat}\right)\ \mathrm{P}\left(\text{non-selectee} \mid \text{threat}\right). \end{aligned}$$

Then the above formulations are derived as

$$P_{TA,S} = \left(\int_{x_1 > u_1} f_{X_1|Z=1}(x_1)\, dx_1 + P_S \int_{x_2 > u_2} \int_{x_1 \le u_1} f_{X_1|Z=1}(x_1)\, f_{X_2|Z=1}(x_2)\, dx_1\, dx_2 \right) \int_{r > k} f_{R|Z=1}(r)\, dr\,, \quad (6)$$

$$P_{TA,NS} = \left(P_S \int_{x_2 > u_2} \int_{x_1 > u_1} f_{X_1|Z=1}(x_1)\, f_{X_2|Z=1}(x_2)\, dx_1\, dx_2 \right) \int_{r \le k} f_{R|Z=1}(r)\, dr\,. \quad (7)$$

Finally, the system false clear probability, $\beta(\boldsymbol{u},k)$, can be obtained by combining Equations (6) and (7) as

$$\begin{aligned} \beta(\boldsymbol{u},k) &= 1 - \left(P_{TA,S} + P_{TA,NS}\right) \\ &= 1 - \left(P_S \int_{x_2 > u_2} \int_{x_1 > u_1} f_{X_1|Z=1}(x_1)\, f_{X_2|Z=1}(x_2)\, dx_1\, dx_2 \right) \int_{r \le k} f_{R|Z=1}(r)\, dr \qquad (8) \\ &\quad - \left(\int_{x_1 > u_1} f_{X_1|Z=1}(x_1)\, dx_1 + P_S \int_{x_2 > u_2} \int_{x_1 \le u_1} f_{X_1|Z=1}(x_1)\, f_{X_2|Z=1}(x_2)\, dx_1\, dx_2 \right) \int_{r > k} f_{R|Z=1}(r)\, dr\,. \end{aligned}$$

3.3. Life-Cycle Cost Model and System Optimization

The screening technologies assessed in the model are significantly differentiated by initial investment costs, operating costs, processing rates, and both false alarm and false clear rates. Therefore, multiple factors should be considered when determining the optimal combination strategy of devices. In this paper, *System life-cycle cost*, instead of *system annual cost* as presented in Virta et al. (2003), is developed to combine all these important factors, which provides a long-term assessment of the cost-effectiveness of a system (Feng et al., 2009). The system life-cycle cost analysis is particularly suitable for the evaluation of alternatives that satisfy a required level of performance but may have different initial investment costs, operating costs, maintenance costs, and possibly different usage lives (Fuller and Peterson, 1995). In addition, this life-cycle cost model captures more cost factors than the cost model given in Virta et al. (2003), such as the passenger prescreening cost and the switching cost that will be described in detail later. Prior to the analysis of the system life-cycle cost, system capability parameters are described as they are required for the formulation of the cost model.

System Capability

The number of machines required at each baggage screening level is determined by the estimated number of items to be screened and the processing rate of the technology to be deployed at that particular level. Note that only one type of technology is designed for each level. Let N_i denote the number of items to be screened at i^{th} level annually at an airport, and N_C represents the annual processing capacity of each type of technology. Then, the number of the devices required at i^{th} level, K_i, can be calculated as $K_i = \lceil N_i / N_C \rceil$. Since all checked baggage, both selectee and non-selectee, is subject to inspection at Level 1, N_1 takes the value of the maximum volume of checked baggage each year, denoted by N. However, N_2 depends on the parameters of controlled sampling that differentiates between selectee and non-selectee bags.

The probability of a passenger is classified as non-selectee, and therefore, the corresponding baggage is screened by Rule 1, is:

$$P_{NSEL} = P_T \int_{r \le k} f_{R\,|\,Z=1}(r)\,dr + (1-P_T) \int_{r \le k} f_{R\,|\,Z=0}(r)\,dr, \tag{9}$$

where P_T is the probability that a bag contains a threat item. For non-selectee baggage as shown in Figure 1, only bags triggering an alarm at Level 1 are to be screened at Level 2 by applying Rule 1. Let P_{A1} be the alarm probability from Level 1. Then,

$$\begin{aligned} P_{A1} &= P(X_1 > u_1 \mid Z = 0)\,P(Z = 0) + P(X_1 > u_1 \mid Z = 1)\,P(Z = 1) \\ &= (1 - P_T) \int_{x_1 > u_1} f_{X_1|Z=0}(x)\,dx + P_T \int_{x_1 > u_1} f_{X_1|\,Z=1}(x)\,dx\,. \end{aligned} \tag{10}$$

