Effect of Preventive Strategies on Influenza Transmission during a Commercial Flight

Mojtaba Zargoush

A Thesis
in
the Department
of
Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science (Industrial Engineering) at
Concordia University
Montreal, Quebec, Canada
31 October 2019

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Mojtaba Zargoush

Entitled: Effect of Preventive Strategies on Influenza Transmission during a Commercial Flight

and submitted in partial fulfillment of the requirements for the degree of

Master of Science in Industrial Engineering

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final Examining Committee:

Dr. Mehdi Hojjati_______________ Chair

Dr. Daria Terekhov______________ Examiner

Dr. Ali Nazemi_________________ Examiner

Dr. Ali Akgunduz_______________Supervisor

Dr. Ketra Schmitt_______________ Supervisor

Approved by _______________________Waizuddin Ahmed___________________

Chair of Department or Graduate Program Director

31 October 2019 ____________________Amir Asif_________________________

Dean of Faculty

ABSTRACT

Effect of Preventive Strategies on Influenza Transmission during a Commercial Flight

Mojtaba Zargoush

Every day Infectious diseases lead to hospitalization and the death of many people all over the world. Among these diseases, influenza has been a big concern to governments and health authorities. This dangerous disease is influenced by developing worldwide transportation networks during the 20th century.

In this study, we are investigating influenza transmission in an airplane cabin (Boeing 787 model in Air Canada Airline) during a commercial flight. Many factors influence the transmission of an infectious disease in an aircraft such as flight duration, ventilation system, interior design of the cabin, and behaviors of passengers and crew members. Along with these factors, several preventive actions can be taken to reduce influenza transmission in this environment, such as vaccination, wearing face mask, performing hand hygiene, and keeping distance from infected passengers.

Many studies have assessed the effect of performing such protective strategies in different settings like hospitals or schools that have the potential of providing a higher chance of getting infected.

Here we are using the Agent-Based-Model approach to simulate the spread of influenza in an airplane cabin. By using this flexible approach, we are showing the effect of performing one protective action or a combination of different actions on influenza transmission. Results show that all preventive strategies can be affected by different levels of efficiency and combination of different preventive strategies has the most effectiveness. In addition, we have concluded that participation of infected individuals in protective actions will increase the efficiency of each strategy more than other individuals.

AKNOWLEDGMENT

First and foremost, I would like to express my honest gratitude to my supervisors, Dr. Ketra Schmitt and Dr. Ali Akgunduz, whose knowledge, expert guidance, and patience encouraged me throughout my study. Their guidance helped me in all the time of research and writing of this thesis. It was a great honor to work with such exemplary mentors and human beings.

Besides, I declare my genuine appreciation to my wife, my parents, and my beloved siblings for their unconditional love and supporting me spiritually throughout my life.

CONTENTS

List of Figures

List of Tables

1 Introduction

1.1 History and Impact

Infectious diseases put people's lives at risk all over the world each year, and governments spend billions of dollars on preventing and curing these diseases. Environmental conditions have a substantial impact on the spread and aggressiveness of the infectious disease virus (Memarzadeh, 2012). With the growing climate change-related concern and its public health impacts, the danger of various infectious diseases such as Ebola, HIV, Mumps, Yellow Fever, and influenza is also on the rise.

Only in 2017-18 of the influenza season, 79,000 deaths, 960,000 hospitalizations and 49 million illnesses have been estimated caused by influenza in US (CDC, 2019.a). Influenza is one of the most frequent contagious diseases and among the most difficult ones to control, due to its rapid evolution, persistence in different environments, and varying starting time and attack rate for each season. There have been four major pandemic influenza in the history that has led to morbidity and mortality of millions of people across the world. According to Johnson & Mueller (2002), between 1918 and 1920, Spanish flu has the highest number of flu-related deaths of approximately 50 to 100 million people. After that, Asian flu (1957-1958), Hong Kong flu (1968-1970), and Swine flu (2009-2010), respectively, resulted in the deaths of 1-2 million, 0.5-2 million, and up to 575,000 individuals (Saunders-Hastings & Krewski, 2016). According to the Centers for Disease Control and Prevention (CDC), in 2003, the United States spent approximately $10.4 billion for the hospitalizations and patient visits caused by influenza alone (Molinari et al., 2007). There are several other significant costs associated with flu such as vaccination, other preventive actions taken by governments and healthcare authorities, and the costs associated with the resulting absenteeism in schools and workplaces. Based on healthcare outcomes in 2015, it was estimated that an average of $11.2 billion economic costs is imposed to healthcare system and country by influenza in the USA each year (Putri, Muscatello, Stockwell, & Newall, 2018).

1.2 Background

Influenza is divided into four groups; A, B, C, and D, where types A and B are usually the leading cause of the influenza outbreak. The influenza virus generally survives up to 24 hours on different surfaces depending on the temperature, humidity, and type of the surface (NHS-UK 2018). It has the most infectiousness rate during the first three-four days of getting infected (CDC, 2019.b). The influenza virus transmits from an infected person to a susceptible person. Viruses can be transmitted when a susceptible person breathes the particles affected by sneezing, coughing, or talking. Direct transmission happens when a susceptible person has a direct human to human contact with an infected person. Indirect transmission, on the other hand, happens when a susceptible person touches a contaminated surface through droplets caused by sneezing, coughing, or talking to an infected person.

The probability of becoming infected by the influenza virus varies depending on many factors such as the attack rate, which can range from 5–10% in adults and 20–30% in children (Tafalla, Buijssen, Geets, & Vonk Noordegraaf-Schouten, 2016). It also depends on the time of the flu season, individual health status, age, and effectiveness of preventive actions like vaccination, washing and sanitizing hands, etc.

1.3 Research Gap and Motivation

Using public transportation is considered risky as it facilitates exposure to infection. Influenza is one of the most dangerous diseases that is influenced by developing worldwide transportation networks during the 20th century (Tatem, Rogers, & Hay, 2006). While most air quality studies indicate that in-flight air quality is quite high, many consider air travel to be particularly a risky mode of transport (Gendreau, 2010). Moreover, Wagner, Coburn, & Blower (2009) discussed that monitoring influenza spread at an airplane cabin, and especially at the time of pandemic had been proven to be an impactful strategy to decrease costs associated with this disease. In this work they have calculated the potential of Influenza spread in different sections of Boeing 747 airplane cabin and resulted that risk of Influenza transmission in the economy parts of the cabin is higher.

According to the International Civil Aviation Organization (ICAO), around 4.3 billion passengers used airplanes for their trips in 2018, a 6.4 % increase from 2017 (ICAO, 2018). Given the large and increasing volume of air travelers, managing influenza virus transmission in airplanes is essential for public health, and this constitutes the main motivation for conducting the current study. In the next paragraph, I will provide more details about the influenza transmission in an airplane.

In addition to the general factors that affect virus transmission, since airplane cabins are enclosed spaces, additional specific transmission risk factors must be considered. These factors include:

- Human movement pattern

During a flight, an infected person movement in a small and closed environment, such as an airplane cabin, has a significant role in spreading the virus. Crew member movements and their contact with passengers, as well as passengers' movement is an important factor for the inflight infectious disease spread (Han et al., 2014).

- Ventilation system

Among all factors impacting disease transmission in an aircraft cabin, the ventilation system in airplanes is one of the most influential ones. Moser et al. (1979) show that as a result of a delay in a three-hour flight, in an airplane that did not have a ventilation system at that time, one influenza-infected person led to the illness of 72% of passengers within three days after that flight.

Fortunately, modern commercial aircrafts use a high-efficiency particulate air filter (HEPA). Installing these filters for cleaning recirculated air in the cabin and regular air exchange during the flight significantly reduces particles transition in an aircraft (IATA, 2018).

- Individual preventive behavior

Several preventive activities such as hand washing, using a face mask, vaccination, regular sanitizing, covering mouth and nose while sneezing, coughing, or talking are very effective in reducing virus transmissions (Jefferson et al., 2008).

- Cabin interior design

Because of the existing airflow during a flight, the cabin interior design can play a vital role in the movement of droplets and particles caused by sneezing or coughing. The personalized ventilation system has been proven to be very efficient in cleaning the personalized air in-breath (Elmaghraby, Chiang, & Aliabadi, 2018).

- Flight duration

Longer flight time allows more opportunity for disease transmission from an infected person to a susceptible person (Wagner et al., 2009).

As one can imagine, an accurate consideration of the above factors in the calculations of the transmission rate of a disease is critical and complex. Most researches investigate only one of these factors at a time. To fill this gap, in this thesis, we aim to determine the inflight transmission rate of the influenza virus from an infected passenger or crew member to a susceptible passenger or crew member using extensive scenario analyses based on Agent-Based Model Simulation (ABMS) approach. To this end, first, we model the whole problem using simulation modeling. We made this choice because the flexibility of the simulation modeling in considering many variables with multitude of parameters and complex relationships. Then, we design several scenarios, where we consider one preventive action or a combination of more than one action to be made by both susceptible and infected persons. Third, we conduct extensive scenario analyses, where we assess the spread of disease and attack rate under each scenario. Finally, for the comparative analytics purposes, after comparing all the scenarios and the associated strategies, we identify the effective strategies for reducing inflight influenza spread.

2 Literature Review

In this chapter, we will talk about different methods and applications that have been applied to study the spread of influenza in the airplane. Then a history of using the Agent-Based Model Simulation and Compartmental model about infectious diseases, especially influenza, will be reviewed.

2.1 Influenza in airplane

There are few documented cases about real flight spread of Influenza viruses. One example involved the spread of Influenza type A during a commercial flight with 54 passengers and crew members by Moser et al. (1979). The result of this study shows that after three days, 72% of the passengers were infected and were showing symptoms like cough, fever, headache, and so on. In this case, the plane had a delay of 3 hours, and during this delay, the ventilation system was out of action. The high rate of transmission in this study was because of an inoperative ventilation system during the delay. Klontz et al. (1989) described the outbreak of Influenza among a military unit. They figured out that the attack ratio was the same, at 37% level, for those who were vaccinated and those who were not.

More studies are available detailing simulated disease spread. Applying Detached-Eddy Simulation model with a Lagrangian technique, Wang, Lin, & Chen (2011) simulated airflow and deposition of particles produced by breathing and coughing in a cabin mock-up with four rows. They tested two kinds of airflow. One was breathing in which they found that 35% of small size (0.7 μm) particles, 55% of medium (10 μm) particles, and 100% of large (100 μm) particles dropped on the surface of the cabin. Besides, they tested the coughing case, and they came up with 48%, 68%, and 100% of the deposition rate for small size, medium-size, and large-size particles, respectively.

In (Han et al., 2014), the spread of aspiratory disease because of passenger and crew member movement was studied. They compared the effect of different movement patterns of susceptible passengers, the infected passengers, and the crew. Based on this research, human movement is an important factor influencing the transmission of infectious diseases significantly.

Chen et al. (2012) developed a mathematical formulation to simulate the most critical generative activities of expiratory droplets. They used the Computational Fluid Dynamic (CFD) technique to see what is happening inside an aircraft cabin when an infected person coughs, sneezes, or talks and how the particles are transmitted inside a cabin. They concluded that the substance airflow has the most significant impact on the particle transmission inside a cabin.

Wagner et al. (2009) modeled the airborne transmission of particles of Influenza A within an aircraft. They came up with the results showing that if the source case is traveling in Economy Class, the virus transmission during the flight is significant. To be more precise, the likely infections are two to five during a flight of 5 hours, 5 to 10 and 7 to 17 during an 11-hour flight, and a 17-hour flight, respectively.

According to (T. Zhang & Chen, 2005), using mixing ventilation (MV) systems may increase the likelihood of getting infected, particularly during a long flight. The main reason is said to be the mixing effect of using such ventilation systems.

An investigation was done by Sze To et al. (2009) in which they simulate a cough in an airplane cabin replica with three rows of seats and each row had seven seats. The result showed that even by equipping 100% fresh air and using high-efficiency particular air filters (HEPA), the expiratory particles were transmitted to the passenger sitting two rows from the source of cough in 20-30 seconds.

Based on (Papineni & Rosenthal, 1997), sneezing, talking, and coughing are three main activities generating particles during a flight. Since the infected person coughs more often than sneezing, the number of particles spread in the air caused by coughing is more than the one caused by sneezing, whereas, in each time that a person sneezes generate more particles than when he coughs. Using real data, Li et al. (2016) examined how airflow designs influence contaminant circulation in an aircraft cabin. The actual data was used to validate the numerical fluid dynamics model (CFD). The study concludes that the airflow patterns inside aircraft cabins can be altered to achieve better control of the spread of airborne contaminants. Using an extensive experimental approach, Dygert & Dang (2012) re-examine the results of the previous CFD studies which investigate the effectiveness of mitigating cross-contamination within an aircraft cabin using local exhaust. The results of these studies agree with the earlier studies and exhibit decreases in exposure to armpit-released contaminants of 30-60%. The effectiveness of personalized ventilation with seat headrest-mounted air supply terminal devices (ATD), also called seat headrest personalized ventilation (SHPV), was assesses in (Melikov, Ivanova, & Stefanova, 2012). In doing so, physical metrics using a breathing thermal manikin were employed to determine its ability to provide clean air to the inhalation system. Tracer gas intensity in the air inhaled by the manikin was used to examine the fresh air supply efficiency of the SHPV. The study suggests a significant improvement in the quality of the inhaled air and a reduced risk of airborne cross-infection in the presence of SHP.

2.2 Agent-Based Model Simulation and Influenza

Agent-Based Model Simulation (ABMS) is an efficient tactic to investigate and model infectious transmission and spread. In this method, each person with specific behavior is called an “agent” which interact with each other based on some rules. Agents have their behavior, location, characters, and movement pattern. Agents’ attributes and behavior can change during the time, they can have their characteristic based on probability distributions, and finally, agents can remember their history in the system at any state. Using this approach helps us to study and explore interactions between agents and the role of each person on spreading infection in an environment under several scenarios and consequently obtaining a strategy to decrease infection spread in a population.

An Agent-Based Model Simulation was developed to study different preventive strategies against influenza in Egypt. In this study, a population of 1000 and potential infected of 3 persons at the beginning of the model running was simulated. Results showed that after ten days and without any control strategy, 608 susceptible people were infected (Khalil, Abdel-Aziz, Nazmy, & Salem, 2012). Karimi, Schmitt, & Akgunduz (2015) used ABMS to see the effect of individual behaviors on influenza spread in a school setting. Their result showed a reduction of 17% in attack rate and 34% in the secondary infected population during the peak of the influenza season.

In 1976, an Agent-Based Model was developed to simulate the Spanish pandemic influenza that happened in 1918. In this study, 1000 people of different ages, living locations, schools, and activity environments were simulated. Based on patterns detected in Asian and Hong Kong flu pandemic, a transmission hazard rate for different age groups were achieved (Elveback et al., 1976).

Results of a study done by Putro et al. (2008) using ABMS in the population of Indonesia suggest that the government, to fight against influenza spread, should consider both medical and social interaction perceptions simultaneously. In another agent-based model done in 2005, optimal vaccine distribution policy was investigated to slow down the attack rate of influenza spread in a population of 2000 people with different age groups (Patel, Longini, & Halloran, 2005).

Many other studies are using ABMS to explore the spread of infectious diseases under different preventive scenarios in the real world among large scale populations (Haber et al., 2007), (Das, Savachkin, & Zhu, 2008).

In one study, an agent-based model simulation was developed to examine the spread of influenza for Poland’s population (38 million), under different transmission rates in both rural and urban areas (Rakowski, Gruziel, Bieniasz-Krzywiec, & Radomski, 2010).

Another simulation model with 1.1 million agents tested different strategies to help healthcare managers to make decisions, at the time of the epidemic by considering many factors such as vaccination, human activities, hospitalization, the status of disease and protective strategies (Das et al., 2008).

There are four potential ways of influenza transmission from a person to another one (Brankston, Gitterman, Hirji, Lemieux, & Gardam, 2007)

- Direct contact: In this case, a susceptible person gets infected through direct physical contact with an infected person.
- Indirect contact: This kind of transmission happens when a potential susceptible host touches surfaces or objects that are contaminated with the virus.
- Droplets: droplets are particles with a size of > 5 µm and results of speaking, coughing, and sneezing of an infected person. When droplets make their way inside the mouth or nose of a susceptible person, transmission happens.
- Airborne: particles with the size ≤ 5µm remain suspended in the air and can be transmitted via breathing.

In many models that investigate influenza spread under various situations, mentioned modes of transmission or a combination of them are usually considered, however, the importance of the fact that behavior characteristics of both infected and susceptible groups can affect all these transmission modes is undeniable.

ABMS allows us to assign a variety of self-protective behavior to our test population to gain different reasonable mitigation strategies.

2.3 Compartmental Model

Toward the end of the 18th century, when smallpox was responsible for a massive number of death of children in Europe and Asia, Daniel Bernoulli developed a model in 1766 to estimate the amount of mortality in a population (Dietz & Heesterbeek, 2002). Although his model and results were not completely clear until the early 20th century, this attempt turned smallpox to be the first infectious disease in which a particular intervention was offered against it (Foppa, 2016).

In 1960 due to improvements in antibiotics, sanitation, and vaccination, scientific society and governments were confident that infectious disease would be eliminated. However, contagious diseases continued to be the main reason for mortality in many countries (Hethcote, 2000).

Mathematical technics can significantly help us to recognize the risk of having the potential pandemic disease in society. To achieve useful and accurate results, the model must be developed as close as possible to reality. However, due to the existing trade-off between complexity and accuracy, usually, several models are designed to assess the same event (Walters, Meslé, & Hall, 2018).

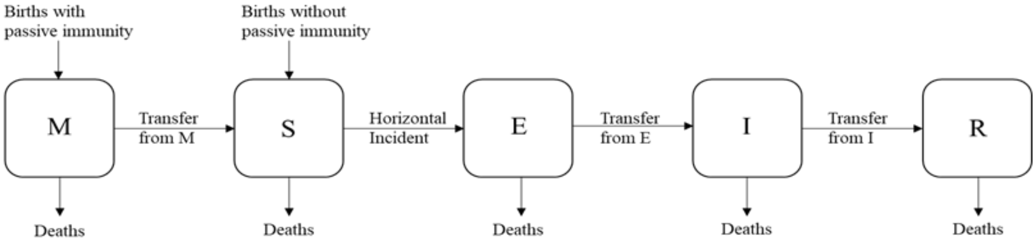
Most of the studies regarding influenza have been using mathematical models to predict different characteristics of an outbreak, support health authorities about health resource distribution and help to choose the best ways of prevention (Nsoesie, Brownstein, Ramakrishnan, & Marathe, 2014).

In the 20th century, a famous mathematical model called Compartmental/MSEIR was developed to track the status of an infectious disease in a population. In this model, the population is assumed to be homogeneous (Hethcote, 2000)

Different labels in this model such as M (mother born with passive immunity), S (Susceptible), E (Exposed), I (Infected), and R (recovered) represent a person's health status regarding the infectious disease. Class M defined for infants who have a temporary passive immunity to the infection because their mother was infected at least once and after that, they enter to susceptible class. Those infants who do not have this passive immunity flow to class S as susceptible.

