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Health screening strategies for international air travelers during an epidemic or pandemic

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ABSTRACT

Air travelers can carry an infectious disease's pathogenic microorganism in their bodies and spread the disease from one country to another in a few days. To delay the spread, health screening stations may be set up at airport terminals to screen travelers. This research tested three different health screening strategies, each with a different combination of screening stations at trip origins, destinations and connecting airports. Discrete event simulations were performed, based on the 2014 to 2016 Ebola virus epidemic, with special focus on travelers from the West African countries traveling to the United States, including travelers who transferred flights at airports in European Union member states. The effectiveness of the screening strategies was analyzed in terms of correct detection, missed detection and false alarm rate. The results showed that exit screening at trip origins brought big improvements in the performance measurements compared to no screening. However, additional screening at the destinations and connecting airports contributed marginal benefits.

1. Introduction

1.1. Spread of infectious diseases by international air transportation

Air transportation enables travelers to reach far away destinations in a relatively short time. Although international air transportation facilitates economic, cultural and social exchanges between countries, it may introduce an infectious disease from one country to another (Mangili et al., 2015). The spread of infectious diseases by air transportation was evident in the Severe Acute Respiratory Syndrome (SARS) epidemic in 2003, and the Ebola virus epidemic from 2014 to 2016 (Wong et al., 2015). The international spread of a disease by air transportation is mainly caused by travelers, who have been infected with the disease, carrying the disease's pathogenic microorganism in their bodies from the country of origin to the country of destination, and transmitting the pathogenic microorganism to susceptible hosts.

The top 20 busiest international airports in the world handled a total of more than 1.6 billion passenger-trips in 2018 (ACI, 2018). The large number of air travelers between countries, combined with international routes between two countries that are served by flights from multiple origins to multiple destinations, some with connecting airports in between, have made the identification and interception of travelers who are carrying the disease's pathogenic microorganism (the infectious agent), a challenging problem.

1.2. The location problem of a health screening system

Health screening systems for air travelers work by using a combination of a questionnaire, trained observers, and screening devices at selected nodes (airports) or links (routes) in the air transportation network to quickly identify travelers who are carrying a targeted infectious agent. If a traveler is suspected to have the infectious disease in question, his or her trip is interrupted. The traveler is then subjected to further examination, laboratory tests, and/or transferred to a medical facility to receive treatment. From systems engineering perspective, a health screening system consists of one or several screening stations. Each station has one or multiple lanes, each equipped with one or
several screening devices. Each station is also staffed with observers who look out for symptomatic travelers, vet the filled survey forms, and if necessary, escort the disease suspects to the associated medical facility. The station also has one or several medical officers whose roles are to perform medical examinations on suspected travelers.

At a station, all travelers are subjected to primary screening, which is typically a questionnaire, an observer, and/or a screening device. If a traveler is found to have a sign associated with the disease, he or she will be examined by a medical officer. This medical examination by an officer is known as secondary screening, which usually takes place within the station’s vicinity, and lasts from a few minutes to a few hours. When a traveler is asked to undergo the secondary screening, his or her trip is said to be interrupted. If, after the medical examination, the officer suspects that the traveler has the infectious disease, the traveler is then escorted to a quarantine station within the airport or to a hospital, for further medical examinations and laboratory tests.

In the design of such a health screening system, the designer must first make the decision of where the screening should take place. For example, to screen all the travelers between two countries, screening stations may be set up at the international terminals of the origin airport, destination airport, and/or the connecting airports. To make this screening location decision, the system designer must know, among others:

(a) The clinical manifestations of the disease, i.e., symptoms and their observable/measureable parameters;
(b) The operating characteristics of the screening technology, such as screening time per traveler and error rate;
(c) The performance targets of the system, such as detection rate, false alarm rate, etc.

1.3. Research questions, objective and goal

During the Ebola epidemic, which occurred from 2014 to 2016, the World Health Organization (WHO) mandated the disease affected countries in West Africa to conduct exit screenings for all international air travelers prior to boarding their departing aircrafts (WHO, 2016b). Later, the United States Center for Disease Control and Prevention (CDC), and Customs and Border Protection (CBP) added entry screenings at five airports in the United States. The CBP diverted flights carrying travelers from the diseased affected West African countries to land at these five airports so that all passengers on board were screened (Brown et al., 2014). However, the European Commission decided not to screen arriving and connecting air travelers at airports in the European Union (E.U) member states (Croft and Guarascio, 2014). The decisions by WHO, CDC, CBP, and European Commission are likely to be the same in future epidemics and pandemics. These decisions have given rise to the following research questions, which are of interest to at least the airlines, airport operators, air transportation authorities, public health authorities and the general public:

(1) During an epidemic or pandemic, WHO mandates the disease affected countries to implement exit screenings at their airports. Among the departing international travelers who are infected with the disease, how many of them or what percentage can be interrupted at the exit screening stations alone?
(2) To delay the spread of the infectious disease from other countries to the United States, CDC and CBP may implement entry screening at airports in the United States, as an additional layer to the exit screening at the disease affected countries. Among the travelers who are infected with the disease, who want to travel from the disease affected countries to the United States, how many of them or what percentage can be interrupted at the entry screening stations at airport terminals in the United States?
(3) If the exit and entry screenings are already implemented at airport terminals in the disease affected country and in the United States, respectively, the European Commission decides to introduce entry screenings at airport terminals in the E.U. member states, how many or what percentage of the travelers from the West African countries to the United States, who are infected with disease, can be interrupted by the entry screening stations at airport terminals in E.U. member states while making connecting flights?