Consider the switching probability, P_S, the number of non-selectee bags to be screened at Level 2 is given by

$$N_{2NSEL} = P_{NSEL}\,N\,P_{A1}\,P_S\,. \tag{11}$$

The probability of a passenger is classified as selectee, and therefore, the corresponding baggage is screened by Rule 2, is:

$$P_{SEL} = P_T \int_{r>k} f_{R\,|\,Z=1}(r)\,dr + (1-P_T) \int_{r>k} f_{R|\,Z=0}(r)\,dr. \tag{12}$$

Let P_{NA1} denote the probability that a bag does not trigger an alarm at Level 1, and

$$\begin{aligned} P_{NA1} &= P(X_1 < u_1 | Z = 0)\,P(Z = 0) + P(X_1 < u_1 \mid Z = 1)\,P(Z = 1) \\ &= (1 - P_T) \int_{x_1 \le u_1} f_{X_1|Z=0}(x)\,dx + P_T \int_{x_1 \le u_1} f_{X|\,Z=1}(x)\,dx. \end{aligned} \tag{13}$$

For selectee baggage, only bags not triggering an alarm at Level 1 are to be screened at Level 2 by applying Rule 2. Then, the number of selectee bags to be screened at Level 2 can be calculated as

$$N_{2SEL} = P_{SEL} N P_{NA1} P_S. \tag{14}$$

As shown in Figure 1, the total number of bags to be screened at Level 2 is obtained by combining Equations (11) and (14) as

$$N_2 = \left(P_{NSEL} P_{A1} + P_{SEL} P_{NA1}\right) N P_S. \tag{15}$$

Life-Cycle Cost Analysis

A system life-cycle cost model is developed to capture four major cost components in the passenger and checked-baggage screening system: the passenger prescreening system cost, deployment cost of screening devices, operating cost of screening devices, and costs associated with system decisions. Passenger prescreening requires the deployment and operation of computing resources to perform risk assessment on the information collected for each passenger. The cost of passenger prescreening system is assumed to be deterministic per passenger screened, denoted as C_{PS} (Barnett et al., 2001). If we assume that each passenger has one checked baggage on average, then the annual passenger volume equals to the annual volume of checked baggage (N), and the passenger prescreening cost can be calculated as $C_{PS} N$.

The *deployment cost* of security devices includes both the initial purchasing cost and the maintenance cost such as periodical maintenance to prevent machine breakdowns. The values of both the purchasing cost per unit C_D and the annual maintenance cost C_M are assumed to be deterministic that can be obtained from manufacturers.

The *operating cost* of screening devices consists of inspection cost and switching cost. The inspection cost per bag, denoted as C_I, is the cost of screening each bag with the aid of security personnel, and the value is assumed to be deterministic that can be estimated based on the labor cost and cost of regular equipment operation such as power consumption. The switching cost is defined as the additional cost of transmitting bags to the subsequent screening device when needed, and the switching cost per bag is denoted as C_S.

System decision costs of screening systems arise from different system decisions. *False alarms* lead to additional procedures, which cause inconvenience to passengers and increased costs. Efforts need to be carried out to clear a *true alarm* as well. Such steps can range from having the bag re-inspected to the evacuation of all or a portion of a terminal. A *false clear* occurs when a threat item is actually present but the system fails to detect it. This can result in destructive economic and social consequences. A *true clear* incurs the least cost, since it requires only regular inspection due to volume processing. Costs associated with system decisions are stochastic depending on the random nature of the events, but the expected values per occurrence can be obtained based on prior information on airport operations.