As can be seen in Figure 2-1 shows the individual flow from each epidemiological class to the next one with a specific rate.

Figure 2-1: The compartmental model; individuals stage transfer(Hethcote, 2000)



Depending on the type of epidemic, population characteristics and situation of case study, there are different patterns between compartments that define several acronyms such as MSEIRS, MSEIR, SEIR, SEIRS, SIR, SIRS, SEI, SEIS, SI, and SIS. (Hethcote, 2000) (Hethcote, 2009).

At any epidemiology class, people might die. Virus transmission happens when a susceptible person has effective contact with infective, then his/her stage changes to E, this stage transformation called "Horizontal Incidence''. When a person is in stage E, she/he is in either latent or incubation periods. Incubation is the period between exposure to infection and appearance of first disease symptoms in which individuals carry the virus but are not able to transmit the infection to a susceptible person. (Hethcote, 2000) (Longini et al., 2005).

Depends on the case, different acronyms of the model can be used. For example, when a person after getting recovered, gains permanent immunity, MSEIR model can be selected, but, if immunity after recovery is temporary, then MSEIRS should be chosen. The SEIR model is considered to be the best method to study influenza infection (Kraemer, 2006).

A study about the influenza outbreak that happened in three Russian cities, Moscow, St. Petersburg, and Novosibirsk, showed that SEIR model fits a majority of outbreak incidence (Leonenko & Ivanov, 2016). Urashima, Shindo, & Okabe (2003) developed a model to study the relation of weather conditions and time of the influenza season in Tokyo, Japan. They used surveillance data from 1999 to 2002 and results validate the model with a 75% correlation.

In another study about the 1918 influenza epidemic, an SEIR model was fitted to pneumonia and influenza death in 45 US cities. The results showed that the similar subtype of influenza could be controlled, and death numbers related to 1918 flu is not as significant as other infectious diseases (Mills, Robins, & Lipsitch, 2004).

In 1926, the concept of thresholds for epidemics was presented by (Kermack & McKendrick, 1991). This concept is usually shown as R_0 and called basic reproduction number, which indicate the last number of infected individuals within a population that can cause epidemics (Pellis, Ball, & Trapman, 2012). R_0 is the average number of individuals who get the infection from one initially infected person. If R_0 is more than one; it means an infected person can transmit the disease to more than one person and consequently leads to the spread of an epidemic. Otherwise, if it is less than one, an infected person will infect less than one individual in the population, and there will be no outbreak (Hethcote, 2000).

Estimating the basic features of a disease can be advantageous to adopt strategies in the level of vaccination and treatment to control influenza. A review study of influenza modeling studies indicates that R_0 for influenza A is estimated to have a value between 1.4 and 1.6. Basic reproduction for pandemic influenza 1918 was estimated to have a mean value of 2, and the range of 1.4 to 2.8 (Coburn, Wagner, & Blower, 2009).

In this study, we will use Susceptible-Exposed-Infected (SEI) acronym of the compartmental model that suits our case study to determine the effect of different preventive strategies during commercial air travel, since except for initial infected passengers, all other passengers are susceptible, and we are assuming that after transformation from susceptible stage to infected, there is no possibility of recovery and death.

3 Modeling and Simulation Development

3.1 Formulating Influenza Transmission

The horizontal incidence which is the same as the health status transformation of a person from Susceptible to Exposed is the first transfer rate to be computed in the MSEIR models in order to determine the number of susceptible individuals in a population who is exposed to the virus. As mentioned before, people who get exposed will enter either latent or incubation period. The probabilities that an exposed person stays in the latent period have been summarized in Table 3-1. These transfer rates can be calculated according to (Hethcote, 2000) and based on the number of infected persons in a population and effective contacts that a susceptible person has with other infected individuals.

Table 3-1: Probability of staying in Latent and infection period(Longini et al., 2005)

Latent Period		**Infection Period**	
Duration (days)	Probability	Duration (days)	Probability
1	30%	3	30%
2	50%	4	40%
3	20%	5	20%
4	-	6	10%

Moreover, two other transfer rates in MSEIR model, which are a: from compartment Exposed to Infected and b: from Infected to Recovered, can be calculated based on the number of individuals in each stage and the average time that individuals stay in the next stage (Hethcote, 2000).

In a simulation model, like ours, which uses the rules of the SEIR model, the total number of individuals in the studied population at the beginning of simulation, denoted by N, is the sum of all individuals in each compartments S, E, I, and R. This number can be changed at any time during the simulation to account for the possibility of deaths. Therefore, at any time t of the simulation, the total population is

$$N(\mathrm{t}) = S(\mathrm{t}) + \mathrm{E(t)} + \mathrm{I(t)} + \mathrm{R(t)}$$

Where $S(t), E(t), I(t),$ and $R(t)$ are the number of susceptible, exposed, infected, and recovered persons at time t.

Accordingly, the fractions of infection, exposed, susceptible, and recovered can be calculated by using equations 1, 2, 3, and 4 respectively, as follows:

$$f_I(t) = \frac{I(t)}{N(t)} \qquad (1)$$

$$f_E(t) = \frac{\mathrm{E}(t)}{N(t)} \qquad (2)$$

$$f_S(t) = \frac{\mathrm{S}(t)}{N(t)} \qquad (3)$$

$$f_R(t) = \frac{\mathrm{R}(t)}{N(t)} \qquad (4)$$

Therefore, if we consider β the average number of contacts that a susceptible person has in a unit time with all types of compartments, the average number of contacts with infectious will be $\frac{\beta I}{N}$, and the number of new cases (incidence) can be computed as $\left(\frac{\beta I}{N}\right) S = \beta I f_N f_S$ (Hethcote, 2000).

Using mathematical or simulation models in order to investigate an infectious disease spread requires collecting accurate data to estimate the parameters. Although many factors influence the results of such research, one of the most critical parameters that need to be accurately quantified is the probability of disease transmission between individuals. Even with a large number of research and experiments in the area of infectious disease transmission and specifically in the literature of influenza transmission, there has been no promising validation of the transmission risk between a susceptible and infected individual (Brankston et al., 2007). However, in most of the simulation models on influenza transmission, hazard rate estimation is usually used to calculate the probability of influenza transmission in a population (Haber et al., 2007). This hazard rate, which depends on the age of both susceptible and infective groups, is denoted by λ. Table 3-2 summarizes different values of this parameter, which are estimated by Haber et al. (2007) for different age groups.

Table 3-2: Transmission rates (λij) from an infected person in age group i to a susceptible person in age group j. (Haber et al., 2007)

	The age group of susceptible j			
The age group of infected i	0–4	5–18	19–64	>65
0–4	0.00059	0.00062	0.00033	0.0008
5–18	0.00058	0.00061	0.00033	0.0008
19–64	0.00057	0.00053	0.00032	0.0008
>65	0.00057	0.00054	0.00029	0.00102

As can be seen, the largest value of this rate is 0.00102 which pertains to individuals aged 65+ years who are considered a high-risk group defined by the Centers for Disease Control and Prevention (CDC, 2018.a). In our study, we are using the hazard rate of 0.00032 which covers individuals (both infected and susceptible) with the 19 to 64 years old age range.

The transmission of the influenza virus can happen when a susceptible individual is in physical contact with an infected one within a radius of 1.88 meters. The probability of this transmission in t minutes can be calculated as:

$$P(infection) = 1 - e^{-\lambda t}$$

Note that a susceptible person might have contact with infected individuals in different locations or with more than one infected person at the same location. Also, in our case, it is possible to have more than one infected passenger sitting beside a susceptible person with a distance of less than 1.88 meters or one person might have many different interactions with the infection in different parts of the airplane (for instance sitting near a sick person or using a contaminated lavatory). Therefore, the infection probability can be calculated for all infectious contacts in the following way:

$$P(infection\ for\ n\ contacts) = 1 - e^{-\lambda \sum_{i=1}^{n} t_i}$$

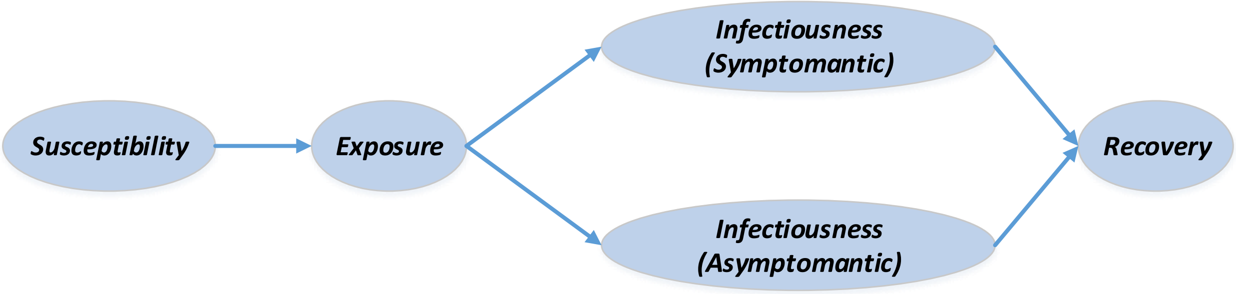
Where t_i is the time that a susceptible person spends in contact with an infected one during contact number i.

3.2 Other Transmission Parameters

As discussed in section 2.3, the choice of the compartmental model and corresponding acronym depends on the disease and scenario being modeled. We explain the choice of an acronym in the following paragraphs.

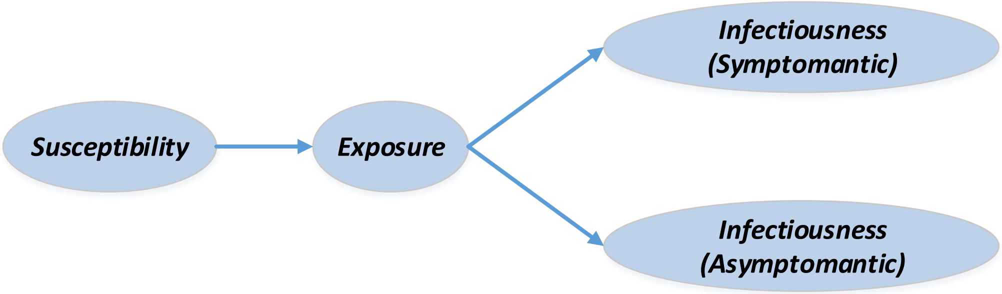
As illustrated in Figure 3-1, when a susceptible person is exposed to an infection, she/he will enter a period which is called latent or incubation period, and in both of these stages, they are not able to transmit the virus. After that, the exposed person becomes infected (stage I). Stage I is into two categories, either symptomatic infected or asymptomatic infected. Finally, the last stage is recovery (R) of the infected person (Elveback et al., 1976). At any model stage, there is a possibility of death for that individual. Due to its insignificant impact, in our study, we neglect the possibility of death.

Figure 3-1: health status of individuals in different stages of disease



In this study, we use an agent-based discrete event simulation model to determine how influenza transmission can be affected by different protective strategies in a commercial flight. Our model does not consider outcomes after leaving the aircraft, which means we do not need to consider recovery stage R in our model. In order to determine the correct acronym for the compartmental model, we note that the average latent period for individuals who are carrying the influenza virus is 1.9 days (Longini, Halloran, Nizam, & Yang, 2004), or about 45 hours. After that time, she/he will enter the infectiousness stage. However, the longest non-stop commercial flight ever took almost 19 hours offered by Singapore Airline (SIA), which was from Singapore to New York USA (Porter, 2018). Therefore, in our model, an exposed individual can become infected, but that individual cannot transmit the virus to other passengers or crew and is only carrying the virus. As a result of this, we will use S-E-I (susceptible-Exposed-Infected) model in our study. Figure 3-2 shows the resulting acronym for our simulation model.

Figure 3-2: Chosen acronym in this study

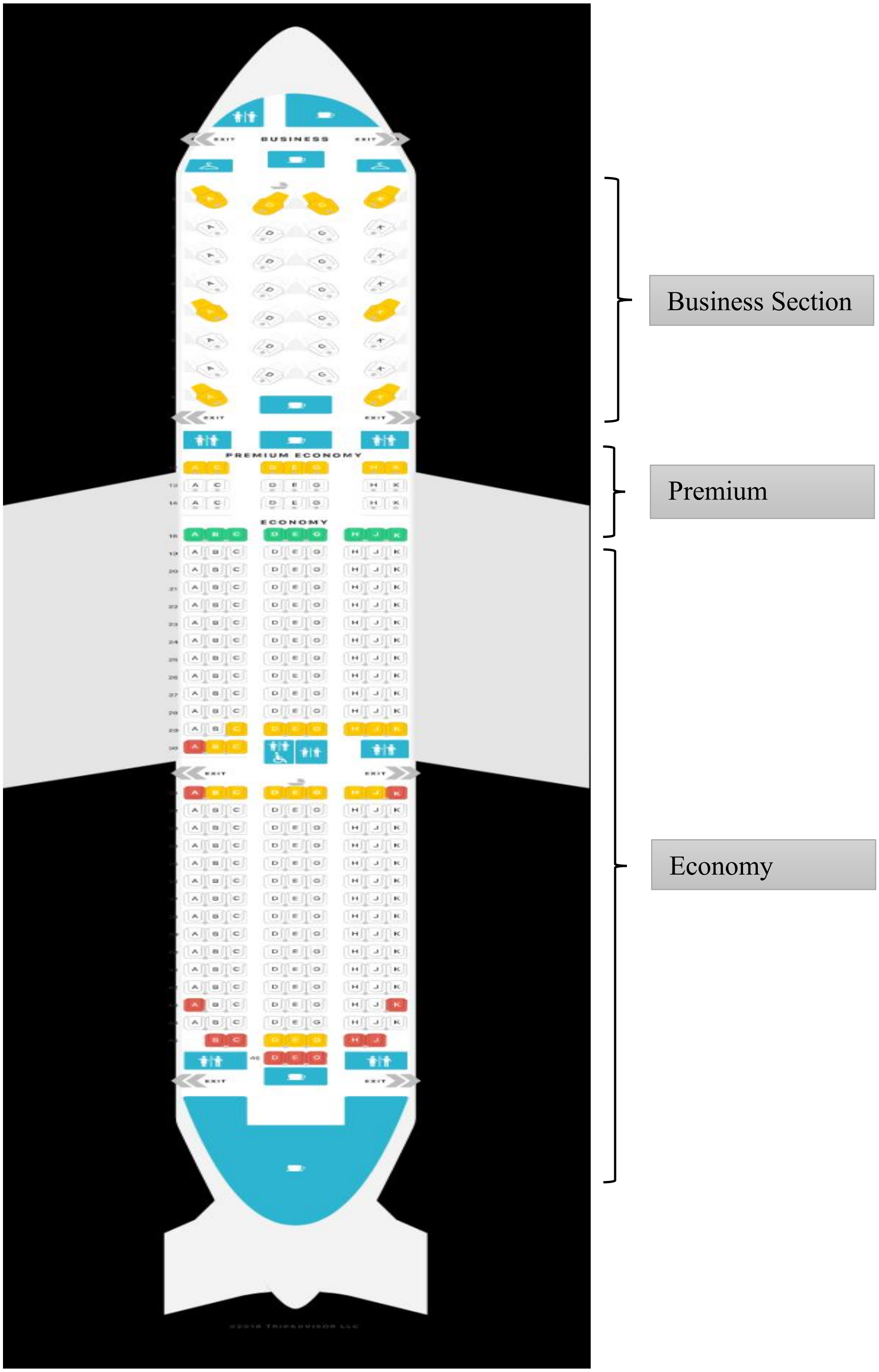


3.3 Airplane and Seating Configurations

In order to accurately model infectious disease transmission in an airplane, it is essential to specify the type of aircraft as well as the airline, which determines the configuration and the number of lavatories. The interior design may vary for the same airplane among or even within airlines. For example, both Air Canada and Emirates airlines use Boeing 777-300ER (77W), Three Class Layout 1. In Air Canada, however, this airplane has 40, 24, and 336 business, premium economy, and economy seats, respectively, and eight lavatories in the whole airplane (www.seatguru.com, a). However, this airplane in Emirates has eight first-class, 42 business, and 304 economy seats with 12 Lavatories overall (www.seatguru.com, b).

In our simulation model, we have chosen the Boeing 787-9 (789) of Air Canada. Figure 3-3 depicts the interior design of this airplane. It should be mentioned that we can change the type of airplane in our model by changing parameters that represent seats' numbers and distances based on the interior design of the studied airplane.

Figure 3-3: Interior design of Boeing 787.9 (789) airplane (www.seatguru.com,c)


BUSINESS
EXIT
PREMIUM ECONOMY
ECONOMY
Business Section
Premium
Economy
©2018 TRIPADVISOR LLC

Other details of the interior design and seat configuration of Boeing 787-9 of Air Canada are summarized in Table 3-3 and 3-4.

Table 3-3: Seating details of Boeing 787

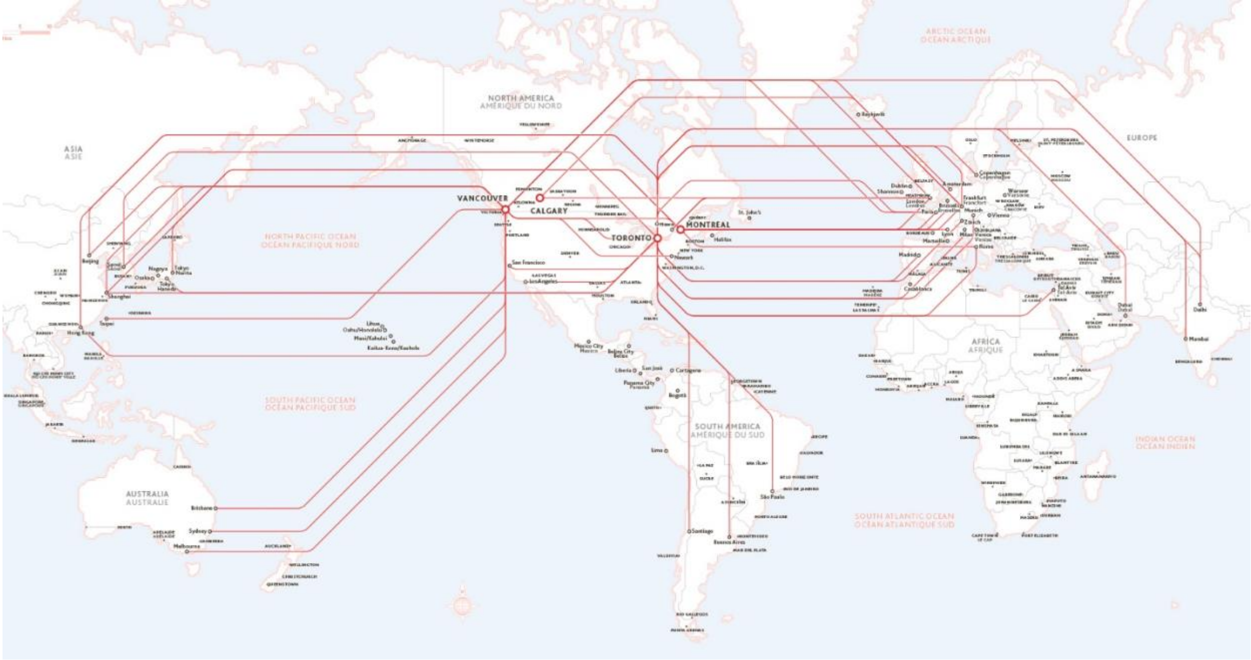
Class	Pitch	Width	Number of Seats
Business	80”	21”	30 flatbed seats
Premium Economy	38”	19”	21 recliner seats
Economy	30”	17”	247 standard seats
Total Number of Seats			360

Table 3-4: Seat Configuration of Boeing 787

Class	Seat Configuration	Rows
Business	1-2-1	1 - 8
Premium Economy	2-3-2	9 - 11
Economy	3-3-3	12 - 40

Moreover, Air Canada uses Boeing 787 for 33 different destinations across the world and from several origins. Figure 3-4 displays the route network for this airplane.