The objective of this research was to analyze and compare the effectiveness of different health screening strategies in interrupting air travelers whose bodies were carrying an infectious agent of the disease of concern. The subjects of interest were the travelers from the disease affected countries to the United States. The health inspection strategies were represented by discrete event simulation models. The simulation model focused on the West African Ebola virus epidemic, which occurred from 2014 to 2016. The health screening strategies analyzed included different combinations of screening station locations (origins, destinations, and/or connecting airports). This research also studied the effectiveness of the screening strategies by varying the percentages of symptomatic travelers who were infected with the infectious disease.

The goal was to, through the answers of the above research questions, recommend the locations (airport terminals) of screening stations that may lead to the most cost-effective strategy of identifying and interrupting travelers whose bodies are carrying the infectious agent of the disease. This research is not concerned with the optimizations of screening station locations within an airport terminal, screening station layout, or work flow.

1.4. Outline of paper

This paper is organized as follows. After this introduction, reviews are conducted for infectious diseases, detection technologies, and international health screening practices. Next, the proposed health screening strategies are described. This is followed by the presentation of the simulation model. The simulation results are then compared and discussed. Finally, conclusions and recommendations are made.

2. Review of background materials

2.1. Infectious diseases

The WHO defines infectious diseases as diseases “caused by pathogenic microorganism such as bacteria, viruses, parasites or fungi, many of which can be transmitted from one person to another” (WHO, 2017a). An individual who is infected with an infectious agent may transmit the pathogenic microorganisms harbored in his or her body to another individual in close contact or expelled bodily fluids.

Travelers who had contracted the pathogenic microorganisms are called travelers who were infected with the disease in this paper. They are either asymptomatic carriers or spreaders. Asymptomatic carriers, or simply carriers, are persons who are infected with the pathogenic microorganism, but do not confer any symptom. Depending on the disease, asymptomatic carriers might, acting as a host, potentially transmit the disease’s pathogenic microorganism to other persons. Asymptomatic carriers are difficult to distinguish from persons who are not sick, by observation and by the devices that detect the signs of the symptom. The term spreader was adopted from “super-spreaders” in CDC (2003a) and Wong et al. (2015). In this paper, spreaders refer to persons who are infected with the agent and symptomatic (e.g., fever). Compared to a carrier, a spreader has a much higher tendency of transmitting the disease’s pathogenic microorganism to another person. A person who is infected with an agent initially becomes a carrier, and is asymptomatic from a few days to a few weeks. After the incubation period, the infected person becomes a spreader. A spreader who travels by air transportation mode could transmit the disease’s pathogenic microorganism to other travelers, to cabin crew on board the same aircraft, to anyone who comes in close contact at the airport terminals and at the
The infected Aedes species (CDC, 2017). Frequently, the symptoms may also include nausea, diarrhea, and rash. The virus was detected in 48 different countries, resulting in at least 18,000 reported deaths (CDC, 2010). In United States alone, the A (H1N1) 2009 virus infected more than 60 million, resulting in 12,469 deaths (CDC, 2014a). The influenza virus can be transmitted from one individual to another through respiratory droplets and direct physical contact with body fluids of an infected individual. The incubation period for influenza is two to seven days. The symptoms are the same as those for common influenza: fever, cough, sore throat, muscle aches, diarrhea, and nausea.

The Ebola Virus Disease, known simply as Ebola, is a viral hemorrhagic fever caused by the Ebolavirus. The Ebolavirus was first discovered in 1976 in Central Africa. Since then, several outbreaks in Africa have been reported. The largest Ebola outbreak occurred in West Africa in 2014, and between 2014 and 2016, where it became an epidemic that infected more than 28,000 individuals. The mortality rate was so high that it resulted in approximately 10,000 deaths (WHO, 2017b). The Ebolavirus can be transmitted from animal to human, and also from human to human through direct contact of bodily fluids. The Ebola's incubation period is 2–21 days. After that, the initial symptoms include fever, fatigue, myalgia, headache, and sore throat. Subsequently, the symptoms may also include nausea, diarrhea, and rash (CDC, 2017).

The Zika Virus Disease, also known simply as Zika, is caused by the mosquito-borne flavivirus. The disease is transmitted by the bite of an infected Aedes species (Ae. aegypti and Ae. albopictus) mosquitos. The Zika Virus Disease was first discovered in Central-Eastern African monkeys in 1947, and in humans in 1952 in the same region. The first major human outbreak occurred in Oceania in 2007. The most recent outbreak began in Brazil in 2015, and has spread to many countries in South America, Central America, Africa, and Asia. Zika can be transmitted from one individual to another through a mosquito bite. In the United States, more than 41,000 Zika cases have been reported between 2015 and 2017. Zika’s incubation period ranges from 3 to 12 days. However, many people who are infected with Zika either do not develop symptoms or develop only mild symptoms. The most common symptoms are fever, rash, arthralgias, conjunctivitis, myalgias, and headache. The feared consequence of the Zika infection is when it occurs during pregnancy. Maternal transmission of Zika virus to the fetus may result in microcephaly, a very serious congenital brain abnormality which leads the brain to be smaller in size (WHO, 2017c).

The following common characteristics have been found based on the above reviews of infectious diseases that developed into epidemics and pandemics:

1. The diseases were introduced from the countries of origin to countries in other parts of the world by individuals who were infected with the viral agent and traveled by air transportation mode;
2. The carriers had incubation periods that ranged from a few days to a few weeks, during which an infected individual was unlikely to transmit the disease’s pathogenic microorganism to another individual, but this person remains asymptomatic, which makes the early identification very difficult; and
3. Spreaders were symptomatic. Detecting a spreader's sign (e.g., by measuring body temperature to detect fever) was the most convenient way for identifying a spreader. However, these symptoms are highly similar to the symptoms of other commonly encountered diseases, which may lead the health screening system to generate false alarms.

