# Disease Containment Protocols for

# Confined Environments

*Major Qualifying Project Submitted to the Faculty of*

**WORCESTER POLYTECHNIC INSTITUTE**

*In Partial Fulfillment of the Requirements for the Degree of Bachelor of Science*

*February 3, 2016*

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# Abstract

Norovirus is a disease that causes gastrointestinal illness and is notorious for causing outbreaks on cruise vessels. In this project, containment protocols are created and evaluated using a computer simulation in order to determine which containment strategies are most effective at preventing the spread of norovirus on cruise ships. This top-down agent-based simulation is carried out to study person-to-person interactions and analyze environmental factors that contribute to the propagation of the virus. After the simulations had been run, the containment strategies were analyzed in terms of how effective they were at preventing infections, how cost effective they were, and how much impact they had on passenger experience. Finally, the best strategies are combined and analyzed to suggest the most effective containment strategy.

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# Chapter 1: Introduction

## 1.1 Problem Statement and Motivation

The purpose of this project is to develop containment strategies for norovirus outbreaks on cruise ships and evaluate their effectiveness and feasibility. Norovirus is notorious for causing outbreaks on cruise ships due to the close quarter nature of its occupants, shared dining areas, and rapid turnover of passengers. Each year, Norovirus causes 19-21 million cases of acute gastroenteritis (stomach inflammation) and contributes to 56,000-71,000 hospitalizations and 570-800 deaths (CDC, 2015). Additionally, norovirus frequently causes outbreak on subsequent cruises and is prone to infecting several hundred people per outbreak, with multiple modes of transmission (Isakbaeva et al., 2005). Analyzing transmission data using a simulation is advantageous because it allows data to be collected and processed quickly without subjecting any actual humans to the disease. Testing containment protocols on the theoretical level will have a real-life impact on society. This project will not only help the cruise industry and its stakeholders, but will provide information on how to prevent outbreaks of infectious diseases in confined spaces.

## 1.2 Previous Studies

### 1.2.1 Norwalk Virus on Cruise Ships

Norovirus, otherwise known as Norwalk virus, is a highly contagious virus that is the number one cause of acute gastroenteritis (GI) cases in the United States (CDC, 3013). As shown in Figure 1.1, 92% of acute gastroenteritis cases are caused by viral infections, the most common of which is norovirus (Freeland, 2016). Acute gastroenteritis is a disease which causes the stomach and intestines to become inflamed. As a result, those who are infected suffer stomach pain, nausea, diarrhea, and vomiting, which can result in dehydration and dizziness. Severe symptoms include fever, headache, and body aches, and extremely severe cases can even result in death (most common in children and the elderly) (CDC, 2015). Colloquially, the illness is known as “food poisoning” or “stomach flu.” There is little treatment for norovirus; since the infection is viral, it cannot be treated with antibiotics. The best course of action is to drink fluids to replace those lost from vomiting and diarrhea in order to prevent dehydration. Extreme dehydration may require hospitalization in order to provide intravenous fluids.

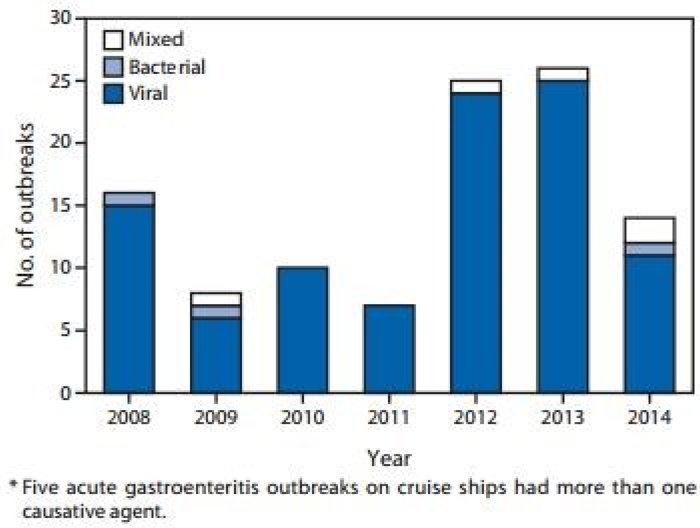



**Figure 1.1. Number of Acute Gastroenteritis Outbreaks on Cruise Ships, by Year and Causative Agent Type**

Norovirus outbreaks are associated with cruise ships due to their close quarter nature. Ships that report more than 3% of either passengers or crew having a gastrointestinal illness are considered to be outbreaks and are investigated (Neri, 2006). While there are safety checks before boarding, some passengers may bring the virus onto the ship without exhibiting any symptoms. Norovirus has a 12-48 hour incubation period before infected individuals start showing symptoms. During this time, they can still infect others before expressing symptoms for one to three days. Individuals infected with the virus are most contagious while they are exhibiting symptoms and are also particularly virulent for a few days after they recover (CDC, 2015). A study conducted by the Baylor College of Medicine observed the viral shedding values in stool for eight weeks after inoculating 16 participants with norovirus. They noticed that the highest fecal concentrations of the virus were detected after symptoms had resolved in 69% of cases. The median peak amount of virus shedding was $95 \times 10^9$genomic copies/gram of feces, and some participants shed at least $100 \times 10^6$copies/g until 14 days after inoculation (Atmar et al, 2008).

Norovirus can be contracted by accidentally ingesting stool or vomit from infected persons. The most common methods of becoming infected include eating food or drinking liquids that are contaminated with norovirus, touching contaminated surfaces and then putting fingers in one's mouth, and having direct contact with someone who is infected with norovirus. Due to the variety of transmission methods, "identifying and interrupting multiple routes of transmission has proved particularly challenging" (Isakbaeva et al., 2005). There are many different types of norovirus, therefore the virus can cause illness to one individual multiple times.

The Center for Disease Control (CDC) recommends practicing proper hand hygiene to prevent the spread of norovirus. The virus can remain in the stool for 2 weeks or more after symptoms stop, so it is important to continue proper hand hygiene. It is also advised to disinfect surfaces, wash soiled laundry, wash fruits and vegetables, and cook meat thoroughly since noroviruses can survive at temperatures as high as 140°F (CDC, 2015).

### 1.2.2 Case Studies

This section will provide an overview of investigatory research for norovirus outbreaks on cruise ships. The goal is to discover how outbreaks have been contained and what protocols were utilized. The following examples are case studies of real ships that experienced norovirus outbreaks and the published studies that were completed following the outbreak investigations.

#### 1.2.2.1 Norovirus Outbreak on Cruise Ship X, January 2009

This case studied a high morbidity norovirus outbreak on a cruise ship, referred to as "Ship X," from January 3-17, 2009. Following the suspected outbreak, investigators boarded the vessel on January 10 to review the ship's infirmary log and collect samples (Figure 1.2). In order to generate a hypothesis regarding the origin and transmission methods of the outbreak, passengers and crew that exhibited symptoms of norovirus were interviewed. Questionnaires were also distributed to everyone on board to obtain additional data such as demographic information, symptoms, risk factors, and behavior regarding hygiene (Wikswo et al., 2011).

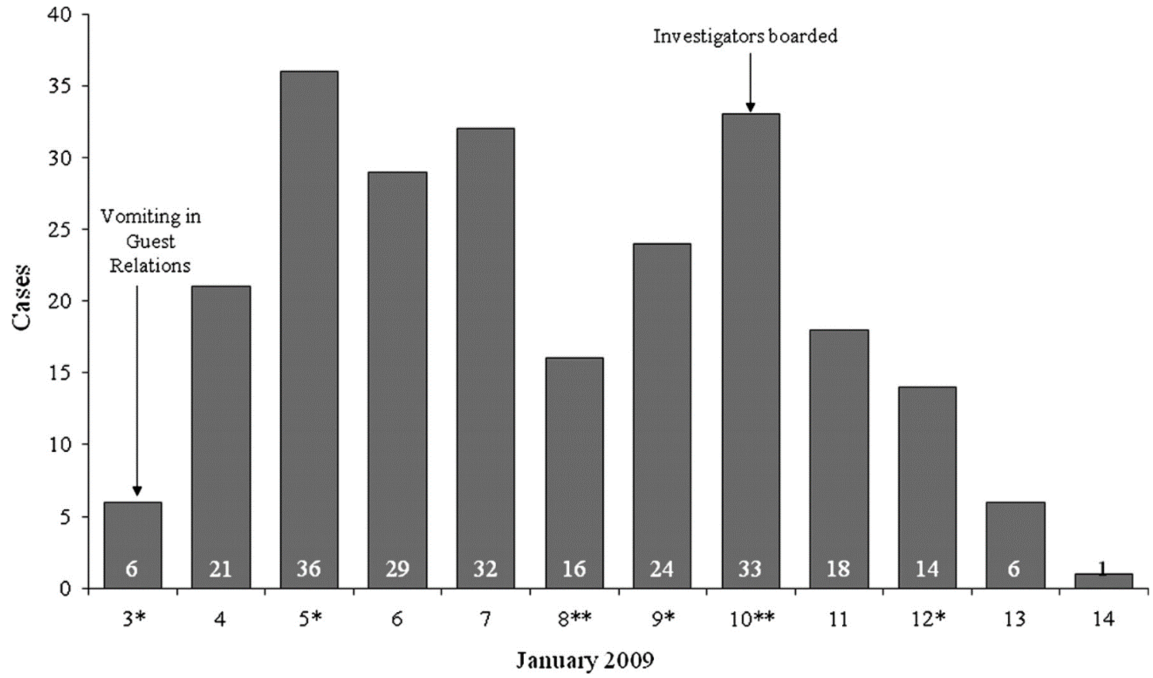



**Figure 1.2. Acute Gastroenteritis Cases by Date of Illness Onset During a Norovirus Outbreak on Cruise Ship X**

There was an 83.2% survey response rate from passengers (1532/1842) and 236 participants met the case definition of acute gastroenteritis. Of the passengers that met the case definition, 95 (40%) did not report to the infirmary. The most common reason that these passengers avoided medical care was because they did not feel ill enough or assumed they would have to pay for the medical care. After the outbreak, 88% of passengers reported changing their normal hygiene practices, the most common of which was increased use of hand sanitizer and handwashing. Additionally, passengers were willing to sacrifice communal activities; well passengers decreased in attendance by 11% and case passengers by 38%. Univariate analysis revealed that having an ill cabin mate and eating at certain dining areas were associated with an increased risk of disease. This lead to the conclusion that person-to-person transmission, including cases of public vomiting, was the primary method of transmission and the initial strain of norovirus was brought on board by one or more passengers. Wikswo et al. suggests that cases need to be identified sooner so that control measures may be implemented more rapidly. Recommended containment strategies include: aggressive sanitation, infection-control policies, and educational campaigns.

#### 1.2.2.2 Management of Norovirus on Board a Cruise Ship

This study analyzed an international cruise around the British Isles and the Netherlands. In this case, a total of 191 of the 1,194 passengers (16%) and 5 crew members (1%) became ill with gastrointestinal symptoms. In order to contain the spread, an international outbreak control group, involving port health authorities and public health agencies, was organized to oversee containment measures and advise the incident management team on board the ship. The team learned that controlling outbreaks on board a cruise ship can be difficult when the ship moves between countries and the leadership of the investigation changes. They also noted that managing a norovirus outbreak while minimizing disruption to passenger enjoyment is difficult (Vivancos et al., 2010).

#### 1.2.2.3 Outbreak of Multiple Norovirus Strains on Cruise Ship in China, 2014

Another instance of a norovirus outbreak occurred on the Yangtze River in April 2014. There was a large spike in the number of persons exhibiting gastrointestinal symptoms, prompting disease containment protocols. These protocols included sealing food and conducting sanitation and disinfection procedures in the galley, public areas, and the medical office. Additionally, symptomatic persons were transferred to a local hospital. Shortly after the removal of symptomatic persons, the outbreak ceased. Out of the 377 people on board, 51 (13.5%) were identified as probable cases. The investigation concluded that it was unlikely that only one ill person introduced norovirus to the ship, as diverse genotypes were identified (Wang et al., 2016).

#### 1.2.2.4 Outbreak of Gastrointestinal Illness Aboard Cruise Ship *MS Zuiderdam*

The norovirus outbreak that occurred on the *MS Zuiderdam* was the model for the simulations designed for this project. On December 30, 2005 the *MS Zuiderdam*, a Vista class cruise ship owned and operated by Holland America Line, embarked on an eight day cruise. The number of passengers (1,888) and crew members (814), as well as the ship deck layout, cruise length (8 days), and initial number of infections (5 crew members) were used in the simulation and gathered from this report.

During the cruise, a norovirus outbreak occurred that resulted in over 139 infections. Figure 1.3 shows that the virus was brought on board initially by five infected crew members on the date of embarkation, December 30, 2005. A peak of 59 persons reported the onset of gastrointestinal illness on January 1, 2006. After the investigation, the CDC recommended that the screening processes before embarkation should be improved, and the cruise company should not penalize passengers who report illness and voluntarily do not board the ship. Other recommendations include proper hand hygiene, disinfecting surfaces, and ensuring that food-handling crew members have little contact with passengers (Neri, 2006).

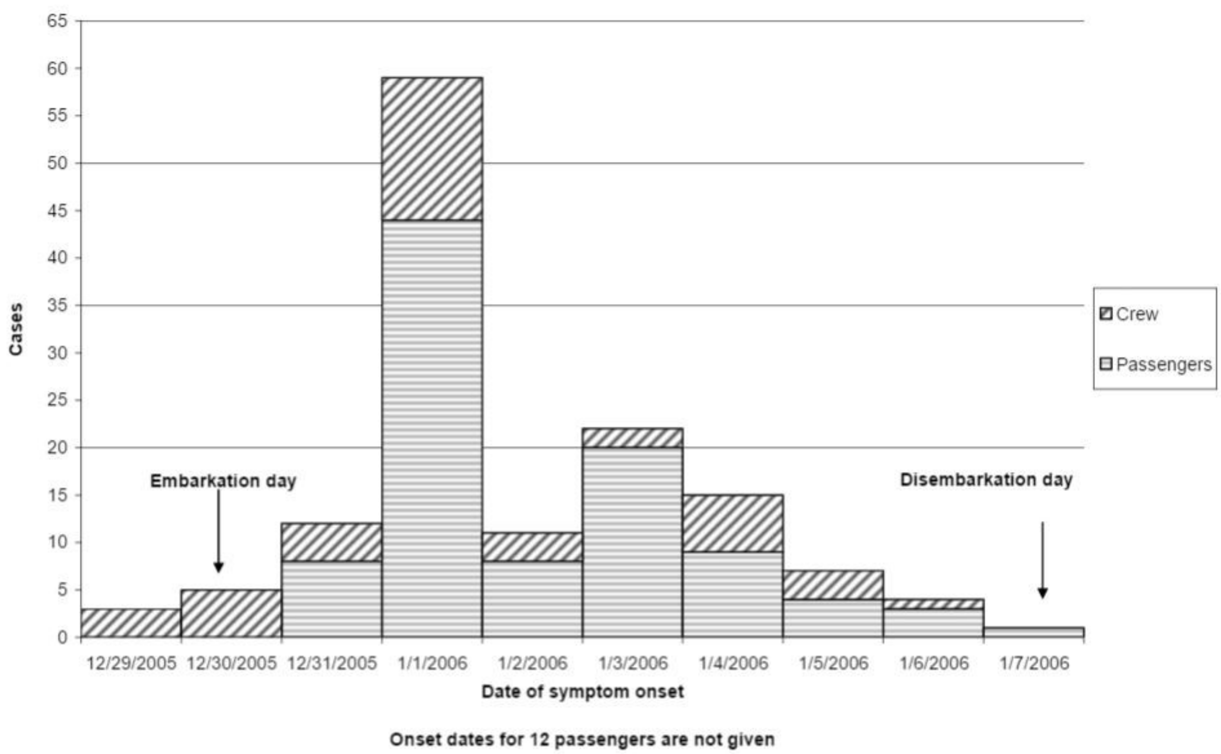



**Figure 1.3.** ***MS Zuiderdam*** **Acute Gastroenteritis Outbreak Epidemic Curve**

### 1.2.3 Existing Modeling Methods

Many systems exist to model the spread of diseases. These systems take advantage of the processing power of a computer and apply this power to study how disease spreads. Simulations allow for a safe and controlled way to attain information by using controlled randomness and virtual agents. The following systems are only two of the vast number of agent based disease simulations.

#### 1.2.3.1 GIS-Agent Based Model

This system was developed by Liliana Perez and Suzana Dragicevic in order to simulate the spread of a communicable disease in an urban environment. The model integrates geographic information systems (GIS) in order to study the results of individuals' actions in a geospatial context. While Perez and Dragicevic acknowledge that the infectious disease can spread through multiple methods such as through water, airborne inhalation, or vector-borne spread, their simulation is designed to model the person-to-person method of transmission. The pair note that a simulation has the advantage over known mathematical approaches, such as differential equation models or mean-field type models due to the fact that simulations can account for spatial and temporal data like variable population density while the equations cannot.

Similar to the cruise ship simulation in this paper, Perez and Dragicevic adopted the Susceptible-Exposed-Infectious-Removed (SEIR) model shown in Figure 1.4. In this model, the agents transition between four states. The first state, susceptible, means the agent is healthy and is able to be infected. Once the agent is infected, they become exposed but do not show symptoms. When symptoms do show up, the agents move to the infectious stage. Finally, they recover they are considered to be immune.

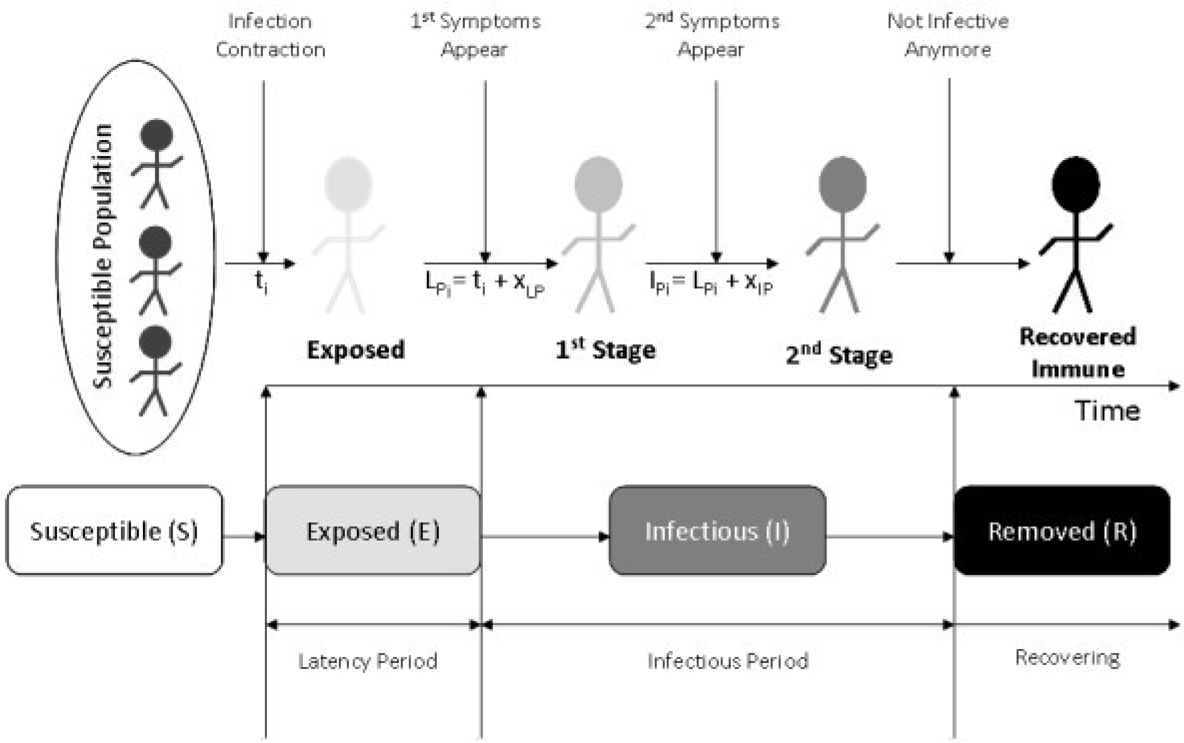



**Figure 1.4. Susceptible-Exposed-Infectious-Removed (SEIR) Model States**

The simulation that Perez and Dragicevic created was used in a case study to model a measles epidemic located within the city of Burnaby, BC, Canada. On January 28th 1997, three cases of measles were reported among university students. By April 1st 1997, 107 cases of measles had been confirmed. Several scenarios were created to model the spread of the highly contagious paramyxovirus Morbillivirus, which causes measles. All scenarios model 1000 individuals with a 12 day latency and 8 day infectious period. The scenarios include: a) Scenario 1: 999 susceptible individuals and 1 infectious individual, b) Scenario 2: 990 susceptible individuals and 10 infectious individuals, c) Scenario 3: 950 susceptible individuals and 50 infectious individuals, d) Scenario 4: 800 susceptible individuals and 200 infectious individuals. Scenario 1 was run for a simulated time frame of 60 days, and scenarios 2, 3, and 4 were run for 30 days.

#### 1.2.3.2 GLEaMviz

"GLEaMviz" is a publicly available software system that simulates the spread of infectious diseases on a global level. The simulation's engine utilizes the Global Epidemic and Mobility (GLEaM) framework, which integrates global high-resolution demographic and mobility data to simulate disease spread on a global level. GLEaMviz allows the user to set parameters like compartment-specific features, transition values, and environmental effects to customize each simulation. The program creates a dynamic map and set of charts so that the evolution of the disease can be analyzed (Gioannini, Gonçalves, Quaggiotto, Colizza, and Vespignani, 2011).

### 1.2.4 Containment

Due to the variety of transmission methods, effective containment strategies "should address all possible modes of [norovirus] transmission, including foodborne, environmental persistence, and person-to-person spread" (Isakbaeva et al., 2005). Cruise ships use several methods to attempt to mitigate the spread of infections during their voyages. The CDC cites three main preventative measures: hand hygiene, exclusion and isolation, and environmental disinfection (Figure 1.5). The first method, hand hygiene, is "likely the single most important method to prevent norovirus infection and control transmission" (CDC, 2011). This is best accomplished by washing hands and foods with plain or antiseptic soap for at least 20 seconds. Alcohol-based sanitizers are also recommended to be used between proper hand washing, but are not to be considered a substitute for proper soap and water hand washings.

Isolation is considered to be "the most practical means of interrupting transmission of virus and limiting contamination of the environment" (CDC, 2011). This is particularly important in settings like the cruise ship, where people both congregate and reside. Isolation attempts to minimize contact with healthy persons during particularly infectious periods of the illness by requesting that ill persons remain in their cabins during their illness and for a 24-48 hour period after their symptoms have resolved. This should be extended to 48-72 hours for crew members that handle food. It is also recommended to use chemical disinfectants to help interrupt the spread of norovirus from contaminated surfaces, with particular attention to bathrooms and high-touch surfaces like doorknobs and hand rails (CDC, 2011). The CDC recommends sodium hypochlorite (chlorine bleach) as a primary disinfectant due to its well documented efficacy. Finally, it is important to have an effective screening process to prevent infected persons from boarding the ship in the first place. This process should offer incentives for symptomatic passengers and offer paid sick leave for crew members in order to prevent introducing new strains aboard the ship (Isakbaeva et al., 2005).


**Figure 1.5. CDC Norovirus Prevention Infographic**

## 1.3 Goal and Objectives (our approach/simulation)

Using object oriented design techniques, the project is aimed to assess disease control in enclosed areas like cruise ships and determine effective containment measures. The ultimate goal is to create a real-time model for forecasting a norovirus outbreak in a confined environment and suggesting optimal containment measures to prevent the spread of disease.

This project will use a simulation to model the spread of Norovirus on a cruise ship. The ship that the simulation is modeled after is the *MS Zuiderdam*, operated by Holland America Line. We have utilized the MASON (Multi-Agent Simulator Of Neighborhoods) framework, which provides support tools for graphical geospatial data. This framework has given the ability to view the relationships between people (agents) on our cruise ship.

Using a simulation to test containment strategies is ideal because it allows us to discover and analyze results without actually putting any human subjects at risk. Additionally, simulations can be run much more quickly than waiting for real test sets, allowing for the collection and analysis of far more data when compared to using real-time tests. The controlled nature also allows manipulating particular variables and scenarios to see how the results are affected; since the randomness is simulated, the same seed can be used to see exactly what would have happened if different conditions occurred.