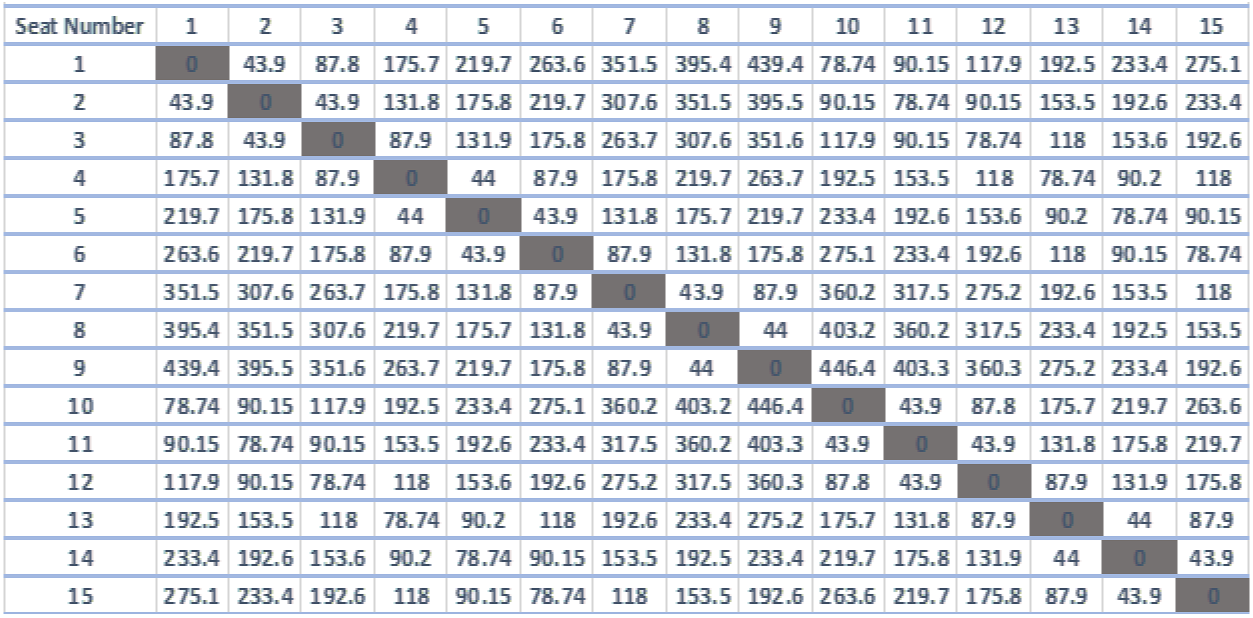
Figure 3-4: Rout network of Boeing 787 in Air Canada airline(captured from aircanada.com)



As shown in Figure 3-4, the economy section of the airplane has a smaller room per passenger. Therefore, passengers are in closer proximity and have a lower individual volume of air. All these factors lead to an increased probability of infection transmission (Wagner et al., 2009). In this study, we design our model for the economy class, which consists of around 247 seats for the passengers. Besides, we consider the seven crew members assigned to the economy section. Three crew members are seated behind seats 109, 110, and 111 in the middle of the airplane, and the other four are seated at the end of the cabin near the last galley. This part of the cabin contains rows 12 to 40 with configuration seating 3-4-3.

Distances between each seat to all other seats and lavatories have been calculated based on the dimensions of the Boeing 787-9 which used by Air Canada. An example of distances for seats 1 to 15 can be seen in Table 3-5. These distances have been calculated for 247 passenger seats, seven lavatories, and seven crew seats and will be used in the calculation of the probability of infection later.

Table 3-5: distance of seats 1 to 15 from each other in Boeing 787 (cm)



Seat Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	43.9	87.8	175.7	219.7	263.6	351.5	395.4	439.4	78.74	90.15	117.9	192.5	233.4	275.1
2	43.9	0	43.9	131.8	175.8	219.7	307.6	351.5	395.5	90.15	78.74	90.15	153.5	192.6	233.4
3	87.8	43.9	0	87.9	131.9	175.8	263.7	307.6	351.6	117.9	90.15	78.74	118	153.6	192.6
4	175.7	131.8	87.9	0	44	87.9	175.8	219.7	263.7	192.5	153.5	118	78.74	90.2	118
5	219.7	175.8	131.9	44	0	43.9	131.8	175.7	219.7	233.4	192.6	153.6	90.2	78.74	90.15
6	263.6	219.7	175.8	87.9	43.9	0	87.9	131.8	175.8	275.1	233.4	192.6	118	90.15	78.74
7	351.5	307.6	263.7	175.8	131.8	87.9	0	43.9	87.9	360.2	317.5	275.2	192.6	153.5	118
8	395.4	351.5	307.6	219.7	175.7	131.8	43.9	0	44	403.2	360.2	317.5	233.4	192.5	153.5
9	439.4	395.5	351.6	263.7	219.7	175.8	87.9	44	0	446.4	403.3	360.3	275.2	233.4	192.6
10	78.74	90.15	117.9	192.5	233.4	275.1	360.2	403.2	446.4	0	43.9	87.8	175.7	219.7	263.6
11	90.15	78.74	90.15	153.5	192.6	233.4	317.5	360.2	403.3	43.9	0	43.9	131.8	175.8	219.7
12	117.9	90.15	78.74	118	153.6	192.6	275.2	317.5	360.3	87.8	43.9	0	87.9	131.9	175.8
13	192.5	153.5	118	78.74	90.2	118	192.6	233.4	275.2	175.7	131.8	87.9	0	44	87.9
14	233.4	192.6	153.6	90.2	78.74	90.15	153.5	192.5	233.4	219.7	175.8	131.9	44	0	43.9
15	275.1	233.4	192.6	118	90.15	78.74	118	153.5	192.6	263.6	219.7	175.8	87.9	43.9	0

3.4 Simulation Procedure

In our simulation model, we use the Agent-Based model approach, which suits our case study since it allows us to define the characteristics and behaviors of our agents. Here, we have defined two different agents containing passengers and crew members who have their seats and activities in the economy section of the cabin.

Activities of each passenger include seating, movements from her/his seat to the lavatory and coming back to the seat, waiting in a lavatory queue and ordering private services such as asking for drinks, blanket, food and so on. Also, many characteristics that contain their desire to have a prevention behavior toward infectious disease which will be mentioned later. Crew members' activities are their responsibilities such as serving passengers with regular food and drink services, answering passengers ' private services and their own activities like sitting and using lavatories.

Based on the existing references and our assumptions, various probability distributions have been assumed for crew and passengers' behaviors and their activities.

Figure 3-5 illustrates activities that are done by crew members during a flight. At the beginning of the simulation, seven crew members with seat numbers, 1 to 7 enter the cabin to serve economy parts of the airplane. They are divided into two groups of 3 and 4 members to serve either part 1 or part 2 of the cabin for regular food and drink services. However, to have a quick and satisfactory private service, the first available crew member will be in charge. Between all three activities of crew members, regular service has the highest priority in our simulation since it is done based on a predetermined schedule in any airline.

During crew movements and activities in the airplane, they might be in interaction with infected passengers or contaminated surfaces. Summation of these interactions' times will be calculated and used to check the health status of a crew member at the end of the flight. Besides, each crew member has its own willingness to do protective behaviors which will affect their health status at the end of the flight.

Figure 3-5: Activities and preventive behaviors of crew members during the flight

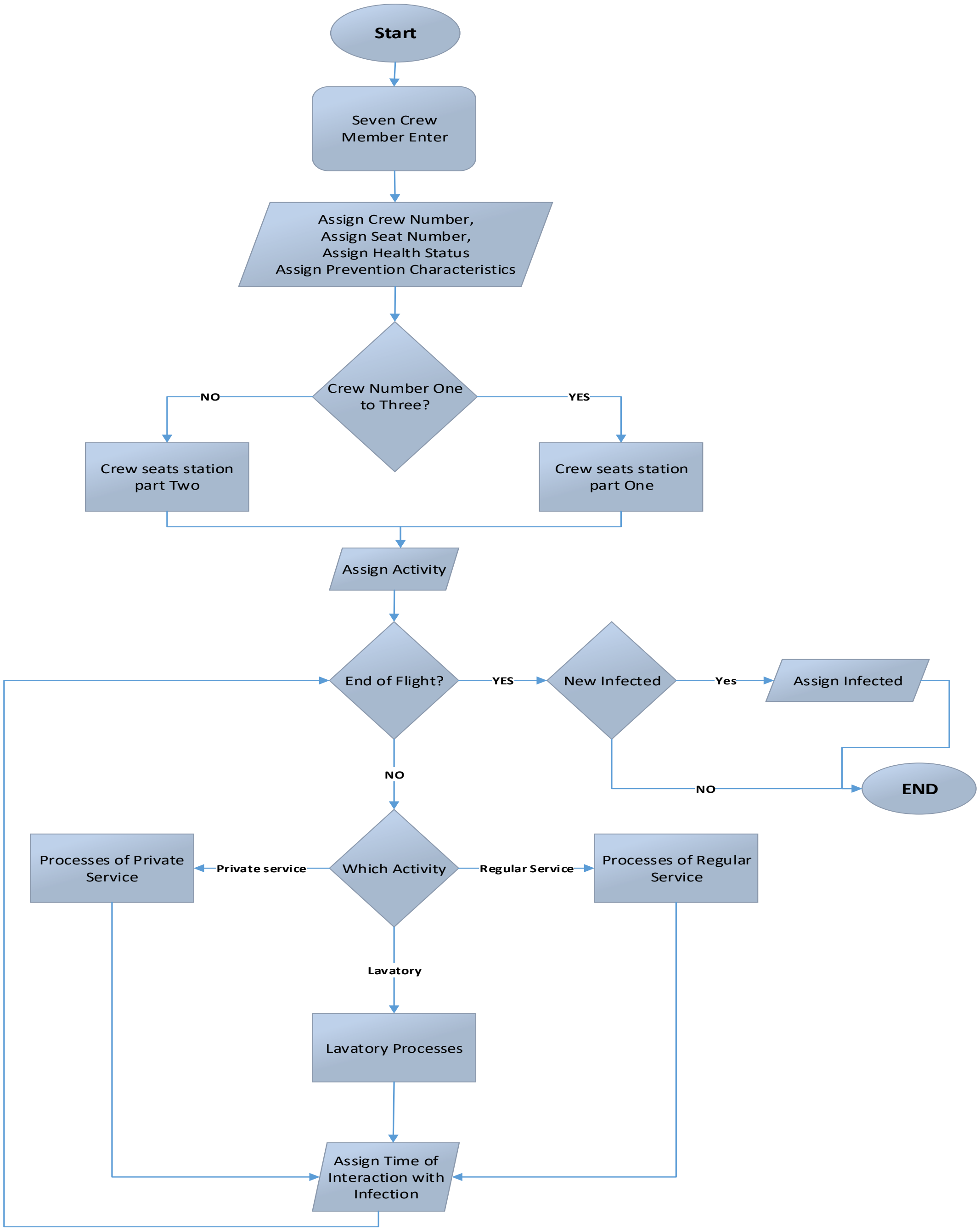
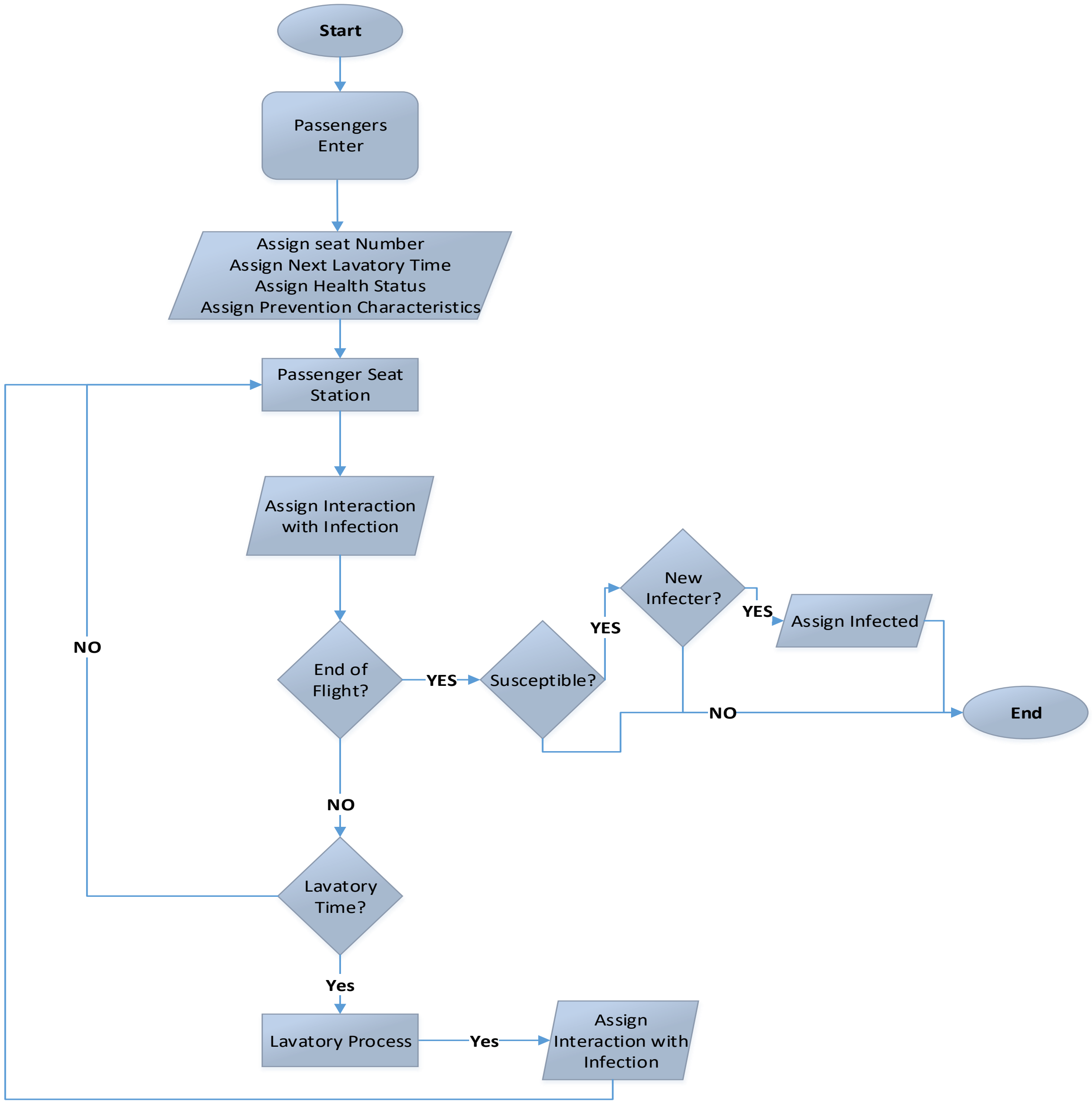


Figure 3-6 summarizes the passengers' activities. At the beginning of flight 247 passengers with different prevention attitudes, enter the airplane, and among them, there are some primary infected persons. The rest are susceptible to infection. Each passenger randomly will be assigned to a seat and get a seat number from seat 1 to seat 247 by using discrete distribution where each passenger has equal chance of getting a seat number. Their activities during the flight determine their chance of becoming ill or remain healthy after the flight. A susceptible passenger might be seated at danger zone that is specified by distance range (less than 1.88 meters) from one or several initial infected passengers or none. Furthermore, she/he has a chance to touch a contaminated surface around the seat or inside a lavatory.

Figure 3-6: Activities and preventive behaviors of passengers during the flight



3.5 Probability Distributions and Assumptions

In this section, we explain all the probability distributions that we derived from literature and the associated assumptions in our model.

3.5.1 Distributions and Assumptions for the Crew Members

- Seven crew members exist in the economy part of the cabin.
- Crew members 1 to 3 are doing regular food and drink services for part 1 of the cabin which includes passengers 1 to 120 and crew 4 to 7 are serving passengers 121 to 247.
- The first available crew member, regardless of her/his location, will answer the private request of a passenger.
- Crew members 1 to 3 only choose lavatories in economy premium part since it is usually empty and close to their seat, and crew members 4 to 7 choose between lavatories in economy part of cabin based on distance and number of persons in waiting line. (They are more likely to choose lavatories at the end of the cabin).
- The time interval between each lavatory usage is exponentially distributed with a mean of 150 minutes.
- Average spending time in a lavatory is assumed to be a Triangular distribution with a minimum of 0.5, mode of 1.5, and a maximum number of 3 minutes.
- Average service time expended during regular service per passenger is assumed to follow a uniform distribution with a minimum of 30 seconds and a maximum of 60 seconds.
- Average private service time per one passenger is uniformly distributed with a minimum of 20 seconds and a maximum of 30 seconds.
- Every 180 minutes, crew members will provide passengers with food and drink services.

- If at the same time, the model asks a crew for more than one activity, including regular service, she/he will first finish the regular service.
- A crew member will not respond to other requests or needs until a scheduled regular service is done.

3.5.2 Distributions and Assumptions for Passengers

- 247 passengers enter the airplane at the beginning of simulation with some of them being infected.
- The number of initially infected passengers is a flexible parameter in the model and can be changed at the beginning of run of simulation.
- The seat number of passengers is randomly assigned to them.
- Each passenger will have different protective approaches to avoid getting sick.
- The time interval between each lavatory usage for each passenger is the same as a crew member: (EXPO (150)).
- Average spending time in a lavatory is assumed to be the same as a crew member: (TRIA(0.5,1.5,3))
- A passenger will choose a lavatory by considering two factors; distance and number of people in the waiting line of that lavatory.
- The time interval between passenger's requests for a private service is exponentially distributed with a mean of 25 minutes.
- A passenger that should be served by a private service is randomly chosen. So, it is possible that one passenger has consecutive requests.
- It is assumed, if an infected passenger goes to the lavatory, she/he will leave contamination on some hard surfaces and contamination will remain for four hours.