2.2. Recent epidemics and pandemic

This section describes four viral infectious diseases that resulted in three epidemics or a pandemic since 2000, to illustrate the importance and to further explain the complexity of the health screening problem for international air travelers.

Severe Acute Respiratory Syndrome (SARS) is a disease caused by the SARS-CoV coronavirus. SARS was first reported in early 2003 in China. It then spread to other countries in Asia, followed by countries in Europe and Americas in the following months. Within six months, the epidemic infected more than 8000 persons, resulting in 774 deaths. The most affected countries/regions were China, Hong Kong, Taiwan, Canada, and Singapore. SARS is mainly transmitted through an individual's respiratory droplets (produced by coughs and sneezes) to another individual who is exposed to these infectious droplets. The incubation period of SARS is two to seven days. After the incubation period, mild or atypical presentations to severe lower respiratory tract illness symptoms of high fever, headache, diarrhea, and body aches can be observed (CDC, 2013b).

Influenza is an infectious viral disease. Many variants of influenza, such as H1N1, H5N1 and H7N9 have been found due to the high mutation rates and frequent genetic reassortments, and new strains are continuing to be discovered. Some influenza viruses are believed to be originated from poultry, but the sources of many influenza viruses are still unknown. Recent outbreaks of H5N1 influenza occurred in 1997 in Hong Kong and H7N9 influenza in 2013 in China. The H1N1 influenza, also known as swine flu pandemic in 2009, was the most widespread. The first H1N1 influenza virus, now known as the A (H1N1) 2009 virus, was first discovered in 2009 in a boy in California. Within a few weeks, the virus was detected in 48 different countries, resulting in at least 18,000 reported deaths (CDC, 2010). In United States alone, the A (H1N1) 2009 virus infected more than 60 million, resulting in 12,469 deaths (CDC, 2014a). The influenza virus can be transmitted from one individual to another through respiratory droplets and direct physical contact with body fluids of an infected individual. The incubation period for influenza is two to seven days. The symptoms are the same as those for common influenza: fever, cough, sore throat, muscle aches, diarrhea, and nausea.

Ebola’s incubation period is 2–21 days. After that, the initial symptoms include fever, fatigue, myalgia, headache, and sore throat. Subsequently, the symptoms may also include nausea, diarrhea, and rash (CDC, 2017).

2.3. Health screening instruments

This section reviews the instruments (methods and devices) currently used in health screening systems at airports. These screening instruments reviewed here include visual observation, questionnaires, body temperature measurement devices, and medical examinations.

Visual observation methods use trained non-medical personnel to observe travelers and identify those who exhibit the diseases' symptoms. Questionnaires are designed to: (1) ascertain if a traveler was in a disease affected area or to determine if a traveler had any possible contact with anyone who was infected with the viral agent; (2) ask the traveler to report his/her symptom(s); and (3) obtain the contact information of the traveler at his or her destination. The survey may be conducted either before a traveler boards to the aircraft, when the traveler is on board, or upon a passenger’s arrival at the destination’s airport terminal. The reliability of the self-reported information is not known. Gostic et al. (2015) assumed that only up to 25% of the travelers who were or potentially will become infected with the viral agent filled out the form truthfully. Real-time processing of the data in the forms is also challenging.

A person who is infected with the abovementioned viral agent eventually develops fever. Therefore, measuring body temperature is the most practical and convenient way of detecting the infected individual at screening stations during an epidemic or pandemic. A Non-Contact Infrared Thermometer (NCIT) is a portable device held by a screening officer between 1.2 and 6 inches (3–15 cm) from the traveler's forehead (CDC, 2014a). The measurement error of NCIT can be up to ± 1.0 °C (Fluke, 2017) and the ability of detecting a fever (sensitivity) ranges from 80% to 99% (CDC, 2014b). The advantages of the NCIT includes the lack of need for frequent recalibration of the device, and low initial cost.

A Non-Contact Infrared Thermal Camera (NCITC) is also known as a thermographic camera or a thermal imaging camera. This camera system collects and analyzes thermal images of travelers in real-time, as they pass the camera’s field of view. NCITCs are commonly used in the airports in Asia. However, they are not approved by the American Medical Association as medical equipment in the United States. Therefore, NCITCs must be used together with approved thermometers.
to confirm the measured temperature (CDC, 2014b). A NCITC has a higher screening capacity than a NCIT. On the other hand, the precision of body temperature measurement is lower, frequent calibration is needed, and the initial cost is higher.

An ear infrared thermometer is usually used as a supplementary body temperature measurement device. It is the only physical contact device used at screening stations at airports. The accuracy of the measured temperature is the largest advantage of this thermometer. Although the purchase cost is low, one obvious disadvantage of the ear infrared thermometers is the need of changing the probe to prevent cross-contamination.

Medical examination is performed by a qualified medical officer in a designated area or a room. The medical officer interviews with the traveler, measures the traveler's vital signs and even performs simple laboratory tests. The examination may take a few minutes to a few hours.

None of the commonly used screening instruments is 100% accurate. Visual observation is subjective, even though a traveler's sign is noticeable. On the other hand, travelers may not fill-out the questionnaire honestly. The devices that measure body temperature also have errors in the measurements. To improve the accuracy of the screening process, some screening stations use a combination of two or more instruments to conduct primary screening. Medical examination requires a medical officer and takes a longer time, which is why it is only used for secondary screening.