Objectives:

1. Understand Existing Code Base
2. Develop and Implement Containment Scenarios
3. Create System to Analyze Effectiveness of Scenarios
4. Comparative Analysis Between Scenarios
5. Combine Strategies for Integrated Protocols

First and foremost, it is important to understand how the base code works before making any modifications. Not only does this provide clarity, but prevents future changes from breaking the project's current build. Second, the containment scenarios need to be created, and research needs to be done to determine which scenarios should be implemented. Several simulations will be run for each scenario in order to determine their effectiveness. The results from those simulations will be analyzed using a system created for this project in order to discover the most effective strategies for preventing norovirus outbreaks. This system will consider not only rates of infection, but also passenger impact and associated cost. These three pieces will be weighted to determine the most practical strategies. Each strategy will then be compared to determine which are most efficient. Finally, the most effective strategies will be combined in an attempt to create an optimal strategy and to test how they interact with each other.

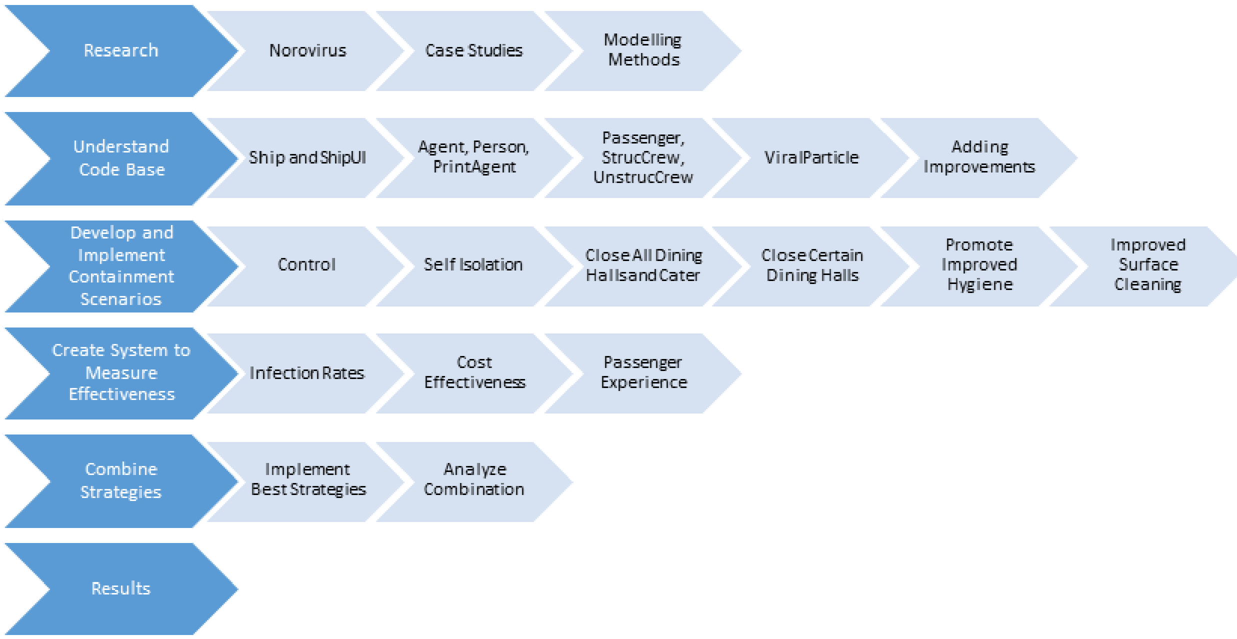



**Figure 1.6. Project Pipeline**

## 1.3 Project Deliverables

There are three main deliverables that will be completed by the end of this project: the updated source code, the containment simulation data, and analysis of the most efficient containment strategies. The updated source code will allow the project to be expanded further. The simulation data can be used to complete analyses outside the scope of this project but still relevant to virology. To complete the main goal to suggest optimal containment protocols, a combination of the most effective protocols will be presented as the standard protocol for preventing norovirus outbreaks.

# Chapter 2: Methodology

## 2.1 Understand Existing Code Base

In order to understand the pre-existing Java code base, I met with two graduate students who had previously worked on the project and had a functional understanding of the class structure. The meetings that we had provided much insight into how the classes interacted with each other and what the responsibilities of each class were. I also corresponded with the individual who originally created much of the framework for this project. I was able to ask him questions about the MASON framework and how it was used within the code. The following sections will contain material about the responsibilities of various classes in the simulation.

### 2.1.1 Ship and ShipUI

The Ship class is responsible for managing functions on deck, such as the number of crew members and passengers, as well as the current time. Each step in the simulation is one second of time, therefore there are 60 steps in a minute, and 86400 steps per day. An eight day cruise will be simulated, with a total of 691200 steps. This class also contains global boolean variables responsible for managing the isolation protocols (selfIsolation, diningClosed, diningRestricted, improvedHygiene, and improvedCleaning). The Ship class is also responsible for the internal structure of the ship, and contains lists of nodes that represent the rooms on the ship. Each room has a designated purpose, from home nodes where the agents sleep, to dining nodes where they report to eat. The ShipUI class uses the Ship class to visually display information about the simulation, and is the class used to run the simulation.

### 2.1.2 Agent, Person, PrintAgent

The Agent class details variables and methods common to all types of agents. Such variables are attributes like moveRate, currentIndex, and homeNode; the room that the agent sleeps in. The Agent class's methods include pathfinding algorithms such as depth first search and breadth first search, as well as movement methods to get them from one node to the next. The Agent class also handles the method involving the infection of other Agents.

Person and PrintAgent both extend the Agent class. PrintAgent is unique in that it does not move or become infected, but prints information to the console and to a .csv file to be analyzed later. Person maintains counters for the number of asymptomatic, symptomatic, and recovered persons, as well as the total number of infections. This class's methods are responsible for state changes in the individual. Most individuals start out healthy, then move to asymptomatic (infected, but show no symptoms due to the incubation period) after they have been infected by another agent. After they have been infected for a day, they become symptomatic (infected and showing symptoms), and two days later they become recovered and cannot be infected again.

All four different states have different shedding values, which are used as probabilities to infect someone they come in contact with. The Person class' step() method is where most of the infections occur. A variable called infectInterval determines when the infection algorithm is called. We have determined that the most accurate infectInterval is every 2000 steps. This algorithm requires all infected individuals to gather agents within a half foot radius and infects them using the probabilities obtained from the shedding values. It is important to note that the agents in the simulation cannot save variables in the class structure, but must use MASON's addXAttribute methods (where X is a data type like Integer or String). This adds limitations on how we can keep track of which state an agent is in.

### 2.1.3 Passenger, StrucCrew, UnstrucCrew

Passenger, StrucCrew, and UnstrucCrew all extend the Person class. These classes manage the behavior for their respective agents. All people have behaviors based on the time of day, with some variance thrown in. Passengers have free time to spend at various locations like the gym or the casino, however the crew members have to work at particular locations. Both passengers and crew have different dining nodes assigned to them out of the six restaurants on the ship, as well as times designated for sleeping.

### 2.1.4 ViralParticle

Infected persons also have a probability to shed viral particles. When this happens, a ViralParticle agent is created. This agent cannot move, but can infect other agents around it in the same way that the Person class can. ViralParticles do however have a set lifespan, and once every day all the particles die. This is to simulate the crew cleaning and disinfecting the ship.

### 2.1.5 Adding Improvements

Several improvements needed to be made to the existing code base in order to track the desired information. These improvements varied from the addition of fields in classes like Ship and Agent, to creating entirely new classes, as was the case with PrintAgent. The additional fields provided more control over the variable that would be manipulated in the simulations, such as the number of initially infected passengers and crew, or boolean variables enabling the various containment protocols.

#### 2.1.5.1 Agent

When I first received the code, there was only a counter to track the total number of infections. It is important to track the infection patterns of both passengers and crew to determine how each containment strategy affects both of these groups. It is also important to keep track of what state the individuals are in (well, asymptomatic, symptomatic, and recovered) as well as the total number of infections. In order to solve the problem of maintaining each agent's state, the agent's unique hash codes are added to ArrayLists when they would change between states, provided that the hash is not already contained in the list. There is an ArrayList for each of the states of infection (asymptomatic, symptomatic, and recovered) and the counters are incremented accordingly. Hash codes are never removed from the lists, otherwise agents could be infected more than once and would be double counted.

#### 2.1.5.2 PrintAgent

The PrintAgent class was created to gather the static variables in the Person class. These variables are then formatted in the PrintAgent class and printed every 2000 steps, which is equivalent to the infectInterval in the simulation. The variables are also output to a file called "CruiseInfo.csv" to be analyzed later. There is only one instance of the PrintAgent, and it cannot become infected and does not move around on the ship.

#### 2.1.5.3 Ship and Containment Classes

In order to implement the containment strategies, five static boolean variables were created in the Ship class. These five variables allowed toggling each containment strategy, which affected other parts of other classes. For example, if the selfIsolation variable is true, passenger and crew will not leave their rooms if they are symptomatic. If diningClosed is true, passengers diningNodes are set to their home nodes, implying that they can only get food from room service. Crew members still report to the dining areas if they work there. If diningRestricted is true, only certain diningNodes are off limits. ImprovedHygiene reduces the chance of infection by 50%, and improvedCleaning makes viralParticles die at a much faster rate (once every six hours instead of once every 24).

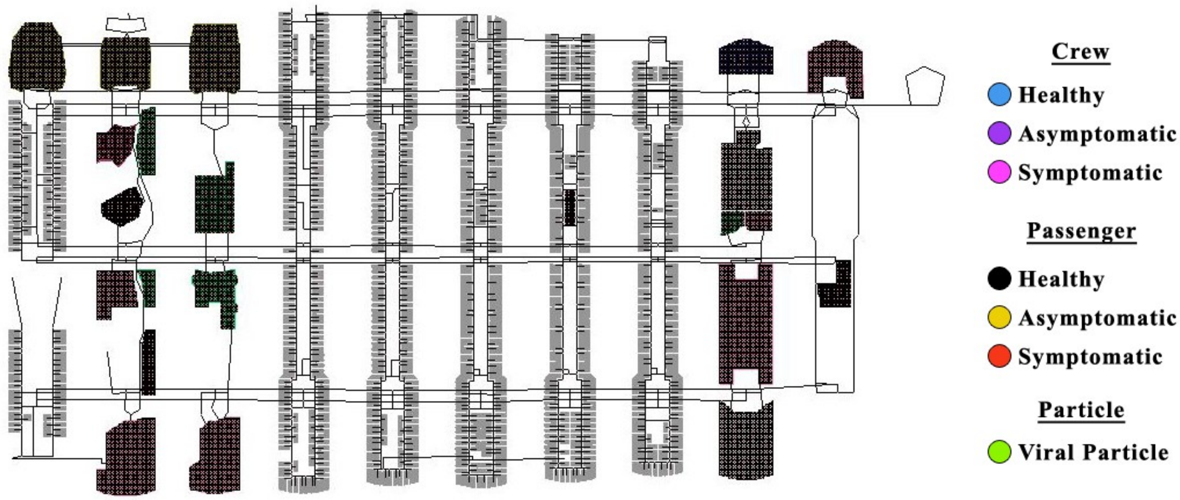
## 2.2 Develop and Implement Containment Scenarios

The core of the project is to analyze the effectiveness of various containment strategies. To do this, several different containment scenarios will be simulated and compared to a control set where no containment protocols have been enacted. The tested scenarios include: control simulation, self isolation, closing particular dining halls, closing all dining halls and instead catering to rooms, promoting improved hygiene, and enforcing strict cleaning policies. All containment protocols are triggered at the beginning of the first day, and are in effect until the end of the cruise.

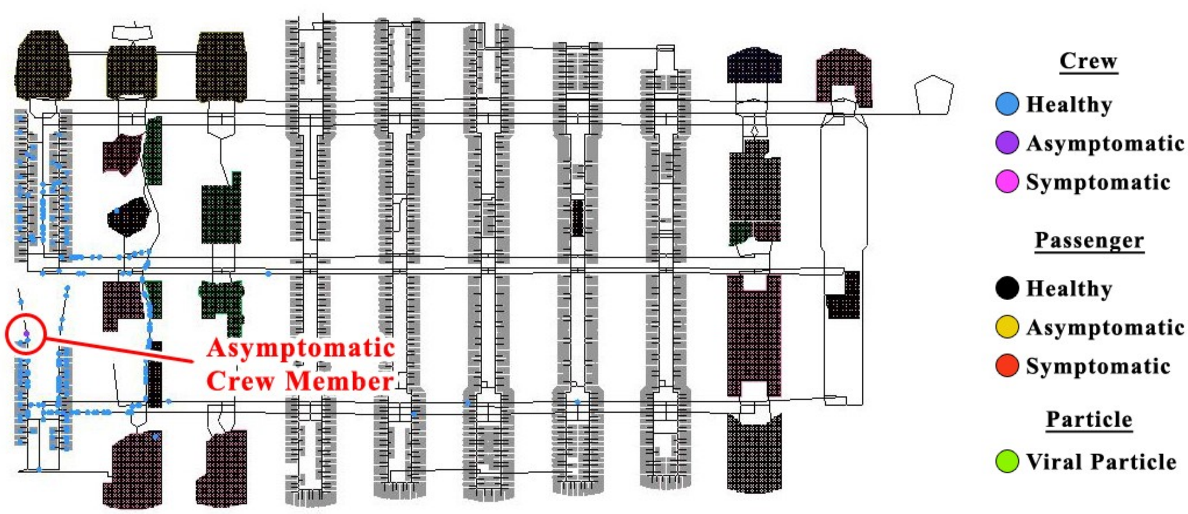
### 2.2.1 Control Simulation

The first scenario was a control simulation. The purpose of this control simulation was to serve as a baseline to examine course of virus without any intervention protocols. A sample simulation is detailed below. It should also serve as a high level overview of how each instance of the simulation was executed. The following simulation is of the control, meaning no containment is enforced:

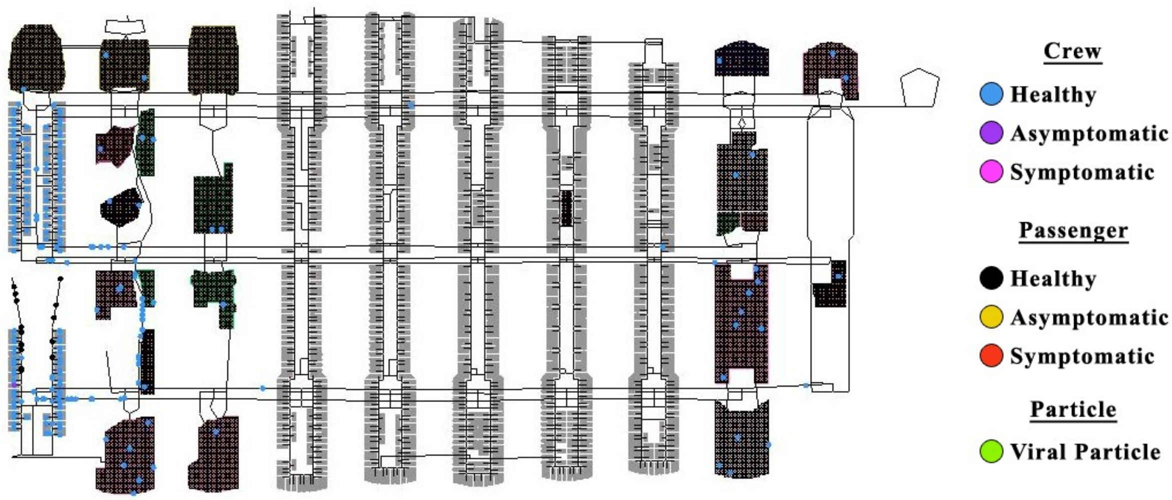
Here is the layout of the ship at 6:00 AM on the first day. No persons have boarded the ship yet.



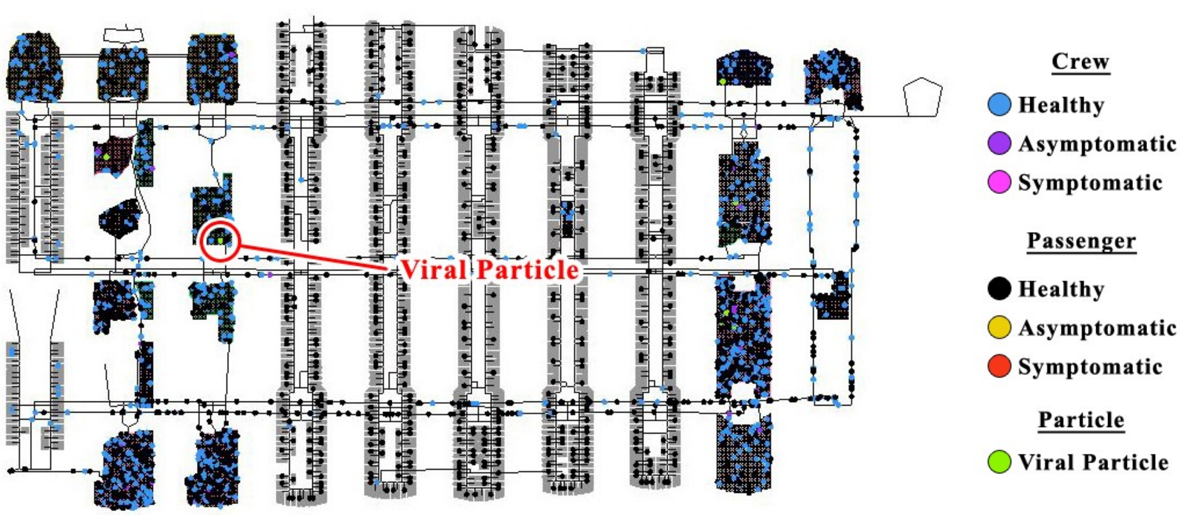

Crew members begin boarding at 6:00 AM. Healthy crew members are represented as blue dots, and infected but asymptomatic crew members are represented as purple dots. No persons showing symptoms are permitted to board the ship.



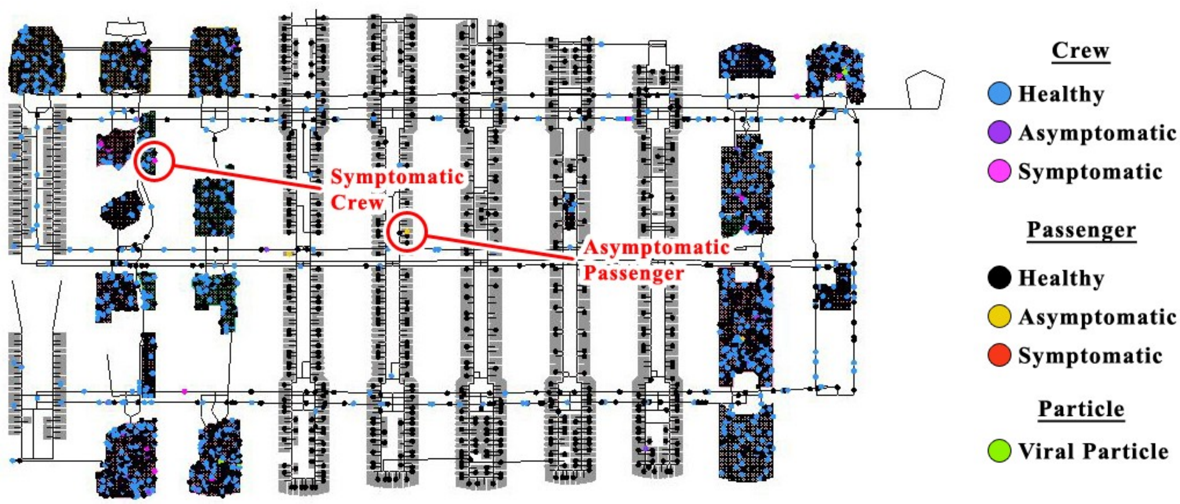
Passengers begin boarding the ship around 7:00 AM. Healthy passengers are represented as black dots. Most crew members have gone to their rooms, and a few have gone to their assigned job nodes.



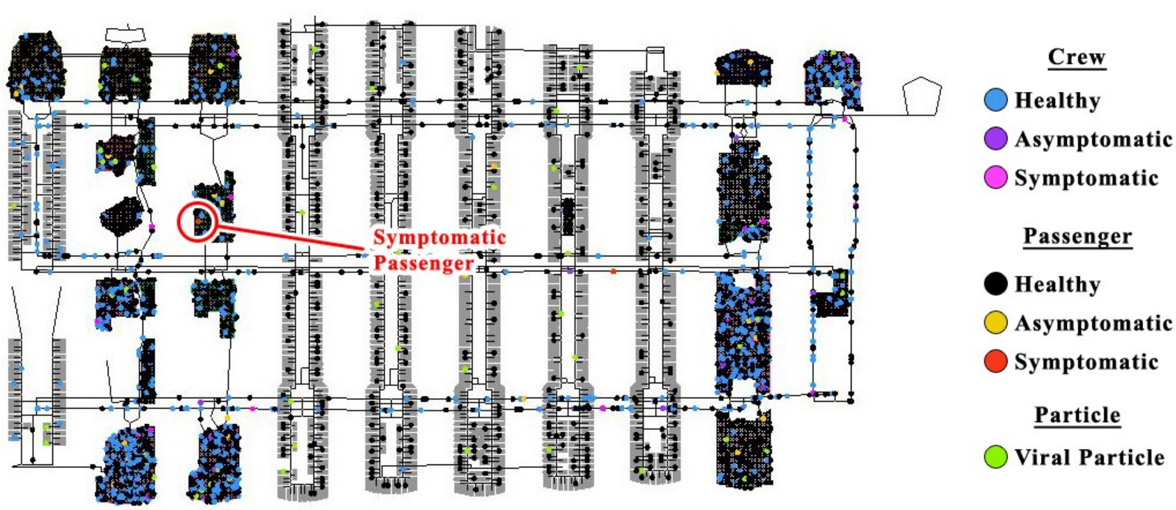

Boarding is finished at 9:30 AM. At this point, most passengers have gone to their rooms, and some have gone to the dining halls or other amenities. Almost all crew members have gone to their assigned job nodes. Infected agents leave viral particles on surfaces, which are represented by green dots.



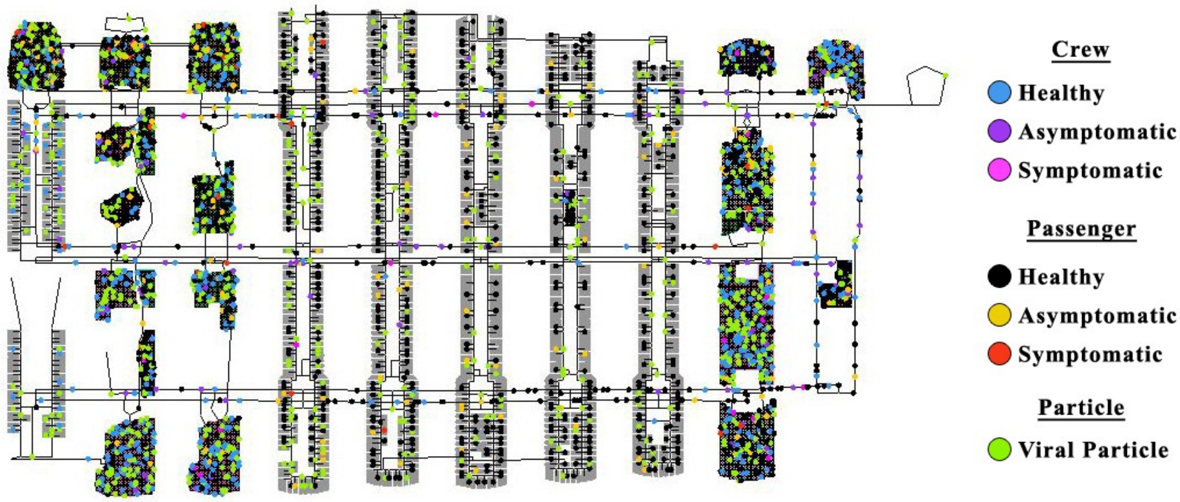
On day 2 at 9:45 AM, we can see that some crew members have become symptomatic. Symptomatic crew members are represented as pink dots. Additionally, some passengers have become infected and are asymptomatic. Asymptomatic passengers are represented by yellow dots.