3.6 Simulation Implementation

To build our simulation model, we used the academic version of Arena simulation software 15.00.00001. In this section, we will show different parts of our simulation model and explain how our passengers and crew activities are described.

Also, it is crucial to determine enough number of iterations in order to achieve results with a small margin of error. To do that, we are using the formula below (Winston, 2000).

$$N = \left[Z \times \frac{S}{E} \right]^2$$

Where:

N	Number of needed iterations
S= 4.48	The standard deviation of a sample of 15 random iterations
Z= 1.96	For 95% confidence interval (Normal Distribution)
E= 1.5	Preferred margin error

Therefore:

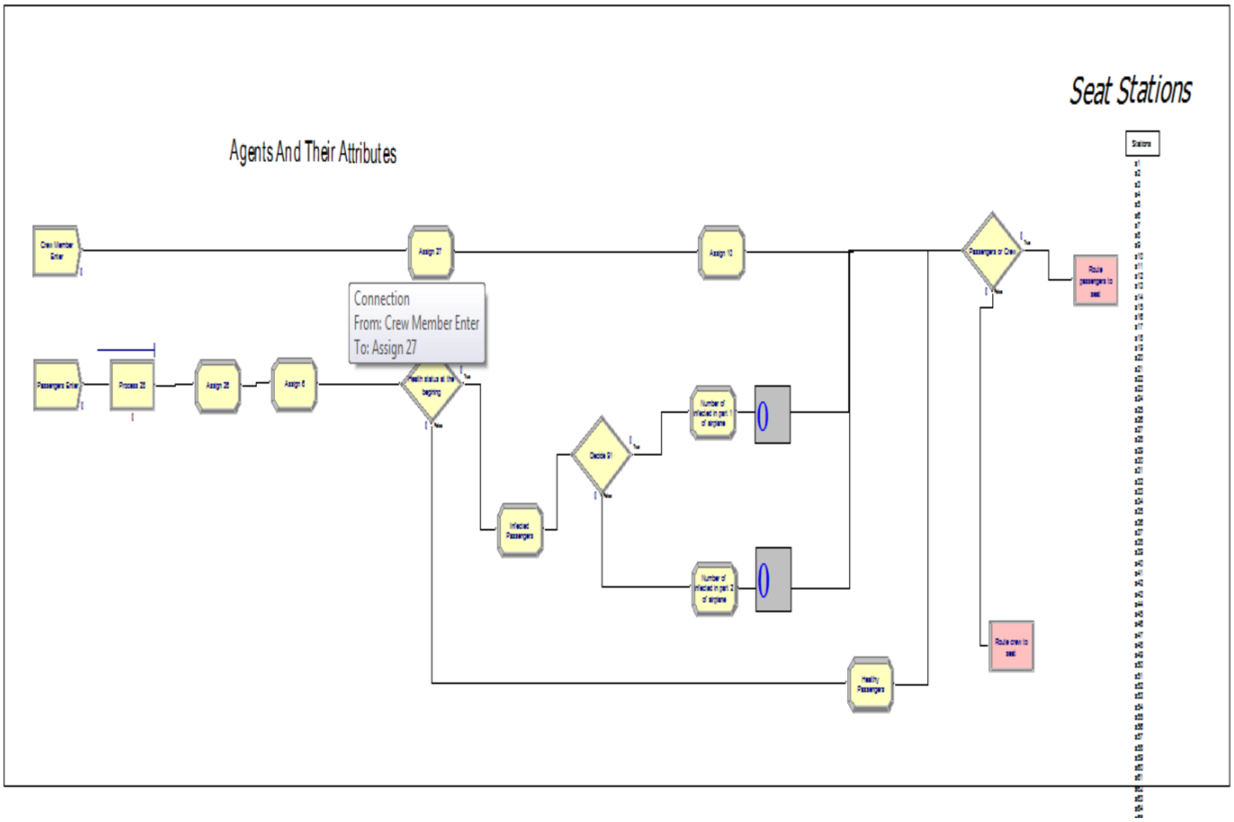
$$N = \left[1.96 \times \frac{4.48}{1.5} \right]^2 = 34.11 \cong 35$$

As a result, we have picked 60 iterations which will give us answers with less margin of error. It should be noted that in addition to this, we have run our simulation for some random scenarios for over 500 iterations and the results were almost the same as running with 60 iterations since our desired margin of error is picked enough small.

3.6.1 Agent's information and their Characteristics

In this section, all agents are created. Crew members and passengers are entering the system and before starting the simulation, all related information and the way that there are acting is attached to them so that the system reads the information. Information provided for passengers in this section including their seat number, lavatory usage distributions, their health status (infected or susceptible), and most importantly their desire to have protective behavior is specified. After giving all the needed information to the system, agents are moved to their seats which are defined as a set of stations in our model. Figure 3-7 shows the Arena software template of this section.

Figure 3-7: Agent’s information and their Characteristics

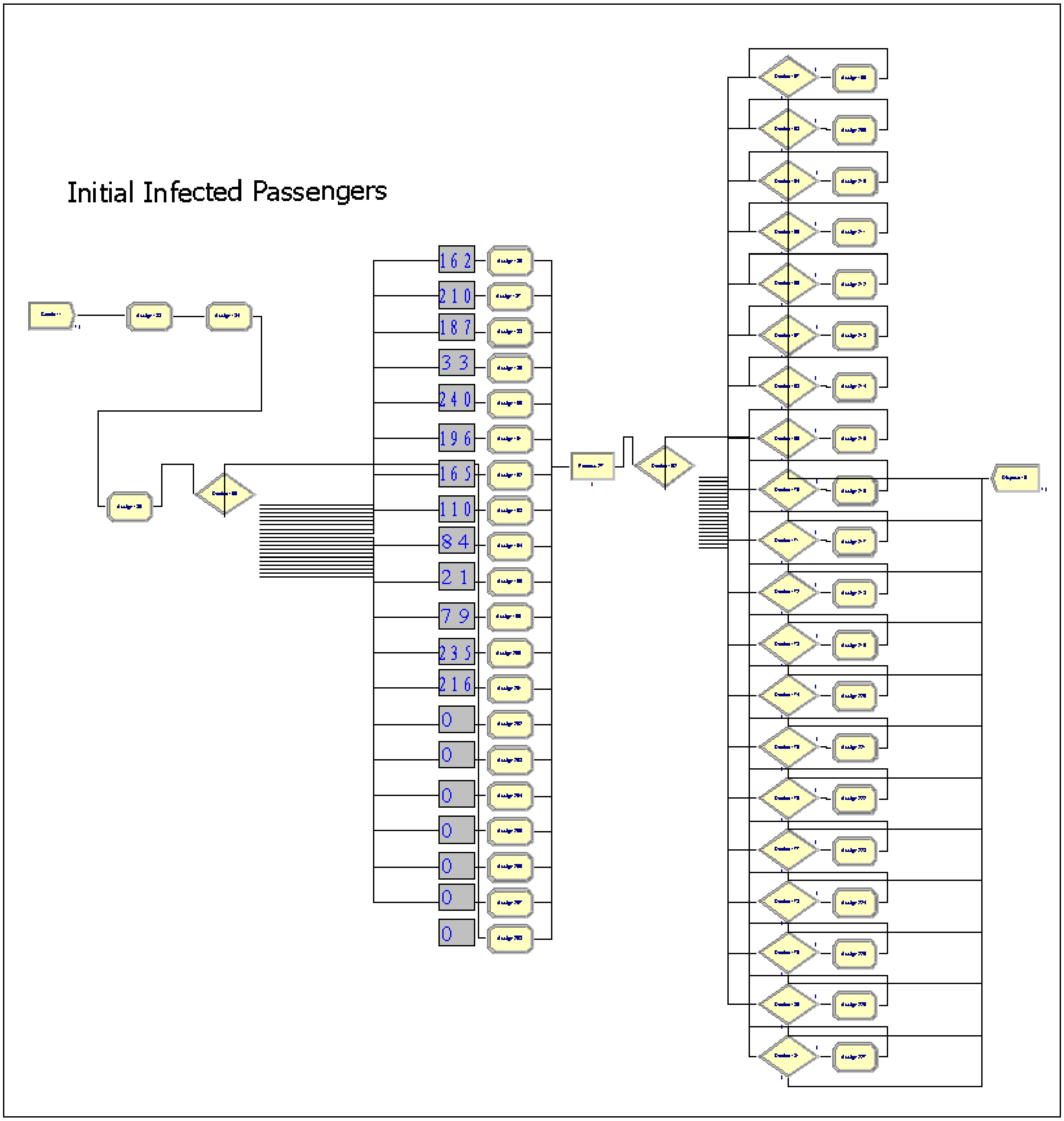


Connection
From: Crew Member Enter
To: Assign 27

3.6.2 Random number generation for initial infected passengers

This section specifies which passengers are infected at the beginning of the flight. An example of 13 initial infected passengers is provided in figure 3-8. These numbers in our baseline model has been randomly chosen 150 times.

Figure 3-8: Random number generation for initial infected passengers

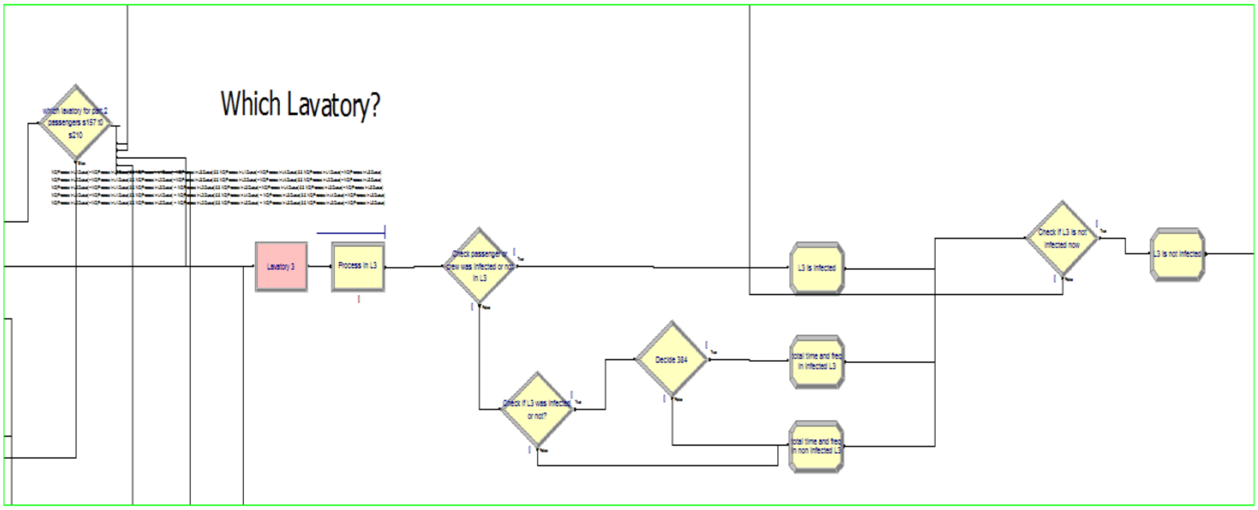


3.6.3 Lavatories station

When the flight starts, everyone is sitting on their stations and wait for their needs or tasks to do. In an airplane, using a contaminated lavatory can be a cause of caching influenza. There are many different areas in a bathroom that can easily be a good spot for hosting viruses and several bacteria. Viruses can stay on hard surfaces like door handles, doorknobs, flush handles and etcetera up to 24 hours if that area is not cleaned (National Health Service, UK 2018). A study showed that just a single germy doorknob is potential to transmit the virus to half of people in a work office setting within hours (CBC News, 2014)

In this section, both crew members and passengers are using the same lavatories except for crew members serving in part 1. They are allowed to use lavatories in the economy premium part of the airplane. Here, she/he will decide which lavatory to use by checking the distance and watching how many people are waiting to use that lavatory. When a person enters lavatory station, based on given distribution, she/he will use the bathroom. At the same time system checks health status of that person. If an infected person uses the bathroom, that bathroom will be marked as contaminated in the system for four hours. When a susceptible person uses a bathroom, at the same time system will check if that lavatory was contaminated or not. If yes, the time that susceptible person spent on that bathroom will be recorded and marked on that person. It is very important to record all times for different activities of a person since it will be used at the end of simulation. Figure 3-9 shows this step of simulation in Arena software.

Figure 3-9: Choosing lavatory by individuals

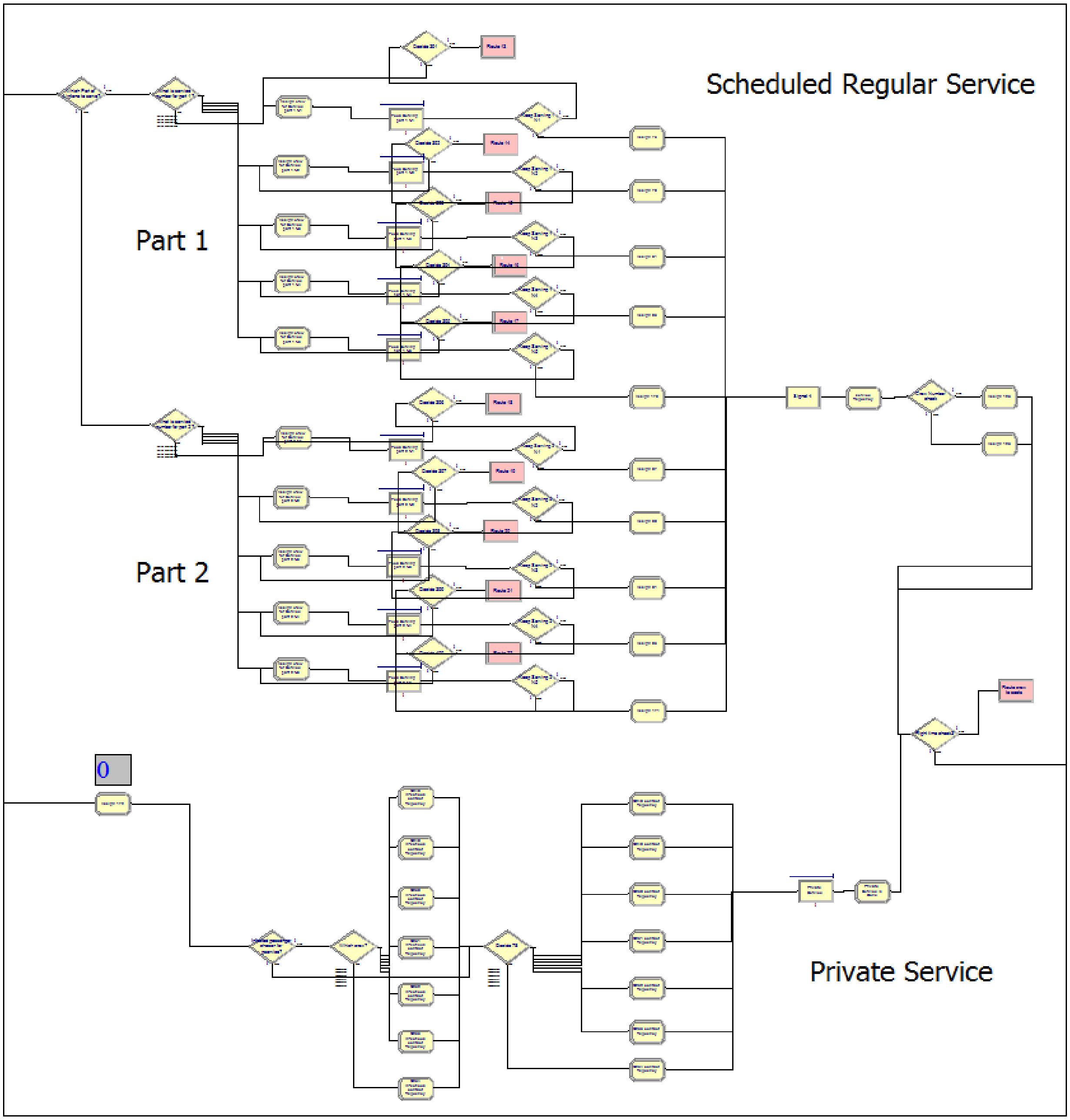


3.6.4 Crew member task section

Figure 3-10 shows crew member's duties area during a commercial flight. They have two main tasks. First, providing passengers with scheduled food and drink serving. This schedule varies in different airlines and different sections of the airplane cabin. In this study, we assumed that every 3 hours the airline serves passengers and the first service occurs 60 minutes after the departure. At this time, the crews will attend passengers' seats one by one in the specified section of the cabin that they are assigned to serve. After serving the last passenger of their section, the system will check how many infected passengers exist in the section that a crew member was serving. The time of serving each infected passenger is reordered and attached to that crew member. Then they will be guided to their seats and wait for the next signal. Average service time expended during regular service per passenger is assumed to follow a uniform distribution with minimum number of 30 seconds and maximum of 60 seconds.

The other task that a crew member is responsible to do is when a passenger has a special request. For this task, crew member seat location is not considered and as soon as a passenger has a request, the first available crew will attend and serve the passenger. Here also, if the passenger was infected, that service time is recorded in the system.