2.4. International practice of screening air travelers

In 2005, the World Health Organization (WHO) issued a legally binding document for all of its member states called the International Health Regulations (IHR). The IHR sets the basic principles against the international spread of diseases during an epidemic or a pandemic (WHO, 2016b). There are also guidelines issued by the International Civil Aviation Organization (ICAO), International Air Transport Association (IATA), Airports Council International (ACI) and other organizations with non-binding recommendations to the air transportation industry.

The three West African countries that were seriously affected by the Ebola epidemic in 2014–2016 (Guinea, Liberia and Sierra Leone) implemented an exit screening process according to the countermeasure stated in the Public Health Emergency of International Concern (PHEIC), which is part of IHR. The exit screening process consisted of administering questionnaires and measuring body temperatures of travelers as the primary screening methods, followed by medical examination as the secondary screening method. In the later phase of the Ebola epidemic, CDC and CBP established entry screening at five international airports in the United States, directed flights carrying air travelers from the Ebola affected countries to arrive at these airports, and screened all of them by questionnaires, visual observation by CBP officers and NCITC. If any of the methods detected a traveler who was possibly infected with the Ebola virus, the traveler was sent to a CDC quarantine station located in the airport terminal for further examination (Brown et al., 2014). The European Commission announced that it was not necessary to screen travelers who arrived at the airports in E.U. member states from West African countries (Croft and Guarasco, 2014). Therefore, most of the E.U. member states did not conduct entry screening at their airports.

During the Ebola epidemic, the Republic of Korea screened arriving passengers from West African countries at primary screening stations by questionnaires and NCITC, and if a fever was suspected, body temperature by ear infrared thermometer. Air travelers found to have a fever at the primary screening station underwent interviews and medical examinations at the secondary screening station, which may have resulted in the travelers being sent to a medical facility for further examination and laboratory tests (Cho and Yoon, 2014).

Similar screening methods (questionnaires and body temperature measurements) were used in Taiwan to delay the spread of SARS in 2004. During the SARS epidemic, the body temperature of both arriving and departing international air travelers at airports in Taiwan were scanned by NCITCs, and if a fever was suspected, passengers were screened by ear infrared thermometers. In addition, each entering and exiting air traveler filled-out a “SARS Survey Form” (Shu et al., 2005).

Gaber et al. (2009) proposed a health screening framework for international air travelers called The Frankfurt Model. It is based on the experience in screening travelers during the 2009 H1N1 influenza pandemic at the Frankfurt International Airport. The Frankfurt Model described the exit screening process at the airport’s departure terminal, and the entry screening process in the aircrafts in detail. Only the process that takes place in the terminal, which is within the scope of this research, is reviewed here. Gaber et al. (2009) proposed that the exit screening in the disease affected country be limited to departing passengers of international flights. Only travelers with valid tickets are allowed to enter the international departure terminal. Once inside the terminal, all travelers’ body temperatures are measured by NCITCs. If the NCITC suspects that a traveler has a fever, the traveler’s body temperature is measured again by an ear infrared thermometer. If either the NCITC or ear infrared thermometer does not indicate that the traveler is having a fever, the traveler is allowed to proceed to the check-in counter. If both the NCITC and ear infrared thermometer suspect that the traveler is having a fever, the traveler is asked to undergo a medical examination. A traveler who “fails” the medical examination (who has also “failed” both the NCITC and ear infrared thermometer tests) is not allowed to check into the departing flight.

The screening processes and instruments reviewed have been incorporated into the simulation model, which will be presented in a subsequent section.

3. Proposed health screening strategies

This section describes the assumed epidemic and the screening strategies that were evaluated in the simulation experiment.

3.1. Assumed epidemic

This research performed analysis on the effectiveness of different screening strategies based on the Ebola epidemic that occurred in West Africa from 2014 to 2016. The three disease affected countries wereGuinea, Liberia, and Sierra Leone. The subjects of interest were the travelers from these three countries to the United States. Other than taking direct flights from airports in these West African countries to airports in the United States, some travelers took flights to airports in E.U. member states (such as Frankfurt, Paris, and London), and then transferred to connecting flights to arrive at airports in the United States. Thus, exit screening may be implemented at the airports of departure in the West African countries (the origins), while entry screening may be implemented at the connecting airports in E.U. member states (the connecting airports), as well as the airports of arrival in the United States (the destinations). From the research questions, the following screening strategies were constructed.

3.1.1. Strategy 0 – no screening

This was the do-nothing strategy where there was no health screening at all. This may represent the situation at the beginning of an outbreak.

3.1.2. Strategy 1 – exit screening at origins

Strategy 1 was based on the practice during the early stage of the Ebola epidemic when the WHO activated the PHEIC protocol. The exit screening process used questionnaires and NCIT as the primary screening methods and medical examination at the secondary screening method. There was no entry screening at the airports in E.U. member states and the United States.
3.1.3. Strategy 2 – exit screening at origins and entry screening at destinations

This screening strategy was implemented at the subsequent phase of the Ebola epidemic when CDC and CBP introduced entry screening at selected airports in the United States. The entry screening process used questionnaires and NCIT as the primary screening methods, and medical examination as the secondary screening method. The CDC also requested airlines and airport employees to observe the arriving international travelers from the West African countries for signs of the disease. There was no screening at the airports in E.U. member states.