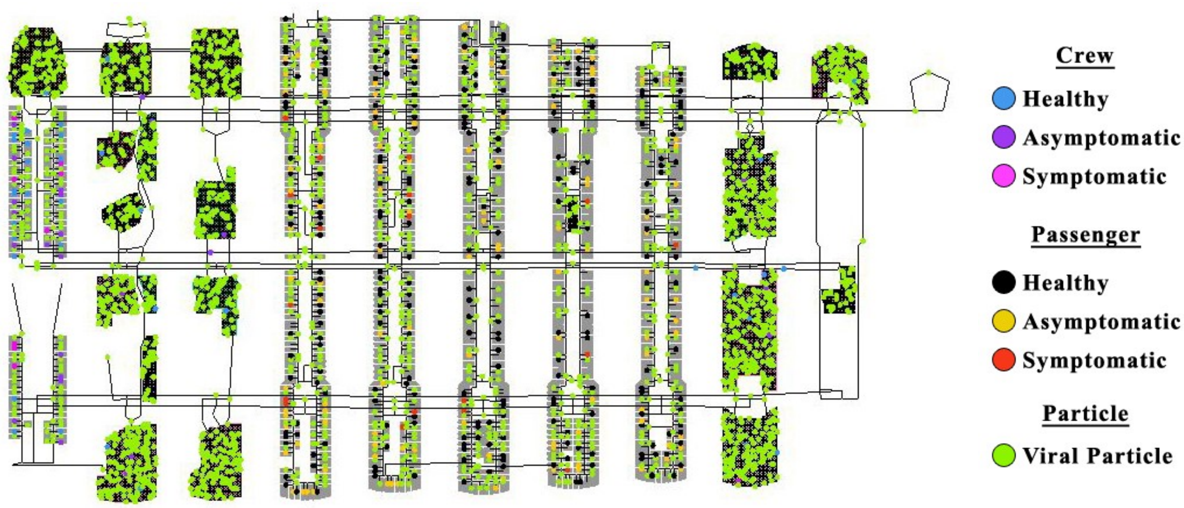

On day 3 at 1:30 PM, the infected passengers start showing symptoms. Symptomatic passengers are represented as red dots.



By 9:00 PM on day 5, a significant portion of the ship's population has been infected. As a result, there are an increased number of viral particles all over the ship.




By the start of day 7, a majority of the ship's population has been infected. Viral particles cover the ship, and most agents are infected in some capacity. As you can see, there is a much more activity between the last two days than there is in the initial five.



### 2.2.2 Self Isolation

The first protocol implemented was isolation. Isolating individuals that exhibit symptoms greatly reduces the possibility that those individuals directly infect others. Person-to-person transmission is one of the primary methods of norovirus spread, and crew members that handle food are incredibly important to isolate (CDC, 2013). In order to implement self-isolation in the simulation, if an agent is symptomatic (meaning they are infected and exhibiting symptoms) then they will remain in their rooms until they have recovered. Optimally, the agents would remain in their rooms for the duration of the infection, but this is unrealistic because asymptomatic passengers (infected but not exhibiting symptoms) would be unaware that they are spreading the disease.

### 2.2.3 Closing All Dining Halls - Cater to Rooms

In the vein of preventing person-to-person transmission, two more containment scenarios were hypothesized. The first involved closing all dining halls to passengers and requiring all meals to be ordered to their rooms. Catering to rooms is a service that many cruise lines offer for free, so this is not an unrealistic scenario. Closing dining halls completely would prevent gathering in groups and would result in a much lower population density. To implement this, each agent's diningNode is set to their homeNode, which represents the passengers remaining in their rooms to eat. Crew members also have a diningNode, but their workNode will allow them to enter the dining halls since they need to prepare meals. They will eat in their rooms in compliance with the containment protocol.

### 2.2.4 Closing Certain Dining Halls

The third scenario involved closing only some of the dining halls to discover how a greater or fewer number of dining options affected infection rates. In order to simulate the closing of designated dining areas, certain zones are excluded from the Ship's available dining locations when the Ship object is instantiated. Modifying the dining options and closely monitoring food sources should help to mitigate the disease's spread since norovirus is the leading cause of illness and outbreaks from contaminated food in the United States (CDC, 2013).

### 2.2.5 Promoting Improved Hygiene

The Center for Disease Control (CDC) recommends proper hand hygiene and thoroughly washing laundry as preventative measures for norovirus (CDC, 2015). This is broken up into two different containment scenarios: improved hygiene and improved cleaning. Improved hygiene encompasses proper hand hygiene and other important aspects of cleanliness to provide a flat reduction in the chance that an agent gets infected. This is implemented by modifying the threshold in the becomesIll method to accept fewer randomly generated values.

### 2.2.6 Improved Cleaning

Finally, the CDC also recommends cleaning and disinfecting contaminated surfaces. Improved cleaning should reduce infections by eliminating viral particles at an accelerated rate. In the control scenario, the ship is cleaned once a day and all viral particles are eliminated. To simulate more rigorous cleaning protocols, viral particles die four times a day when the improvedCleaning flag is set.

## 2.5 Create System to Measure Qualitative Effectiveness

In order to evaluate the effectiveness of the containment strategies presented, some formal system must be established. This system should not simply consider the effectiveness of the containment scenario solely based on the number of infections, but should also consider the costs associated with implementing the procedures, as well as their impact on customer experience. The following sections will justify the scoring system that will be used during evaluation.

### 2.5.1 Infection Rates

The primary measurement of how successful a given containment scenario is revolves around the rates of infection. This metric has been weighted more heavily compared to cost effectiveness and customer experience since it affects both the cruise companies as well as the passengers. The more effective the containment, the lower the number of infections. The total infections of the various containment scenarios will be compared to the total number of infections in the control case. The score for infection rates will adhere to the following formula:

$$60 - \left(60 \times \frac{I_s}{I_c}\right)$$

In the formula, ($I_s$) represents the total number of infections in the scenario being examined and ($I_c$) represents the total number of infections in the control scenario. The maximum score that the scenario can get is a 60, and the score decreases based on the ratio of total infections between the scenario being tested and the control scenario. The control scenario receives a score of 0. Containment scenarios that are more effective score higher than 0, with a maximum score of 60 if no persons were infected. If the containment scenario was worse than the control, it will receive a negative score.

### 2.5.2 Cost Effectiveness

An additional concern when evaluating the effectiveness of a particular containment strategy is how cost effective it is. While the passengers are not greatly affected by this, the cruise industry certainly is. This metric can reach a minimum score of 0, and a maximum score of 20. Higher scores mean that the containment strategy costs less money. The baseline control case receives a score of 10. Figure 2.1 shows the operating costs of several expenses as percentages of the total operating cost. This table will be referenced in scoring the cost effectiveness of particular containment scenarios.

| Year Ended December 31, | 2014 | 2013 | 2012 |
|---|---|---|---|
| Passenger ticket revenues | 73.0% | 71.9% | 72.8% |
| Onboard and other revenues | 27.0 | 28.1 | 27.2 |
| Total revenues | 100.0 | 100.0 | 100.0 |
| Cruise operating expenses: | | | |
| Commissions, transportation and other | 17.0 | 16.5 | 16.8 |
| Onboard and other | 7.2 | 7.1 | 6.9 |
| Payroll and related | 10.5 | 10.6 | 10.8 |
| Food | 5.9 | 5.9 | 5.8 |
| Fuel | 11.7 | 11.6 | 11.8 |
| Other operating | 13.3 | 14.9 | 15.0 |
| Total cruise operating expenses | 65.7 | 66.7 | 67.1 |
| Marketing, selling and administrative expenses | 13.0 | 13.1 | 13.2 |
| Depreciation and amortization expenses | 9.6 | 9.5 | 9.5 |
| Impairment of Pullmantur related assets | — | — | 5.0 |
| Restructuring and related impairment charges | 0.1 | 0.7 | — |
| Operating income | 11.7 | 10.0 | 5.2 |
| Other expense | (2.2) | (4.1) | (5.0) |
| Net income | 9.5% | 6.0% | 0.2% |

**Figure 2.1. Royal Caribbean Operating Costs as Percentages of Total Revenue**

### 2.5.3 Customer Experience

In addition to the cruise lines, passengers have stake in the containment scenarios as well. While passengers most likely do not want to spend their cruise being sick, they also want to enjoy their time on board doing activities and interacting with each other. Huang and Hsu note that customer to customer interactions have a direct positive effect on the cruise experience, specifically in the areas of relaxation and learning, which were shown to increase the overall vacation satisfaction. The two primary measurements for improving customer experience through customer to customer interaction were quantity and quality of interaction (Huang and Hsu, 2009). While our simulation cannot account for quality, conclusions can be drawn about the quantity of interaction between passengers. This metric aims to give more restrictive policies a lower score. An extremely strict set of rules will result in a lower score, the lowest number being 0. Total freedom would result in a maximum score of 20. The baseline control case receives a score of 10. When combined with the evaluation for infection and cost, there is a total maximum score of 100 points.

## 2.6 Combine Strategies for Integrated Protocols

Once the most effective strategies have been determined, those strategies will be combined to determine how effective they are together. This combined strategy will be compared to the baseline control case as well as the containment strategies it was derived from. Results from this section will determine which containment strategies are recommended for future use or study.

# Chapter 3: Results

After collecting the results of the simulations, the .csv files generated by each simulation were collected and analyzed in Microsoft Excel. Each .csv file contained the step number that every data point was collected, the corresponding time in the simulation, and counters for symptomatic, asymptomatic, recovered, and total (the sum of the previous three) infections for the passengers, the crew members, and the total (Appendix 1). Each scenario was run five times, and there were six scenarios. Simulations were started with both five initial infected crew members (5C) and five initial infected passengers (5P). This resulted in a total of 60 simulations.

Each containment scenario averaged the five trials to produce one set of data which was then compared to the other containment scenario sets. Figure 3.1 shows the total number of infections (symptomatic + asymptomatic + recovered) for the scenarios where five crew members are initially infected, and Figure 3.2 shows what percentage of the control these values are. Similarly, Figure 3.3 shows the total number of infections for the scenarios where five passengers are initially infected, and Figure 3.4 shows the percentages.

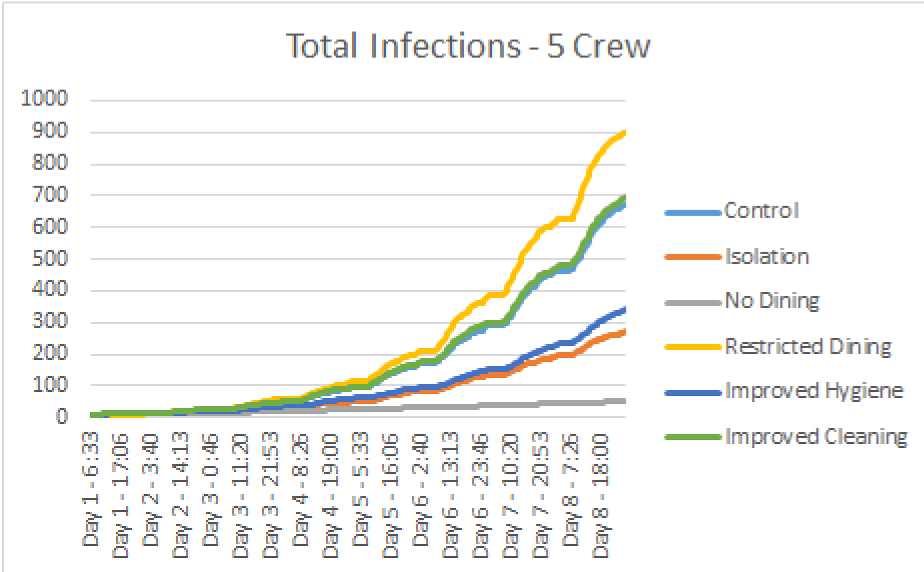



**Figure 3.1. Total Infections for 5 Initial Crew Members Infected**

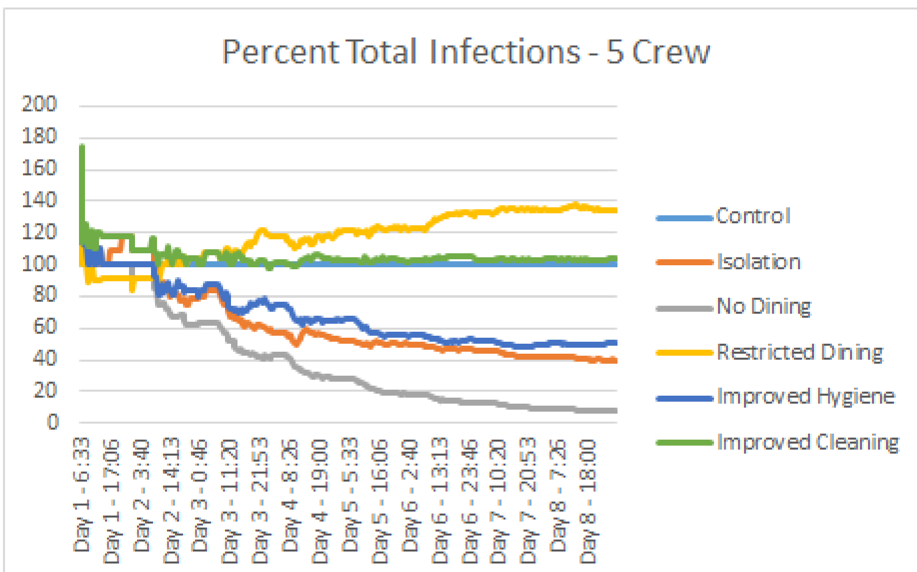



**Figure 3.2. Total Infection Percentage of Control for 5 Initial Crew Members Infected**

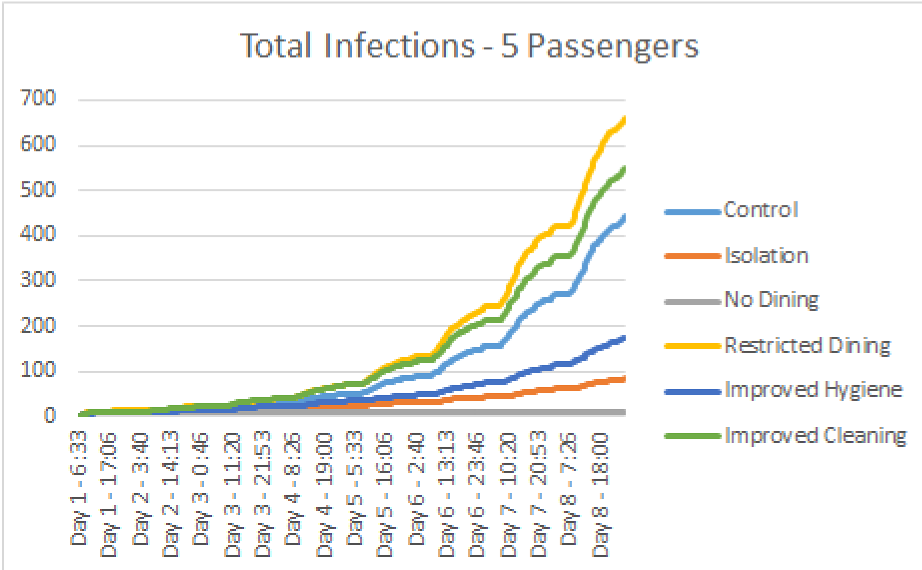



**Figure 3.3. Total Infections for 5 Initial Passengers Infected**

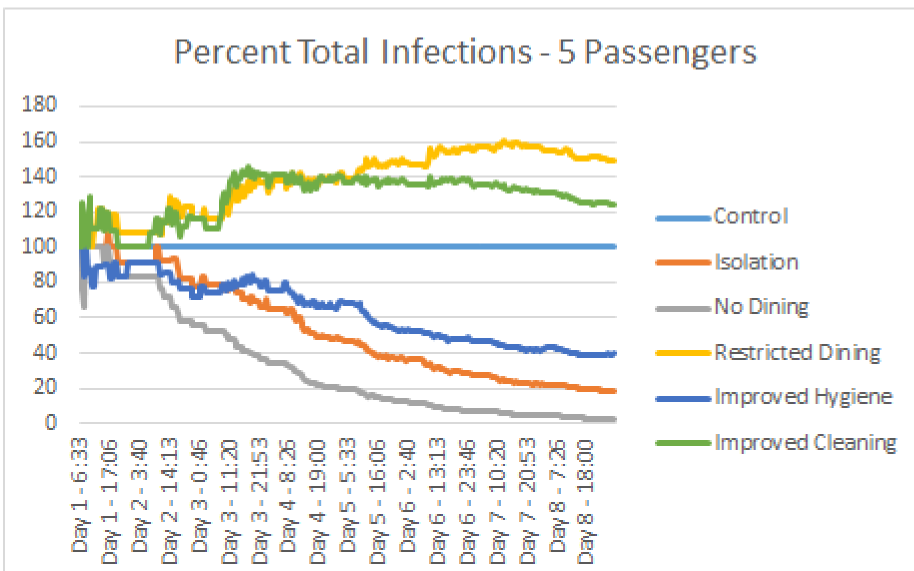



**Figure 3.4. Total Infection Percentage of Control for 5 Initial Passengers Infected**

Additionally, Figures 3.5 and 3.6 show how many people were infected per day for five initial crew infections and five initial passenger infections, respectively.

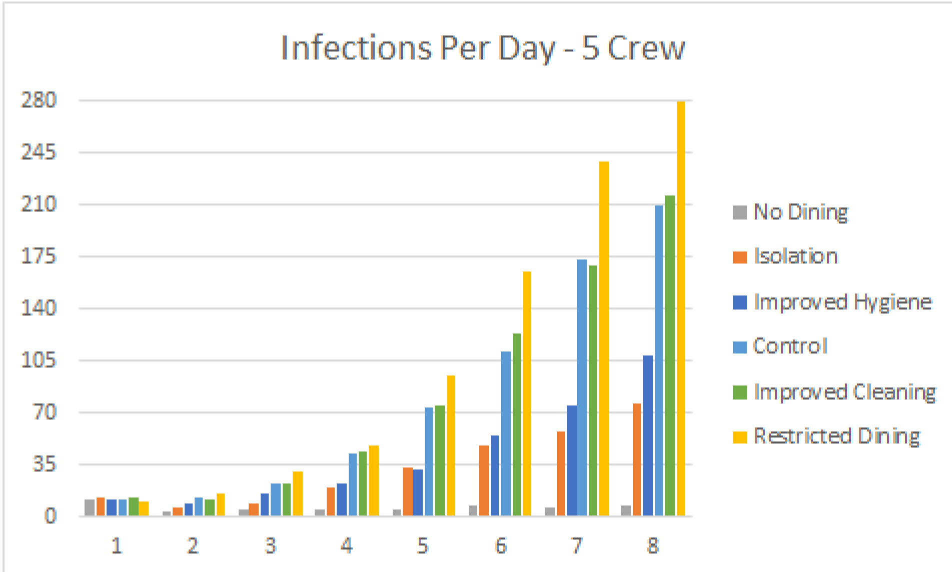



**Figure 3.5. Infections Per Day for 5 Initial Crew Members Infected**

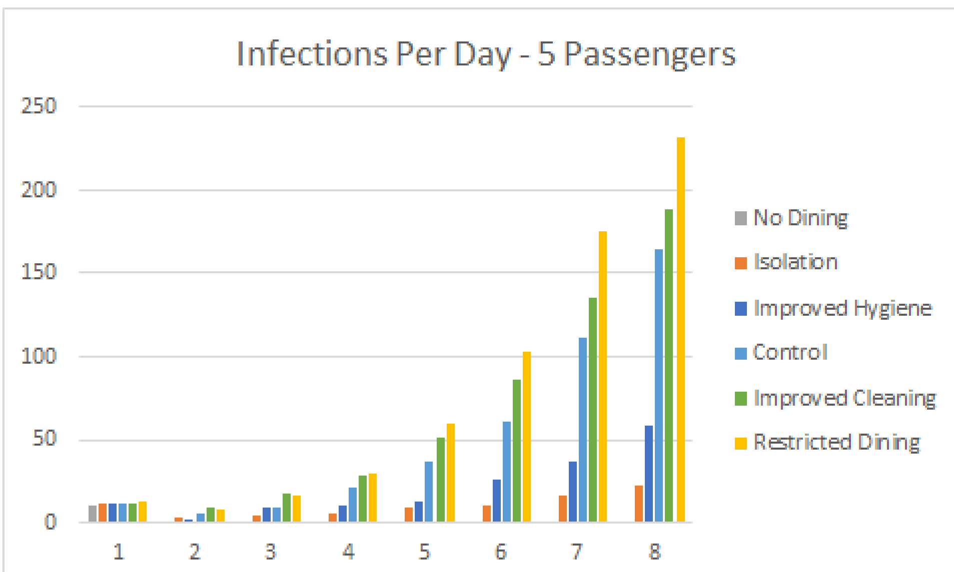



**Figure 3.6. Infections Per Day for 5 Initial Passengers Infected**

Figures 3.1 through 3.6 all show how the various containment scenarios performed in comparison to the control case. Out of the five containment scenarios, three emerged as effective containment strategies with lower infection rates than the control. The remaining two scenarios were ineffective as they had similar or higher rates of infection. As a benchmark, the control case had an average of 676 persons infected (466 passengers and 210 crew) for five initial crew infections, and had an average of 445 persons infected (286 passengers and 159 crew) for five initial passenger infections. Tables 1 and 2 shows how the other containment scenarios compared to the control.

**Table 1. Scenario Comparison for Five Initially Infected Crew Members**

| Scenario | Total Infections | Passengers Infected | Crew Infected | Percent of Control Total | Percent of Control Pass | Percent of Control Crew |
|---|---|---|---|---|---|---|
| Control | 676 | 466 | 210 | 100 | 100 | 100 |
| Isolation | 270 | 171 | 99 | 39.9408284 | 36.69527897 | 47.14285714 |
| No Dining | 52 | 2 | 50 | 7.692307692 | 0.429184549 | 23.80952381 |
| Restricted Dining | 904 | 634 | 270 | 133.7278107 | 136.0515021 | 128.5714286 |
| Improved Hygiene | 345 | 225 | 120 | 51.03550296 | 48.2832618 | 57.14285714 |
| Improved Cleaning | 699 | 472 | 227 | 103.4023669 | 101.2875536 | 108.0952381 |

**Table 2. Scenario Comparison for Five Initially Infected Passengers**

| Scenario | Total Infections | Passengers Infected | Crew Infected | Percent of Control Total | Percent of Control Pass | Percent of Control Crew |
|---|---|---|---|---|---|---|
| Control | 445 | 286 | 159 | 100 | 100 | 100 |
| Isolation | 83 | 51 | 32 | 18.65168539 | 17.83216783 | 20.12578616 |
| No Dining | 12 | 9 | 3 | 2.696629213 | 3.146853147 | 1.886792453 |
| Restricted Dining | 664 | 447 | 217 | 149.2134831 | 156.2937063 | 136.4779874 |
| Improved Hygiene | 176 | 111 | 65 | 39.5505618 | 38.81118881 | 40.88050314 |
| Improved Cleaning | 552 | 366 | 186 | 124.0449438 | 127.972028 | 116.9811321 |

## 3.1 Containment Protocols

### 3.1.1 Self Isolation

One of the best options was isolation. Preventing symptomatic individuals from walking around greatly reduced the number of infections and viral particle spread. Table 1 shows that 270 people (171 passengers and 99 crew) were infected for 5C, which is 39.941% of the control value. This would give self-isolation an infection score of 36.04. Additionally we see that for the 5P scenarios, only 83 (51 passengers and 32 crew) were infected, which is only 18.652% of the control and an infection score of 48.81. Averaging these scores together, the total infection score for self-isolation is 42.42. The cost for this scenario is non-existent since no special protocols are enacted that would incur an extra cost, so self-isolation receives a cost score of 10. Forcing the passengers to stay in their rooms does inhibit their freedom, but they only must stay there while they are sick. Most passengers elect to self-isolate anyway (Neri, 2006), and would rather spend time recovering than socializing. As a result, passenger experience receives a score of 8, for a total of 60.42 out of 100.

### 3.1.2 Closing All Dining Halls - Cater to Rooms

The most effective scenario was to shut down all dining areas and require food to be ordered directly to the rooms. Table 1 shows that for the 5C scenarios, only 52 persons (2 passengers and 50 crew) were infected. This is only 7.692% of the total infection count for the control scenario for an infection score of 55.38. Similarly, Table 2 shows that for the 5P scenarios, only 12 persons (9 passengers and 3 crew) were infected, resulting in only 2.697% of the control's infection count and an infection score of 58.38. This averages to an infection score of 56.88 for closing down all the dining halls. There would most likely be an increased cost to this method since the staff members have to deliver food much more than they normally would. This may be slightly offset by the reduced amount of cleaning necessary, but closing all dining halls receives a cost score of 7. Passengers will experience much less customer to customer interaction if they cannot eat in communal spaces, so the no dining scenario receives a 5 for passenger experience score for a total of 68.88.

### 3.1.3 Closing Certain Dining Halls

Restricting the dining options performed decidedly worse than the control case. In the 5C case, 904 persons (634 passengers and 270 crew) were infected, which is 133.728% of the control value. This results in a negative infection score of -20.24, since this strategy performed much worse than the baseline control case. In the 5P case, 664 persons (447 passengers and 217 crew) were infected, which is 149.213% of the control value, resulting in a score of -29.53. Averaging the infection scores together yields a final infection score of -24.88. This strategy does actually save the cruise company money since they do not need to spend as many resources running multiple dining halls (saving in the "food" and "other operating" categories of Figure 2.1). As a result, restricted dining receives a cost score of 13. The passenger experience is impacted due to the fewer dining options, so it only receives a score of 8 for a total of -3.88.