Figure 3-10: Crew member task section

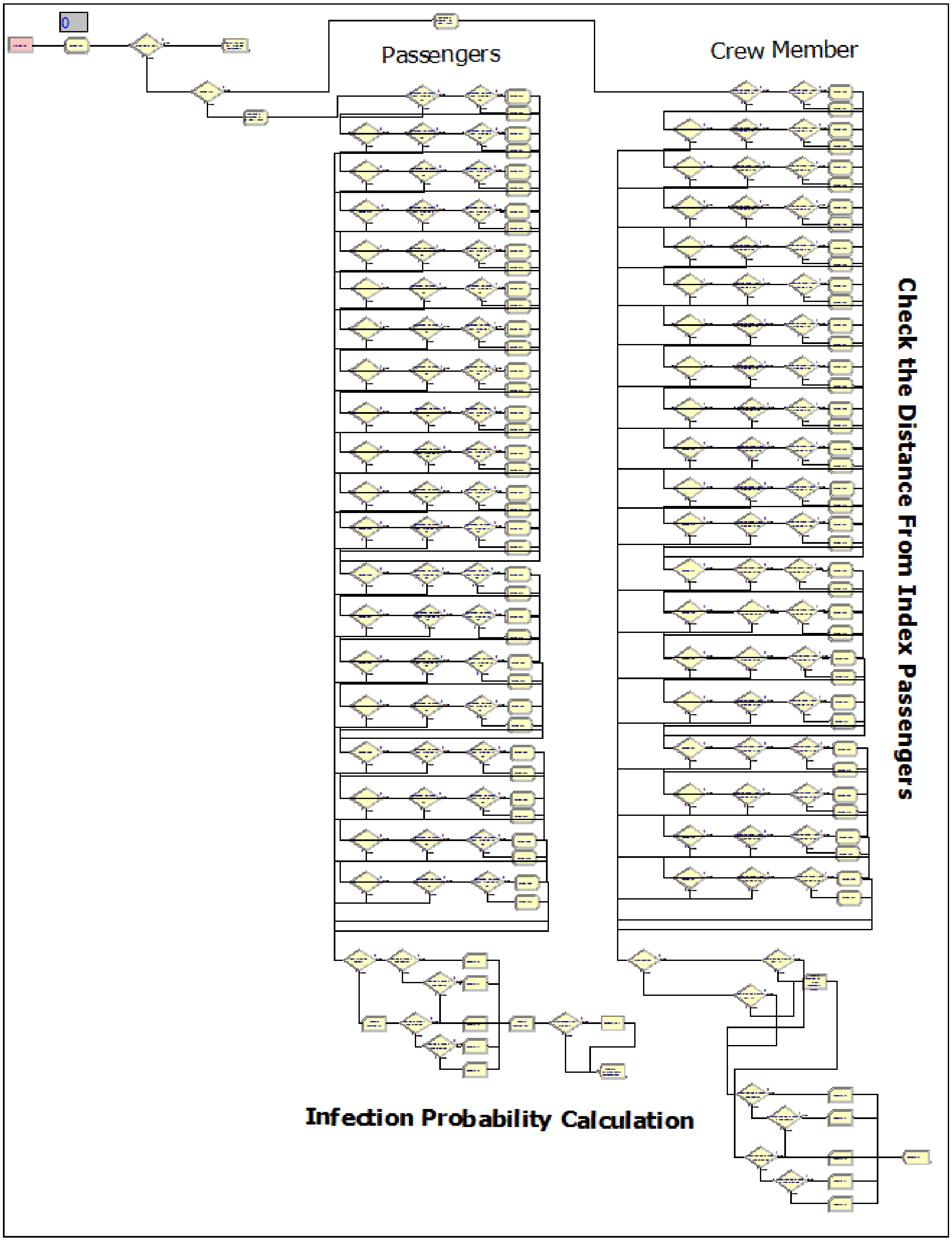


3.6.5 Calculating the probabilities of infection

The last section of our model will determine the health status of an agent at the end of the simulation. Each person has a probability of becoming a new infected one, based on the summation of times which that person has been in contact with contamination. For a passenger, this time includes times that she/he was sitting in danger zone or summation of times that have been spent in a contaminated bathroom. And for a crew member is the same time as a passenger, plus times that she/he was serving an infected passenger.

Finally, the system uses calculated times for each person in the probability of infection equation and will give us the answer of the studied scenario. Figure 3-11 shows the Arena software of this section.

Figure 3-11: Calculating the probability of infection



3.7 Transmission Rate and Hazard Radius in Airplane

As mentioned before, Haber et al. (2007) have calculated the transmission rate from an infected person to a susceptible one based on their age. We assume the age range to be between 19 to 64 years old. In this case, the transmission rate λ, which is used in equation $P(infection) = 1 - e^{-\lambda t}$, is 0.00032. This value will be used when a susceptible person is in the distance range of 1.88 meters from an infected person. This equation with this transmission rate can be used for different locations and situations like schools, homes, hospitals, etc. It is reasonable to say the closer you are seating near an infected person the higher risk of getting sick especially in the case of airplane cabin (CDC, 2019.c) (Government of Canada C. C. for O. H. and S., 2019).

According to World Health Organization, a large droplet greater than 5µm transmission happens through close contact at a distance of less than one meter (World Health Organization, 2018), while the U.S. Occupational Safety and Health Administration considers distance range of 1.82 meters (CDC, 2018.b).

Three main causes of the influenza spread, namely, airborne, fomite, and close contact, have been investigated using simulation modeling in a classroom to investigate the behavior of students and the effect of their activities on the influenza transmission (N. Zhang & Li, 2018). They have found that close contact contributes to 44.5 % of transmission. Also, they defined close contact to be within a radius of one meter from the infected person. In a different study, (Lei et al., 2018) simulate the transmission of three different infections (Influenza, severe acute respiratory syndrome (SARS) and coronavirus) in a similar airplane cabin environment to see the effect of all transmission reasons. For influenza they concluded that close contact has the most significant route of transmission with contribution of 70%.

In another study, a simulation model was used to study the behavior of passengers during flight and influenza transmission (Hertzberg et al., 2018). In this study, having contact was defined to be within a one-meter radius, and as a result, only passengers and crew seating within two-seat distance or one row in front or behind of an infected person are likely to have contact. However, they considered a high transmission rate of 0.018 per 1 minute for a susceptible passenger and quarter of this rate (0.0045) when a crew member is sick since a crew member is less likely to have a flight during an extreme sickness. The transmission rate of 0.018 is a high number that was based on the in-flight influenza transmission that happened during the 1977 outbreak in a commercial flight that had a delay for hours, and there was no ventilation system on.

As a result, in this study, we have decided to define two different danger zone for a person who is seating within 1.88 meters from an infected case, and each zone has a different transmission rate. The first zone is assumed to be sitting within 1 meter from an infected person, and the second zone is between 1 meter and 1.88 meters. For the second zone, we use the same transmission rate that (Haber et al., 2007) calculated for influenza transmission between people with 19 to 64 years old range (namely, 0.00032 per one minute of contact). Despite existence of extensive research about influenza and other infectious diseases in airplane, transmission rate of flu in an aircraft is still unknown (Hertzberg et al., 2018) and there is no accurate estimation of this rate. Therefore, we have decided to assume this rate based on an estimate that other papers are using in their simulation (Hertzberg et al., 2018), (Lei et al., 2018), (N. Zhang & Li, 2018).

According to these studies, a close contact that is happening in zone 1 with a distance less than one meter from the index case contributes to 44.5% to 70% of influenza transmission. This means that at most, the transmission rate in zone 1 can be 70/30 = 2.33 times greater than transmission rate in zone 2. Denoting this parameter by α, transmission rate in zone one will be equal to λ and transmission rate in zone two equals λ', where $\lambda' = \alpha \times \lambda$.

To find a proper α for our simulation, we have run our model with different values of α ranging from 1 to 2.33 for a 12 hours flight, 7 initial infected passengers at the beginning of the simulation, and 150 replications. The results with the margin error of less than 0.88 for all simulations can be seen in Table 3-6. As can be seen, the secondary infected passengers increase by increasing α. This shows a higher risk of getting infected in zone 1 and almost no difference in secondary cases in zone 2, which is reasonable. Also, it can be seen that with $\alpha = 1\ to$ 1.3, the number of new infected passengers in zone 2 is still more than those in zone 1 since usually zone 2 covers more passenger seats than zone 1.

NOTE: After checking the results, we observed that disease transmission to crew member has a very low rate and can be ignored. From now on, we only investigate disease transmission to susceptible passengers.

Table 3-6: Results of simulation for different alphas

ALPHA (α)	**Total New Infected**	**Half-Width**	**Infected Zone 1**	**Half-Width**	**Infected Zone 2**	**Half-Width**
1	25.0	< 0.76	10.88	< 0.44	13.55	< 0.60
1.1	25.8	< 0.77	11.59	< 0.46	13.57	< 0.60
1.2	26.5	< 0.77	12.31	< 0.47	13.57	< 0.60
1.3	27.3	< 0.81	13.01	< 0.50	13.57	< 0.60
1.4	28.0	< 0.81	13.76	< 0.51	13.57	< 0.60
1.5	28.7	< 0.83	14.43	< 0.53	13.59	< 0.60
1.6	29.4	< 0.83	15.09	< 0.53	13.60	< 0.60
1.7	30.2	< 0.84	15.87	< 0.53	13.61	< 0.60
1.8	30.8	< 0.86	16.41	< 0.54	13.61	< 0.60
1.9	31.5	< 0.86	17.01	< 0.56	13.64	< 0.60
2	32.1	< 0.86	17.59	< 0.56	13.65	< 0.60
2.1	32.7	< 0.87	18.20	< 0.57	13.66	< 0.60
2.2	33.2	< 0.87	18.65	< 0.59	13.67	< 0.60
2.3	33.7	< 0.88	19.17	< 0.60	13.68	< 0.60
2.33	33.9	< 0.88	19.33	< 0.61	13.68	< 0.60

Figure 3-12 shows that the number of total new infected passengers increases linearly with α. As we do not know the precise value of α, and because the above numbers show a reasonable range of its values, we take the midpoint of this range (i.e., 1.665) as our baseline value. As a result, we will use $\alpha = 1.665$ in our simulation. Therefore, the transmission rate in zone 1 will be:

$$\lambda' = \alpha \times \lambda \; = \; 1.665 \times \; 0.00032 = \; 0.00053$$

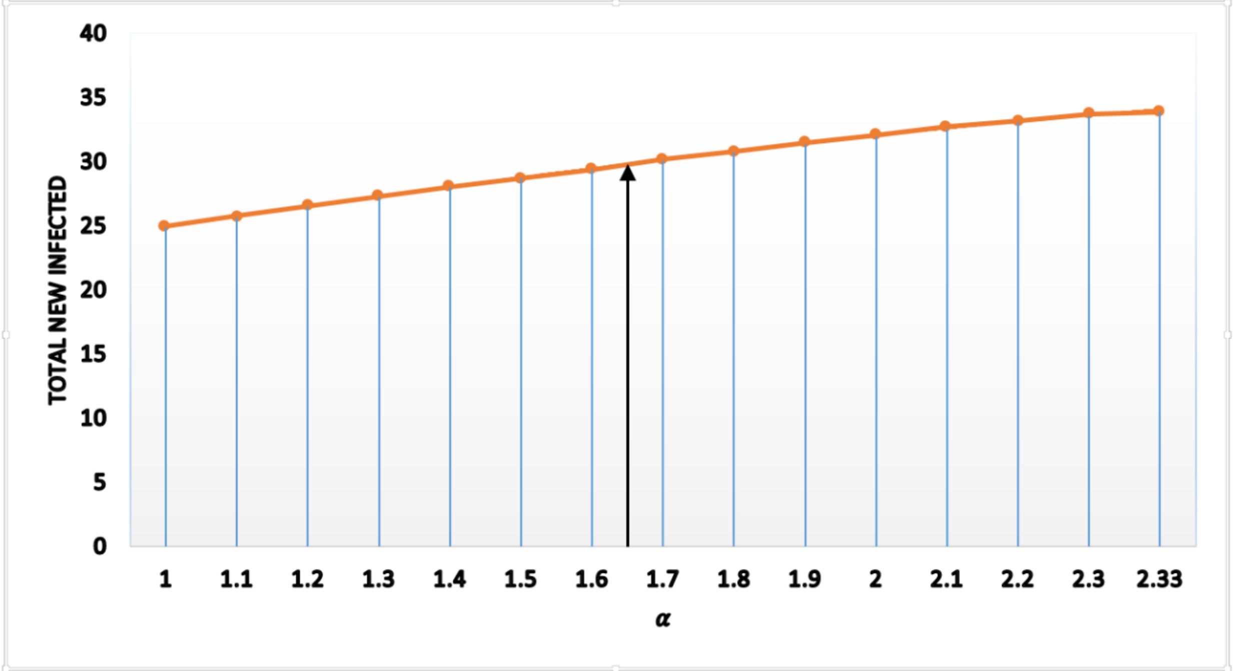
and

$$P(infection \; in \; zone \; 1) = 1 - e^{-0.00053t}$$

$$P(infection \; in \; zone \; 2) = 1 - e^{-0.00032t}$$

$$P(infection \; in \; zone \; 1 \; \& \; zone \; 2) = 1 - e^{-\lambda t - \lambda' t'}$$

Figure 3-12: Number of new infected passengers for different alphas



4 Numerical Results

Various actions can be taken by individuals to reduce their risk of transmitting or receiving the infection. In this section, we design various scenarios to study the effect of some of the essential preventive behaviors or combinations of them and to assess their impacts on the attack rate of influenza during a flight.

4.1 Analysis 1: The impact of flight duration and the number of infected passengers at the beginning of the simulation

Multiple studies have investigated different aspects of influenza transmission during a flight using simulation methods or tracking passengers' health status after a real flight. In (Wagner et al., 2009), they found that longer flight duration results in a higher risk of infection. They considered two different long-haul flights and passengers from separate sections of the cabin. Their results were obtained based on surveys.

In this study, we will execute our model for eight different flight time and eight different initial infection numbers. Therefore, our model will conduct 64 sub-scenarios, each with 60 iterations. Among all the 64 sub-scenarios, we pick the one, as the baseline-scenario, in which no preventive strategy was taken. Then, the results of our preventive scenarios will be compared against the baseline scenario and each other.

NOTE: The detailed results of all simulation runs are provided in the appendix.

Table 4-1: Results of simulation for different flight duration and different initial infected passengers

		Flight duration (hours)							
		3	5	7	10	12	15	17	19
Initial infected	2	2.3	4.5	5.9	8.5	10.6	11.9	13.2	14
	5	6.2	10.2	13.8	19.5	22.1	27.9	28.9	32.2
	8	10.1	15.9	21.4	28.8	34.2	40.8	44.4	47.5
	10	11.9	18.6	25.2	34.9	40.9	49.3	53.4	58.1
	13	15.6	23.8	33.5	45.3	50.8	60.4	64.9	68.9
	15	17.5	27.4	36.8	49.9	55.8	66.8	73.1	79.1
	17	18.7	30.6	42.4	56.1	62.8	75	80.4	84.8
	20	22	34.6	45.8	63.2	70.3	84.6	89.9	94.5

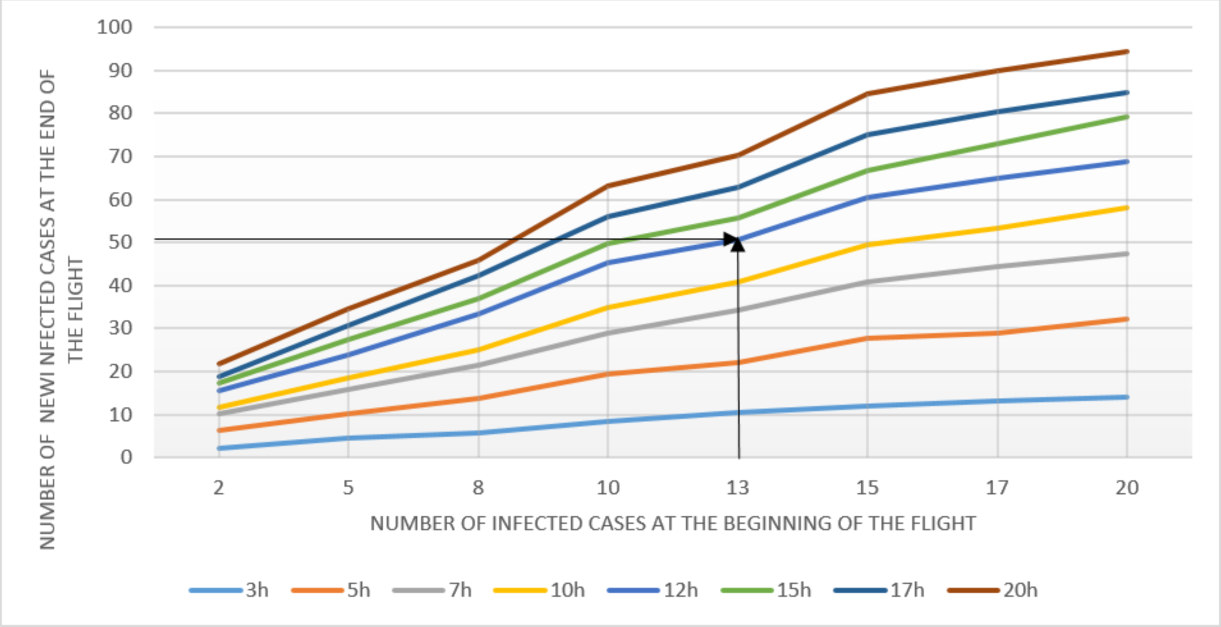
Figure 4-1 and Table4-1 depicts the results of such analysis with different flight duration. As expected, both the flight duration as well as the number of initial cases have directly affected the number of secondary cases. More specifically:

As the number of initial cases increases, the number of newly infected cases, at the end of the flight, increases almost linearly,

As the flight duration increases, so does the newly infected cases at the end of the flight.

As the most surprising observation, an apparent super-additivity (i.e., synergic) effect can be observed, in the sense that as one of the two factors (i.e., flight duration or number of initial cases) increases, the impact of the other factor on the number of secondary cases increases too. For example, the higher the number of initial infections, the larger is the impact of the flight duration on the total number of new infections. This can be seen in the increased distance between the plots as we go to the right or the increased slope of the plot as we go up in the graph.

Figure 4-1: Results of simulation for different flight duration and different initial infected passengers



It is interesting to look at a particular scenario with the flight duration of 12 hours and 13 initial infections since we want to test our strategy for a common long-haul flight. For this scenario, our simulation resulted in 50.8 new infected passengers. It should be noted that we can choose any of the mentioned sub-scenarios as our baseline scenarios since at the end we can compare the results of our preventive strategy with the same the results of base-line scenario.

Now that we have a clear understanding regarding the impact of changing these two factors (both jointly and separately), from now on, we will run all other scenarios for flight duration =12 hours, and the number of infected cases at the beginning of the flight =13, when investigating the impact of other preventive strategies.

4.2 Analysis 2: The impact of Vaccination Coverage (VC)

Vaccination is one of the most vital strategies to control infectious diseases. Vaccination coverage and vaccination time have always been important factors for the governments and health care institutions when designing their prevention strategies, which entail determining when to provide the public with access to the flu shot and how many flu shots to provide.

In Canada, each provincial government has its own policy for the Influenza vaccination. To this end, they need to determine how many flu shots to buy and the best time of starting vaccination (Canada, 2017). The Health Agency of Canada has a close relationship with the health ministry of each province and helps them to avoid any shortage in supplying the flu shots. In a rare situation that the demand for vaccine exceeds the supply, the agency will contact other health authorities in the country to provide the shortage. (Canada, 2015).

In each season, the efficacy of the vaccination for a person depends on many factors such as age, gender, how many times the person has been vaccinated, and the health status of the person. A review study of three meta-analysis shows that vaccination efficacy between adults (18-64 years old) varies from 19% to 67%. In our simulation model, we assume the vaccination efficacy to be 50% for our simulation (Manzoli, Ioannidis, Flacco, De Vito, & Villari, 2012).

It is essential to know that a vaccinated person is either susceptible or infected. Since, it is estimated that if a vaccinated person becomes ill, she/he is 50% less infectious, therefore, considering an infected passenger who has got the flu shot before, is crucial (Longini et al., 2005). We perform this analysis using two sub-scenarios.

