The Price of Security: A Cost–Benefit Analysis of Screening of Checked Baggage

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Summary

This report examines a model constructed to optimize the number of EDS machines necessary to provide desired security at airports. Based on this model, we recommend 16 EDS systems for airport A and 18 for airport B. Furthermore, we provide a set of security objectives for the airline as well as an ideal flight-scheduling solution. We find that a three-level EDS and human inspection system is best.

However, EDS is not a permanent solution to the security screening problem; it is too inefficient for the expense incurred. In addition, we currently see little reason to incorporate ETD systems into our security proposal. The best hope for the baggage screening problems that we face today lies in future technology; neutron-based detection and quadruple resonance offer the most promising solutions.

Problem Approach

The model of the baggage screening system can be broken down into three phases:

- Check-In Phase, which consists of:
  - Arrival rate of passengers to the airport

The UMAP Journal 24 (2) (2003) 153–168.

Table 1.
Symbols used.

μ	mean arrival time of passengers before departure (min)
σ	standard deviation of normal distribution of passenger arrival to airport (min)
P_A	number of passengers that arrive in a 10 min interval at the airport (passengers/10 min)
$r(t)$	arrival rate per minute. A function of time and the normal distribution shown in Appendix B
P_T	total number of passengers to arrive in airport during peak hours
L_F	load factor (percent of plane seats that are filled)
C_p	percentage of passengers traveling on connecting flights
l	queue length at every 10-min interval
T	number of ticket agents
T_r	service rate of ticket agents (passengers/min)
ΔT	number of ticket agents to be added based on queue length
l_o	optimal passenger line length (passengers)
P_p	number of passengers processed through ticket counter
l_i	line length at beginning of 10-min interval (passengers)
B_N	number of bags added in system to be inspected every 10 min
$\max I_R$	maximum inspection rate of EDS (bags/min)
EDS	Number of EDSs in the system
EDS_r	EDS inspection rate (bags/min)
l_B	bag line length for EDS (bags)
ΔEDS	number of EDS to add to system
l_{BO}	optimal baggage line length for EDS (bags)
EDS_O	number of operational EDSs
$\max I_{RH}$	maximum inspection rate of human operated EDS (bags/min)
EDS_H	number of human operated EDS (machines)
l_{BH}	bag line length for human operated EDS (bags)
EDS_{rH}	human operated EDS inspection rate (bags/min)
ΔEDS_H	number of human operated EDS to add to system
l_{BOH}	optimal baggage line length for human operated EDS (bags)
$\max I_{R\text{Hand}}$	maximum inspection rate of hand inspectors (bags/min)
Hand	number of hand inspectors available
$l_{B\text{Hand}}$	bag line length for human inspectors (bags)
Hand_r	human inspection rate (bags/min)
$l_{BO\text{Hand}}$	optimal baggage line length for human inspectors (bags)
ΔHand	number of human inspectors to add to system

  - Passenger check in rates to ticket counters

- Baggage Inspection Phase

- Movement Phase—Movement of inspected baggage to appropriate planes

Our initial approach was to implement the model in the simulation software system Arena [Rockwell Software 2000]. However, the version of the software did not have the capacity, allowing only 100 entities in the system, instead of the 5,000 that we needed for proper testing. As a result, our second implementation model uses Microsoft Excel.