### 3.1.4 Promoting Improved Hygiene

The final beneficial solution was promoting improved hygiene in the form of handwashing. This scenario was coded to give a 50% resistance to agents when they might get infected. This is accurate to the 5C case where 345 agents (225 passengers and 120 crew) were infected, which is 51.036% of the control case. This results in an infection score of 29.38. In the 5P case, 176 agents (111 passengers and 65 crew) were infected. The 5P case resulted in only 39.551% of the total number of control infections for a score of 36.27. The averaged infection score is 32.82. Promoting hygiene and providing additional hygiene resources like soaps and sanitizers would cost more money than the control case, but only affects the “other operating” segment of the ships expenses (Figure 2.1). As a result, improved hygiene receives an 8 as its cost score. The passengers experience does not greatly change from the control case, so improved hygiene receives a 10, for a total of 50.82.

### 3.1.5 Improved Cleaning

Improved cleaning did not provide the expected results. Hypothetically, cleaning the ship more frequently should result in lower rates of infection. However, the 5C case shows that 699 people (472 passengers and 227 crew) were infected in the improved cleaning case. This is 103.402% of the control case for an infection score of -2.04. The 5P simulations performed even worse than the 5C cases, with 552 people (336 passengers and 186 crew) infected. This was 124.045% of the control value and an infection score of -14.43 for an average of -8.23. Possible causes for the unexpected results and potential improvements will be explained later in this paper. Improved cleaning would certainly incur a greater cost due to the additional cleaning products and potentially additional crew members that would need to be hired. As a result, improved cleaning receives a cost score of 5. The effect on passenger experience is negligible, and receives a 10 for a total of 6.77.

### 3.1.6 Evaluating Effective Protocols

Table 3 shows the various scores for all containment strategies, as well as the control strategy. The best strategies for managing infections were closing all dining halls and catering to rooms, enforcing self-isolation, and promoting improved hygiene. The most cost effective strategy was to close down certain dining halls. While this protocol was the only one that cost less than the control case, it also performed the worst overall. No protocols improved passenger experience, but improved hygiene and improved cleaning tied with the control case. Overall, the most effective strategies were closing all dining halls and catering to rooms, enforcing self-isolation, and promoting improved hygiene, all of which scored at least 30 points more than the control case.

**Table 3. Score Comparison for Containment Protocols**

| Containment | Infection Score | Cost Score | Passenger Experience Score | Total |
|---|---|---|---|---|
| Control | 0 | 10 | 10 | 20 |
| Isolation | 42.42 | 10 | 8 | 60.42 |
| No Dining | 56.88 | 7 | 5 | 68.88 |
| Restricted Dining | -24.88 | 13 | 8 | -3.88 |
| Improved Hygiene | 32.82 | 8 | 10 | 50.82 |
| Improved Cleaning | -8.23 | 5 | 10 | 6.77 |

## 3.2 Integration of Protocols

In order to create an optimal containment strategy, the most effective individual strategies were combined together. These individual strategies were closing all dining halls, isolating symptomatic individuals, and promoting good hygiene. Fortunately, none of these behaviors contradicts the others, so they can all be implemented simultaneously. The scenario was run 10 times, five for the case where five crew members are initially infected and five for the case where five passengers are initially infected. Combination of these individual strategies shows a drastic improvement over many of the other protocols.

Table 4 shows how the combination strategy compares to the control case and the scenarios that contributed to it for the case of five initially infected crew members. Instead of the control's 676 infections, the combination protocol has only 17 infections (2.515% of the control's infections). Sixteen of these are crew members, meaning that only 11 more crew were infected past the initial five. This is extremely low considering that most agents sleep in the same room as other agents and due to the extremely close proximity, roommates are almost guaranteed to become infected (Neri, 2006). In addition to the low crew infection rate, there was only one passenger infected.

**Table 4. Scenario Comparison for Combination Protocol and Contributors for Five Initially Infected Crew Members**

| Scenario | Total Infections | Passengers Infected | Crew Infected | Percent of Control Total | Percent of Control Pass | Percent of Control Crew |
|---|---|---|---|---|---|---|
| Control | 676 | 466 | 210 | 100 | 100 | 100 |
| Isolation | 270 | 171 | 99 | 39.9408284 | 36.69527897 | 47.14285714 |
| No Dining | 52 | 2 | 50 | 7.692307692 | 0.429184549 | 23.80952381 |
| Improved Hygiene | 345 | 225 | 120 | 51.03550296 | 48.2832618 | 57.14285714 |
| Combination | 17 | 1 | 16 | 2.514792899 | 0.214592275 | 7.619047619 |

Similarly, Table 5 shows the combination strategy and its contributors for five initially infected passengers. There were only nine total infections for the combination case. Again, this is most likely due to the fact that most agents stay in a room with other agents. This number is astonishingly low when compared to the control case's 445 infections; only 2.022% of the control value was infected in the combination protocol. Another shocking fact is that no crew members were infected over the average of five simulations.

**Table 5. Scenario Comparison for Combination Protocol and Contributors for Five Initially Infected Passengers**

| Scenario | Total Infections | Passengers Infected | Crew Infected | Percent of Control Total | Percent of Control Pass | Percent of Control Crew |
|---|---|---|---|---|---|---|
| Control | 445 | 286 | 159 | 100 | 100 | 100 |
| Isolation | 83 | 51 | 32 | 18.65168539 | 17.83216783 | 20.12578616 |
| No Dining | 12 | 9 | 3 | 2.696629213 | 3.146853147 | 1.886792453 |
| Improved Hygiene | 176 | 111 | 65 | 39.5505618 | 38.81118881 | 40.88050314 |
| Combination | 9 | 9 | 0 | 2.02247191 | 3.146853147 | 0 |

The data shows that while certain containment strategies are efficient, a combination of the most effective strategies is superior. If possible, it would be beneficial for cruise liners to enforce these three containment measures. It is also important to avoid ineffective measures like restricting the dining options. Conversely, providing additional dining choices should help to mitigate disease spread even further.

# Chapter 4: Discussion

Two of the three effective scenarios are recommendations made by the Center for Disease Control (CDC); isolation and improved hygiene (in the form of good hand hygiene). These two strategies are the second and third most effective, respectively. The most effective scenario was completely restricting passengers from visiting the dining halls and requiring them to order food to their rooms. It is notable that in the scenario with five initial crew infections, only two passengers become infected. While it is important to mitigate as many infections as possible, it is more important for the cruise companies to keep passenger satisfaction as high as possible. With this in mind, keeping the passenger infection rate low is a top priority, but preventing passengers from socializing in dining halls may negatively impact their cruise experience. Since isolation and improved hand hygiene are already recommended by the CDC, these methods do not negatively impact passenger opinion. The only additional consideration is that not all passengers will follow the scenarios rules as perfectly as every agent did. All in all, combining these three strategies (isolation, closed dining halls, and improved hygiene) seems to be the best strategy.

Interestingly enough, restricting the dining options caused an increase in the infection rates. While completely preventing the access to dining halls was the most effective scenario, prohibiting access to several dining areas was the least effective. This is most likely because the passengers that would have been dining in the closed halls instead grouped together inside the remaining dining halls. This caused a much greater population density in the remaining areas of the ship, resulting in the increased rate of infection. The information resulting from this test is still important even though the scenario was least effective; the lower the population density, the lower the rates of infection. Lowering the population density can be achieved in two ways: let less people onto the cruise ship or increase the size of the ship and its dining options.

# Chapter 5: Conclusion

This project, motivated by the frequency of norovirus outbreaks on cruise vessels, aimed to develop and analyze containment strategies in order to prevent outbreaks. Several containment methods were analyzed using an agent-based modeling simulation built in Java which used the blueprint of the *MS Zuiderdam*. Tested containment methods included: self-isolation, closing all public dining areas and catering to rooms, closing down particular dining areas, promoting improved hygiene, and enforcing a more strict cleaning policy. Each of these scenarios, as well as a control scenario with no containment implemented, was simulated 10 times; five times with five crew members as the initial source of infection (as was the case in the *MS Zuiderdam* case study), and five times with five passengers as the initial source of infection.

Once the data was gathered from the simulations, the results were analyzed to discover which containment scenarios prevented the most infections. Additional consideration was given to the cost effectiveness and impact on passenger experience to determine which strategies were the best overall choices. Using this metric, the top performing strategies (self-isolation, closing dining halls, and promoting improved hygiene) were implemented together and this combination of strategies was analyzed. This combination was compared to the control study as well as its individual components and was shown to perform significantly better. The successful implementation of these protocols provides a key insight into the field of epidemiology and future studies of agent based simulations.

# Chapter 6: Potential Problems and Future Studies

While the project goal of implementing a model for forecasting the outbreak of norovirus in a cruise setting was a success, there are several problems that can be addressed for the future.

1. The improved cleaning simulations did not perform as expected. This is most likely due to how viral particles were implemented. During instantiation, a viralParticle is given a dose which is dependant on the overall infectivity of the ship. This dose remains constant until the viralParticle dies. Normally, this means that the viralParticle will go through one whole day with a relatively low dose until it gets cleaned and dies, since two viralParticles cannot occupy the same space. During the improved cleaning scenario, viralParticles are wiped every six hours. While this ensures that particles have less time on the ship's surfaces, it also opens up space for newer and more virulent particles since the dose of the particle is related to the number of infections, which increases with time. This behavior causes the less virulent particles to be replaced with particles that are more infectious, which is not what would realistically happen. In order to improve this, the viralParticles should have a constant dose, or the dose should be able to be updated if a new particle would be created in the same node.
2. The second problem is that humans will not follow the protocols as accurately as the agents in the simulation. For example, in the isolation case, every agent (100%) will remain in their cabin until they stop exhibiting symptoms and fully recover. In the *MS Zuiderdam* case study, only 93% of passengers that sought medical help received instructions to isolate. This is worrisome since only 63% of ill passengers reported their symptoms, therefore a larger percentage of passengers should have self-isolated (Neri, 2006). Unfortunately, the contrast between the simulation and the actual case study is vast. In order to make the simulation more realistic, probabilistic weights can be given which will determine an agent's likelihood of following the proper protocol.
3. In a real-life scenario, containment protocols would most likely not be enacted until the outbreak threshold (3% of the ship's population) was reached (CDC, 2011). In the simulations tested in

this project, the protocols were enacted before people even set foot on the ship. While ideally containment protocols were followed as soon as passengers entered the ship, the simulation is unrealistic. On the other hand, an additional recommendation would be to enforce policies sooner and with greater rigor.

# References


Norovirus Overview. (2013, July 26). Retrieved November 23, 2015, from http://www.cdc.gov/norovirus/about/overview.html

Norovirus Symptoms. (2013, July 26). Retrieved November 23, 2015, from http://www.cdc.gov/norovirus/about/symptoms.html

Norovirus Transmission. (2015, December 10). Retrieved December 16, 2015, from http://www.cdc.gov/norovirus/about/transmission.html

Preventing Norovirus Infection. (2015, December 10). Retrieved December 16, 2015, from http://www.cdc.gov/norovirus/preventing-infection.html

Norovirus Treatment. (2012, April 12). Retrieved December 16, 2015, from http://www.cdc.gov/norovirus/about/treatment.html

U.S. Trends and Outbreaks. (2015, December 10). Retrieved January 18, 2016, from http://www.cdc.gov/norovirus/trends-outbreaks.html

Vinjé, J., Lopman, B., Park, G. W., Yen, C., Gregoricus, N., & Parashar, U. (2011). *Updated norovirus outbreak management and disease prevention guidelines*. US Department of Health and Human Services, Centers for Disease Control and Prevention.

Isakbaeva, E. T., Widdowson, M. A., Beard, R. S., Bulens, S. N., Mullins, J., Monroe, S. S., ... & Glass, R. I. (2005). Norovirus transmission on cruise ship. *Emerging infectious diseases*, *11*(1), 154.

Centers for Disease Control and Prevention. *Vessel Sanitation Program Operations Manual 2011*. Atlanta, GA: US Department of Health and Human Services, Centers for Disease Control and Prevention, 2011.

Neri, A. (2006, May 31). Final Epi-Aid Trip Report: Outbreak of Gastrointestinal Illness Aboard Cruise Ship MS Zuiderdam, Fort Lauderdale, Florida, and Nassau, Bahamas, 2005 [Letter to Douglas Hamilton].

Wikswo, M. E., Cortes, J., Hall, A. J., Vaughan, G., Howard, C., Gregoricus, N., & Cramer, E. H. (2011). Disease transmission and passenger behaviors during a high morbidity Norovirus outbreak on a cruise ship, January 2009.*Clinical infectious diseases*, *52*(9), 1116-1122.

v, R., Keenan, A., Sopwith, W., Quigley, C., Mutton, K., Nichols, G., ... & Reid, J. (2010). Management of an international outbreak of norovirus on board a cruise ship. *International Journal of Infectious Diseases*, *14*, e135.

Wang, X., Yong, W., Shi, L., Qiao, M., He, M., Zhang, H., ... & Ding, J. (2016). An outbreak of multiple norovirus strains on a cruise ship in China, 2014. *Journal of applied microbiology*, *120*(1), 226-233.

Freeland, A. L. (2016). Acute Gastroenteritis on Cruise Ships—United States, 2008–2014. *MMWR. Morbidity and mortality weekly report*, *65*.

Atmar, R. L., Opekun, A. R., Gilger, M. A., Estes, M. K., Crawford, S. E., Neill, F. H., & Graham, D. Y. (2008). Norwalk virus shedding after experimental human infection. *Emerging infectious diseases*, *14*(10), 1553.

Huang, J., & Hsu, C. H. (2009). The impact of customer-to-customer interaction on cruise experience and vacation satisfaction. *Journal of Travel Research*.

Perez, L., & Dragicevic, S. (2009). An agent-based approach for modeling dynamics of contagious disease spread. *International journal of health geographics*, *8*(1), 1.

Gioannini, C., Gonçalves, B., Quaggiotto, M., Colizza, V., & Vespignani, A. (2011). The GLEaMviz computational tool, a publicly available software to explore realistic epidemic spreading scenarios at the global scale. *BMC infectious diseases*, *11*(1), 1.

Figure 1.1. Number of Acute Gastroenteritis Outbreaks on Cruise Ships, by Year and Causative Agent Type: http://www.cdc.gov/mmwr/volumes/65/wr/mm6501a1.htm

Figure 1.2. Acute Gastroenteritis Cases by Date of Illness Onset During a Norovirus Outbreak on Cruise Ship X: Wikswo, M. E., Cortes, J., Hall, A. J., Vaughan, G., Howard, C., Gregoricus, N., & Cramer, E. H. (2011). Disease transmission and passenger behaviors during a high morbidity Norovirus outbreak on a cruise ship, January 2009.*Clinical infectious diseases*, *52*(9), 1116-1122.

Figure 1.3. *MS Zuiderdam* Acute Gastroenteritis Outbreak Epidemic Curve: Neri, A. (2006, May 31). Final Epi-Aid Trip Report: Outbreak of Gastrointestinal Illness Aboard Cruise Ship MS Zuiderdam, Fort Lauderdale, Florida, and Nassau, Bahamas, 2005 [Letter to Douglas Hamilton].

Figure 1.4. Susceptible-Exposed-Infectious-Removed (SEIR) Model States: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2729742/figure/F1/

Figure 1.5. CDC Norovirus Prevention Infographic: http://www.cdc.gov/features/norovirus/norovirus_a580px.jpg

Figure 2.1. Royal Caribbean Operating Costs as Percentages of Total Revenue: http://www.rclcorporate.com/content/uploads/RCL-2014-Annual-Report1.pdf

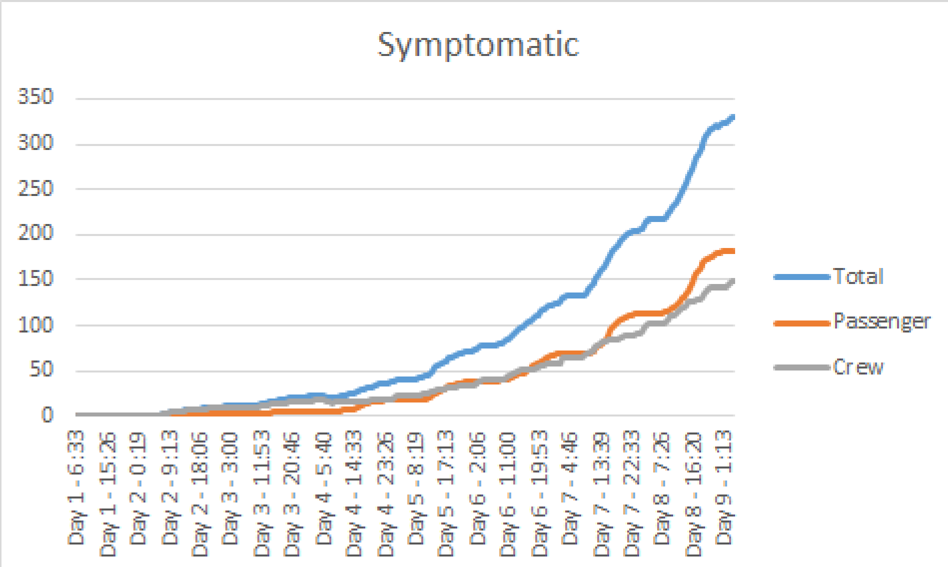
# Appendices

## Appendix A. Sample Output of Control Scenario (2 Days)

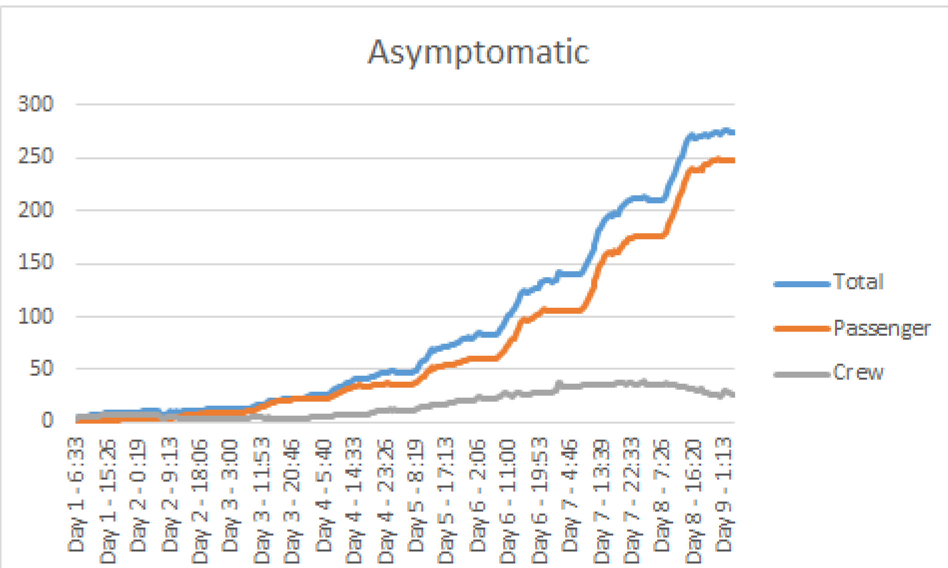
| STEP | TIME | TOTAL SYMPTOMATIC | TOTAL ASYMPTOMATIC | TOTAL RECOVERED | TOTAL INFECTIONS | SYMPTOMATIC PASSENGERS | ASYMPTOMATIC PASSENGERS | RECOVERED PASSENGERS | INFECTED PASSENGERS | SYMPTOMATIC CREW | ASYMPTOMATIC CREW | RECOVERED CREW | INFECTED CREW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 | Day 1 - 6:33 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 4000 | Day 1 - 7:06 | 0 | 3 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 3 |
| 6000 | Day 1 - 7:40 | 0 | 3 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 3 |
| 8000 | Day 1 - 8:13 | 0 | 4 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 4 |
| 10000 | Day 1 - 8:46 | 0 | 5 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 5 |
| 12000 | Day 1 - 9:20 | 0 | 5 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 5 |
| 14000 | Day 1 - 9:53 | 0 | 5 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 5 |
| 16000 | Day 1 - 10:26 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 18000 | Day 1 - 11:00 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 20000 | Day 1 - 11:33 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 22000 | Day 1 - 12:06 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 24000 | Day 1 - 12:40 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 26000 | Day 1 - 13:13 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 28000 | Day 1 - 13:46 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 30000 | Day 1 - 14:20 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 32000 | Day 1 - 14:53 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 34000 | Day 1 - 15:26 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 36000 | Day 1 - 16:00 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 38000 | Day 1 - 16:33 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 40000 | Day 1 - 17:06 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 42000 | Day 1 - 17:39 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 44000 | Day 1 - 18:13 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 46000 | Day 1 - 18:46 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 48000 | Day 1 - 19:20 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 50000 | Day 1 - 19:53 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 52000 | Day 1 - 20:26 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 54000 | Day 1 - 21:00 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 56000 | Day 1 - 21:33 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 58000 | Day 1 - 22:06 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 60000 | Day 1 - 22:40 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 62000 | Day 1 - 23:13 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 64000 | Day 1 - 23:46 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 66000 | Day 2 - 0:19 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 68000 | Day 2 - 0:53 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 70000 | Day 2 - 1:26 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 72000 | Day 2 - 2:00 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 74000 | Day 2 - 2:33 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 76000 | Day 2 - 3:06 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 78000 | Day 2 - 3:40 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 80000 | Day 2 - 4:13 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 82000 | Day 2 - 4:46 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 84000 | Day 2 - 5:19 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 86000 | Day 2 - 5:53 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 88000 | Day 2 - 6:26 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 90000 | Day 2 - 7:00 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 92000 | Day 2 - 7:33 | 0 | 6 | 0 | 6 | 0 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| 94000 | Day 2 - 8:06 | 0 | 7 | 0 | 7 | 0 | 1 | 0 | 1 | 0 | 6 | 0 | 6 |
| 96000 | Day 2 - 8:40 | 0 | 7 | 0 | 7 | 0 | 1 | 0 | 1 | 0 | 6 | 0 | 6 |
| 98000 | Day 2 - 9:13 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 100000 | Day 2 - 9:46 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 102000 | Day 2 - 10:19 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 104000 | Day 2 - 10:53 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 106000 | Day 2 - 11:26 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 108000 | Day 2 - 12:00 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 110000 | Day 2 - 12:33 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 112000 | Day 2 - 13:06 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 114000 | Day 2 - 13:40 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 116000 | Day 2 - 14:13 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 118000 | Day 2 - 14:46 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 120000 | Day 2 - 15:20 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 122000 | Day 2 - 15:53 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 124000 | Day 2 - 16:26 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 126000 | Day 2 - 17:00 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 128000 | Day 2 - 17:33 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 130000 | Day 2 - 18:06 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 132000 | Day 2 - 18:39 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 134000 | Day 2 - 19:13 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 136000 | Day 2 - 19:46 | 0 | 8 | 0 | 8 | 0 | 1 | 0 | 1 | 0 | 7 | 0 | 7 |
| 138000 | Day 2 - 20:20 | 1 | 7 | 0 | 8 | 0 | 1 | 0 | 1 | 1 | 6 | 0 | 7 |
| 140000 | Day 2 - 20:53 | 1 | 7 | 0 | 8 | 0 | 1 | 0 | 1 | 1 | 6 | 0 | 7 |
| 142000 | Day 2 - 21:26 | 1 | 8 | 0 | 9 | 0 | 1 | 0 | 1 | 1 | 7 | 0 | 8 |
| 144000 | Day 2 - 22:00 | 1 | 8 | 0 | 9 | 0 | 1 | 0 | 1 | 1 | 7 | 0 | 8 |
| 146000 | Day 2 - 22:33 | 1 | 8 | 0 | 9 | 0 | 1 | 0 | 1 | 1 | 7 | 0 | 8 |
| 148000 | Day 2 - 23:06 | 1 | 8 | 0 | 9 | 0 | 1 | 0 | 1 | 1 | 7 | 0 | 8 |
| 150000 | Day 2 - 23:39 | 1 | 8 | 0 | 9 | 0 | 1 | 0 | 1 | 1 | 7 | 0 | 8 |

# Appendix B. Control Simulations for 5C - Graph Data

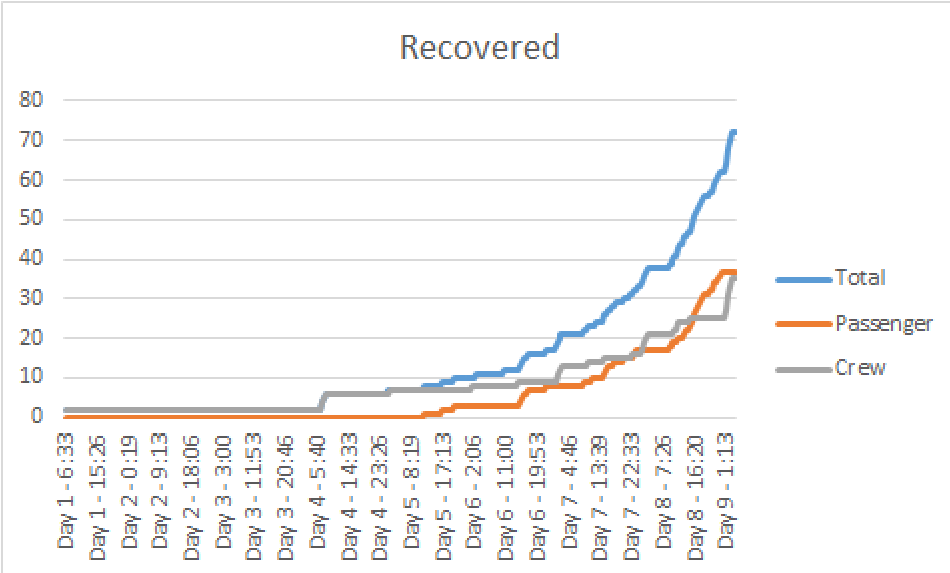
## Appendix B1. Average Symptomatic for 5C Control - 5 Simulations