4.2.1 Scenario 2.1: vaccinating both susceptible and initially-infected individuals

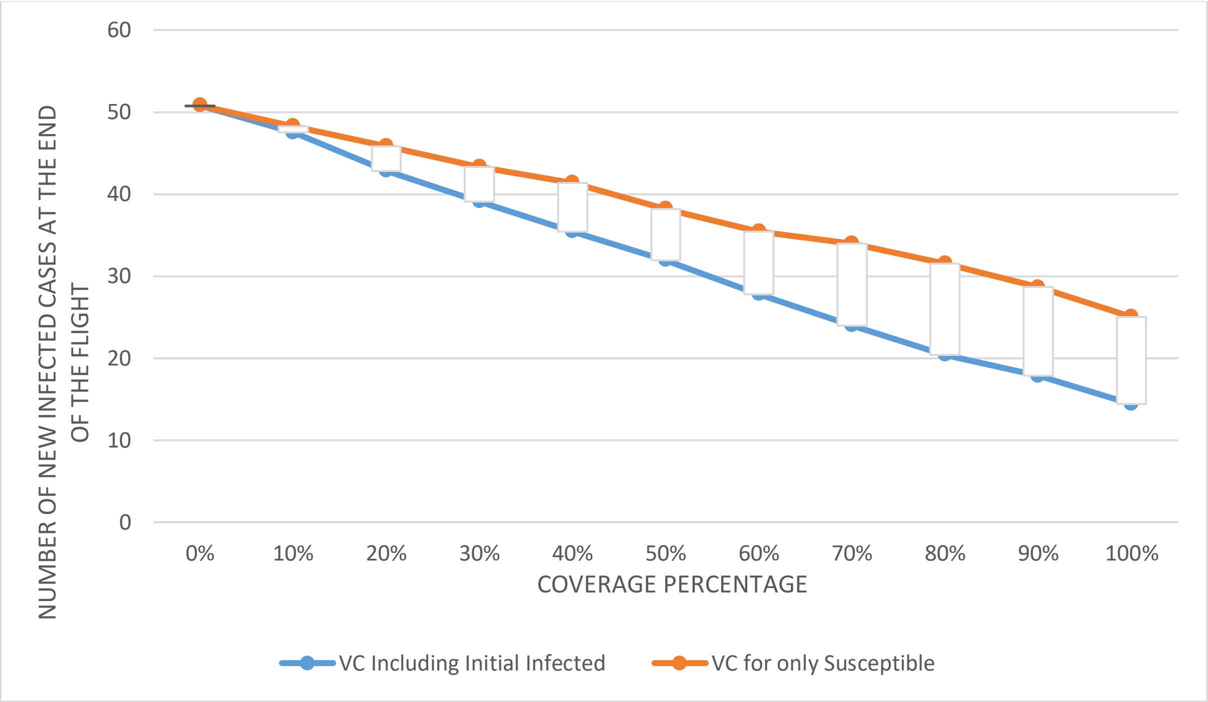
In this sub-scenario, we investigate the influence of vaccinating both susceptible and initially infected passengers. Note that various proportions of crew members and passengers, including initial infected and susceptible, have the chance to be considered vaccinated. The results of the impact of such variation on the outcomes are illustrated in Figure 4-2.

4.2.2 Scenario 2.2: vaccinating only susceptible individuals

In this sub-scenario, we investigate the influence of vaccinating a percentage of only the susceptible passengers.

As can be seen in Figure 4-2, the effect of vaccination coverage for susceptible and initial infected shows that the higher the vaccination coverage, the lower will be the number of secondary cases (i.e., higher effectiveness), almost in a linear fashion. Also, the higher the coverage, the higher will be the difference between the two strategies. As expected, sub-scenario 2.2 exhibits lower effectiveness, since in this sub-scenario, the initially-infected passengers had the chance to be considered vaccinated.

Figure 4-2: Effect of vaccination coverage on the number secondary infected



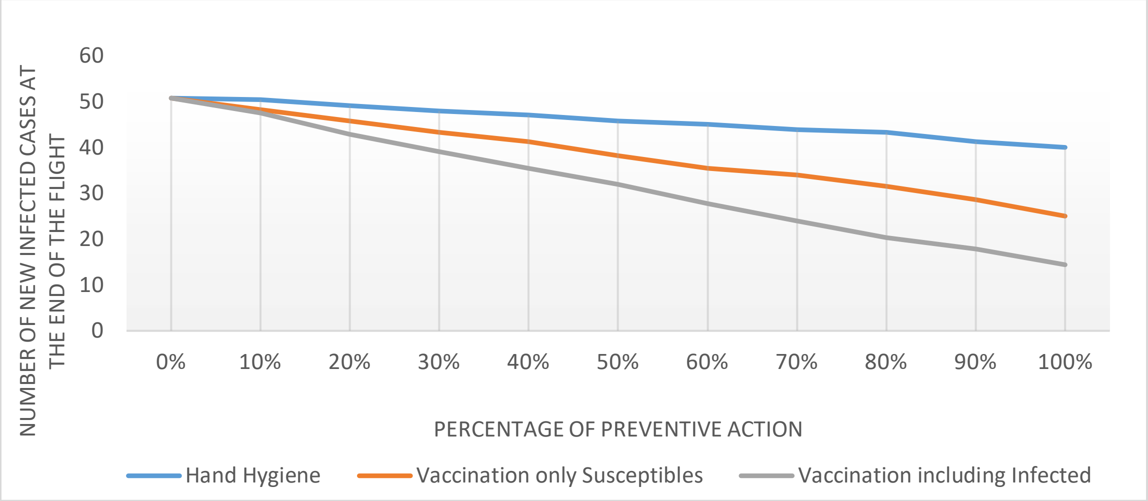
4.3 Analysis 3: The Impact of Hand Hygiene (HH)

Hand hygiene (HH), like hand washing and using alcohol-based hand sanitizers, has always been considered a practical, simple, and inexpensive strategy to decrease the infection risk. Many studies have investigated the effect of this strategy in different settings like home, schools, work office, and etcetera. Most studies have concluded the effectiveness of the strategy (Larson, Cohen, & Baxter, 2012), (Stebbins et al., 2011), (Godoy et al., 2012), (Bloomfield, Aiello, Cookson, O'Boyle, & Larson, 2007).

Our assumption for the effectiveness of hand hygiene on influenza transmission is based on a meta-analysis conducted by (Aiello, Coulborn, Perez, & Larson, 2008), which shows 21% effectiveness against respiratory illnesses.

In this analysis, we run the model, assuming that a proportion of the flight attendants is performing hand hygiene using alcohol-based hand sanitizers offered by the airline. After running the model, our results reveal that if all passengers and crew perform hand hygiene, the number of secondary cases drops from 50.8 to 40. The results of this analysis, as well as the difference of this scenario with the two vaccine coverage scenarios, are shown in Figure 4-3. First of all, as the HH rate increases, the disease spread decreases, almost linearly. Secondly, the difference between all three strategies increases when the rate of them increases equally.

Figure 4-3: Effect of different rate of HH performing in the number of secondary cases and comparison with the vaccination coverage scenario



4.4 Analysis 4: The Impact of Using Face Mask (FM)

Many studies show that using face masks can have a significant effect on reducing infectious disease, especially disease that can be transmitted through inhalation. (Lai, Poon, & Cheung, 2012), (MacIntyre et al., 2009), (Smith et al., 2016), (Zhou et al., 2018), (L. Zhang et al., 2013.). Different types of face masks are suggested to fight against infectious disease transmission. The three most known types of them are N-95, N100, and surgical face mask (SFM). The name of N-95 and N-100 mask is driven based on their ability to block particles. More specifically, N-95 and N-100 can filter 95 and 99.99% of droplets and airborne particles. However, N100 is ten times more expensive than N-95 (Weiss, Weiss, Weiss, & Weiss, 2007).

In our simulation, we choose the surgical face mask (SFM) to be used either by susceptible passengers and crew or by infected passengers only. The reason for choosing SFM is that this mask is more common to be used by the public and it is disposable and cheaper, which makes it easier to convince airlines to provide such masks for specific situations. A study conducted by (Aiello et al., 2010) investigated the effect of using face mask between 1437 young adults at least 18 years old in a university residence hall setting during the 2006-2007 influenza season. The results of using surgical face mask show that the effectiveness varies between 28% to 35%. In our study, we took the midpoint of this range (i.e., 31.5%) to be the effectiveness of wearing SFM.

Like the vaccination coverage scenario, using a face mask will be analyzed in two sub-scenarios.

4.4.1 Scenario 4.1: Wearing face masks by both susceptible and initially-infected individuals

In this scenario, we are assuming that a percentage of all crew members and passengers, including initial infected and susceptible, have the chance to wear face masks.

4.4.2 Scenario 4.2: Wearing face masks only by initially-infected individuals

In this scenario, the difference is that only a percentage of the infected passenger is using face masks. We are applying this strategy to investigate the difference in strategies where the health status of aimed individuals is not the same. The results of both sub-scenarios can be seen in Figure4-4.

Figure 4-4: Effect of using face mask on the number of secondary infected

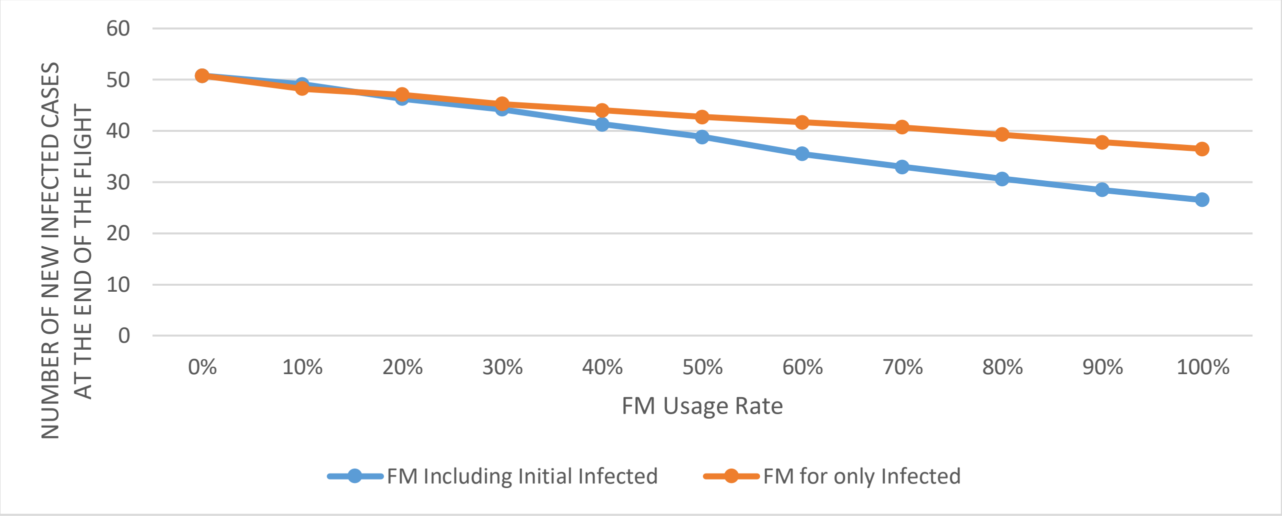
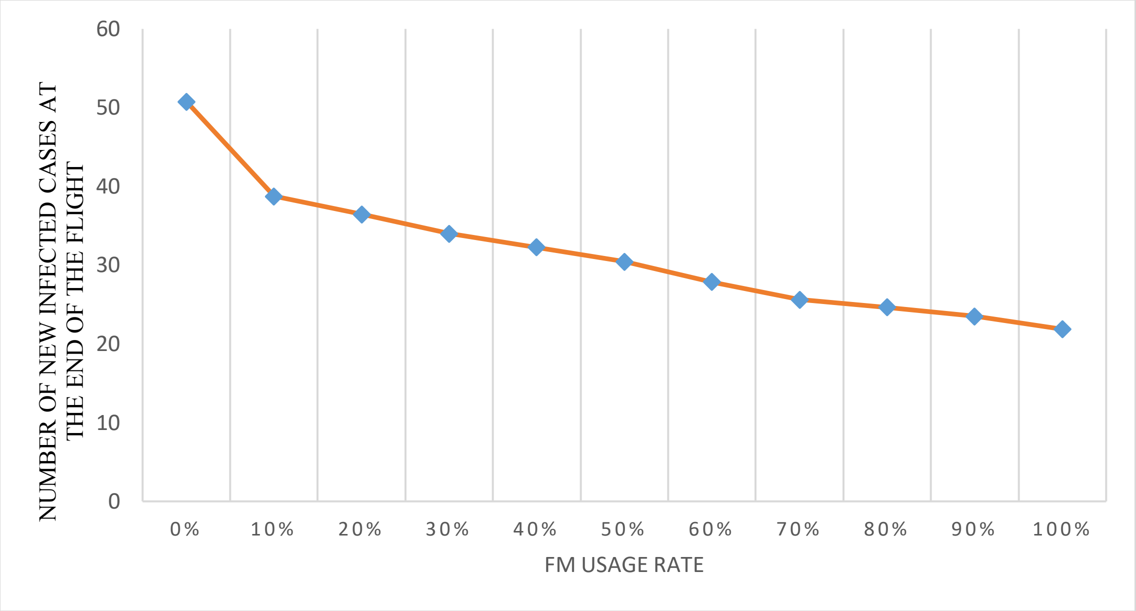


Figure 4-4 shows the importance of using face masks, especially by an infected passenger. The reason for this is that when susceptible passengers are using face mask, they are protecting themselves only. However, wearing a face mask by an infected passenger prevents virus transmission to all other passengers sitting in danger zone 1 or 2 of that infected passenger. Also, the higher the usage rate, the higher is the difference between the two strategies.

4.5 Analysis 5: The influence of using face mask by a percentage of all passengers including initially infected cases, where, all flight attendants perform hand hygiene

In this scenario is a combination of two preventive actions; hand hygiene (HH) and face mask (FM). Here we assume that the airline is offering hand hygiene materials (alcohol-based sanitizers) to everyone regularly, and a proportion of passengers are using face masks. The results of this analysis are shown in Figure 4-5.

Figure 4-5: Effect of using FM and performing HH on the number of secondary infected



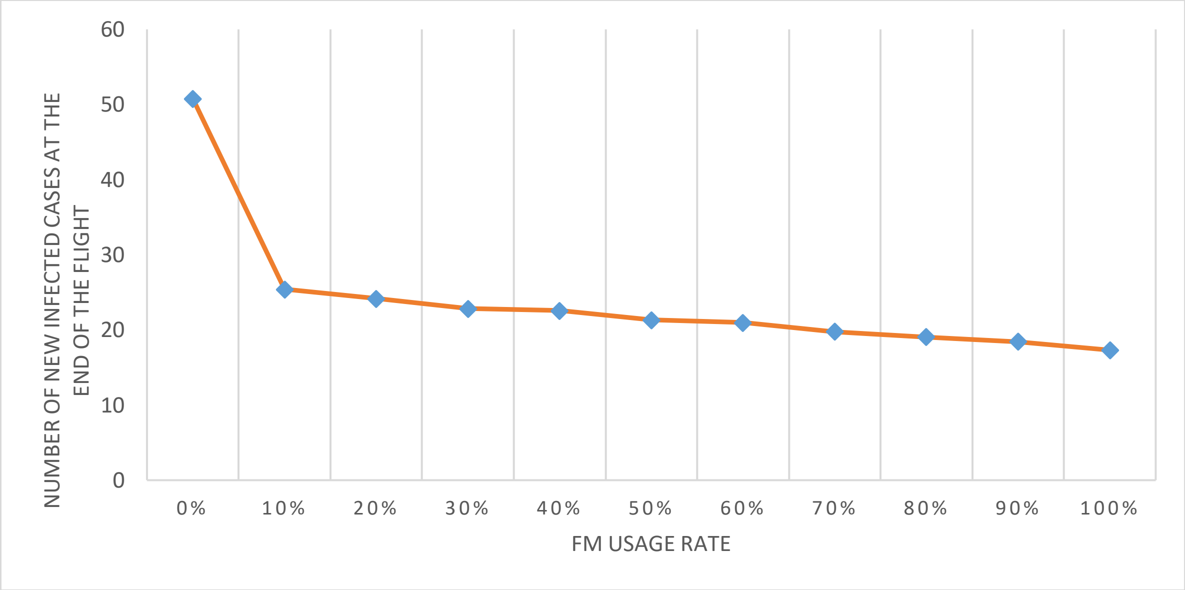
As an be seen the number of secondary infected cases decreases, almost linearly. The effect of this strategy in a 100% usage rate shows that the number of secondary infected cases falls by 56% to 21.8 percent.

4.6 Analysis 6: A percentage of susceptible are using SFM while hand hygiene is offered to all flight attendants, all infected passengers are using face mask, and vaccination coverage is the same as vaccine coverage in Canada during season 2017-2018 for only susceptible passengers.

In this scenario, hand hygiene (HH) is offered to all flight attendants and a percentage of susceptible passengers are using SFM. Also, all infected passengers are using face masks, and vaccination coverage is the same as the coverage in Canada during season 2017-2018 for our studied population whose age is between 19 to 64 years old. Based on the Public Health Agency of Canada, in the 2017-2018 season, 29.7% of all adults 18-64 years old have received an influenza vaccine (Government of Canada, P. S. and P. C., 2018.).

Figure 4-6 shows the results of analyses under this scenario. As can be seen, this strategy is one of the most effective approaches to decrease influenza transmission in an airplane.