3.1.4. Strategy 3 – exit screening at origins, entry screening at destinations and connecting airports

Strategy 3 added entry screening at the airports in E.U. member states to Strategy 2. The same primary screening method of using questionnaires and NCIT, as well as secondary medical examination, were implemented at the airports in E.U. member states. This strategy was hypothetical, and tested the “what if” scenario when the airports in E.U. member states also screen arriving and connecting travelers.

Fig. 1 shows the logics of the four screening strategies simulated in the experiment. The human observation processes in Strategies 2 and 3...
were not included in the simulation models because of the lack of data on the performance of human observers. The secondary screenings in Strategies 1, 2 and 3 were not modelled because when a traveler was subjected to secondary screening, his or her trip had already been interrupted. Even if the traveler was not infected with a viral agent, he or she had an increased risk of missing the departing or connecting flight. There was no prior statistical data on the decisions made by medical officers in similar examinations.

4. Simulation modeling and execution

4.1. Duration of epidemic

The simulated time period was 600 days, from August 8, 2014 to March 29, 2016, which was the duration of the PHEIC declared by the WHO (WHO, 2016b).

4.2. Traveler volume

The number of air travelers from the disease affected countries in West Africa was calculated based on Brown et al. (2014). This report stated that from August to October 2014 (three months), approximately 80,000 persons traveled by air from the three disease affected countries to all over the world, and 15% of them headed to the United States. The destinations of the remaining 85% of the travelers were divided between E.U. member states and the rest of the world. Based on the flight frequencies and aircraft capacities of major routes that originated from the airports in these three West African countries, approximately 35% of the 80,000 passengers traveled to E.U. member states and the remaining 50% traveled to countries other than United States and E.U. member states.

4.3. Health conditions of travelers

In the simulation model, the health conditions of travelers were assigned when they arrived at the airport terminals in the three West African countries. The health categories are shown in Fig. 2. All the travelers were first classified as sick (S) or not sick (¯S). Travelers who were sick could have the Ebola disease (S) or another illness (¯S). Furthermore, all the sick travelers (in categories S and ¯S) may have fever (F) or no fever (¯F). Therefore, a traveler’s health status is assigned to one of the five categories: not sick (¯S), sick with Ebola (S, S), sick with Ebola without fever (S, S), sick with another illness without fever (S, ¯F), sick with another illness with fever (S, F) and sick with another illness without fever (S, ¯F). A person who has a health category as S or is an Ebola carrier. A person who has a health category as S is likely an Ebola spreader. The purpose of health screening stations is to identify travelers with health status S, i.e., S, S and S, S, and interrupt their trips. However, existing technologies (screening instruments) are not perfect. They are not capable of detecting all the travelers with health statuses of S and S. The instruments may wrongly identify limited number of travelers with health statuses of S and S as suspected cases. One of the challenges in designing screening strategies is to maximize the detection of travelers with health statuses of S and S, but doing so will usually increase the alarms caused by travelers with health statuses of S and S.

Based on the data by WHO (2016b), there were 28,610 persons infected with Ebolavirus in the three West African countries during the epidemic. The total population of the three affected countries was 23,207,613 (CIA, 2014). The probability that a traveler was infected with Ebolavirus was estimated by dividing the number of persons infected with Ebolavirus by the total population of these countries. That was, \( P(\bar{S}) = 28,610/23,307,613 = 0.00123 \). Furthermore, 87% of the people who were infected with Ebolavirus showed symptoms of fever (Gostic et al., 2015). This gave \( P(\bar{S}F) = 0.00123 \times 0.87 = 0.00107 \), and it followed that \( P(F|\bar{S}) = 0.001123 \times 0.23 = 0.00016 \). The probability of a traveler infected with another agent was arbitrarily set to \( P(\bar{S}) = 0.010 \), out of which 95% did not have fever (\( P(\bar{S}F) = 0.01 \times 0.95 = 0.0095 \)) and 5% had fever (\( P(F|\bar{S}) = 0.01 \times 0.05 = 0.0005 \)). The value \( P(S) = 0.010 \) was estimated by dividing the 178,837 cases of leather infectious diseases other than Ebola, which occurred in the three Ebola affected counties (WHO, 2016a; Knoema World Data Atlas, 2011–2018), by the population of these three countries. The initial estimation gave the probability of 0.0077. Considering that there were many unreported cases of such infectious diseases, the probability was arbitrarily increased to \( P(\bar{S}) = 0.010 \) in the simulation experiment. Due to the uncertainty associated with the estimation of \( P(\bar{S}) \), the \( P(S) \) value was later varied between 0.005 and 0.015. Three \( P(\bar{S}) \) values of 0.005, 0.010 and 0.015 were used to test the sensitivity of the screening strategies in detecting travelers who were sick with Ebola (health status of S), while there was an unknown fraction of travelers who had other leather infectious diseases (health status of \( \bar{S} \)), in the absence of good estimates of the upper and lower bound values of the \( P(\bar{S}) \). The rest of the travelers were not sick.

4.4. Health screening technologies and station work flow

As shown in Fig. 1, each screening station at the origins, destinations and connecting airports were identical, and they used both NCITs and questionnaires to identify travelers who were infected with Ebola. When a station screened a traveler as possibly infected, it made a binary decision on the traveler: trip interruption (I) or no trip interruption (I). No trip interruption meant the traveler continued with his or her trip without any intervention. Trip interruption resulted in the traveler being sent to a secondary screening station for a medical examination, which may take a few minutes to a few hours. If, after the medical examination, the traveler was suspected to be infected with Ebola, he or she was then transferred to a quarantine facility or a hospital. The medical examination and its resulting actions were not part of the simulation. Based on the data in Gostic et al. (2015) and Fluke (2017), and with several assumptions, the operating characteristics for the two detection methods (combined) at a station, as described in Table 1, were used as inputs to the simulation model.