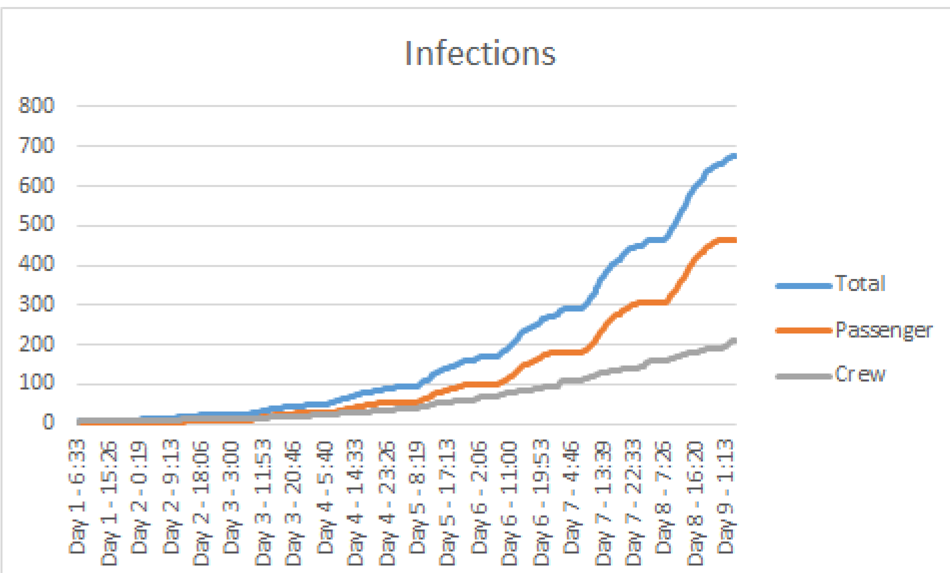

## Appendix B2. Average Asymptomatic for 5C Control - 5 Simulations



Appendix B3. Average Recovered for 5C Control - 5 Simulations

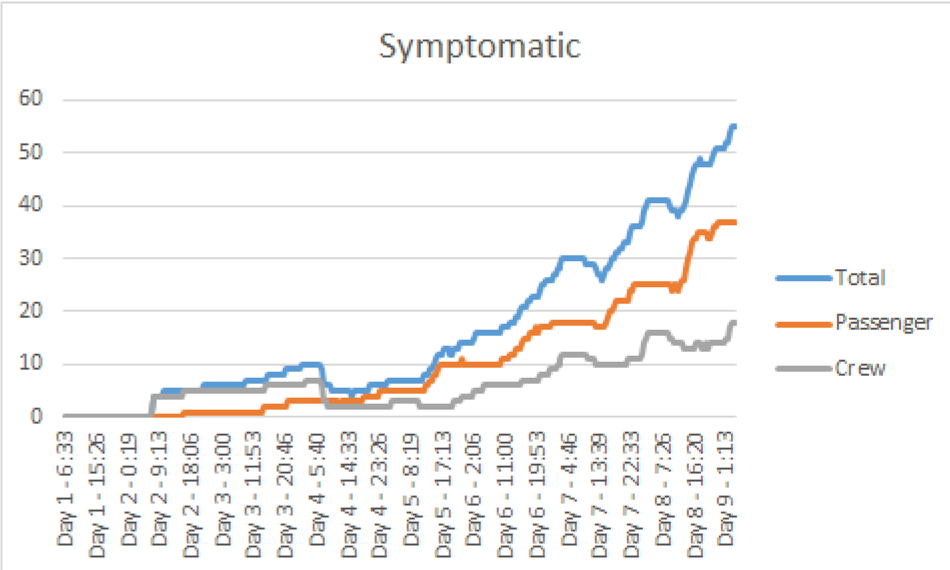



Appendix B4. Average Infections for 5C Control - 5 Simulations

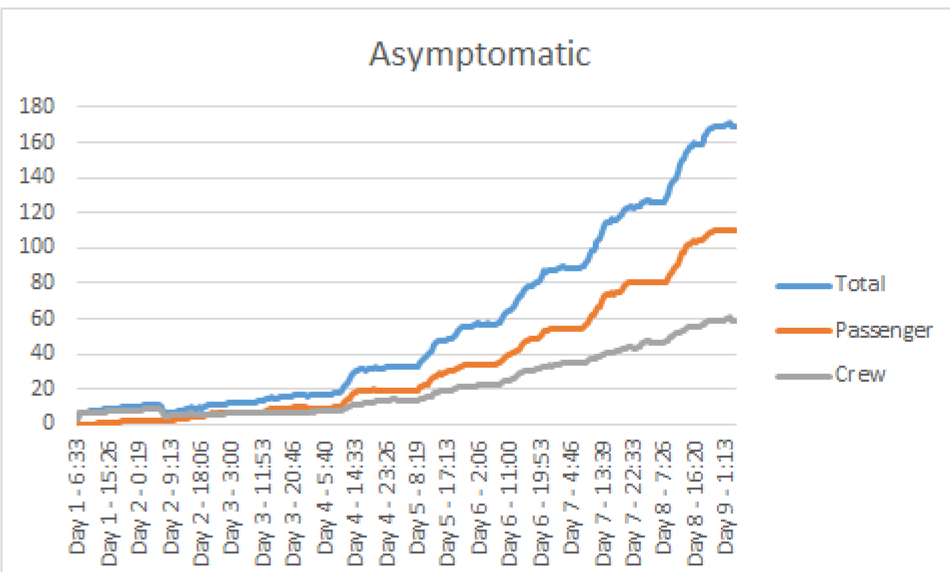


# Appendix C. Isolation Simulations for 5C - Graph Data

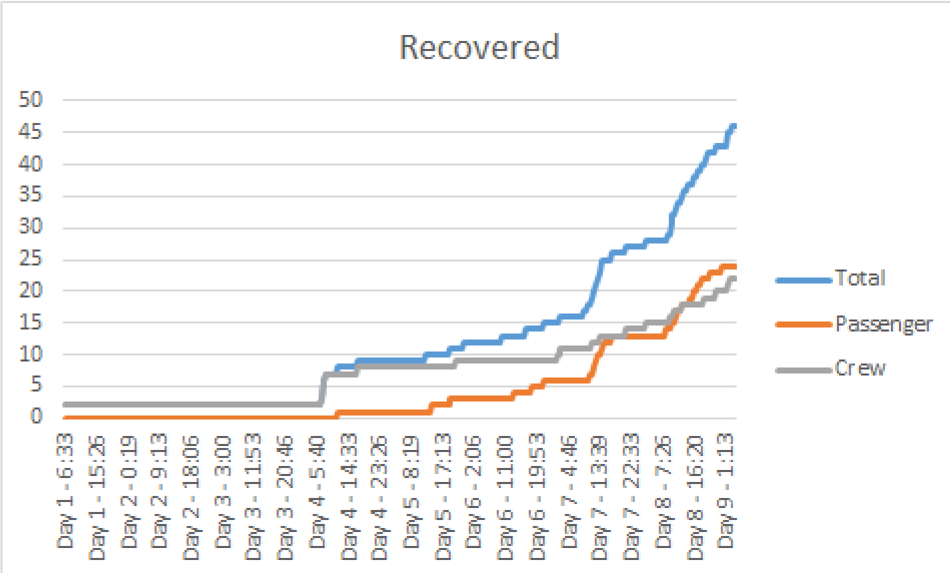
## Appendix C1. Average Symptomatic for 5C Isolation - 5 Simulations



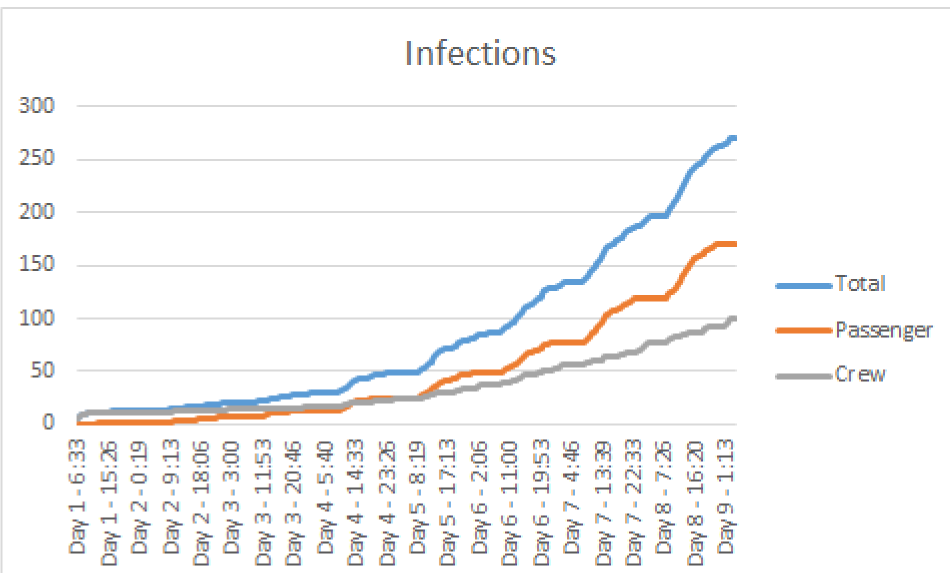

## Appendix C2. Average Asymptomatic for 5C Isolation - 5 Simulations



Appendix C3. Average Recovered for 5C Isolation - 5 Simulations

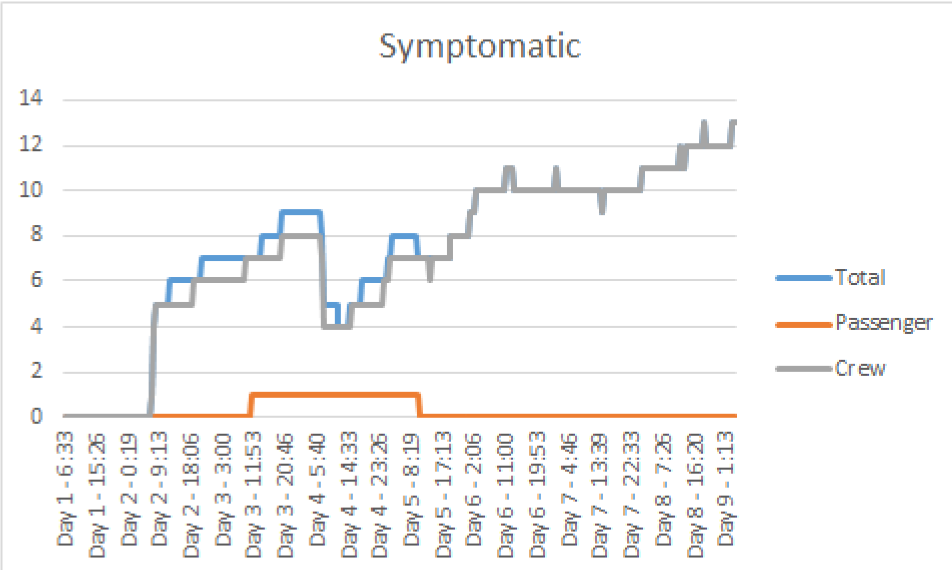



Appendix C4. Average Infections for 5C Isolation - 5 Simulations

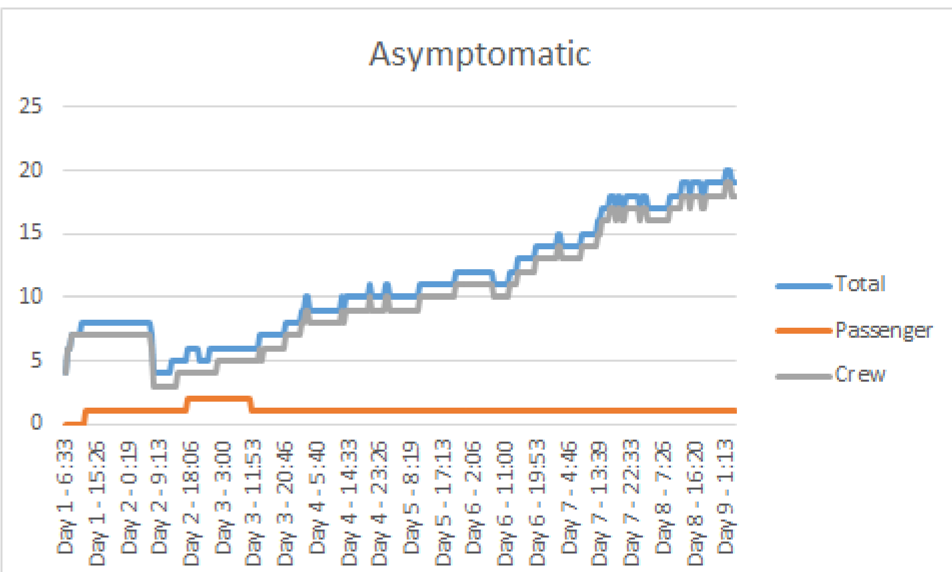


# Appendix D. No Dining Simulations for 5C - Graph Data

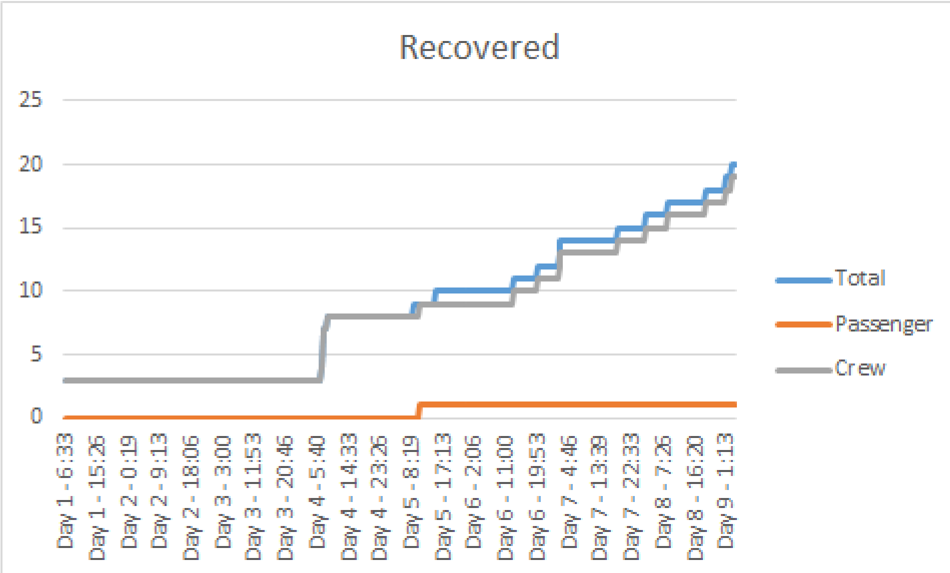
## Appendix D1. Average Symptomatic for 5C No Dining - 5 Simulations



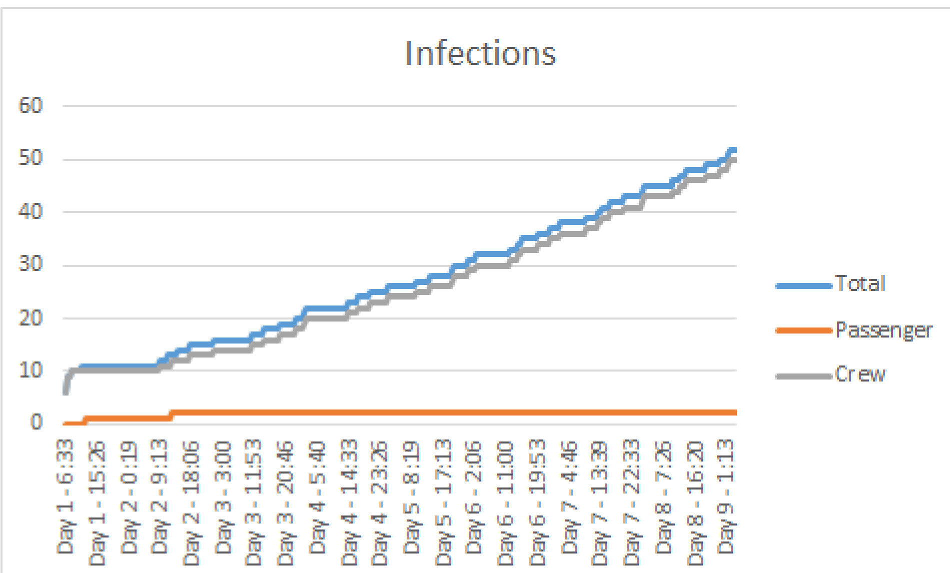

## Appendix D2. Average Asymptomatic for 5C No Dining - 5 Simulations



Appendix D3. Average Recovered for 5C No Dining - 5 Simulations

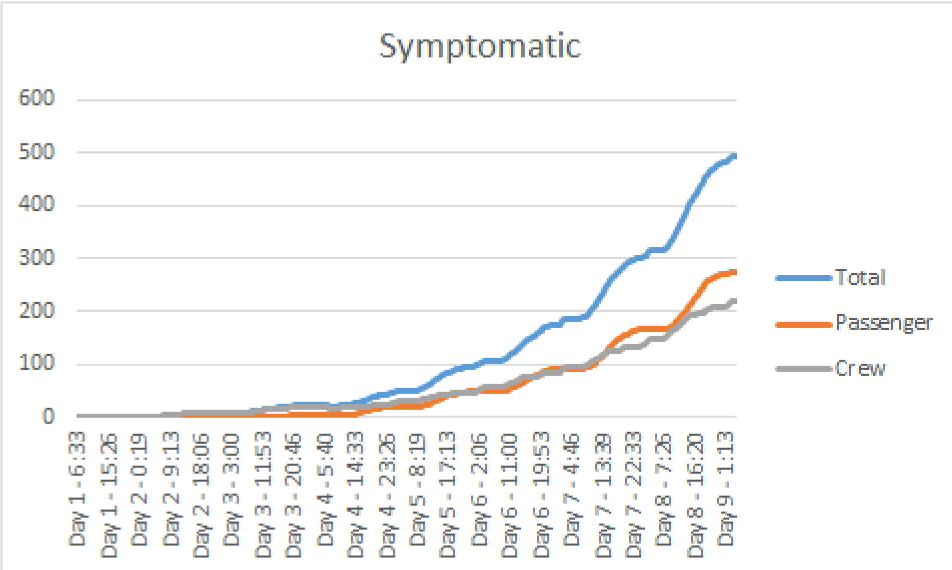



Appendix D4. Average Infections for 5C No Dining - 5 Simulations

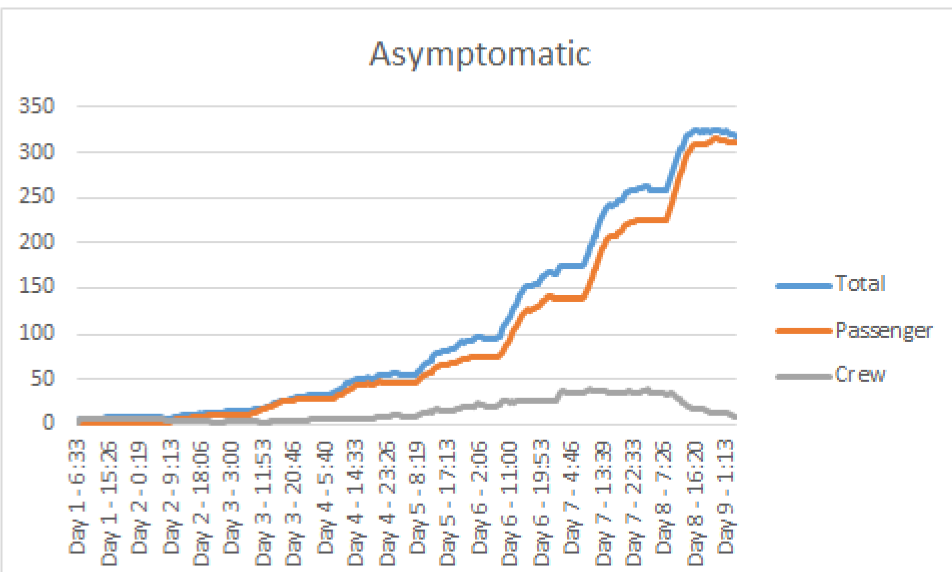


## Appendix E. Restricted Dining Simulations for 5C - Graph Data

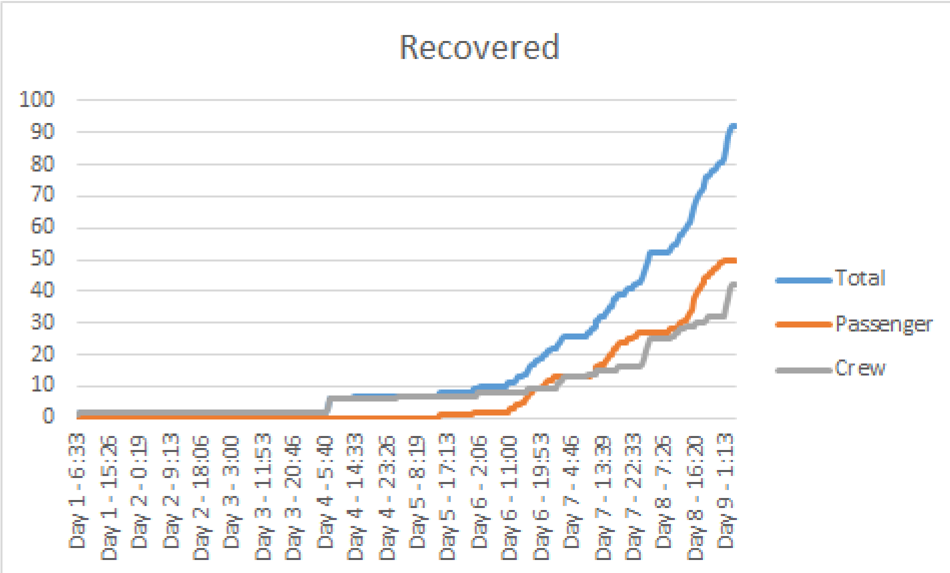
### Appendix E1. Average Symptomatic for 5C Restricted Dining - 5 Simulations