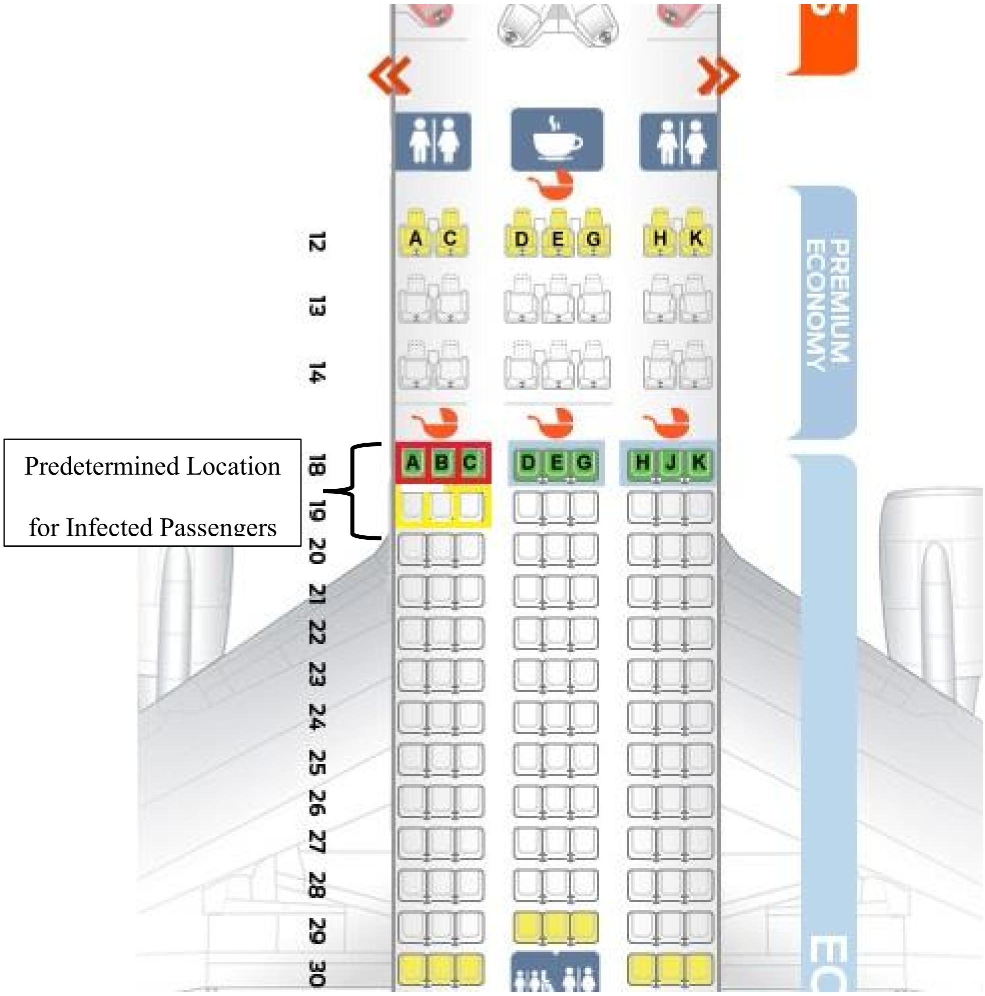
Figure 4-6: effect of different FM usage by susceptible, where everyone is doing HH, all infected using FM, and VC is 29.7



4.7 Analysis 7: The impact of allocating infected passengers in predetermined seats at the beginning of the flight on the number of secondary infected cases

In this scenario, we are considering hand hygiene to be offered to everyone regularly and allocate some of the predetermined infected in front of the cabin and give them a face mask. First, we allocate three initial infected in seats 1, 2, and 3. Then, we assume to allocate six infected passengers in seats 1, 2, 3 for three of them, and the other three behind them in seats 10, 11, 12 as can be seen in Figure 4-7.

Figure 4-7: Predetermined seats for initial infected passengers



Predetermined Location for Infected Passengers

(Captured from theflight.ifo website)

Running the simulation, we observed 34.8 new infected (with a half-width of 1.33) and 28.6 (with a half-width of 1.52), respectively, for allocating 3 and 6 infected passengers in predetermined seats. Our results indicate the importance of the location of an infected passenger can affect the spread of disease in an airplane cabin setting. If an airline offers hand sanitizers for long haul flights and only three infected passengers (out of 13 initial infected passengers) are seated in a place that offered by the airline (to minimize the contact) while face mask is used to protect other passengers, the secondary infected passengers will drop by 31%.

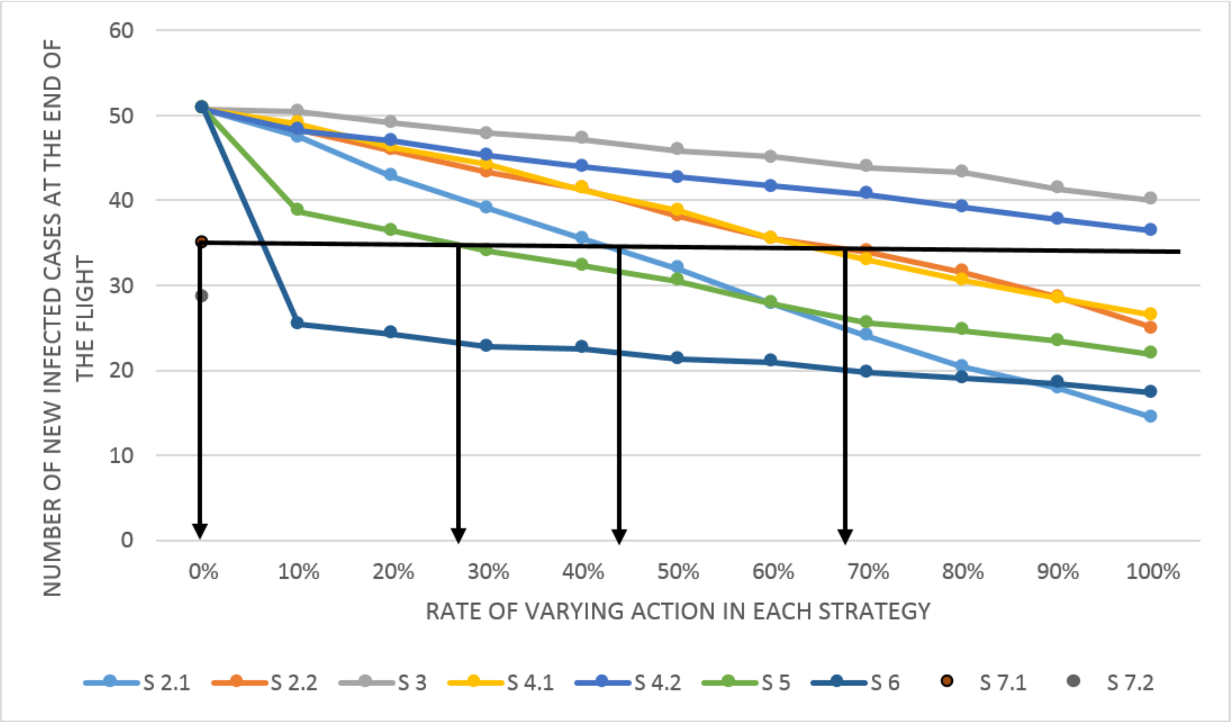
4.8 Comparative Analysis of all Preventive Strategies

Figure 4-8 summarizes the results of all preventive strategies we considered in this study. This helps us to have a deeper understanding of the effectiveness of the various strategies. To recap, the description of all scenarios is briefly explained in Table 4-2.

Table 4- 2: Summary of all strategies

Strategy Code	Description
S 2.1	Vaccination percentage of all flight attendants
S 2.2	Vaccination percentage of Susceptible passengers
S 3	Hand Hygiene percentage of all flight attendants
S 4.1	Face mask usage rate of all flight attendants
S 4.2	Face mask usage rate of only infected passengers
S 5	Face mask usage rate of all flight attendants when everyone is performing hand hygiene
S 6	Face mask usage rate, when vaccination coverage is 29.7%, everyone is performing hand hygiene, and infected passengers are using face masks
S 7.1	Allocating three initially infected cases in predetermined seats while they are using face masks, and everyone receives sanitizers
S 7.2	Allocating six initially infected cases in predetermined seats while they are using face masks, and everyone receives sanitizers

Figure 4-8: Results of all strategies



There are various interesting observations.

First, comparing all the scenarios, when the varying rate is 100%, we see that scenario 2.1 is the most effective strategy where the number of new infected passengers drops by 71% from 50.8 to 14.4 since everyone is vaccinated. Although performing such preventive action has always been an ideal goal for healthcare authorities, it is almost impossible to have a full vaccination coverage in a population because of various reasons such as lack of vaccine and wrong timing of vaccination. Second, having a look at strategy number 6, we can observe its effectiveness, quicker than other preventive actions. This is because in this strategy we are combining all preventive actions.

Thirds, Strategy 6 shows the impressive effect of using face masks and the existence of alcohol-based hand hygiene when we are applying the real vaccination coverage that happened in the 2017-18 influenza season in Canada for our aimed population in this study. This strategy has the highest effectiveness among all other strategies until we reach the vaccination coverage of 90% for all population.

Forth, when the face mask usage rate is 100%, the number of new infected passengers, falls by 47% and 29%, respectively, in strategies 4.1 and 4.2. The effectiveness difference between these two actions is 18%. However, here, we should note that in strategy 4.1, all individuals (254 persons) are using face masks, but, in strategy 4.2, only 13 infected passengers are using face masks.

Fifth, by comparing strategies 2.2 and 4.1, we can see that their effectiveness is following the same pattern most of the time. This means that using face masks in an airplane cabin has almost the same effect as vaccinating susceptible populations. Imagine the situation when we are coping with an infectious disease spreading similar to influenza while a vaccine has not been discovered or is unavailable. Also, infected passengers either are not willing to present themselves, or they are not aware of having the disease. In this situation, only using face mask, can act as a vaccine with 50% effectiveness.

Finally, let us have a look at the last scenario in which we are assuming that some of the infected passengers are willing to sit in locations offered by the airline, and they will use face masks. In strategy 7.1, only three out of 13 infected persons, feel responsibility and follow this preventive strategy. As we can see, this action has the same effectiveness as a situation where one of the following preventive actions is happening;

- almost 30% of all population is using face masks, and 100% of them are doing hand hygiene
- Covering almost 45% of the studied population with the vaccine. (15% higher effectiveness compare to real vaccine coverage in Canada)

- Using face masks by almost 70% of all flight attendants
- Vaccinating almost 70% of the susceptible population

5 Conclusion

The main objective of this study was to analyze the effectiveness of various preventive strategies that can help us reduce the spread of influenza in an airplane cabin during commercial air travels. Among several different strategies that we studied (also suggested in the literature or considered by healthcare authorities), we have focused on four major approaches; hand hygiene, vaccination, using face masks and finally the effect of individual locations in disease transmission.

Thinking more deeply about the suggested strategies, we realize that they are different, in nature, in terms of implementation, management, policy, and cost. For example, providing sufficient and timely vaccination, creating a policy that forces airlines to provide passengers with face masks or hand hygiene in particular situations, can happen through governments and policymakers, while, the knowledge and willingness of individuals to do take protective actions are initiatives that are administered by individuals.

To conduct our quantitative analysis, we chose the Agent-Based Simulation approach. The reason for this choice is the power and flexibility of simulation methods to capture the complexity of a model which has a large number of variables and parameters, where, model-based mathematical approaches, despite their theoretical results, usually fail to capture such complexity.

In this thesis, we have achieved impressive analytical results for all mentioned preventive strategies. The effectiveness of all approaches was illustrated using extensive scenario analysis. Note, however, that for the same level of implementation, the strategies were not equally effective and their effectiveness were dependent on many factors such as the number of protective actions in one strategy, the efficacy of each action, and the health status of individuals who choose to apply a protective action.

One of the most exciting and notable results achieved from this study was that the most effective preventive approaches were those which involved "human participation" (i.e., who were infected at the beginning of the fight). For example, three protective scenarios that had the highest effectiveness than other scenarios in all levels of implementation (Strategies 2.1, 5, and 6), involved the participation of infected passengers. This important finding shows that this aspect of preventive strategies (i.e., voluntary human participation) should always be emphasized and promoted by policymakers and governments for public health applications.

6 Future Work:

The flexibility of our simulation model in an airplane cabin setting allows us to study many different aspects of infectious disease spread in this situation. Considering the effect of age and gender of passengers in the attack rate is an essential factor that should be considered in extending this study. Also, sensitivity analysis of key parameters used in this study, such as transmission rate in zone 1 or zone 2, the efficacy of the vaccine and other preventive strategies can give us a deeper sight of each parameter importance.

Besides, in this study, we have proven that different protective approaches can result in reducing influenza spread. However, a critical factor that determines how much governments and airline policymakers are willing to perform such preventive activities is cost. In the future, we will study the cost-effectiveness of mentioned strategies. We will extend our study to figure out a trade-off between the amount of spent money on each strategy and the saved money due to elimination of many costs such as hospitalizations, treatment, work and school absences, and so forth.

Also, our model enables us to examine the spread of many other infectious diseases like Ebola that have the same transmission nature as influenza.

7 References

Aiello, A. E., Coulborn, R. M., Perez, V., & Larson, E. L. (2008). Effect of Hand Hygiene on Infectious Disease Risk in the Community Setting: A Meta-Analysis. American Journal of Public Health, 98(8), 1372–1381.

Aiello, A. E., Murray, G. F., Perez, V., Coulborn, R. M., Davis, B. M., Uddin, M., Monto, A. S. (2010). Mask use, hand hygiene, and seasonal influenza-like illness among young adults: A randomized intervention trial. The Journal of Infectious Diseases, 201(4), 491–498.

Aircanada.com, https://www.aircanada.com/us/en/aco/home/fly/onboard/fleet/dreamliner.html

Bloomfield, S. F., Aiello, A. E., Cookson, B., O'Boyle, C., & Larson, E. L. (2007). The effectiveness of hand hygiene procedures in reducing the risks of infections in home and community settings including handwashing and alcohol-based hand sanitizers. American Journal of Infection Control, 35(10, Supplement 1), S27–S64.

Brankston, G., Gitterman, L., Hirji, Z., Lemieux, C., & Gardam, M. (2007). Transmission of influenza A in human beings. The Lancet Infectious Diseases, 7(4), 257–265.

Canada, P. H. A. of. (2015, June 30). Vaccine supply [Education and awareness], From: https://www.canada.ca/en/public-health/services/vaccine-supply.html

Canada, P. H. A. of. (2017, March 24). Provincial and Territorial Immunization Information [Service description]. From Aem website: https://www.canada.ca/en/public-health/services/provincial-territorial-immunization-information.html#a3

CBC NEWS (2014) One germy doorknob can infect half your office within hours. (2014). from https://www.cbsnews.com/news/one-germy-doorknob-can-infect-half-your-office-within-hours

CDC (2019.a). Disease Burden of Influenza, from https://www.cdc.gov/flu/about/burden/index.html

CDC, (2018.a) People at High Risk of Flu. from Centers for Disease Control and Prevention website: https://www.cdc.gov/flu/highrisk/index.htm

CDC. (2018.b). Interim Guidance on Follow-up of Close Contacts of Persons Infected with Novel Influenza A Viruses Associated with Severe Human Disease and on the Use of Antiviral Medications for Chemoprophylaxis | Avian Influenza (Flu). https://www.cdc.gov/flu/avianflu/novel-av-chemoprophylaxis-guidance.htm

CDC,(2019.b),Key Facts About Influenza (Flu)|.from https://www.cdc.gov/flu/about/keyfacts.htm

CDC, (2019.c). Review of Scientific Data Regarding Transmission of Infectious Agents in Healthcare Settings, from https://www.cdc.gov/infectioncontrol/guidelines/isolation/scientific-review.html

Chen, Q., McDevitt, J. J., Gupta, J. K., Jones, B. W., Mazumdar, S., Poussou, S. B., & others. (2012). Infectious disease transmission in airliner cabins. Qingyan, Report No. RITE-ACER-CoE-2012-01.

Coburn, B. J., Wagner, B. G., & Blower, S. (2009). Modeling influenza epidemics and pandemics: Insights into the future of swine flu (H1N1). BMC Medicine, 7(1), 30.

Das, T. K., Savachkin, A. A., & Zhu, Y. (2008). A large-scale simulation model of pandemic influenza outbreaks for development of dynamic mitigation strategies. Iie Transactions, 40(9), 893–905.

Dietz, K., & Heesterbeek, J. A. P. (2002). Daniel Bernoulli’s epidemiological model revisited. Mathematical Biosciences, 180(1–2), 1–21.

Dygert, R. K., & Dang, T. Q. (2012). Experimental validation of local exhaust strategies for improved IAQ in aircraft cabins. Building and Environment, 47, 76–88.

Elmaghraby, H. A., Chiang, Y. W., & Aliabadi, A. A. (2018). Ventilation strategies and air quality management in passenger aircraft cabins: A review of experimental approaches and numerical simulations. Science and Technology for the Built Environment, 24(2), 160–175.

Elveback, L. R., Fox, J. P., Ackerman, E., Langworthy, A., Boyd, M., & Gatewood, L. (1976). An influenza simulation model for immunization studies. American Journal of Epidemiology, 103(2), 152–165.

Foppa, I. M. (2016). A Historical Introduction to Mathematical Modeling of Infectious Diseases: Seminal Papers in Epidemiology. Academic Press.

Gendreau, M. (2010). Tuberculosis and Air Travel: Guidelines For Prevention and Control, 3rd Edition. Perspectives in Public Health; London, 130(4), 191.

Godoy, P., Castilla, J., Delgado-Rodríguez, M., Martín, V., Soldevila, N., Alonso, J., … Castro, A. (2012). Effectiveness of hand hygiene and provision of information in preventing influenza cases requiring hospitalization. Preventive Medicine, 54(6), 434–439.

Government of Canada, C. C. for O. H. and S. (2019, September 19). Good Hygiene Practices - Reducing the Spread of Infections and Viruses: OSH Answers. from http://www.ccohs.ca/

Government of Canada, P. S. and P. C. (2018). Information archivée dans le Web. from http://publications.gc.ca/site/archivee-archived.html?url=http://publications.gc.ca/collections/collection_2019/aspc-phac/HP40-198-2018-eng.pdf

Haber, M. J., Shay, D. K., Davis, X. M., Patel, R., Jin, X., Weintraub, E., … Thompson, W. W. (2007). Effectiveness of Interventions to Reduce Contact Rates during a Simulated Influenza Pandemic. Emerging Infectious Diseases, 13(4), 581–589.

Han, Z., To, G. N. S., Fu, S. C., Chao, C. Y.-H., Weng, W., & Huang, Q. (2014). Effect of human movement on airborne disease transmission in an airplane cabin: Study using numerical modeling and quantitative risk analysis. BMC Infectious Diseases, 14(1), 434.

Hertzberg, V. S., Weiss, H., Elon, L., Si, W., Norris, S. L., & Team, T. F. R. (2018). Behaviors, movements, and transmission of droplet-mediated respiratory diseases during transcontinental airline flights. Proceedings of the National Academy of Sciences, 115(14), 3623–3627.

Hethcote, H. W. (2000). The Mathematics of Infectious Diseases. 42(4), 599–653.

Hethcote, H. W. (2009). AGE-STRUCTURED EPIDEMIOLOGY MODELS AND EXPRESSIONS FOR R0. In Mathematical Understanding Of Infectious Disease Dynamics (pp. 91–128). World Scientific.

IATA (2018), Cabin Air Quality - from https://www.iata.org/whatwedo/safety/health/Documents/cabin-air-quality.pdf

ICAO (2018). The World of Air Transport in 2018. from https://www.icao.int/annual-report-2018/Pages/the-world-of-air-transport-in-2018.aspx

Jefferson, T., Foxlee, R., Mar, C. D., Dooley, L., Ferroni, E., Hewak, B., … Rivetti, A. (2008). Physical interventions to interrupt or reduce the spread of respiratory viruses: Systematic review. BMJ, 336(7635), 77–80.

Johnson, N. P. A. S., & Mueller, J. (2002). Updating the Accounts: Global Mortality of the 1918-1920 “Spanish” Influenza Pandemic. Bulletin of the History of Medicine, 76(1), 105–115.

Karimi, E., Schmitt, K., & Akgunduz, A. (2015). Effect of individual protective behaviors on influenza transmission: An agent-based model. Health Care Management Science, 18(3), 318–333.

Kermack, W. O., & McKendrick, A. G. (1991). Contributions to the mathematical theory of epidemics—I. Bulletin of Mathematical Biology, 53(1), 33–55.