Assumptions

- The average amount of time that a passenger spends at a ticket counter is 105 to 150 ; we assume 120 s.
- The passenger arrival distribution at Las Vegas Airport is representative of airports throughout the country and in the Midwest.
- Passenger arrival is normally distributed, an assumption supported by analysis in later sections.
- Ticket counters are uniformly distributed throughout the airport, and all ticket counters work for all airlines.
- All airlines follow the same basic system: Passengers check in at a ticket counter, an agent checks bags, and the airline delivers them to the plane.
- There is no curbside check-in, which in fact is only a small part of the overall baggage checking. Also, with the advent of new security measures, curbside check-ins will have to be much more secure [Federal Aviation Administration 2001, 104], and we assume that most airlines will be unwilling to incur this additional cost.
- Passengers departing during the peak hours of flight operations are the only passengers we need to be concerned about. This is because at peak hours the maximum number of bags are checked,l hence this is the most important time to consider.
- Airports A and B are single-terminal airports. The reason for this assumption is that EDS machines must be centrally located to ensure reliability and a rapid flow rate. If the EDSs were spread out, then our model would not be valid, since there would be transportation time between the ticket counters and the EDS machines. In multiple-terminal airports, the EDS machines should be positioned centrally in each individual terminal.
- When adding a new ticket agent, EDS, or inspector to the system, the change is instantaneous; there is no warm-up period and no transit time. Although this assumption is a little unrealistic, it allows for an easier representation of the data and a smoother analysis.
- Since we are modeling two of the largest airports in the Midwest, we base any additional information needed on the Chicago O'Hare Airport, the largest airport in the region and the second largest in the world [Aviation Statistics 2002]. For example, the percentage of passengers on connecting flights (55%) is from Chicago O'Hare [Merringer 1996].
- The data given in the problem statement about the distribution of the number of bags that passengers check is accurate. We want to process every entity through the system with 30 min remaining to allow for the movement stage.

However, we recognize that this isn't possible because of extraneous factors that we don't control, such as late arrivals. Therefore, our model requires that 95% of the passengers and bags are processed before that 30-min window before departure.

- The EDS reliability rate (92%) and speed (160 to 210 bags/ min) in the problem statement are accurate.

Model Design

Check-In Phase

The key to the check-in phase is determining the distribution of passengers arriving; in other words, we need to find the rate at which passengers arrive at the airport. The second part is determining the length of the queue so that we can estimate the number of ticket agents and the time required for passengers to get through ticket lines to check their bags.

Arrival Rate of Passengers

Data from Las Vegas Airport are given in **Figures 1** and **2**.

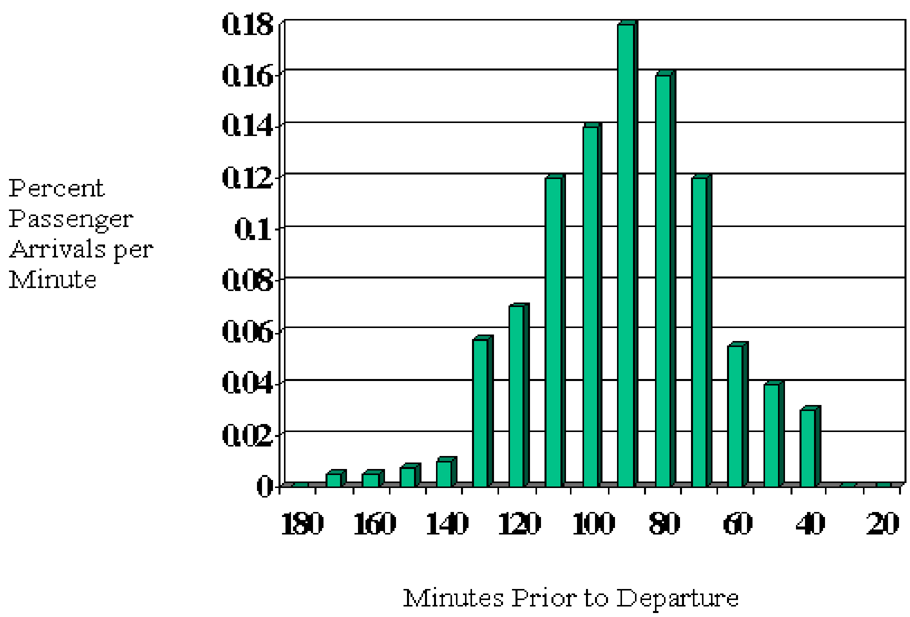

Figure 1. Las Vegas Airport passenger arrival distribution [Leaving . . . 2003].