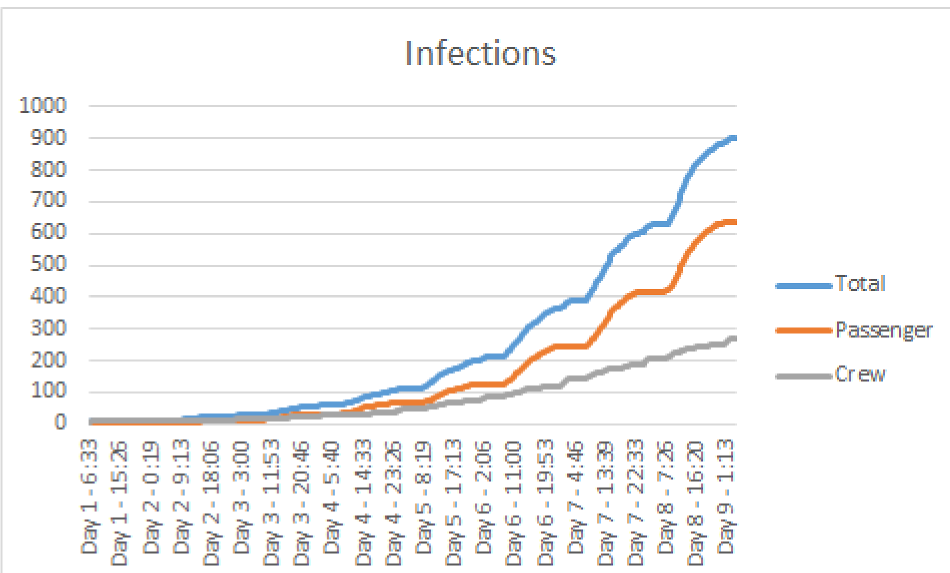

### Appendix E2. Average Asymptomatic for 5C Restricted Dining - 5 Simulations



Appendix E3. Average Recovered for 5C Restricted Dining - 5 Simulations

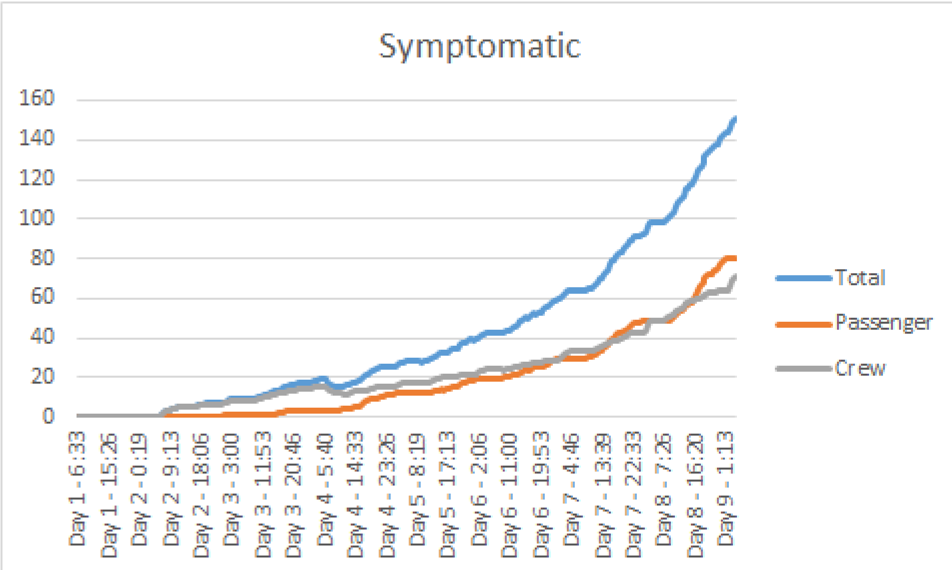



Appendix E4. Average Infections for 5C Restricted Dining - 5 Simulations

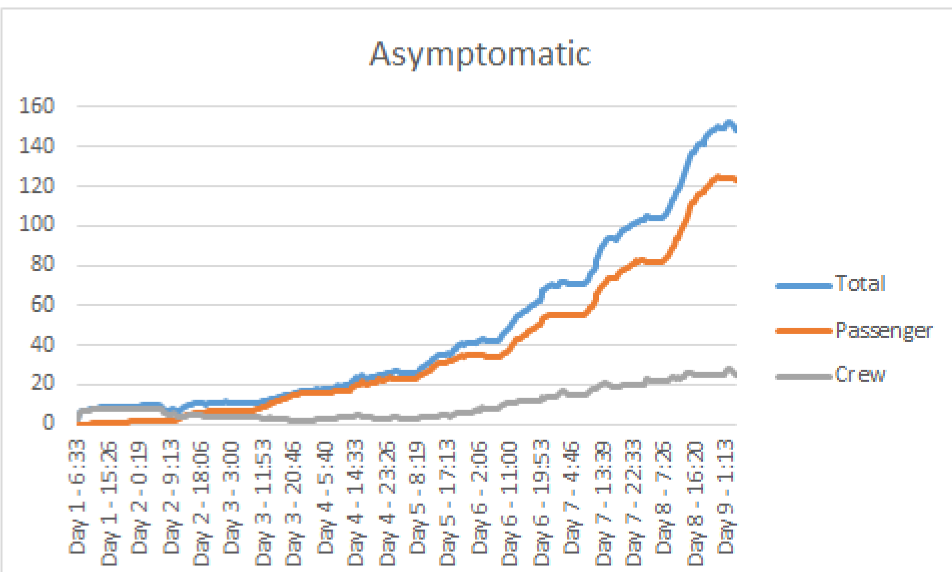


# Appendix F. Improved Hygiene Simulations for 5C - Graph Data

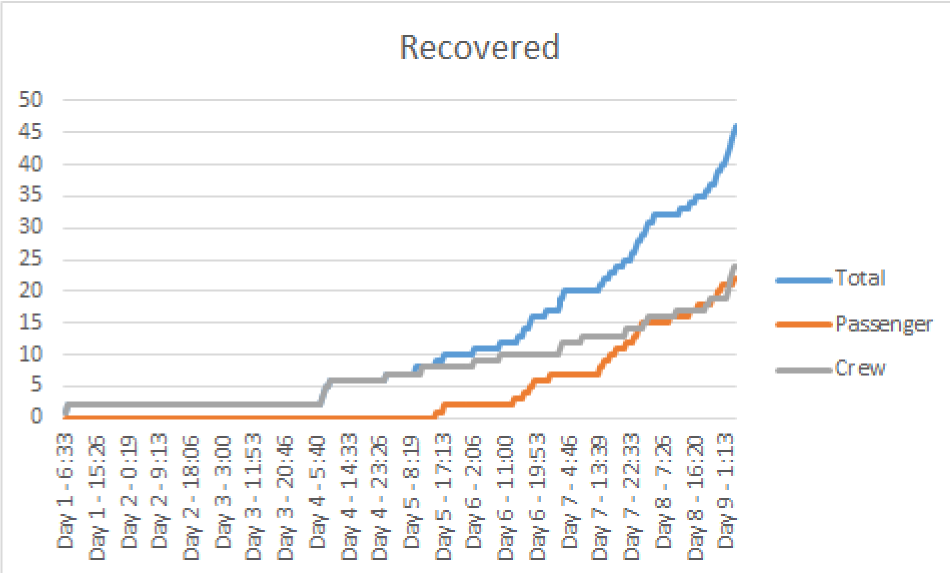
## Appendix F1. Average Symptomatic for 5C Improved Hygiene - 5 Simulations



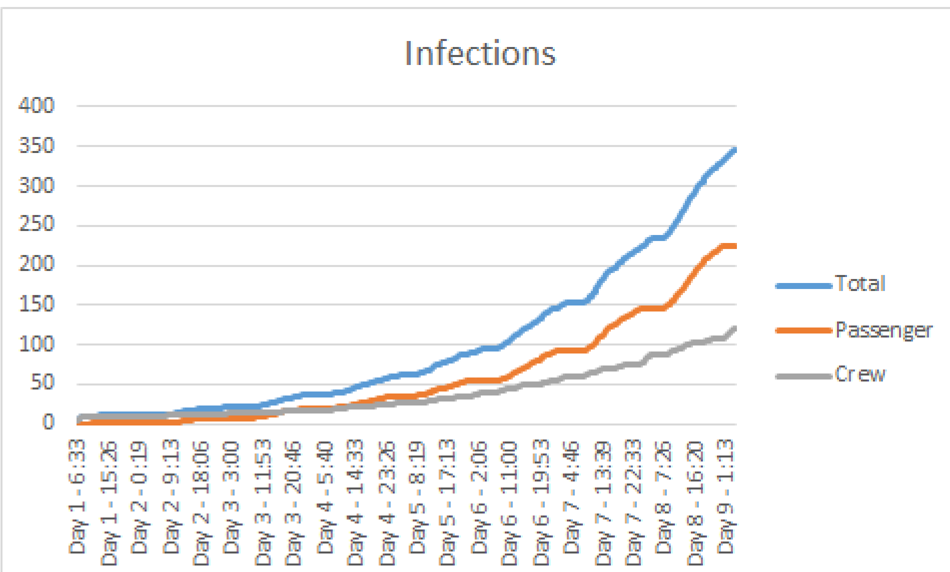

## Appendix F2. Average Asymptomatic for 5C Improved Hygiene - 5 Simulations



Appendix F3. Average Recovered for 5C Improved Hygiene - 5 Simulations

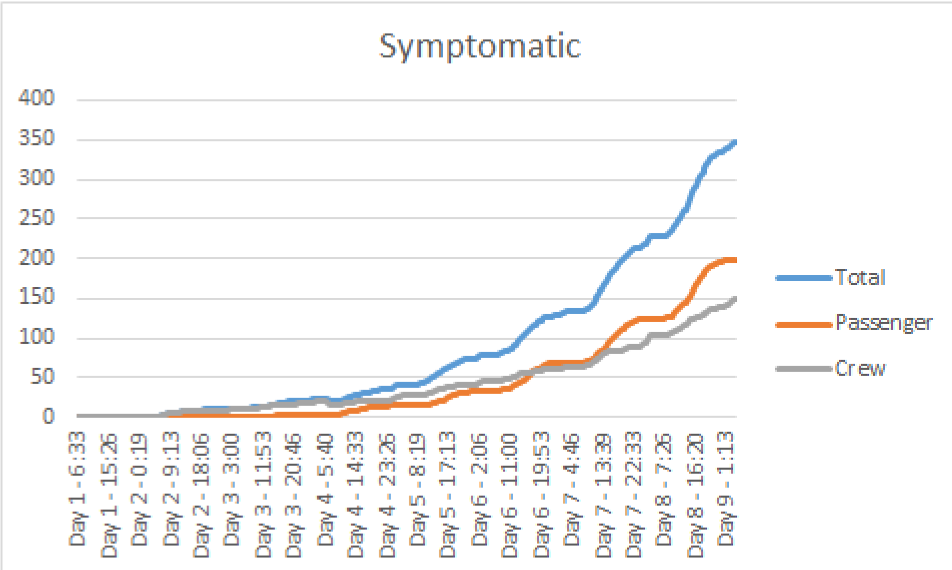



Appendix F4. Average Infections for 5C Improved Hygiene - 5 Simulations

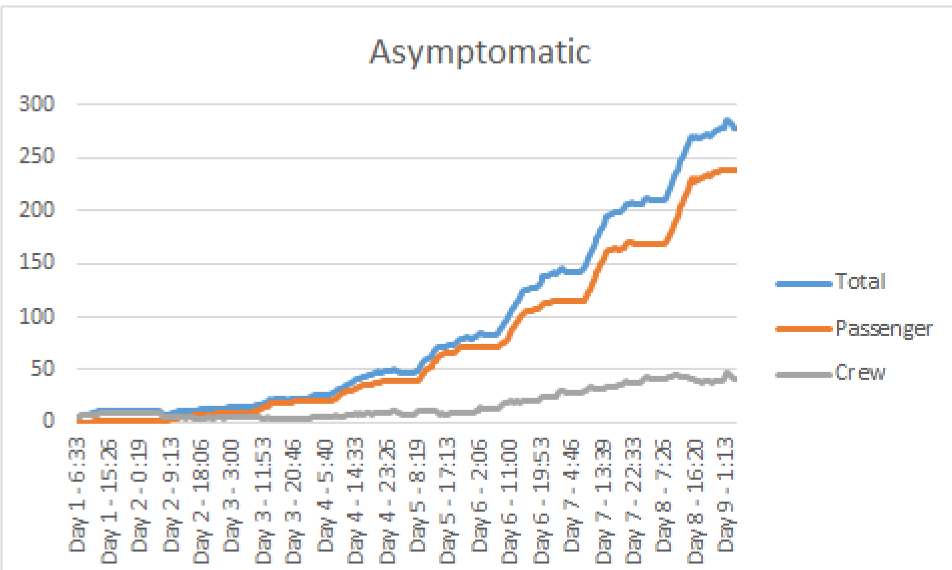


# Appendix G. Improved Cleaning Simulations for 5C - Graph Data

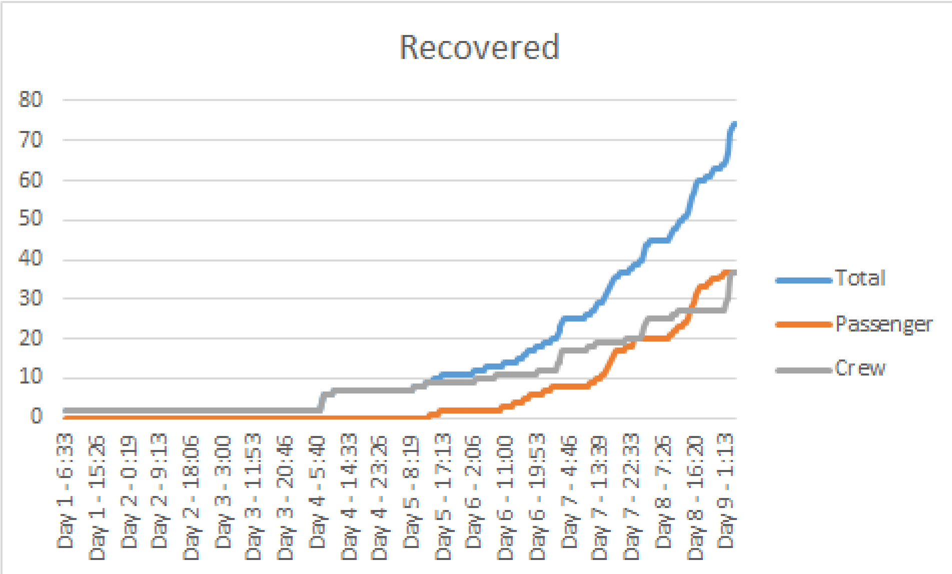
## Appendix G1. Average Symptomatic for 5C Improved Cleaning - 5 Simulations



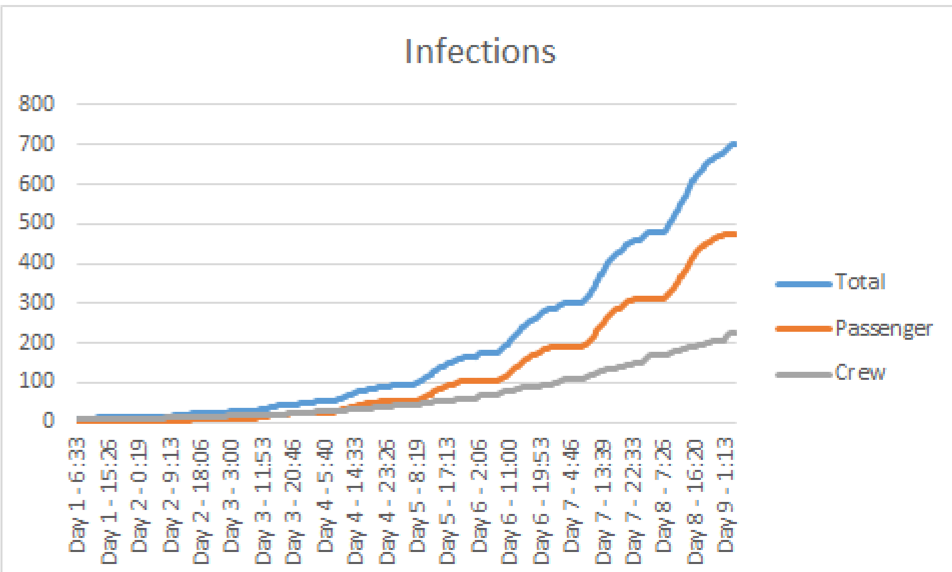

## Appendix G2. Average Asymptomatic for 5C Improved Cleaning - 5 Simulations



Appendix G3. Average Recovered for 5C Improved Cleaning - 5 Simulations

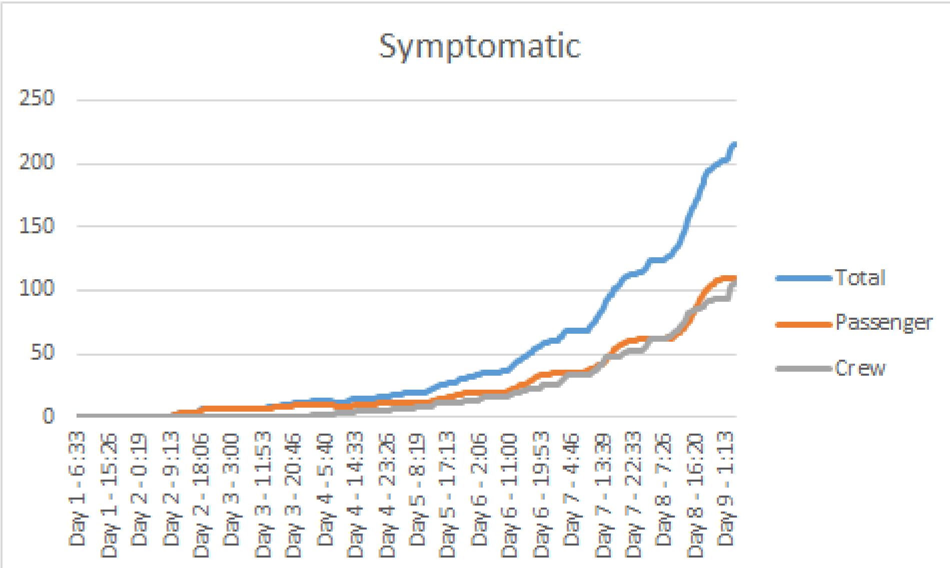



Appendix G4. Average Infections for 5C Improved Cleaning - 5 Simulations

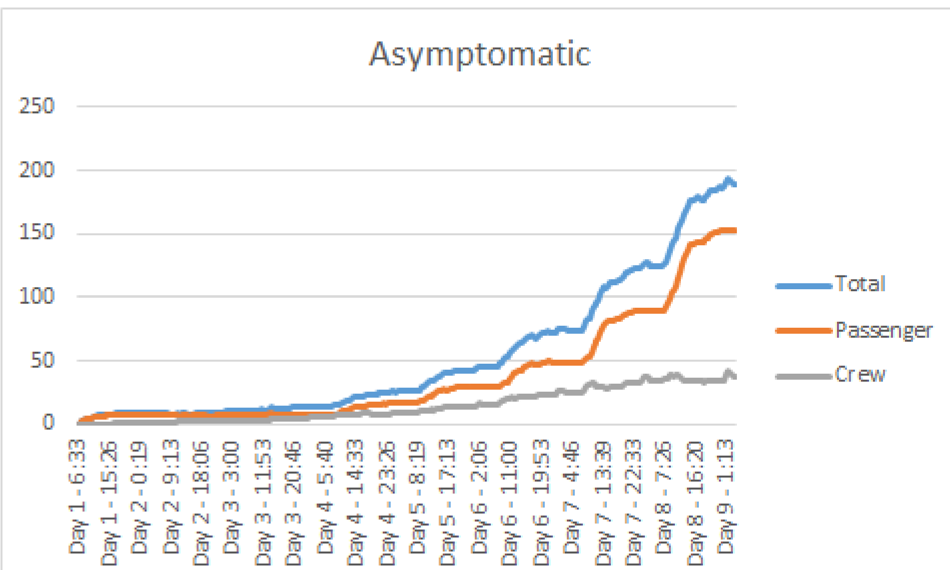


# Appendix H. Control Simulations for 5P - Graph Data

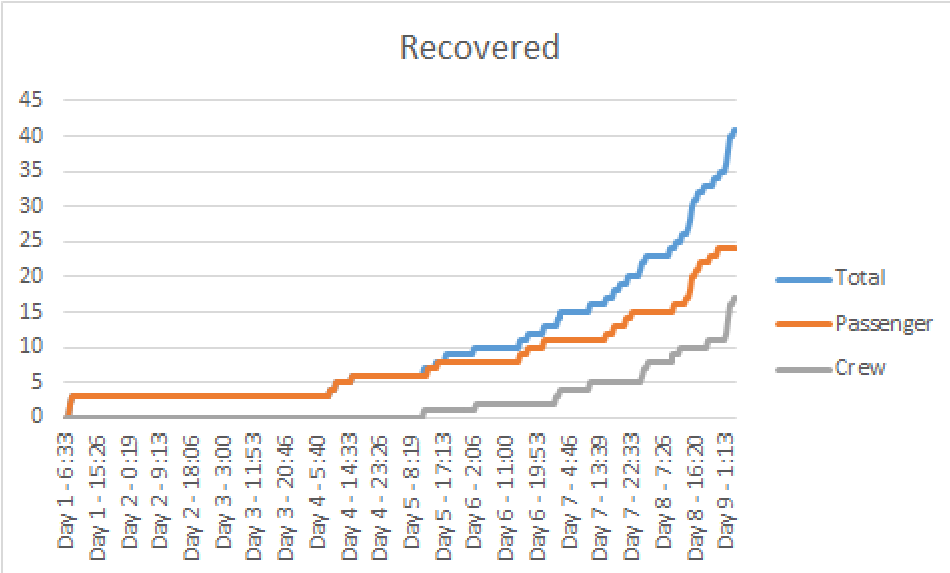
## Appendix H1. Average Symptomatic for 5P Control - 5 Simulations



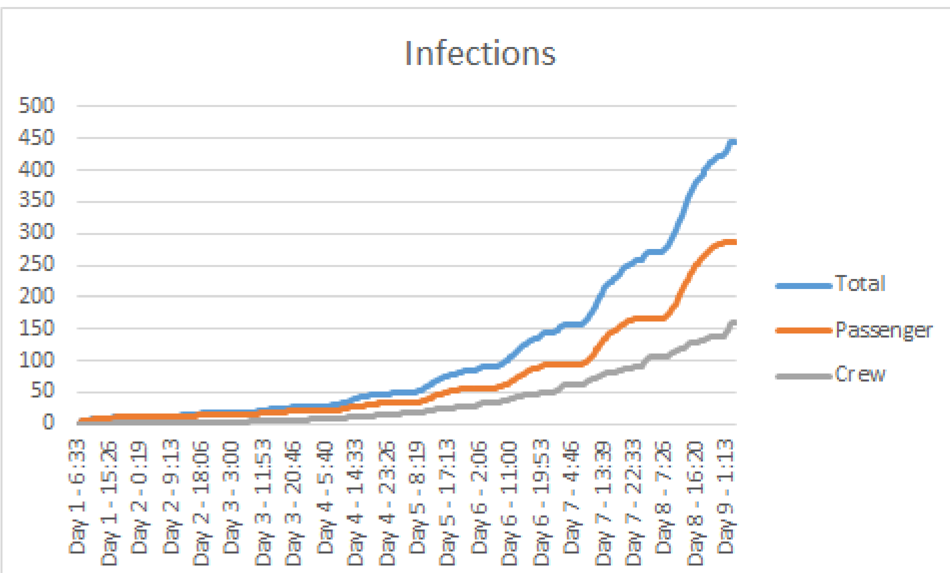

## Appendix H2. Average Asymptomatic for 5P Control - 5 Simulations



Appendix H3. Average Recovered for 5P Control - 5 Simulations

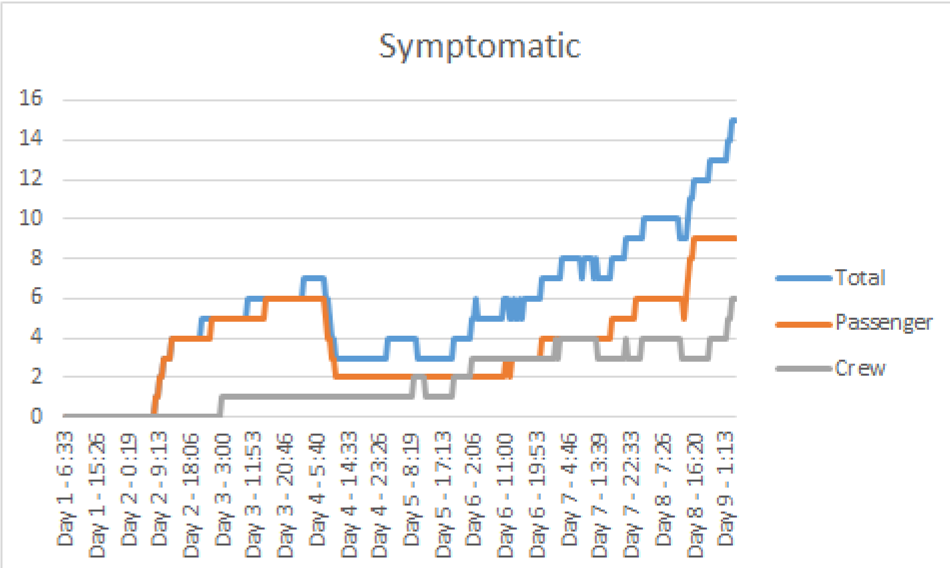



Appendix H4. Average Infections for 5P Control - 5 Simulations

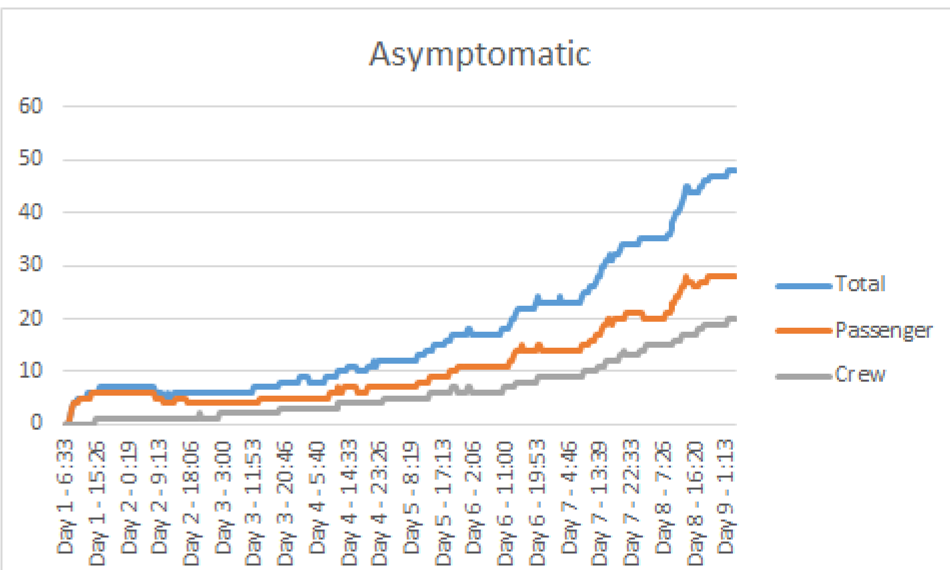


# Appendix I. Isolation Simulations for 5P - Graph Data

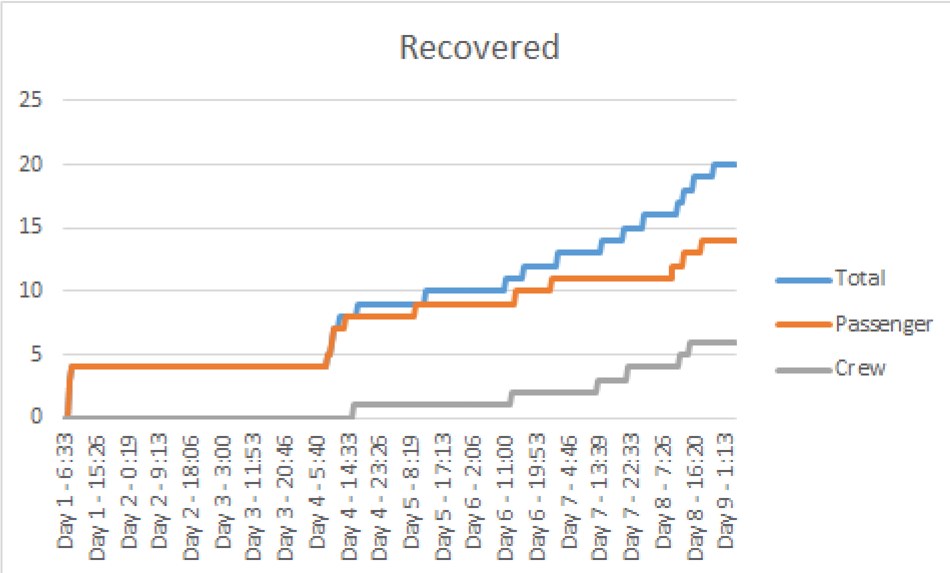
## Appendix I1. Average Symptomatic for 5P Isolation - 5 Simulations