Table 1

| Operating characteristics | Questionnaire | NCIT |
|---------------------------|--------------|------|
| \( P(IS|\bar{S}F) \)       | 0.25         | 0.90 |
| \( P(IS|\bar{S}E) \)       | 0.20         | 0.50 |
| \( P(IS|S) \)             | 0.15         | 0.90 |
| \( P(IS|\bar{S}E) \)       | 0.10         | 0.005|
| \( P(IS|\bar{S}F) \)       | 0.0           | 0.005|
| Capacity (number of lanes)| 2            | 1    |
| Average service time (seconds/traveler) | 30  | 5    |
| Service time distribution | Exponential | Exponential |

Fig. 2. Health statuses of air travelers.
4.5. Simulation execution

The experiment was conducted using the simulation software SIMIO, Version 8.139.13727.0, University Enterprise Edition (SIMIO, 2016). SIMIO is an object-oriented modeling tool. It supports both discrete event and continuous simulations. SIMIO has the ability to represent created models and objects in three-dimensional view, thus helping analysts visualize the simulation process and results. Fig. 3 shows the coded models in two-dimensional space, one for each screening strategy. For each of the four scenarios previously described, the simulation was run for 100 replications. Each replication simulated 600 days of air transportation network operations.

In the real world scenario, travelers departed from multiple airports in the disease affected countries. They arrived at multiple airports in the United States. Some of them transferred flights at different airports in E.U. member states. Therefore, the air transportation network may be modelled as a network with multiple origin nodes, multiple destination nodes, and multiple intermediate or transshipment nodes. Statistically, the effectiveness of the health screening strategies was independent of the number of nodes (airports) in the simulation model, as long as all travelers were screened when they passed the origins, destinations and/or connecting airports, as specified in the strategies. Therefore, as
shown in Fig. 3, each model had only one station at the origins, destinations and/or connecting airport, respectively.

In Fig. 3, each logic that represents a screening strategy starts with a node named “arrival”. This process represents the arrival of a traveler at the airport of origin. The traveler is assigned a health status, a trip destination, and if applicable the need to go to an airport in E.U. member states to take a connecting flight to the United States. At this airport, the traveler is screened by “Questionnaire 1” and “NCIT1”, the questionnaire and NCIT respectively. The same primary screening methods are applied when a traveler arrives at the airport in the United States. In Fig. 3(b) and (c), the questionnaire and NCIT screening processes in an airport in the United States are labeled “Questionnaire 2” and “NCIT2” respectively. In the similar way, the correspond processes that take place in an airport in E.U. member states are denoted by “Questionnaire 3” and “NCIT3”. A traveler who is subjected to the different screening strategies as depicted in Fig. 3 ends up in one of the four possible outcomes: (1) “Other Destination” – he or she boards a flight to a destination other than E.U. member states or the United States; (2) “USA” – the traveler arrives and is allowed to enter the United States, (3) “Europe” – the traveler arrives at a E.U. member states and is allowed to enter the E.U. or to take a connecting flight to the United States; (4) “Interrupted” – the traveler “fails” the primary screening test at any airport and his or her trip is interrupted.

Our simulation differed from the simulation performed by Malone et al. (2009) in many ways. The main differences are:

- Malone et al. (2009) assumed direct flights from all over the world landed at 18 airports in the United States; while our model consisted of travelers who took direct flights from the three Ebola affected countries to multiple airports in the United States, plus travelers who flew from the three Ebola affected countries to airports in E.U. member states and took connecting flights to airports in the United States. Our simulation experiment did not put a limit on the arriving airports in the United States, because all travelers were screened in Strategies 2 and 3.
- Malone et al. (2009) assumed that exit screening and entry screening were already in place, while we tested different combinations of exit and entry screening locations, including the connecting airports.
- Malone et al. (2009) classified travelers into three health categories: not sick, sick with influenza and sick with others; while this research further classified travelers into five different statuses (not sick, sick with Ebola with fever, sick with Ebola without fever, sick with another illness with fever, sick with another illness without fever) as shown in Fig. 2.

5. Results and discussions

5.1. Performance measures

The effectiveness of the health screening strategies was evaluated using several quantitative measures. They are defined in this section before the presentation of simulation results.

The main purpose of health screening was to detect air travelers with a health status of SE. As shown in Fig. 2, the travelers had five different health statuses. When they passed through a screening station, the station either interrupted their trip (I), or let them proceed with their trips without interruption (F). The combinations of health statuses and screening stations’ decisions led to several outcomes, each with a different consequence. They are summarized in Table 2, and are discussed below.

- If a traveler was sick with Ebola (SE), i.e., is a carrier or spreader, and the screening system interrupted his or her journey (I), the system made a correct detection or the outcome was true positive.
- If a traveler was sick with Ebola (SE) and the screening system failed to interrupt his or her trip (F), the system missed a detection or the outcome was false negative.

The average number of travelers generated in the respective health statuses are listed in Fig. 4. These values were the average of 100 simulation replications, and they are the same for Strategies 0 to 3. Note that, because the simulations were run with three different P(SE) values, Fig. 4 consists of three sub-figures, for P(SE) values of 0.005, 0.010 and 0.015, respectively. The boxes for ¯S, ¯S, S, S, SEF and SEF in the sub-figures have different number of travelers. The number of travelers who were sick with Ebola (health status SE) remained the same, regardless of the P(SE) value. Therefore, the analysis presented in Sections 5.2, 5.3, 5.6 and 5.7 are independent of the P(SE) value.