We assume that Las Vegas Airport provides us with arrival information that is consistent with airports in the rest of the country. This passes the common-sense test, since people behave similarly throughout the country.

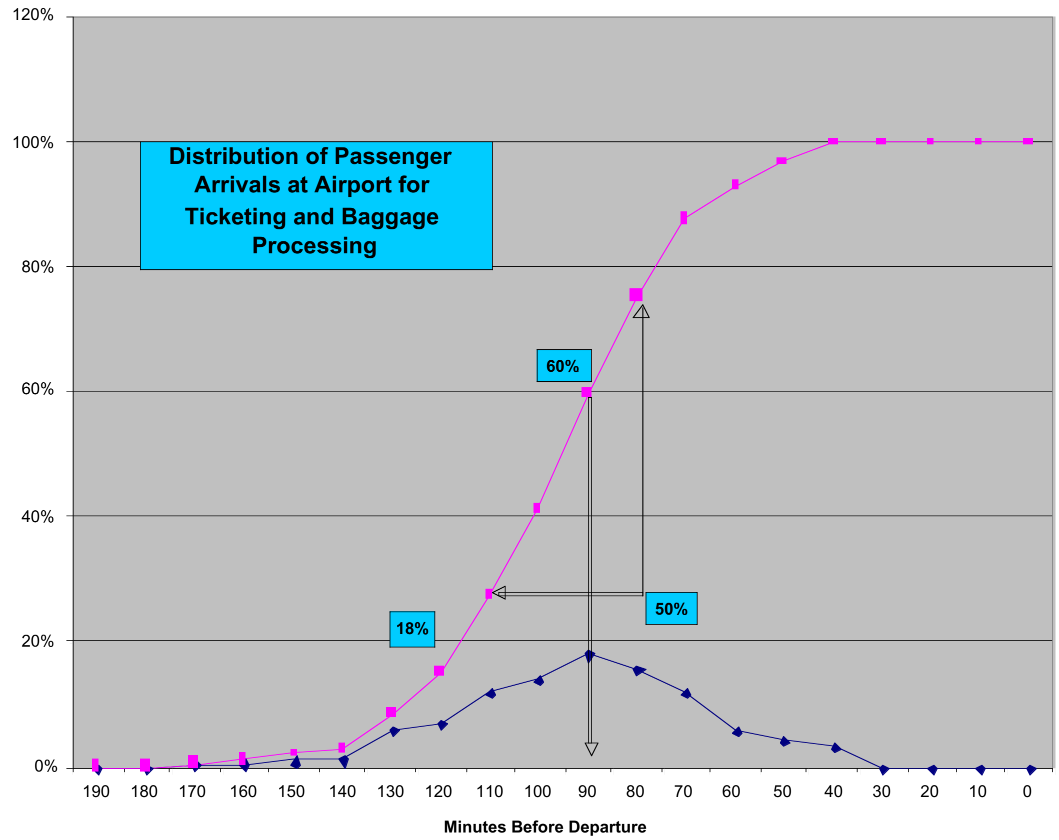

Figure 2. Las Vegas Airport passenger arrival distribution: lower curve, probability density function; upper curve, cumulative distribution function [Leaving . . . 2003].

The arrivals seem to follow a normal distribution. However, the graphs were created with discrete values, and not a function; we have the percentage of passengers that arrive every 10 min from 190 min to 0 min prior to departure. For these data, the sample mean is 91.15 min, and 50% of passengers arrive between 70 min and 100 min prior to departure. To get a continuous function, we adjust the mean and standard deviation of a normal distribution to fit the data; the simulated distribution has $\mu = 99.8$ min and $\sigma = 21.2$ min (see **Figure 3**).

Flow Rate

The second part of the check-in phase is the flow rate through the ticket counters. Using the information from the problem statement, we calculate the number of passengers arriving during peak hours by multiplying the number of seats in a flight times the number of flights with that many seats. The total over all flight types gives the total number of passengers: 5,396 passengers for airport A and 5,781 for airport B.