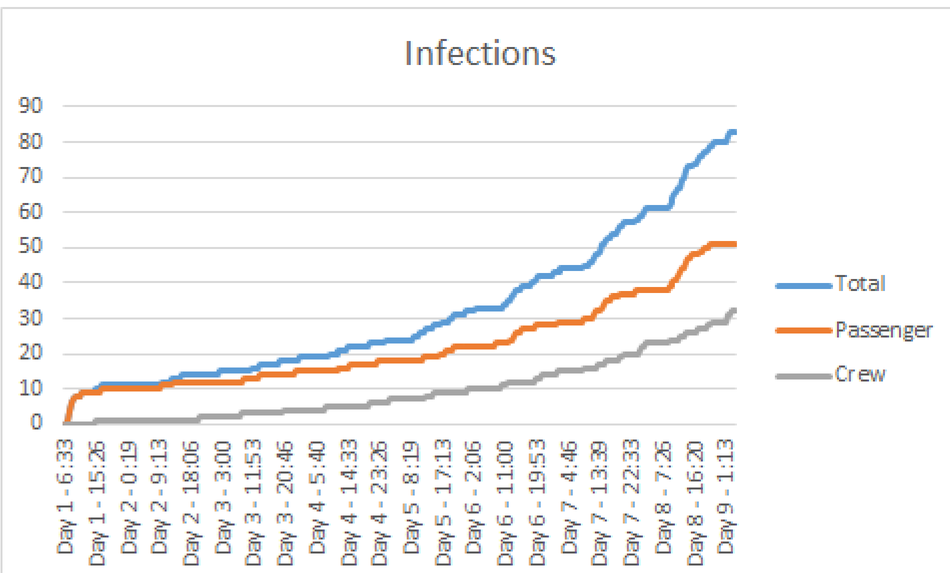

## Appendix I2. Average Asymptomatic for 5P Isolation - 5 Simulations



Appendix I3. Average Recovered for 5P Isolation - 5 Simulations

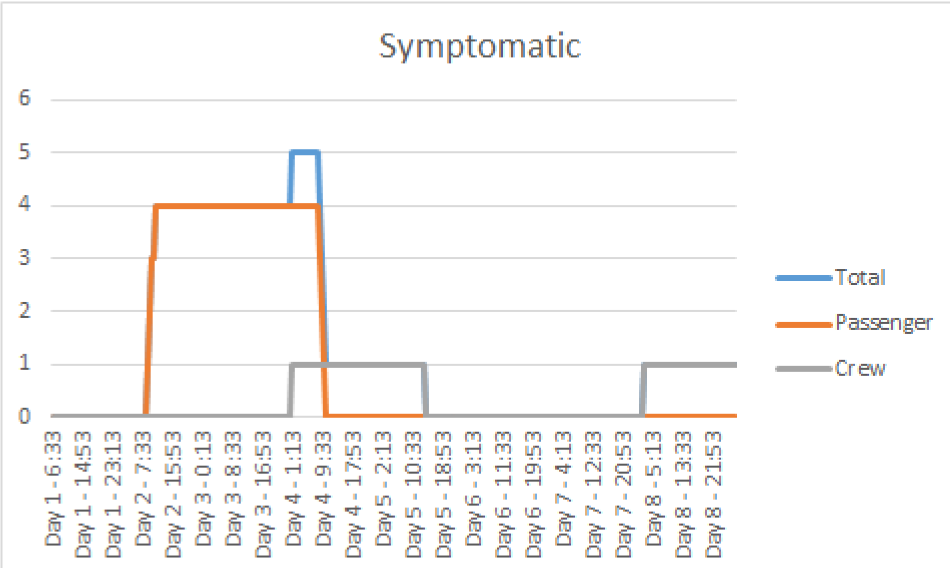



Appendix I4. Average Infections for 5P Isolation - 5 Simulations

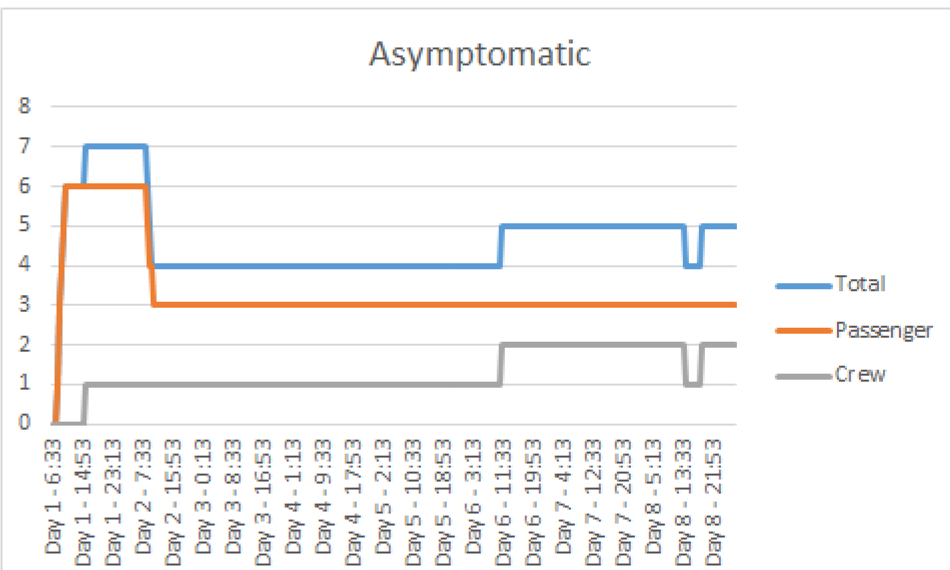


# Appendix J. No Dining Simulations for 5P - Graph Data

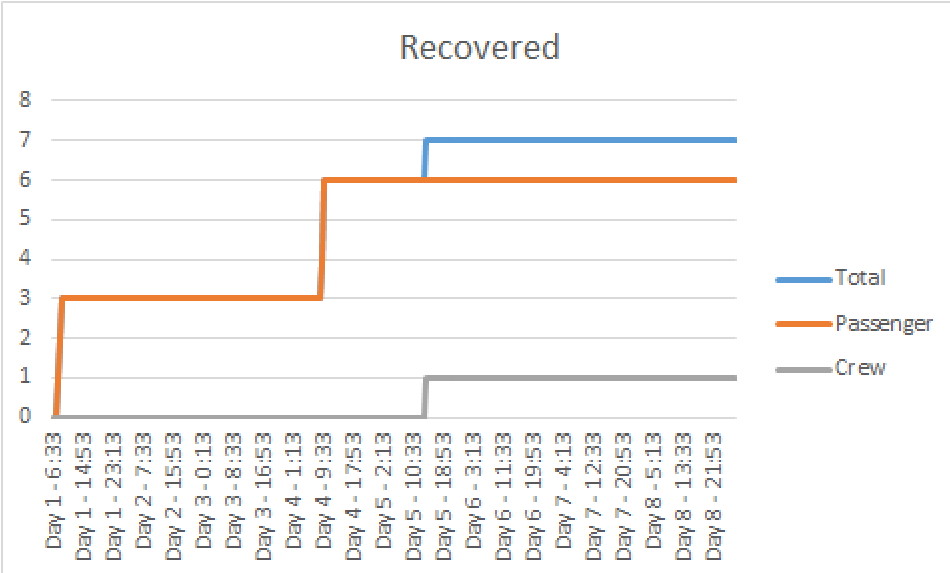
## Appendix J1. Average Symptomatic for 5P No Dining - 5 Simulations



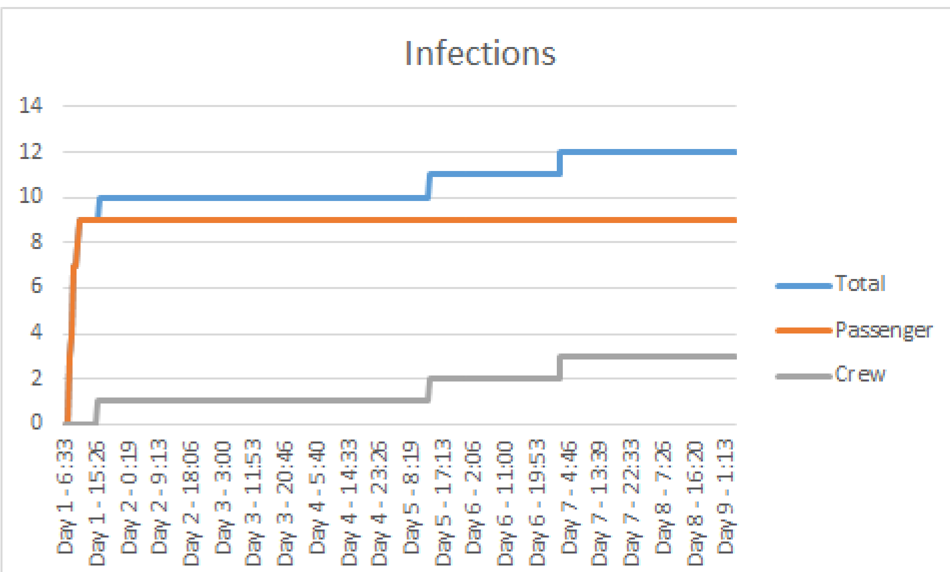

## Appendix J2. Average Asymptomatic for 5P No Dining - 5 Simulations



Appendix J3. Average Recovered for 5P No Dining - 5 Simulations

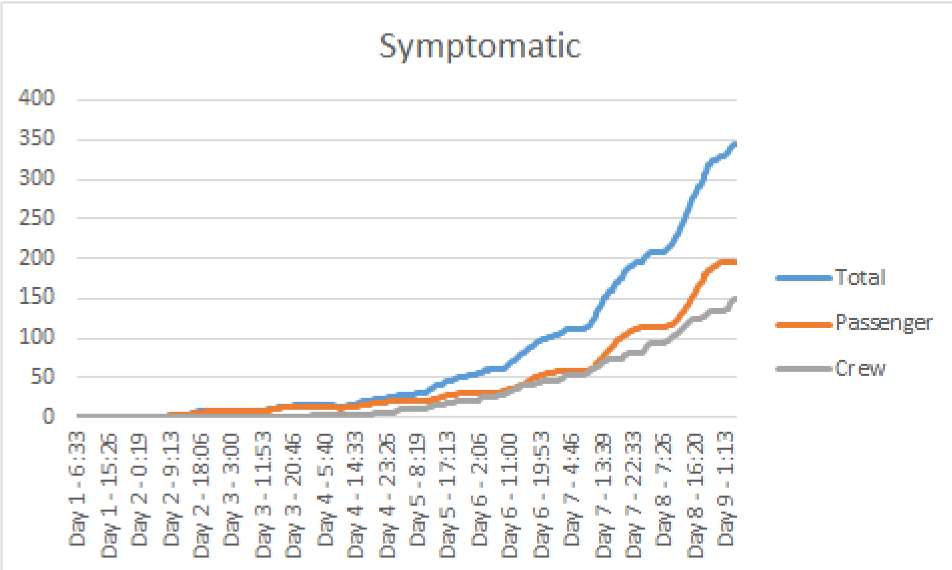



Appendix J4. Average Infections for 5P No Dining - 5 Simulations

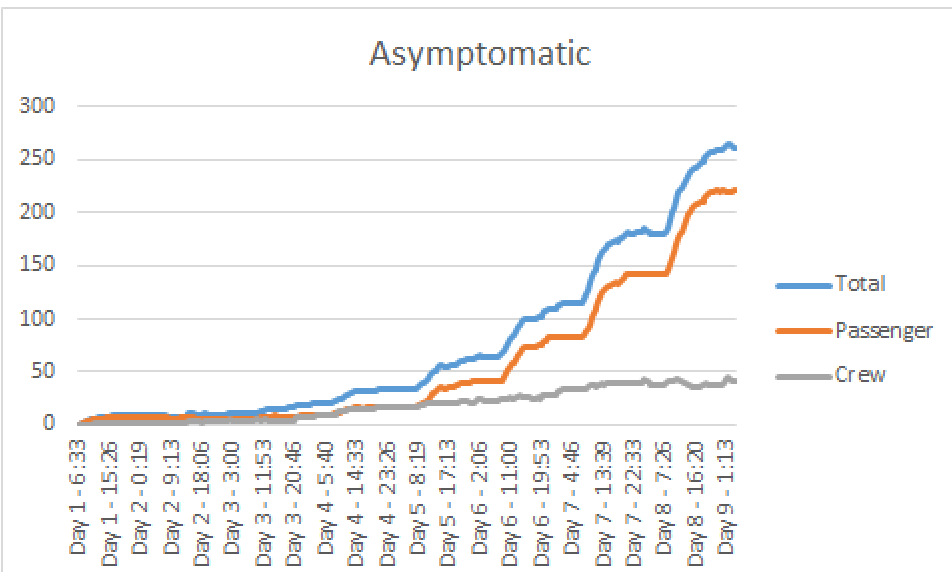


# Appendix K. Restricted Dining Simulations for 5P - Graph Data

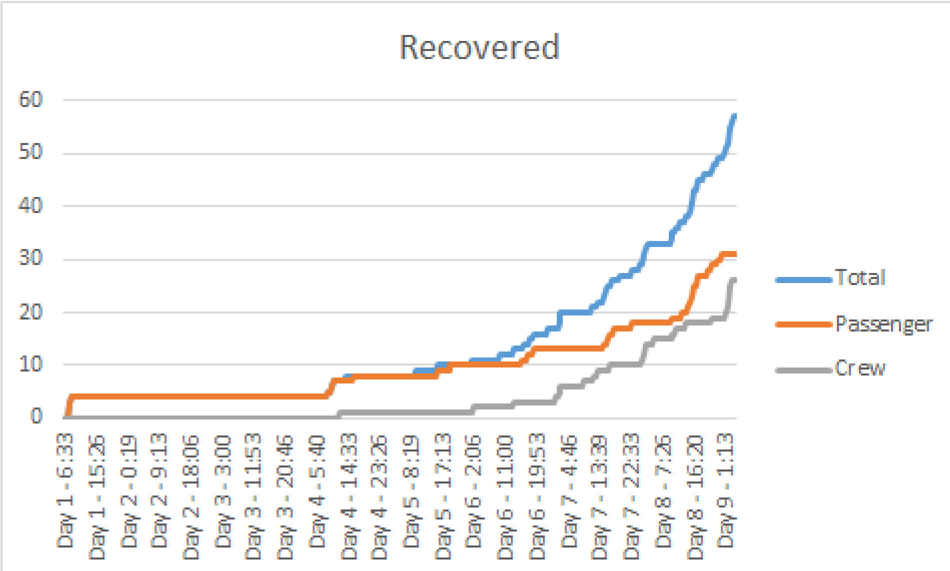
Appendix K1. Average Symptomatic for 5P Restricted Dining - 5 Simulations



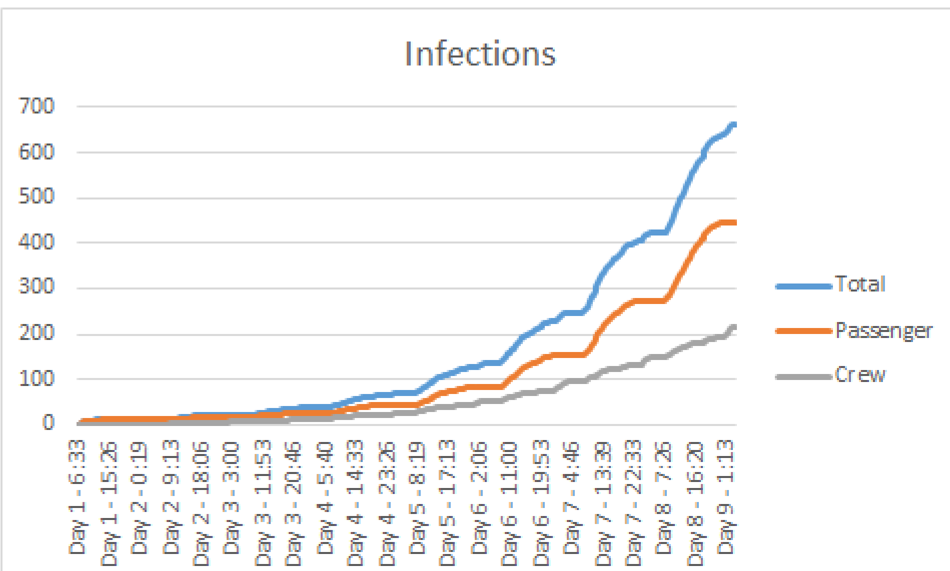

Appendix K2. Average Asymptomatic for 5P Restricted Dining - 5 Simulations



Appendix K3. Average Recovered for 5P Restricted Dining - 5 Simulations

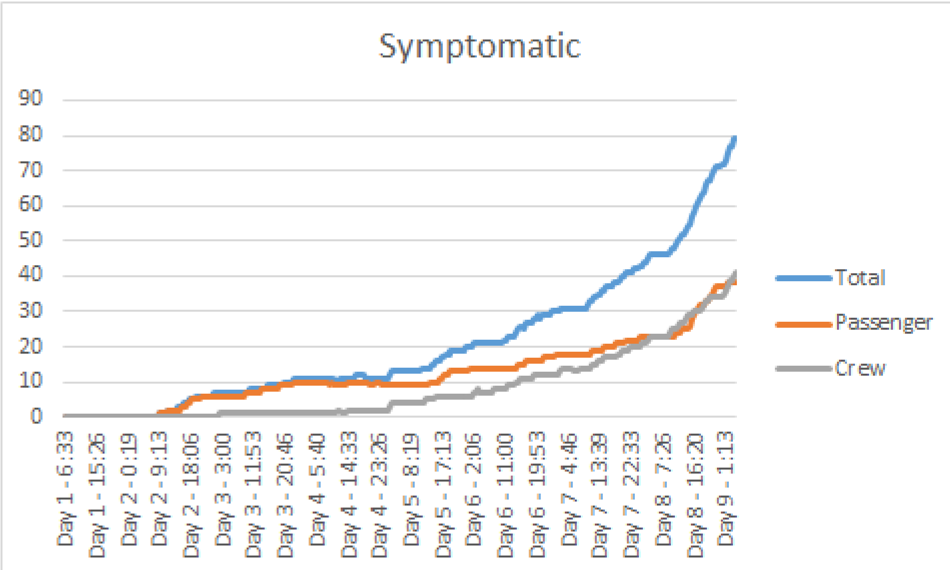



Appendix K4. Average Infections for 5P Restricted Dining - 5 Simulations

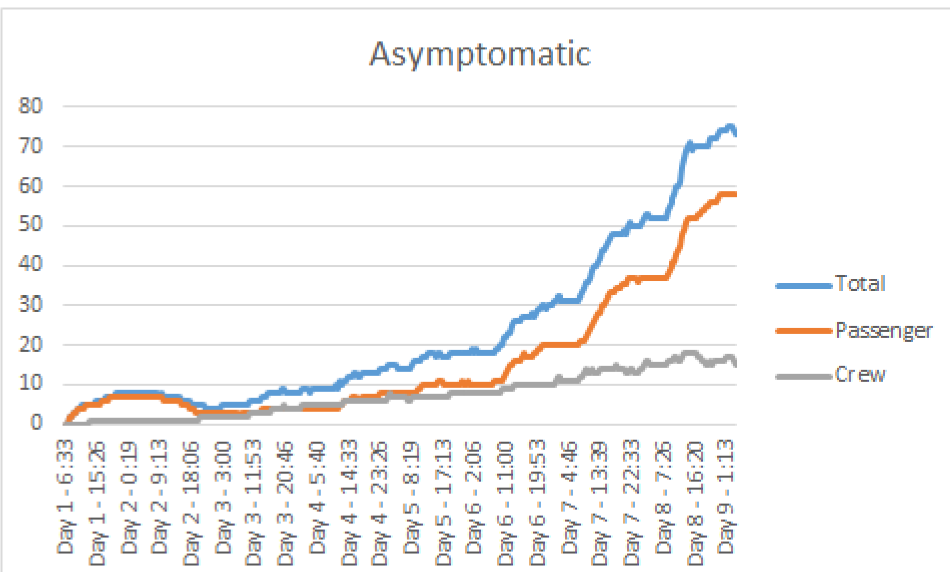


# Appendix L. Improved Hygiene Simulations for 5P - Graph Data

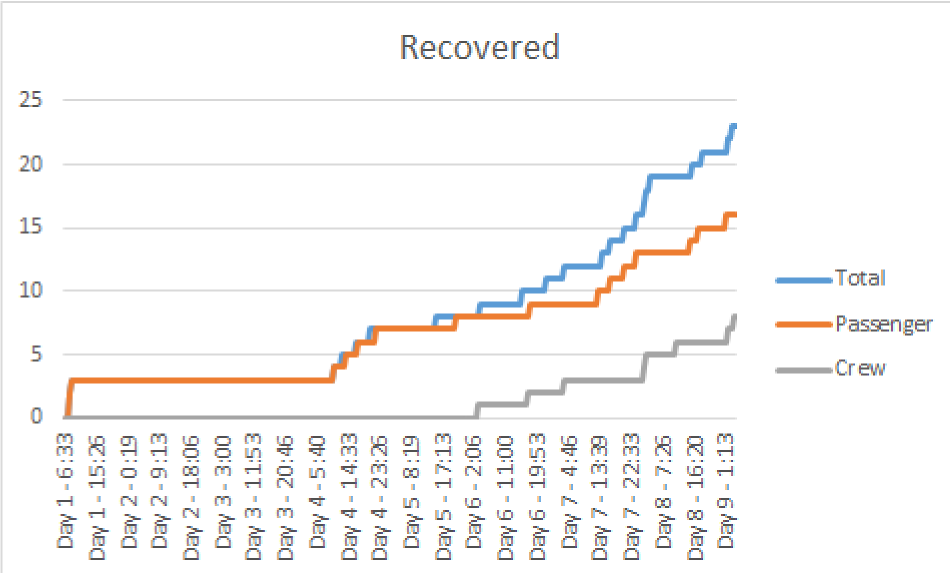
## Appendix L1. Average Symptomatic for 5P Improved Hygiene - 5 Simulations