5.2. Correct detection rate

Fig. 5 plots the correct detection rates and missed detection rates of the strategies tested. The correct detection rates are independent of the P(SE) values. In Strategy 0, there was no health screening at all. The implementation of exit screening at airports of disease affected countries alone interrupted 84.31%, or 541 of the 641 travelers who were sick with Ebola (health status SE). The system still failed to interrupt 100 of them. This was because the questionnaire and NCIT could not identify all the travelers who were sick with Ebola without fever (health status SEF), and some of the travelers who were sick with Ebola with fever (health status SE). When an additional layer of entry screening was implemented at the airports in the United States (Strategy 2), the correct detection rate increased by only 0.63%, from 84.31% to 84.94%. The slight increase was because most of the “travelers” who were sick with Ebola (health status SE) had already been prevented from leaving the diseased affected countries by the exit screening process. Adding another entry screening process at airports in E.U. member states (Strategy 3) improved the overall detection rate to 87.67%. The benefits of the increase in detection rates must be evaluated against the costs to carry out the additional screening, but these costs are beyond the scope of this research. On the other hand, at this

| Table 2 |
| Classification matrix |
| Health status of air traveler | | |
| | SE | S |
| Screening decision | I | Correct detection (true positive) | Missed detection (false negative) | Detection - others (other positive) | Non-detection – others (other negative) | False alarm (false positive) |
| | | | | | | Correct decision (true negative) |

- If a traveler was not sick (S) and the screening system interrupted his or her trip (I), the system declared a false alarm or the outcome was false positive.
- If a traveler was not sick (S) and the screening system did not interrupt his or her trip (F), the system made a correct decision or the outcome was true negative.
- If a traveler was sick with an illness other than Ebola (S) and the screening system’s output was positive, the traveler’s trip was interrupted (I). In this case, detecting a traveler who was not sick with Ebola but had another illness was considered as a bonus. Thus, the output was labeled detection - others or the outcome was other positive.
- If a traveler was sick with an illness other than Ebola (S) and the screening system failed to detect this illness and let him/her continue his or her trip without interruption (F), the system made a nondetection - others or the outcome was other negative.
high correct detection rate of 87.67%, there still exists 12.33% of the travelers who were sick with Ebola but their trips remained uninterrupted.

5.3. Missed detection

The failure of a screening system to interrupt even one traveler who was sick with the infectious disease might result in the transmission of the disease to others. The lack of symptoms during the incubation period of a disease, or the development of either mild or no symptoms with some diseases, makes developing a fool-proof screening system impossible. Fig. 6 plots the number of travelers who were sick with Ebola (health status $SE$), uninterrupted by the screening strategies, and were allowed to enter the E.U. member states and the United States. The consequence and cost of a missed detection were beyond the scope of this research. Like the correction detection rates, the missed detection rates remained the same regardless of the $PSE(\bar{S})$ values.

In Fig. 6, the statistics at airports in E.U. member states were higher because there were more travelers from the three countries in West Africa who went to the E.U. member states than to the United States. There were, on average, 319 travelers who were sick with Ebola (health status $SE$) generated by the simulation model. In Strategy 0, without screening, 225 of them entered the E.U. member states and another 94 entered the United States. These uninterrupted travelers were reduced to 38 and 18, respectively, with the implementation of exit screening in the Ebola affected countries in Strategy 1. When the United States implemented entry screening at its airports (Strategy 2), the number of travelers who were sick with Ebola, but were uninterrupted and entered the United States, was reduced to 8 persons. From this point of view, the implementation of Strategy 2, with entry screening at the airports in the United States, interrupted nine travelers who were sick with Ebola (at the rate of 1 in every 67 days) when they arrived at the United States. Comparing Strategy 3 with Strategy 2, the additional entry screening measure at airports in E.U. member states in Strategy 3 further reduced the number of travelers who were sick with Ebola from entering E.U. member states and the United States, from 38 to 20, and from 8 to 7, respectively.

5.4. False alarm rate

A false alarm occurred when the screening system interrupted a traveler who was not sick (outcome $IS$). The False Alarm Rate (FAR) was calculated by dividing the number of interrupted travelers who were in fact not sick (outcome $IS$), by the total number of travelers who were not sick (health status $S$). The values of the numerator and denominator in the FAR calculation varied depending on the $PSE(\bar{S})$ value used to generate the number of travelers with specific health statutes (see Fig. 4). From the simulation results, the calculations of FARs are
summarized in Table 3. When the value of $P(\bar{SE})$ is the same the number of travelers, who were not sick (health status $\bar{S}$) was the same for all the screening strategies tested. In Strategy 0, there was no false alarm because there was no screening. When Strategies 1, 2 and 3 were implemented respectively, the number of false interruptions increased with every additional station added to a traveler’s trip. With higher $P(SE)$ values, there were more travelers sick with other illnesses. This led to fewer travelers who remained not sick. When these travelers were screened by the three strategies, the number of false alarms reduced correspondingly but the FAR remained the same. From the results in Table 3, one can conclude that the FAR is dependent on the screening strategy but independent of the $P(SE)$ value.