To determine the number of passengers who arrive in a particular 10-min interval before departure, we multiply the proportion of arrivals per minute

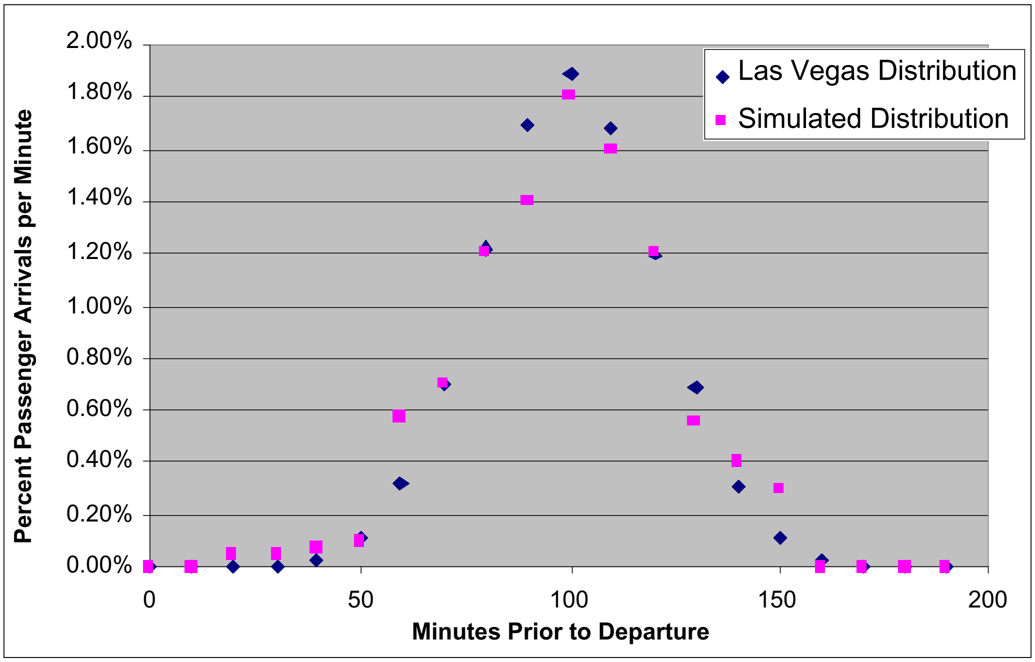

Figure 3. Hypothesized normal distribution of arrivals compared with data. Note: Labels for the distributions are reversed: The diamonds in fact are for the simulated distribution and the squares for the Las Vegas distribution. The correction could not be made by press time.

$r(t)$ (calculated from the normal distribution) by 10 min and then by the total number of passengers (P_t) who arrive at the airport. Also, we have to consider the load factor (L_F: percentage of the flight that is actually filled) and the percentage of passengers on connecting flights (C_p) who arrive but don't have to check in. The overall equation is

$$P_A = r(t) \times 10 \times P_T \times L_F \times (1 - C_P).$$

Since 55% of passengers are taking connecting flights, we have $C_P = .55$

To find the overall load factor, we divide the total number of passengers by the total number of seats available: 80.4% for airport A and 80.7% for airport B.

For airport A, the final equation for the number of passengers arriving to check in is

$$P_A = r(t) \times 5396 \times 10 \times .804 \times .45.$$

We use Excel to simulate the dynamic arrival rate, using the normal distribution calculated earlier. To determine the queue length (l) at every 10-min interval, we simply consider the number of ticket agents (T) available, multiply by the server rate (T_r) and by 10 min, and then subtract the result from the number of passengers who have checked in:

$$l = P_A - 10 \times T \times T_r.$$

We assume that the server rate is 0.5 passengers/min, or 2 min per passenger [EDS Bag Screening Analysis n.d.].

At the start of every 10-min interval, there is an initial line length, which consists of both the additional passengers that arrive and the final line length from the iteration before. In other words, in each interval, new passengers are added at the end of the line—i.e., we have first-in, first-out queueing.