Khalil, K. M., Abdel-Aziz, M., Nazmy, T. T., & Salem, A.-B. M. (2012). An Agent-Based Modeling for Pandemic Influenza in Egypt. In J. Lu, L. C. Jain, & G. Zhang (Eds.), Handbook on Decision Making: Vol 2: Risk Management in Decision Making (pp. 205–218).

Klontz, K. C., HYNES, N. A., GUNN, R. A., WILDER, M. H., HARMON, M. W., & KENDAL, A. P. (1989). An outbreak of influenza A/Taiwan/1/86 (H1N1) infections at a naval base and its association with airplane travel. American Journal of Epidemiology, 129(2), 341–348.

Kraemer, J. (2006). Quantitation of social variables in epidemics: A computational modeling approach. Master's Thesis at Bloomberg School of Public Health.

Lai, A. C. K., Poon, C. K. M., & Cheung, A. C. T. (2012). Effectiveness of facemasks to reduce exposure hazards for airborne infections among general populations. Journal of the Royal Society, Interface, 9(70), 938–948.

Larson, E. L., Cohen, B., & Baxter, K. A. (2012). Analysis of alcohol-based hand sanitizer delivery systems: Efficacy of foam, gel, and wipes against influenza A (H1N1) virus on hands. American Journal of Infection Control, 40(9), 806–809.

Lei, H., Li, Y., Xiao, S., Lin, C.-H., Norris, S. L., Wei, D., Ji, S. (2018). Routes of transmission of influenza A H1N1, SARS CoV, and norovirus in air cabin: Comparative analyses. Indoor Air, 28(3), 394–403.

Leonenko, V. N., & Ivanov, S. V. (2016). Fitting the SEIR model of seasonal influenza outbreak to the incidence data for Russian cities. Russian Journal of Numerical Analysis and Mathematical Modelling, 31(5), 267–279.

Li, F., Liu, J., Ren, J., Cao, X., & Zhu, Y. (2016). Numerical investigation of airborne contaminant transport under different vortex structures in the aircraft cabin. International Journal of Heat and Mass Transfer, 96, 287–295.

Longini, I. M., Halloran, M. E., Nizam, A., & Yang, Y. (2004). Containing pandemic influenza with antiviral agents. American Journal of Epidemiology, 159(7), 623–633.

Longini, I. M., Nizam, A., Xu, S., Ungchusak, K., Hanshaoworakul, W., Cummings, D. A., & Halloran, M. E. (2005). Containing pandemic influenza at the source. Science, 309(5737), 1083–1087.

MacIntyre, C. R., Cauchemez, S., Dwyer, D. E., Seale, H., Cheung, P. S. P., Browne, G. J., … Ferguson, N. M. (2009). Face Mask Use and Control of Respiratory Virus Transmission in Households. Emerging Infectious Diseases, 15, 233–241.

Manzoli, L., Ioannidis, J. P. A., Flacco, M. E., De Vito, C., & Villari, P. (2012). Effectiveness and harms of seasonal and pandemic influenza vaccines in children, adults and elderly: A critical review and re-analysis of 15 meta-analyses. Human Vaccines & Immunotherapeutic, 8(7), 851–862.

Memarzadeh, F. (2012). Literature Review of the Effect of Temperature and Humidity on Viruses. ASHRAE Transactions, 118.

Mills, C. E., Robins, J. M., & Lipsitch, M. (2004). Transmissibility of 1918 pandemic influenza. Nature, 432(7019), 904.

Molinari, N.-A. M., Ortega-Sanchez, I. R., Messonnier, M. L., Thompson, W. W., Wortley, P. M., Weintraub, E., & Bridges, C. B. (2007). The annual impact of seasonal influenza in the US: Measuring disease burden and costs. Vaccine, 25(27), 5086–5096.

Moser, M. R., Bender, T. R., Margolis, H. S., Noble, G. R., Kendal, A. P., & Ritter, D. G. (1979). An outbreak of influenza aboard a commercial airliner. American Journal of Epidemiology, 110(1), 1–6.

National Health Service UK, (2018), How long do bacteria and viruses live outside the body?. from Nhs.uk website: https://www.nhs.uk/common-health-questions/infections/how-long-do-bacteria-and-viruses-live-outside-the-body/

NHS-UK (2018). How long do bacteria and viruses live outside the body? from Nhs.uk website: https://www.nhs.uk/common-health-questions/infections/how-long-do-bacteria-and-viruses-live-outside-the-body/

Nsoesie, E. O., Brownstein, J. S., Ramakrishnan, N., & Marathe, M. V. (2014). A systematic review of studies on forecasting the dynamics of influenza outbreaks. Influenza and Other Respiratory Viruses, 8(3), 309–316.

Papineni, R. S., & Rosenthal, F. S. (1997). The size distribution of droplets in the exhaled breath of healthy human subjects. Journal of Aerosol Medicine, 10(2), 105–116.

Patel, R., Longini, I. M., & Halloran, M. E. (2005). Finding optimal vaccination strategies for pandemic influenza using genetic algorithms. Journal of Theoretical Biology, 234(2), 201–212.

Pellis, L., Ball, F., & Trapman, P. (2012). Reproduction numbers for epidemic models with households and other social structures. I. Definition and calculation of R0. Mathematical Biosciences, 235(1), 85–97.

Porter, S. (2018, October 12). Take off for the longest non-stop flight. BBC News. from https://www.bbc.com/news/business-45795573

Putro, U. S., Novani, S., Siallagan, M., Deguchi, H., Kantani, Y., Kaneda, T., … Tanuma, H. (2008). Searching for effective policies to prevent bird flu pandemic in Bandung city using agent-based simulation. Systems Research and Behavioral Science, 25(5), 663–673.

Rakowski, F., Gruziel, M., Bieniasz-Krzywiec, \Lukasz, & Radomski, J. P. (2010). Influenza epidemic spread simulation for Poland—A large scale, individual based model study. Physica A: Statistical Mechanics and Its Applications, 389(16), 3149–3165.

Saunders-Hastings, P. R., & Krewski, D. (2016). Reviewing the History of Pandemic Influenza: Understanding Patterns of Emergence and Transmission. Pathogens (Basel, Switzerland), 5(4).

SeatGuru.com, a. Seat Map Air Canada., from https://www.seatguru.com/airlnes/Air_Canada/Air_Canada_Boeing_777-300ER_Three_Class_v3.php

SeatGuru.com, b Seat Map Emirates. from https://www.seatguru.com/airlines/Emirates_Airlines/Emirates_Airlines_Boeing_777-300ER_3class_private.php

SeatGuru.com, c Seat Map Air Canada. from https://www.seatguru.com/airlines/Air_Canada/Air_Canada_Boeing_787-900.php

Smith, J. D., MacDougall, C. C., Johnstone, J., Copes, R. A., Schwartz, B., & Garber, G. E. (2016). Effectiveness of N95 respirators versus surgical masks in protecting health care workers from acute respiratory infection: A systematic review and meta-analysis. CMAJ, 188(8), 567–574.

STEBBINS, S., CUMMINGS, D. A. T., STARK, J. H., VUKOTICH, C., MITRUKA, K., THOMPSON, W., BURKE, D. S. (2011). Reduction in the Incidence of Influenza A but Not Influenza B Associated with Use of Hand Sanitizer and Cough Hygiene in Schools: A Randomized Controlled Trial. The Pediatric Infectious Disease Journal, 30(11), 921–926.

Tafalla, M., Buijssen, M., Geets, R., & Vonk Noordegraaf-Schouten, M. (2016). A comprehensive review of the epidemiology and disease burden of Influenza B in 9 European countries. Human Vaccines & Immunotherapeutics, 12(4), 993–1002.

Tatem, A. J., Rogers, D. J., & Hay, S. I. (2006). Global transport networks and infectious disease spread. Advances in Parasitology, 62, 293–343.

Theflight.ifo. Seat map Boeing 787-8 Dreamliner Air Canada. Best seats in plane. from http://theflight.info/seat-map-boeing-787-8-dreamliner-air-canada-best-seats-in-plane/

Urashima, M., Shindo, N., & Okabe, N. (2003). A seasonal model to simulate influenza oscillation in Tokyo. Japanese Journal of Infectious Diseases, 56(2), 43–47.

Wagner, B. G., Coburn, B. J., & Blower, S. (2009). Calculating the potential for within-flight transmission of influenza A (H1N1). BMC Medicine, 7(1), 81.

Walters, C. E., Meslé, M. M., & Hall, I. M. (2018). Modelling the global spread of diseases: A review of current practice and capability. Epidemics, 25, 1–8.

Wang, M., Lin, C.-H., & Chen, Q. (2011). Determination of particle deposition in enclosed spaces by Detached Eddy Simulation with the Lagrangian method. Atmospheric Environment, 45(30), 5376–5384.

Weiss, M. M., Weiss, P. D., Weiss, D. E., & Weiss, J. B. (2007). Disrupting the Transmission of Influenza A: Face Masks and Ultraviolet Light as Control Measures. American Journal of Public Health, 97(Supplement_1), S32–S37.

Winston, W. L. (2000). How Many Trials Do We Need? The Book Simulation Modeling Using@ RISK.

Zhang, L., Peng, Z., Ou, J., Zeng, G., Fontaine, R. E., Liu, M., Yu, H. (2013). Protection by Face Masks against Influenza A(H1N1)pdm09 Virus on Trans-Pacific Passenger Aircraft, 2009—Volume 19, Number 9—September 2013—Emerging Infectious Diseases journal—CDC.

Zhang, N., & Li, Y. (2018). Transmission of Influenza A in a Student Office Based on Realistic Person-to-Person Contact and Surface Touch Behaviour. International Journal of Environmental Research and Public Health, 15(8).

Zhang, T., & Chen, Q. (2005). Comparison of different ventilation systems for commercial aircraft cabins. Proceedings of Indoor Air, 4, 3205–3210.

Zhou, S. S., Lukula, S., Chiossone, C., Nims, R. W., Suchmann, D. B., & Ijaz, M. K. (2018). Assessment of a respiratory face mask for capturing air pollutants and pathogens including human influenza and rhinoviruses. Journal of Thoracic Disease, 10(3), 2059–2069.

APPENDIX I: Detailed Results of Analysis 1

Flight Duration (hours)	Initial Infected	Total new infected passengers	Half-Width	Infected in zone 1	Half-Width	Infected in zone 2	Half-Width	Total new infected crew	Half-Width
3	2	2.28	0.34	1.23	0.28	1.00	0.25	0.02	0.03
	5	6.22	0.66	3.32	0.43	2.77	0.41	0.00	0.00
	8	10.10	0.68	5.32	0.47	4.67	0.48	0.02	0.03
	10	11.85	0.81	6.95	0.61	4.78	0.58	0.03	0.05
	13	15.62	0.99	9.75	0.69	5.68	0.53	0.10	0.08
	15	17.48	1.01	11.25	0.91	6.08	0.55	0.17	0.10
	17	18.70	1.05	12.02	0.85	6.67	0.58	0.12	0.10
	20	21.95	1.09	14.87	0.92	7.07	0.71	0.10	0.08
5	2	4.48	0.52	1.85	0.33	2.42	0.41	0.03	0.05
	5	10.18	0.80	5.33	0.53	4.58	0.56	0.02	0.03
	8	15.88	1.10	8.55	0.78	7.10	0.64	0.03	0.07
	10	18.58	1.11	10.67	0.86	7.67	0.64	0.08	0.07
	13	23.78	1.40	15.23	1.08	8.33	0.87	0.10	0.08
	15	27.40	1.41	17.85	1.01	9.38	0.78	0.17	0.13
	17	30.60	1.33	20.25	1.11	10.20	0.64	0.18	0.11
	20	34.58	1.28	23.80	1.09	10.67	0.73	0.22	0.13
7	2	5.88	0.59	2.63	0.39	2.90	0.42	0.00	0.00
	5	13.77	0.94	7.25	0.62	6.20	0.73	0.08	0.09
	8	21.38	1.35	11.75	0.90	9.20	0.94	0.00	0.00
	10	25.17	1.46	14.88	1.03	9.95	9.95	0.12	0.11
	13	33.45	1.55	20.02	1.25	13.18	0.84	0.22	0.13
	15	36.83	1.48	23.77	1.14	12.85	0.83	0.30	0.15
	17	42.43	1.58	27.68	1.28	14.55	1.01	0.22	0.11
	20	45.82	1.61	31.12	1.40	14.45	1.01	0.35	0.18
10	2	8.48	0.66	3.90	0.46	4.15	0.53	0.00	0.00
	5	19.52	1.31	10.12	0.69	8.60	0.98	0.00	0.00
	8	28.83	1.26	15.45	0.81	12.93	0.85	0.00	0.00
	10	34.90	1.42	19.87	0.97	14.58	1.04	0.00	0.00
	13	45.53	1.68	28.03	1.18	17.21	1.01	0.21	0.13
	15	49.85	1.81	31.68	1.52	17.88	1.23	0.00	0.00
	17	56.13	1.63	35.72	1.06	20.18	1.30	0.00	0.00
	20	62.36	2.22	42.08	1.61	20.00	1.19	0.33	0.16
12	2	10.62	0.99	4.60	0.49	5.52	0.78	0.00	0.00
	5	22.10	1.25	10.62	0.59	10.65	1.02	0.00	0.00
	8	34.18	1.48	18.93	0.92	14.77	1.10	0.00	0.00
	10	40.88	1.41	23.92	1.14	16.22	1.02	0.00	0.00
	13	49.96	1.54	30.50	1.06	19.01	1.06	0.13	0.09
	15	55.75	1.94	33.78	1.29	21.40	1.28	0.00	0.00

	17	62.75	2.01	40.12	1.36	22.27	1.16	0.00	0.00
	20	69.15	1.99	46.41	1.49	22.50	1.25	0.36	0.14
15	2	11.88	0.87	5.22	0.49	5.70	0.70	0.05	0.07
	5	27.88	1.12	13.35	0.69	13.55	0.93	0.05	0.06
	8	40.83	1.83	22.28	1.08	17.73	1.29	0.17	0.12
	10	49.33	1.76	27.65	1.02	20.70	1.58	0.28	0.17
	13	60.35	1.85	35.70	1.24	24.10	1.22	0.33	0.18
	15	66.83	2.06	41.17	1.30	25.20	1.43	0.47	0.20
	17	75.03	2.01	47.40	1.38	27.10	1.35	0.38	0.19
	20	84.60	2.08	55.57	1.58	28.68	1.26	0.52	0.21
17	2	13.23	0.98	5.65	0.43	6.52	0.78	0.05	0.07
	5	28.93	1.28	13.73	0.75	14.03	1.11	0.13	0.13
	8	44.43	1.76	23.02	1.05	20.22	1.26	0.23	0.16
	10	53.43	1.88	29.80	1.08	22.73	1.25	0.28	0.17
	13	64.88	1.73	38.60	1.10	25.53	1.35	0.35	0.16
	15	73.07	2.42	44.32	1.61	28.35	1.33	0.42	0.20
	17	80.35	1.90	50.12	1.34	29.62	1.32	0.48	0.21
	20	89.93	2.12	58.95	1.76	30.65	1.37	0.65	0.21
19	2	13.97	0.92	6.30	0.49	6.77	0.72	0.07	0.08
	5	32.20	1.55	15.13	0.84	15.87	1.14	0.10	0.09
	8	47.50	2.07	25.00	1.01	21.35	1.42	0.25	0.15
	10	58.12	1.85	31.73	1.23	25.57	1.37	0.23	0.13
	13	68.87	2.18	40.10	1.40	28.10	1.37	0.40	0.19
	15	79.07	1.90	47.48	1.56	30.80	1.21	0.38	0.19
	17	84.83	2.01	52.57	1.54	31.65	1.37	0.45	0.21
	20	94.48	2.15	61.63	1.48	32.38	1.49	0.68	0.23

APPENDIX II: Detailed Results of Analysis 2.1

Different vaccination coverage for all flight attendants		
Vaccine Coverage	New Infected Passengers	Half-Width
0%	50.78	1.69
10%	47.5	1.7
20%	42.83	1.73
30%	39.08	1.65
40%	35.45	1.77
50%	31.96	1.68
60%	27.8	1.39
70%	23.98	1.51
80%	20.4	1.18
90%	17.85	1.05

100%	14.41	0.95

APPENDIX III: Detailed Results of Analysis 2.2

Different vaccination coverage for susceptible		
Vaccine Coverage	New Infected Passengers	Half-Width
0%	50.78	1.69
10%	48.28	1.72
20%	45.83	4.44
30%	43.31	1.63
40%	41.35	1.84
50%	38.18	1.53
60%	35.45	1.48
70%	33.96	1.32
80%	31.53	1.14
90%	28.65	0.99
100%	25.03	1.36

APPENDIX IV: Detailed Results of Analysis 3

Effect of performing HH	
Hand Hygiene	Secondary cases
0% (baseline Model)	50.78
10%	50.5
20%	49.1
30%	47.9
40%	47.1
50%	45.8
60%	45.1
70%	43.9
80%	43.3
90%	41.3
100%	40.0

APPENDIX V: Detailed Results of Analysis 4.1

Using face masks by various percentages of all flight attendants		
FM Usage	**New Infected Passengers**	**Half-Width**
0%	50.78	1.69
10%	49.06	1.64
20%	46.25	1.68
30%	44.18	1.76
40%	41.25	1.85
50%	38.8	1.7
60%	35.48	1.69
70%	32.95	1.41
80%	30.61	1.26
90%	28.48	1.09
100%	26.48	1.18

APPENDIX VI: Detailed Results of Analysis 4.2

Using face masks by various percentage of infected passengers		
FM Usage	**New Infected Passengers**	**Half-Width**
0%	50.78	1.69
10%	48.2	1.74
20%	47.05	1.71
30%	45.26	1.63
40%	43.98	1.66
50%	42.71	1.69
60%	41.66	1.61
70%	40.68	1.54
80%	39.26	1.54
90%	37.78	1.38
100%	36.48	1.38

APPENDIX VII: Detailed Results of Analysis 5

Using face masks by various percentage of all flight attendants and everyone receives HH		
FM Usage	**New Infected Passengers**	**Half-Width**
0%	50.78	1.69
10%	38.73	1.1
20%	36.46	1.31
30%	33.98	1.36
40%	32.28	1.49
50%	30.45	1.41
60%	27.85	1.24
70%	25.63	1.12
80%	24.63	1.11
90%	23.5	1.29
100%	21.86	1.08

Dropped

APPENDIX VIII: Detailed Results of Analysis 6

Using face mask by % of Susceptible, All receive HH, All infected Using FM, VC 29.7 In Canada 2017-2018		
FM Usage	New Infected Passengers	Half-Width
0%	50.78	1.69
10%	25.38	1.19
20%	24.18	1.17
30%	22.83	1.18
40%	22.56	1.28
50%	21.33	1.1
60%	20.98	0.97
70%	19.76	0.93
80%	19.05	1.08
90%	18.45	0.98
100%	17.31	0.84