In most situations, false clears result in catastrophic social and economical consequences, which make the cost of false clear intangible. Although a large number can be assigned to false clear cost, it is quite challenging to specify a specific value. Hence, the tangible or direct system decision cost is considered in the system life-cycle cost, which does not include the false clear cost. Therefore, the expected direct system decision cost as a function of the threshold values on the security responses and risk estimates, $ESDC(\mathbf{u},k)$, can be expressed as

$$ESDC(\mathbf{u},k) = C_\alpha \alpha(\mathbf{u},k)(1-P_T)N + C_{TC}(1-\alpha(\mathbf{u},k))(1-P_T)N + C_{TA}(1-\beta(\mathbf{u},k))P_T N, \qquad (16)$$

where C_α is the cost of a false alarm, C_{TC} is the cost of a true clear, and C_{TA} is the cost of a true alarm. The calculation for $\alpha(\mathbf{u},k)$ and $\beta(\mathbf{u},k)$ can be found in Equations (5) and (8).

Time parameters in the system life cycle need to be specified for the system life-cycle cost model. A machine may be replaced every T_1 years due to regulation and maintenance policies, or wear out due to mechanical erosion in T_2 years. T_1 is assumed to be deterministic, whereas T_2 is the expected lifetime of a device, which is available to be gathered from manufacturers. Therefore, the life-cycle service time of a device is determined by $\min(T_1, T_2)$. Let T_{1i} and T_{2i} be the number of years until the replacement and the expected life time at the i^{th} level, respectively. The life-cycle service time of the two-level screening system is determined by $\min_{i=1,2}(T_{1i}, T_{2i})$.

By combining four major cost components, i.e., (i) the passenger prescreening cost (C_{PS}), (ii) the device-related costs including the purchasing cost per unit (C_{Di}) and maintenance cost per year (C_{Mi}), (iii) the operating costs including the inspection cost per bag (C_{Ii}) and the switching cost (C_S), and (iv) the expected direct system decision cost given in Equation (16), the expected system life-cycle cost of the security screening system, $ELCC(\mathbf{u},k)$, is then formulated as:

$$ELCC(\boldsymbol{u},k) = \sum_{i=1}^{2} K_i C_{Di} + \left(\sum_{i=1}^{2} K_i C_{Mi} + \sum_{i=1}^{2} C_{Ii} N_i + C_{PS} N + C_S N_2 + ESDC(\boldsymbol{u},k) \right) \min_{i=1,2} \left(T_{1i}, T_{2i} \right), \quad (17)$$

where $\boldsymbol{u}$ and k are the thresholds of security responses and risk estimates, respectively.

Optimization Model

The deployment of a baggage screening system is usually constrained by the budget provided to an airport. To maximize security level, the probability of wrongly accepting a threat item (i.e., false clear probability) should be minimized under the budget constraint, which is developed as:

$$\min_{\boldsymbol{u},k} \beta(\boldsymbol{u},k) \tag{18}$$

$$\text{subject to } ELCC(\boldsymbol{u},k) \le B_0,$$

where B_0 is the maximum available budget set by federal agencies for an airport, and the decision variables are $\boldsymbol{u}$ and k. This constrained nonlinear problem can be solved by implementing a Sequential Quadratic Programming (SQP) method provided by a MATLAB function *fmincon*.

4. Numerical Analysis

The false clear probability optimization model given in (18) is analyzed for all arrangements of two-level screening using image-based technologies: Explosive Detection Systems (EDS), Backscatter X-ray (BX), Dual-energy X-ray (DX), and Multiview Tomography (MVT). The data required in (18) are classified into two categories as system parameters and device parameters. The expected values of system parameters and device parameters are provided in Table 1 and Table 2, respectively.

Data reported in the tables are representative and obtained from Virta et al. (2003), Jacobson et al. (2006), and Barnett (2001), and the exact values can be secured from manufacturers and TSA. The parameters of beta distributions for various devices provided in Table 2 are chosen to reflect the relative accuracy levels of four technologies. EDS is assumed to have the highest accuracy among these technologies, followed by MVT, BX, and DX, respectively (Feng, 2007; Feng and Sahin, 2007; Feng et al., 2009). For instance, the conditional probability distribution for MVT given a threat item is defined as $X \mid Z = 1 \sim Beta\ (6,1)$. The shapes of beta distributions were shown in Feng (2007), Feng and Sahin (2007), and Feng et al. (2009). The exact values of parameters in applications can be obtained by statistical estimation based on sampling data.