A unique element in the model is that we allow for an increase in ticket agents if the queue increases. Based on the optimal line length (l_O) or on the acceptable length of the line as set by the airport, the model adds ticket agents (ΔT). The maximal acceptable length of the queue is twice the service rate in a 10-min interval, in other words, the number of passengers who can be served in 20 min. If the actual line length (l) is longer than the acceptable line length, then, based on how much longer, the model adds additional ticket agents, using the equation

$$\Delta T = (l - l_o) \times 10T_r.$$

The model also removes ticket agents when the line is under the optimal line length, since a negative ΔT is possible when $\ell < l_o$.

With these equations, the model tracks the time that it takes for all the passengers to get through the ticket counters. We find the number of passengers processed by taking the difference in the line length at the end of the interval (l_f) and the line length at the beginning of the interval (l_i). This difference is the passengers processed (P_P):

$$P_P = l_f - l_i.$$

Inspection Phase

Overall Picture

In the inspection phase, baggage is sent through the EDS machines and checked for explosive components, following the simple flowchart in **Figure 4**.

Initial EDS Inspection

The number of passengers P_p who get through the check-in and deposit their bags each 10-min interval is based on the Check-In Phase calculations. This number of passengers is then the number of passengers who have bags to check and be screened.

According to the problem statement, 20% of passengers check 0 bags, 20% check 1, and 60% check 2, for a weighted average of 1.4. The total number of bags B_N checked in a 10-min interval is

$$B_N = 1.4P_P.$$

According to the the problem statement, EDSs are operational only 92% of the time. Therefore, the number of operational EDSs (EDS_O) is

$$\text{EDS}_O = .92\text{EDS}.$$

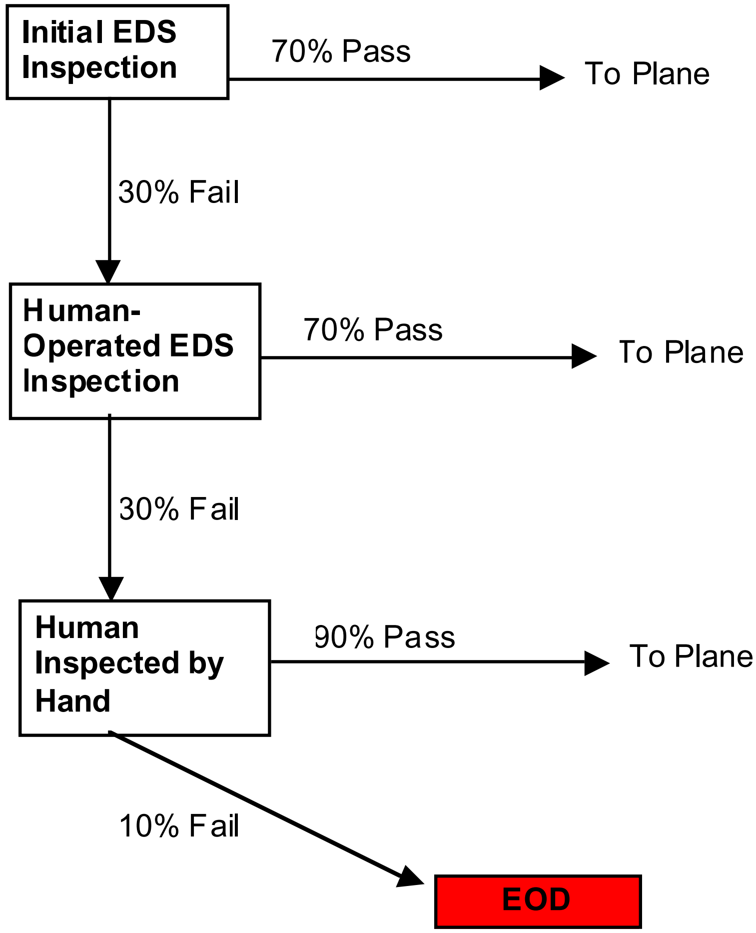

Figure 4. Flowchart of inspection stage.