### 5.5. Detection of other diseases

Some travelers who were sick with some virulent agent other than Ebola and have a fever (health status $SEF$) were also interrupted by the health screening strategies. Since these other positive cases imposed additional work load to medical officers, the Other Positive Alarm Rate (OPAR) was also of interest to the system designer. If a traveler who was sick with another illness with fever, and his or her trip was interrupted at a screening station (in airports in the United States, the traveler was sent to the CDC’s quarantine station within the airport terminal), the subsequent medical response is required but it is beyond the scope of this research. The OPARs were computed by dividing the number of interrupted travelers who were sick with other illnesses with fever (outcome $ISEF$), by the total number of travelers who were sick with other illnesses (health status $S$). The computations of OPARs were presented in Table 4. As in FAR, in Strategy 0, OPAR = 0.00% because there was no screening. As Strategies 1, 2 and 3 were implemented, the number of interrupted travelers who were sick with other illnesses with fever (outcome $ISEF$) increased. However, when $P(SE)$ remained constant, the total number of travelers who were sick with other illnesses (health status $S$) stayed the same. The ratio of the two caused the OPAR to increase with Strategies 1, 2 and 3. It was observed that for the same screening strategy, when $P(SE)$ was varied between 0.005 and 0.015, both the number of positive alarms as well as the number of travelers who were sick with other illnesses increased. Overall, with the same screening strategy, when the $P(SE)$ was tripled from 0.005 to 0.015, the increase in OPAR was at most 0.12%. Comparing the magnitude of 0.12% with OPAR in the range of 14.56%–20.01%, it was concluded that, although the $P(SE)$ estimate was not certain, the OPAR was insensitive to the change in $P(SE)$ values.

### 5.6. Comparison with historical statistics

Brown et al. (2014) reported that, between August and October 2014, 80,000 travelers left the Ebola affected countries, of which 18,000 arrived in the United States. The exit screening at the airports of the disease affected countries in West Africa did not identify any traveler who was sick with Ebola (carrier or spreader, with health status $SE$). There was no entry screening at airports in the United States during that period. This screening scenario was similar to Strategy 1 but most likely without proper execution, and the results were similar to what was obtained with Strategy 0. In this situation, the correct detection rate was zero, even when the number of travelers with health status $SE$ who entered the United States uninterrupted. In fact, their health status was $SEF$ at the time of arrival, but they developed a fever not long after. The missed detection rate could not be estimated because the number of travelers with a health status of $SE$ between August and October 2014 was unlikely to be zero. There were two travelers with health status $SE$ who entered the United States uninterrupted. In fact, their health status was $SEF$ at the time of arrival, but they developed a fever not long after. The missed detection rate could not be estimated because the number of travelers with a health status $SE$ was not known. The discussion here highlights the difficulty in determining the effectiveness of a health screening strategy due to insufficient data or good estimates of the number of travelers in each of the health categories.

### 5.7. Sensitivity of fever prevalence rate

The analysis presented in the previous sections assumed that 87% of the travelers who were sick with Ebola had a fever (i.e., fever prevalence rate of 87%, or $P(SEFSE) = 0.87$). This percentage is based on the estimation by Gostic et al. (2015). This section presents the cases when the fever prevalence rate increased to 95% (i.e., the fever became more common among the travelers who were sick with Ebola) and dropped to 50% (i.e., fever becomes less common among the travelers who were sick with Ebola). The results gave an indication on the effectiveness of the health screening strategies if the characteristic of the observable sign is different. Obviously, if the fever prevalence rate was only 50%, detecting the person infected with viral agent by measuring body temperature was not as effective as anticipated. Similar to Section 5.3, the analysis present in this section is independent of the $P(SE)$ value.

Fig. 7 plots the correct detection rates of the four screening strategies, each simulated with fever prevalence rates of 95%, 87% and 50%, respectively. When there was no screening, the fever prevalence rate did not matter. For the same screening strategy, the correct detection rate increased with the fever prevalence rate. This figure shows the importance of understanding the symptoms of the infectious disease, health status disparities, and the symptoms’ prevalence rates. The screening stations should be designed for detecting the sign that has the highest prevalence rate as the indirect way of identifying travelers who are sick with the disease.

Fig. 8 plots the missed detection rates for the four simulated health screening strategies each with fever prevalence rates of 95%, 87% and 50%, respectively. In all these screening strategies, the number of
tried to leave the three West African countries for the United States and detected 83.4% of the travelers who were sick with Ebola, and who occurred in West African countries from 2014 to 2016. Based on the simulation results, we concluded that the correct detection rate increased in a parallel fashion with the fever prevalence rate. Based on the results of the experiment, the following recommendations are suggested:

1) The most effective way to identify travelers who are infected with an infectious disease is to detect the symptom of the disease that has the highest prevalence rate;

2) If health screening resources are limited during an epidemic or pandemic, screening stations should first be set up at the departure terminals at the airports of the disease affected countries to conduct exit screening;

3) If additional resources are available, and if the authority wishes to achieve a higher correct detection rate and lower missed detection rate, additional health screening stations may be established at terminals at the destinations and/or connecting airports. Prior to making this decision, the decision maker should perform an incremental benefit/cost analysis, using the simulation framework established in this research to evaluate the increase in the correct detection rate. The benefits of interrupting the trips of additional travelers who are infected with the infectious viral agent is compared against the cost of space, devices, printing of questionnaires and staff at the new screening stations. The cost of a miss detection should also be considered.

The main contributions of this research are the results of the simulation experiment, which led to the above recommendations. This research has also established a framework to conduct simulation experiments to evaluate the effectiveness of health screening strategies that can be applied to other infectious diseases.

The health screening strategies investigated in this research produced different outcomes of interest to at least two major stakeholders in the air transport industry. If health screening is to be implemented at an airport, the airport management will be concerned with the space in terminals to set up the screening stations. The number of travelers interrupted at the trip origins and transfer airports affect the passenger load and flight schedule. More importantly, airlines will be concerned with the health condition of its staff and customers.

Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jairtraman.2018.11.006.

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