Table 1. System Parameters

System parameters	**Expected values**
N	2,625,000
C_α	\$9.16/event
C_{TC}	\$0/event
C_{TA}	\$1,000,000/event
C_S	\$0.01/bag
C_{PS}	\$0.20/passenger
P_T	1.00×10^{-9}
P_S	0.995
B_0	\$40,000,000

Table 2. Device Parameters

Device Parameters	**EDS**	**BX**	**DX**	**MVT**
ρ $(Z=0)$	1	1	1	1
τ $(Z=0)$	7	5	4	6
ρ $(Z=1)$	7	5	4	6
τ $(Z=1)$	1	1	1	1
C_D	\$800,000/unit	\$333,333/unit	\$500,000/unit	\$1,000,000/unit
C_M	\$125,000/year	\$41,667/year	\$62,500/year	\$80,000/year
C_I	\$0.19/bag	\$0.09/bag	\$0.03/bag	\$0.12/bag
T_1	10 years	10 years	10 years	10 years
T_2	10 years	10 years	10 years	10 years
Nc^*	394,200	547,500	3,285,000	3,285,000
Processing Rate	180 bags/h	250 bags/h	1500 bags/h	1500 bags/h

* The annual processing capacity (N_C) is calculated based on the processing rate of each technology.

For the two-level baggage screening system with passenger prescreening, the optimization model in (18) is solved for all sixteen possible device arrangements using the four technologies. The optimal threshold values on security responses ($\boldsymbol{u}^*$) and risk estimates (k^*) are determined to identify the screening strategies that minimize the false clear probability (β^*) with constrained budget. The optimal values of false alarm and false clear probabilities are presented in Figure 2. The 16 arrangements can be classified into four groups according to the technology used at Level 1: EDS group, BX group, DX group, and MVT group. With the same amount of budget ($40 million), EDS group shows lower probabilities in both false clear and false alarm compared to the other groups. The overall high performance of EDS group in enhancing security is mainly due to the high accuracy level of this technology.

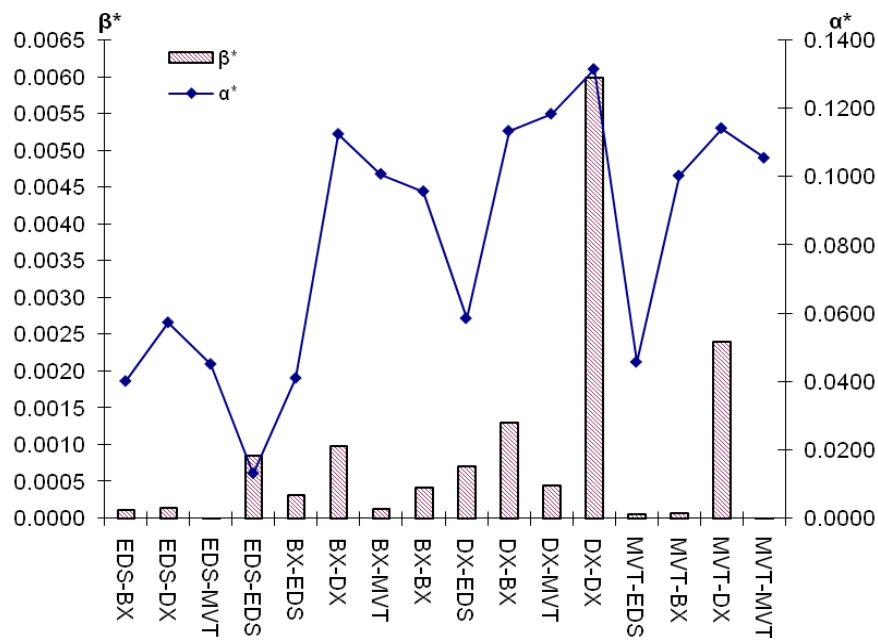

Figure 2: Optimal values of two types of errors

As shown in Figure 2, the optimal device configuration that minimizes the false clear probability under the budget constraint is MVT-MVT (2.13×10^{-5}), which is slightly lower than of EDS-MVT combination (3.01×10^{-5}). When using MVT-MVT system, the threshold values on security responses provided by the optimal solution are 0.3479 and 0.4360. It suggests that if the continuous security response from a device (e.g., the matching ratio between an X-ray image to a known threat item) is larger than the corresponding threshold, the item will trigger an alarm at that level. The optimal threshold value on passenger risk estimates (0.0046) similarly suggests that if the perceived risk level of a passenger is higher than 0.0046, this passenger will be classified as a selectee, and the corresponding baggage will be subject to extensive screening using Rule 2.