The maximum number of bags that can be inspected in a 10-min interval depends on the number of EDSs in the system (EDS) and their inspection rate, which we take to be 180 bags/hour, or 3 bags/min. The maximum inspection rate is

$$\max I_R = (3\text{ bags/min}) \times \text{EDS}_O \times (10\text{ min}).$$

This model is similar to that of the ticket agent and the passenger. Using the same techniques and only mildly changing the equations, we find the number of bags that are checked in each interval ($\text{EDS} \times \text{EDS}_r \times 10$) and then determine the line length of the bags (l_B):

$$l_B = B_N - \text{EDS}_O \times \text{EDS}_r \times 10.$$

As with the passenger queue, we bring additional EDS machines into service based on need. When the queue gets to be longer than the optimal line length (l_{BO}), we add the appropriate number of EDSs to the system (ΔEDS):

$$\Delta\text{EDS} = (l_B - l_{BO}) \times 10 \times \text{EDS}_r.$$

Conversely, we subtract machines when the line length falls below the optimal length.

Human-Operated EDS

Because of the 30% false-positive rate for the EDSs, we run positives through a human-controlled EDS, which is a more thorough and accurate inspection [Butler and Poole 2002, 4]. This system follows the same process and equations as the initial baggage screening on the EDSs. However, the difference is that the flow rate is reduced to 1.2 bags/min, since it takes 50 sec for a human-operated EDS to inspect a bag [Recommended Security Guidelines . . . , 102]. So EDS_{RH}=1.2 and we have

$$\max I_{RH} = (1.2 \text{ bags/min} \times \text{EDS}_H \times (10 \text{ min}).$$

Since only 30% of bags screen as positive, the number of bags to inspect is now 30% of the original number:

$$I_{BH} = 0.3B_N - (\text{EDS}_H \times \text{EDS} \times 10).$$

Human-operated machines are added and taken away based on need and queue length:

$$\Delta\text{EDS}_H = (l_B - l_{BOH}) \times 10 \times \text{EDS}_{rH}.$$

Bags that pass inspection are routed to their planes; bags that fail are routed to the hand inspection.

Hand Inspection

In addition to the bags that register positive with the human-operated EDS inspection, we pull off 30% to hand inspect, as an additional safety measure to double check the machines and human operators for accuracy. A number (Hand) of trained inspectors inspect at a rate (Hand_r) that is much slower: 0.286 bags/minute, or 3.5 min/bag, the average between 2 and 5 bag/min [Butler and Poole 2002, 2].

$$\max I_{R\text{Hand}} = (0.286 \text{ bags/min}) \times \text{Hand} \times (10 \text{ min}).$$

The length of the line of bags awaiting hand inspection is

$$l_{B\text{hand}} = 0.09B_{N\text{Hand}} - \text{Hand} \times \text{Hand}_r \times 10.$$

Again, inspectors are added or subtracted as needed, and the number of bags left in the system is tracked throughout the 190 min of peak time.

$$\Delta\text{Hand} = (l_{B\text{Hand}} - l_{BO\text{Hand}}) \times 10 \times \text{Hand}_r.$$

From here, bags that are negative go to planes, while bags with explosive devices or compounds go to Explosive Ordnance Disposal teams.

Movement Phase

After a bag has been inspected and cleared, it is routed to its flight. The time that it takes a bag to get to its flight after inspection is the time to get to the plane (5 min, say) plus the time to be loaded into the plane (10 min, say). Hence we need to ensure that all bags are through inspection some 15 min before departure. However, we are not sure of this exact number and do not have any supporting data; so, to play it safe, we ensure that 95% of bags are finished being processed 30 min before departure, so that there will be no flight delays because of screening.

Results and Discussions

Using Microsoft Excel, we put into simulation the model formed from the equations and theory described above for both airports A and B. The results are given below.