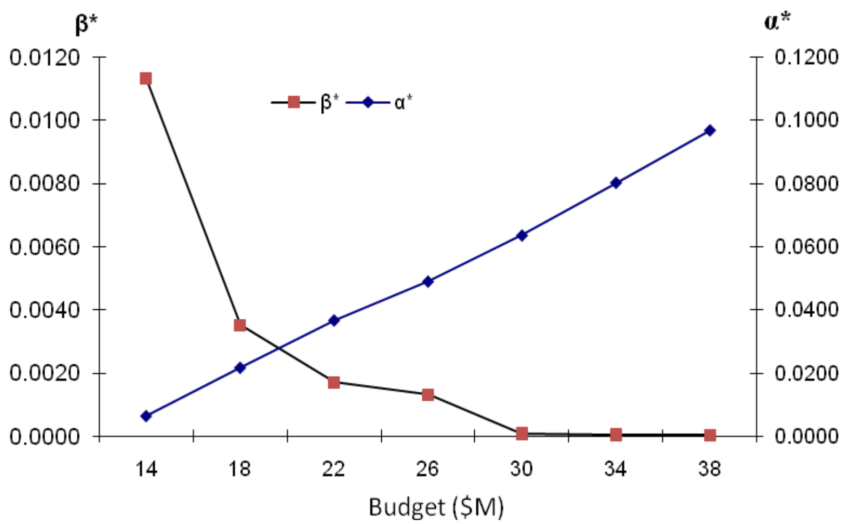

Figure 3: Sensitivity analysis of budget constraint for MVT-MVT

For the optimal device configuration (MVT-MVT), sensitivity analysis should be performed on the budget constraint to analyze the tradeoff between the security level and the expected life-cycle cost. The motivation is that the risk due to the misclassification errors can be reduced by increasing budget that allows a higher percentage of passengers to be screened using more costly but sensitive devices and/or procedures. As shown in Figure 3, increasing the available budget in millions of dollars ($M) tends to lead to lower aviation security risks in terms of false clear probabilities. It can be observed that for the budget values less than $30 million there is a considerable increase in the risk level related to the false clear probability.

5. Conclusions

To enhance security at both national and global levels, airport security screening systems must be designed with high efficiency and cost-effectiveness, which are determined by both screening technologies and operational procedures for utilizing those technologies. To address the economic and operational concerns on the uniform screening procedure that is currently mandated, we propose a selective screening procedure for screening all passengers and their checked-baggage sequentially. The proposed 100% selective screening strategy consists of two parts: passenger prescreening and two-level checked-baggage screening. The security system first classifies passengers and their checked baggage into two subsets as selectees and non-selectees, and then assigns them to two different screening procedures, which are designed using two different system decision rules. The integrated strategy for *screening passengers and checked-baggage sequentially* utilizes the distinctive procedures in selective screening while satisfying the 100% checked-baggage screening requirement as mandated by the federal law. With appropriate data, the work in this paper can provide insights into the design of aviation security passenger and baggage screening systems.

Using probability theory, statistical and optimization techniques, we assess and compare risk and cost-effectiveness of various combinations of screening technologies in a two-level screening system by incorporating passenger prescreening information. The objective is to determine the optimal device combination that minimizes system false clear level subject to budget constraint on the system life-cycle cost. By utilizing continuous risk estimates and security responses, the setting of thresholds on passenger risk estimates and system security responses are investigated as well. In addition to the current deployment of EDS and ETD machines, this paper considers the emerging image-based technologies including Dual-Energy

X-ray, Backscatter X-ray, and Multiview Tomography for serving as critical components of airport security systems. Based on the system and device information available from literature, the results suggest that for two-level screening systems with the same budget constraint, EDS group provides the lowest overall rates of errors, although MVT-MVT combination results in slightly lower false clear probability.

The model developed for two-level screening systems can be readily extended to evaluate baggage screening systems with multiple levels. Using the model for multi-level systems, the arrangement of technologies in a system can be determined by examining the trade-off between expected system life-cycle cost and false alarm/false clear probabilities.

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