Airport A

Using the initial conditions for airport A given in the problem statement, we calculate the optimal numbers of counter workers, automated EDS machines, human-operated EDS machines, and human inspectors required to meet the goal of 95% of passengers and baggage processed by 30 min prior to departure. The last set of initial conditions necessary are the maximal acceptable line lengths shown in **Table 2**.

Table 2.

Optimal line lengths for airport A.

Counter line	10	people
Bag line	20	bags
Human bag scan line	12	bags
Hand search line	2.86	bags

For airport A, 16 EDSs are required to handle peak-hour traffic. In addition, 35 ticket agents, 7 EDS operators, and 8 human inspectors are needed.

Looking deeper at the average line lengths throughout the whole peak hour process, we get **Table 3**, which confirms that the line lengths stay below the maximum acceptable lengths.

Costs

The cost of installation of EDS machines at airport A is $17.6 million, and worker cost is $1,639 per 190 min period. The worker cost for the 190 min period will not exceed $4 million/year.

Table 3.
Line lengths for airport A.

	Ave.	Max.	
Counter line	6.0	20	people
Bag line	17.5	21	bags
Human bag scan line	6.9	11	bags
Hand search line	1.6	2.86	bags

Airport B

Similar analysis shows that airport B requires 18 EDSs, 38 ticket agents, 8 EDS operators, and 9 human inspectors to achieve the same maximum acceptable line lengths. The corresponding average line lengths are 5.9, 19.1, 9.0, and 1.4, and the costs are $19.8 million for equipment and $1,807 worker costs per 190-min period.

Flight Departure Scheduling Model

There are two major considerations for a departure schedule:

- We must distribute the flight operations throughout the peak hour so that the runways are never more crowded than other times.
- We must distribute the various flights and their sizes so that the number of people departing at any given time during peak hour can be represented by a uniform distribution.

The time before departure that passengers arrive is independent of the number of seats on the flight.

First, we build a matrix for possible flight departure times. We split the hour window into six 10-minute windows, each with four 2.5-min smaller windows. Next, we record every flight's passenger load.

On a spreadsheet, we fill in a matrix, inserting flights into the flight schedule so that flights are evenly distributed by number and size of passenger load. We accomplish this by inserting the largest flights first. After the largest flights are entered, we use the small flights to fill in passenger-load disparities. Finally, to balance flight loads and passenger loads, we can always swap flights once we've placed them. For both airports, we achieve the goal that every 10-min and 2.5 min interval has an equal flight operation rate, and the number of passengers departing in each 10-min interval is nearly constant.

Recommendations

$\boxed{\textbf{We recommend against a combined EDS/ETD system.}}$

Such a system provides meager security improvements over an all-EDS system, increases fixed costs, and increases the possibility of baggage delays. We give details of our reasoning.

Re-screen positives Because of the high false-positive rate (30%) for EDS machines, bags that fail a first EDS test should be give a second one before any further screening.

Use ETDs on a 10% sample Airports A and B can incorporate the use of ETD machines into the proposed EDS model if they replace each human inspection point with an ETD machine. The ETD machines should inspect all bags that fail the first two EDS machine tests. Since ETDs use mass spectrometry technology, as opposed to the computed tomography technology that EDS machines use, the airports' security systems should send 10% of all bags that pass the initial EDS machines into ETDs, to try to find explosives that EDSs normally will not find, such as minute traces of explosive residue on the lining of a bag.

Open bags for ETD inspection ETDs most accurately detect explosives when security agents use the "open bag" form of trace detection. It takes additional time to open bags and prepare them to enter the ETD machine, but doing so reduces the machine's false negative rate (rate at which the machine fails to recognize explosive material) by nearly 50%. Open-bag ETD inspections take 2–2.5 min per bag, which is less than or equal to the time it takes for a physical human inspection (2–5 min) [Butler and Poole 2002]. This means that it will not take more to send the bags that fail the two EDS tests through an ETD machine than for a human to inspect each of these bags. It will, however, take more time to test 10% of the bags that pass the initial EDS machine.

How many ETDs? In addition to the 16 EDS machines, airport A will require 5 ETD machines; airport B, in addition to its 18 EDS machines, will require 4 ETD machines.

Greater possibility of delays Both airports can still meet departure schedules even if they conduct the additional ETD inspections on 10% of bags that pass the EDS machines. However, the length of the lines at an ETD machine suggest greater possibility of delay.

Actual costs According to Butler and Poole [2002, 7], installing 50,480 ETD machines would cost \$3.0 billion, or \$59,500 per machine. However, the same report indicates that the installation cost of 6,000 EDS machines is \$6.0 billion, or \$1 million per EDS machine. These costs include both the cost of the machines and the associated cost of placing them in the airport, and they substantially agree with those in the problem statement.

Cost comparison One can argue that ETD machines cost nearly ten times as much to operate as EDS machines because they inspect bags at one-tenth the rate of EDS machines. However, the ETD system that we suggest does not require any human inspectors. The costs (fixed and variable) of EDS and of EDS/ETD differ unsubstantially, for either airport A or airport B.

Security is not enhanced The security benefits of incorporating ETD machines into an all-EDS system do not appear significant. ETD machines are less accurate in detecting explosive materials than an EDS machine [Kavuar et al. 2002] and fail to identify explosive materials in 15% of bags that actually contain explosive materials [Butler and Poole 2002].

We recommend investment in development of new technologies.

We specifically suggest quadrupole resonance and neutron-based detection systems, which have the potential to lower costs while increasing security system effectiveness. We describe various research opportunities.

Quadrupole resonance: Quantum Magnetics is conducting research on quadrupole resonance (QR) to detect explosives, contraband, and weapons. QR-based technology may be cheaper, faster, and more accurate than EDS and ETD machines. QR detection systems are very simple to operate: a red light appears if a bag contains hidden explosives or biochemical agents, a green light appears if the bag contains no explosives or biochemical agents. The simplicity of use reduces the possibility of human error, which can occur with EDS technology if the operator poorly judges the machine's X-ray images. QR technology may also reduce airports' variable costs if they do not have to compensate security personnel for the technical education EDS operators receive [InVision Technologies 2002].

Neutron-based detection: Neutron-based devices can quickly detect hidden substances, such as liquid explosives hidden in a sealed container or plastic explosives stuffed inside a baseball. The HiEnergy Technologies Corporation has conducted tests in which neutron-based devices detected concealed explosives in less than 10-sec, nearly half the time it takes for an EDS machine to inspect a bag. Like QR technology, neutron-based systems determine the chemical formula of hidden substances, which reduces the likelihood of false positives that occur in EDS machines when the machine cannot accurately distinguish explosives from other objects with similar sizes and densities. Neutron-based technology also eliminates the need for drawn-out human interpretations [Fast neutron technologies ... 2002].

Elastic (coherent) X-ray scatter: This technology is currently in use in Germany at Cologne, Düsseldorf, and Munich airports. X-ray scatter detection systems can only inspect 60–240 bags/h [Butler and Poole 2002, 3], but they have a false positive rate well below 1% [Automatic detection ... 1998], much more efficient than EDS machines with their 30% false positive rate.

Millimeter and microwave imaging: This technology can improve overall airport security but is more applicable to inspecting passengers than baggage. Millimeter and microwave systems use temperature and emissivity to create images: the greater the contrast, the sharper the image. This is an excellent way to detect a passenger carrying a gun, since human bodies have high emissivity while metal objects have low emissivity [Murray 2001].

Recommendation for further research: Our model shows that if manufacturers can make enough EDS systems, and if airports can fit them and train enough operators, then they should be able to screen all bags checked in at least 30 min before departure. However, screening all checked baggage does not guarantee detecting all explosives; EDS and ETD machines cannot be a permanent solution. Investing in research and development opportunities is the only way to ensure that airlines are safe while minimizing space and labor costs. Ultimately, "The common goal should be a fully functioning air transportation system that provides passengers with safe, efficient, and convenient means of carrying out the nation's business" [Kavuar et al. 2002, 7].

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