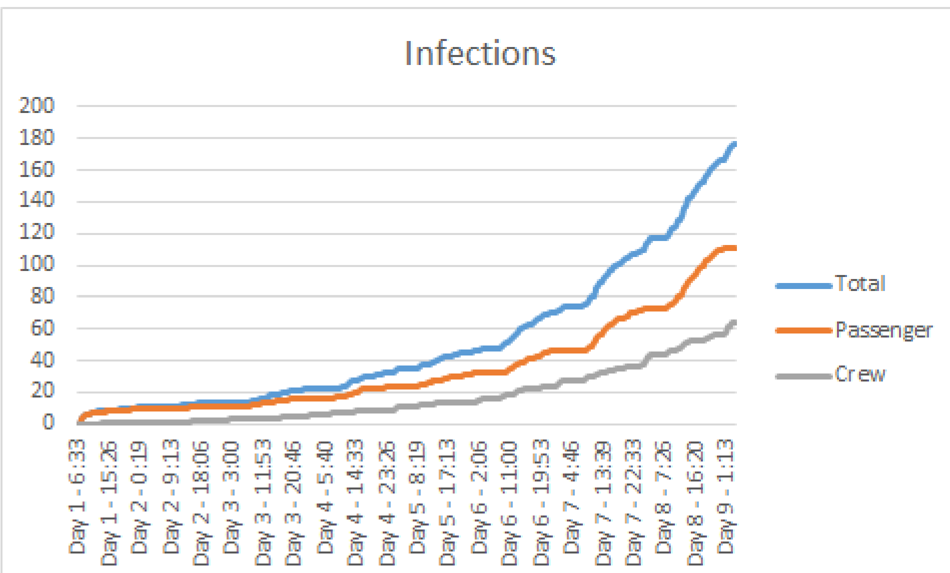

## Appendix L2. Average Asymptomatic for 5P Improved Hygiene - 5 Simulations



Appendix L3. Average Recovered for 5P Improved Hygiene - 5 Simulations

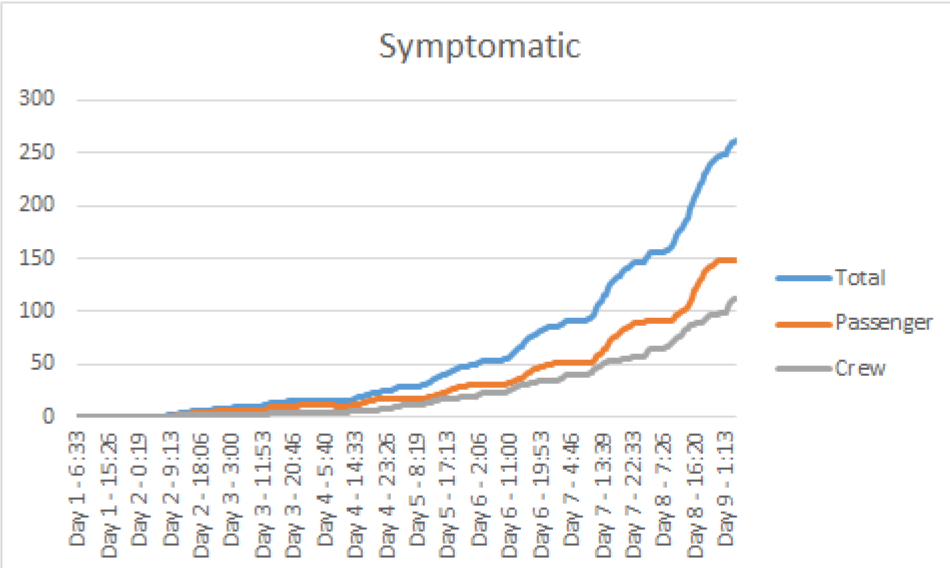



Appendix L4. Average Infections for 5P Improved Hygiene - 5 Simulations

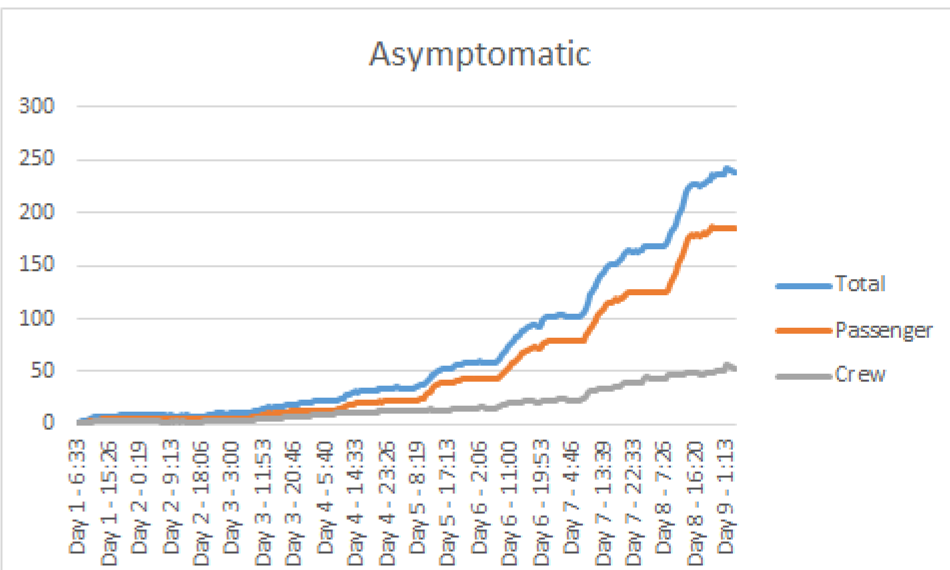


## Appendix M. Improved Cleaning Simulations for 5P - Graph Data

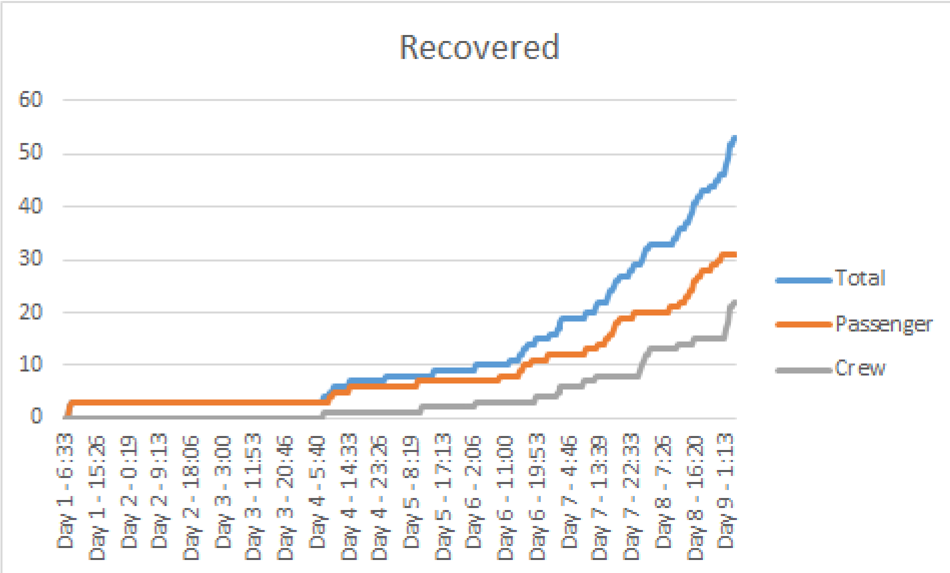
### Appendix M1. Average Symptomatic for 5P Improved Cleaning - 5 Simulations



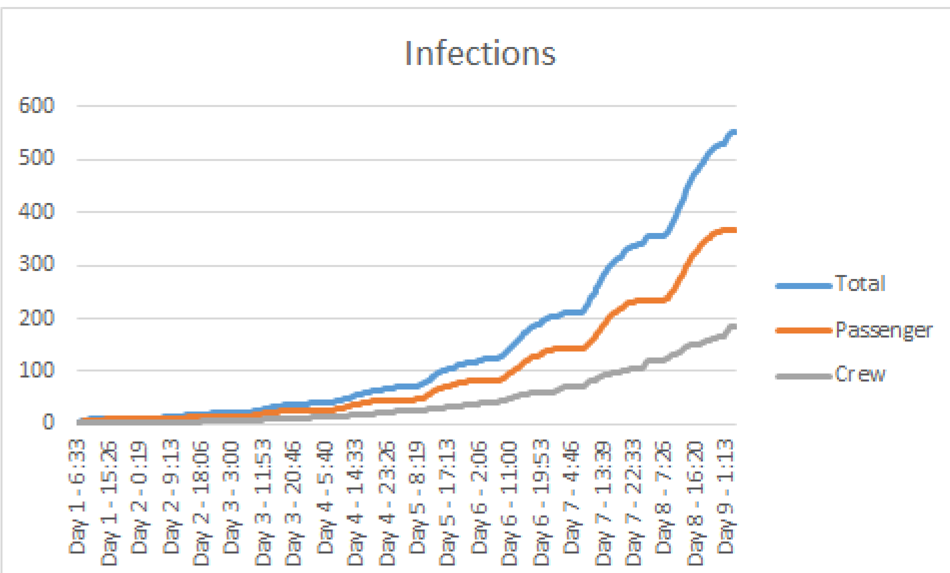

### Appendix M2. Average Asymptomatic for 5P Improved Cleaning - 5 Simulations



Appendix M3. Average Recovered for 5P Improved Cleaning - 5 Simulations

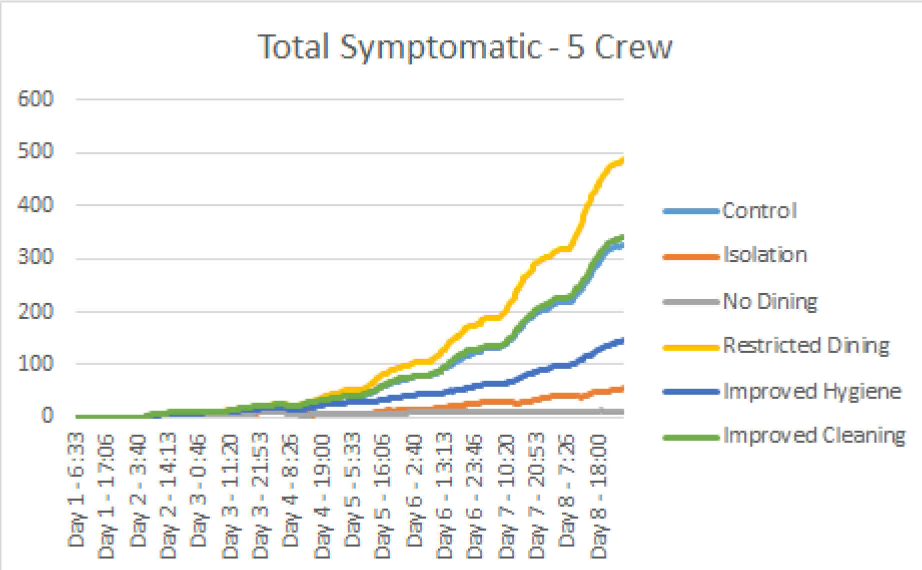



Appendix M4. Average Infections for 5P Improved Cleaning - 5 Simulations

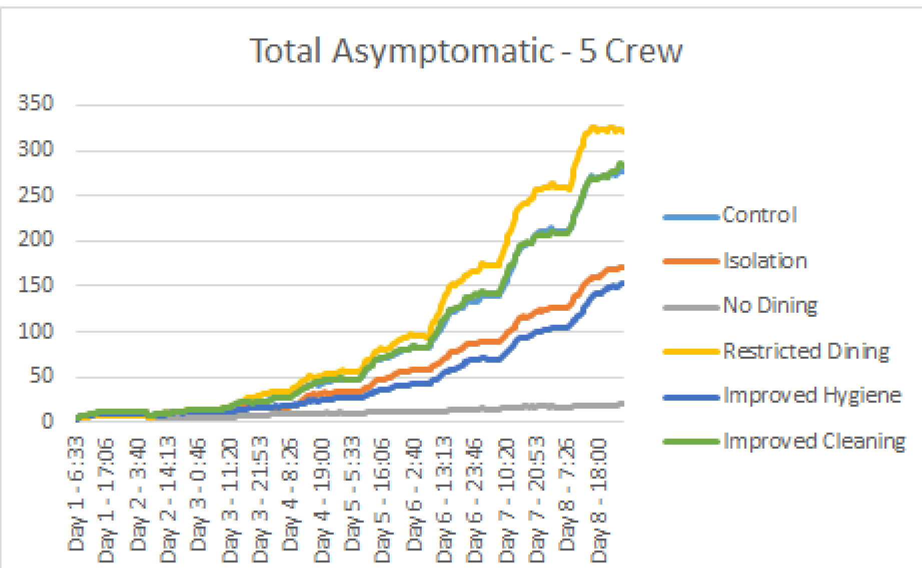


# Appendix N. Combined Charts for 5C Case

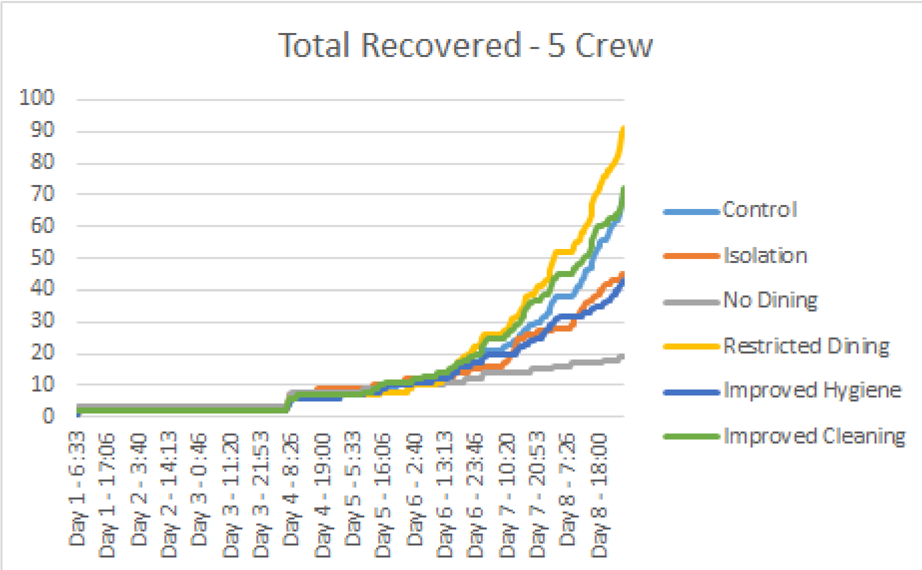
## Appendix N1. Total Average Symptomatic for 5C Cases



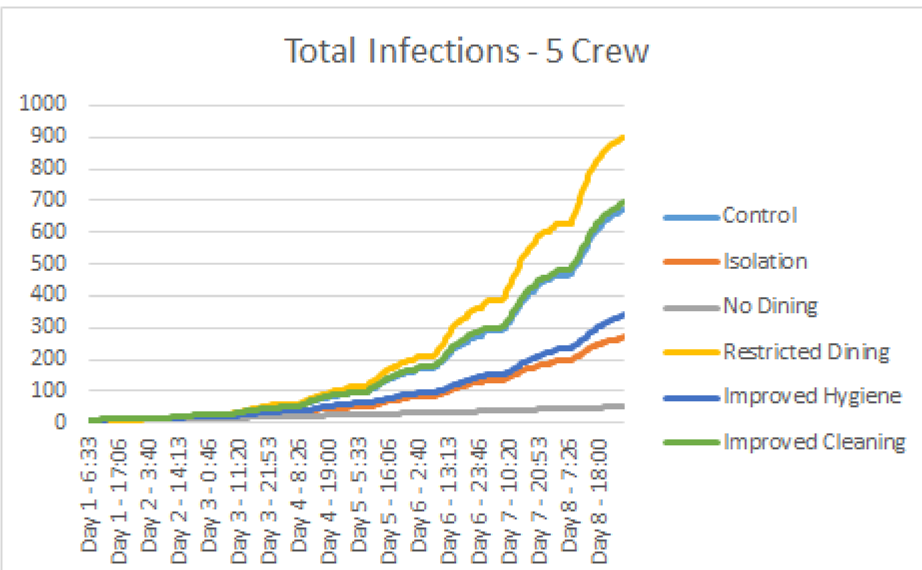

## Appendix N2. Total Average Asymptomatic for 5C Cases



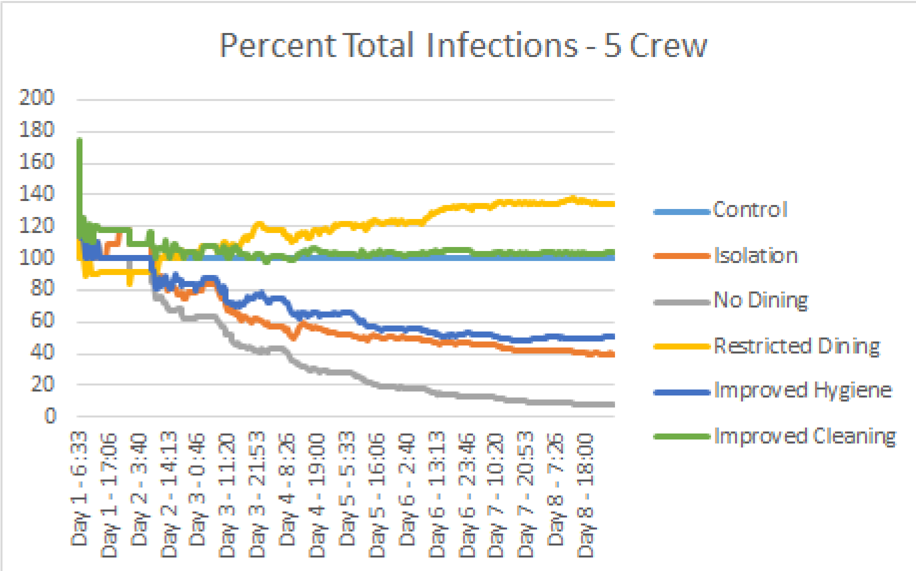
Appendix N3. Total Average Recovered for 5C Cases



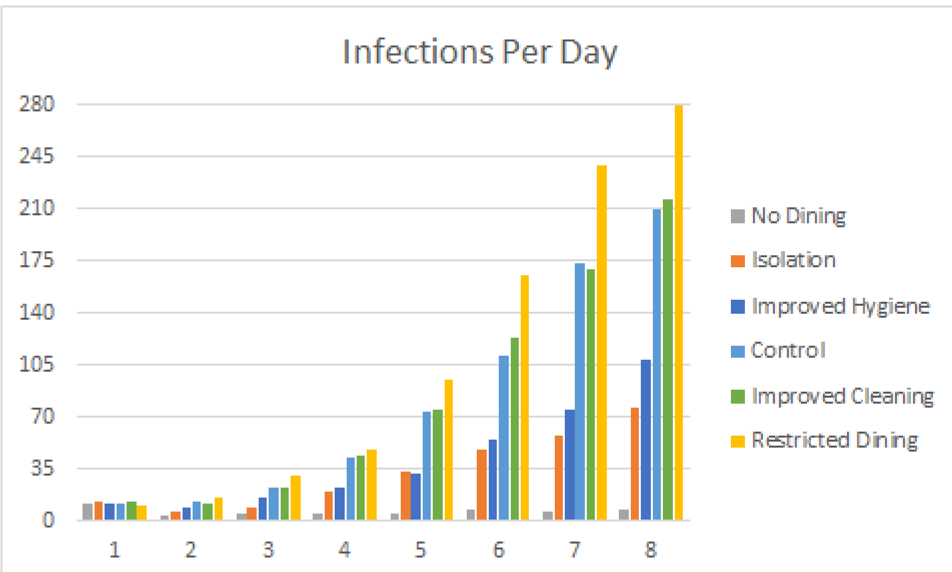

Appendix N4. Total Average Infections for 5C Cases



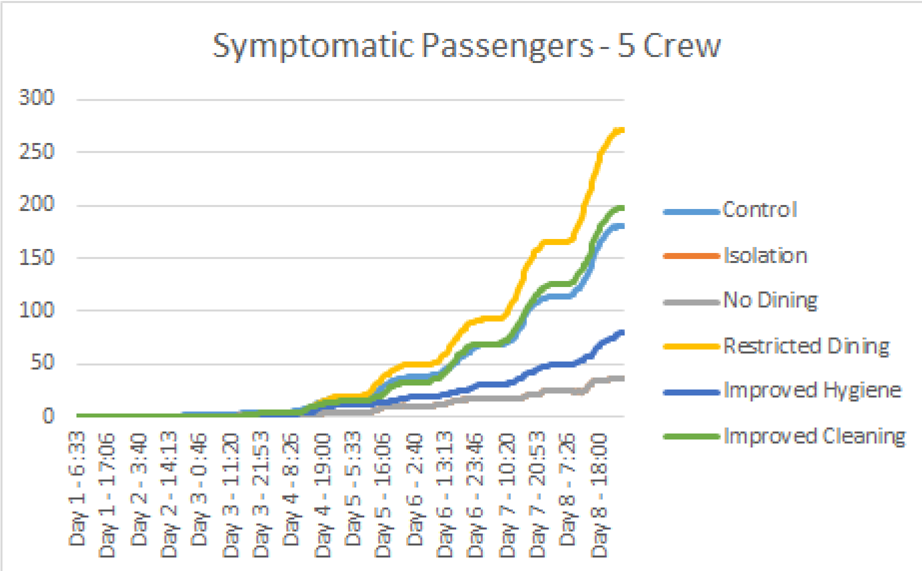
Appendix N5. Percentage of Control Infections for 5C Cases



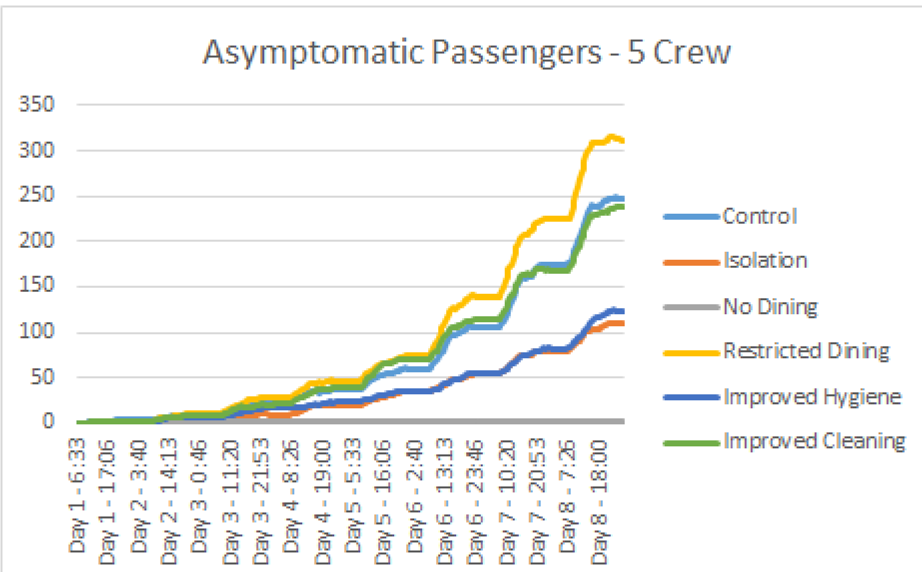

Appendix N6. Total Infections Per Day for 5C Cases



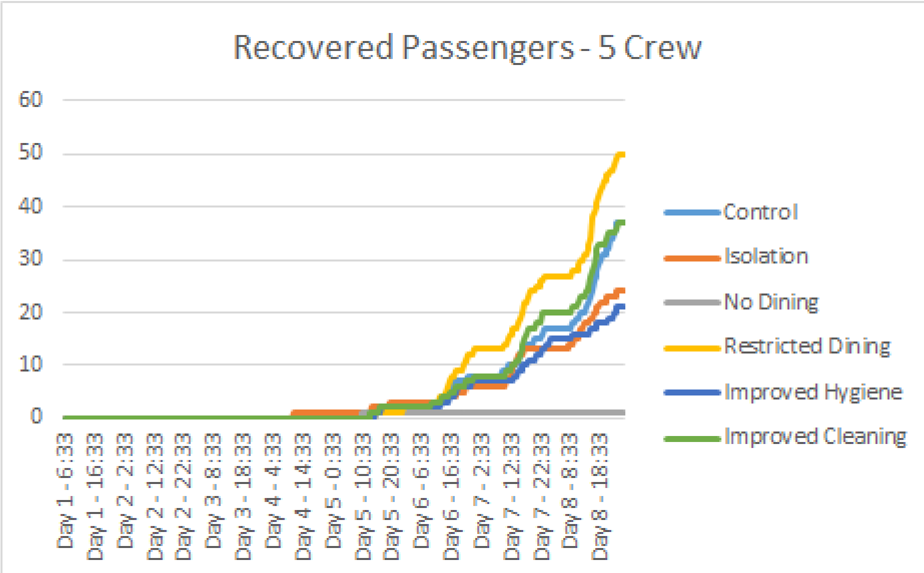
Appendix N7. Passenger Average Recovered for 5C Cases



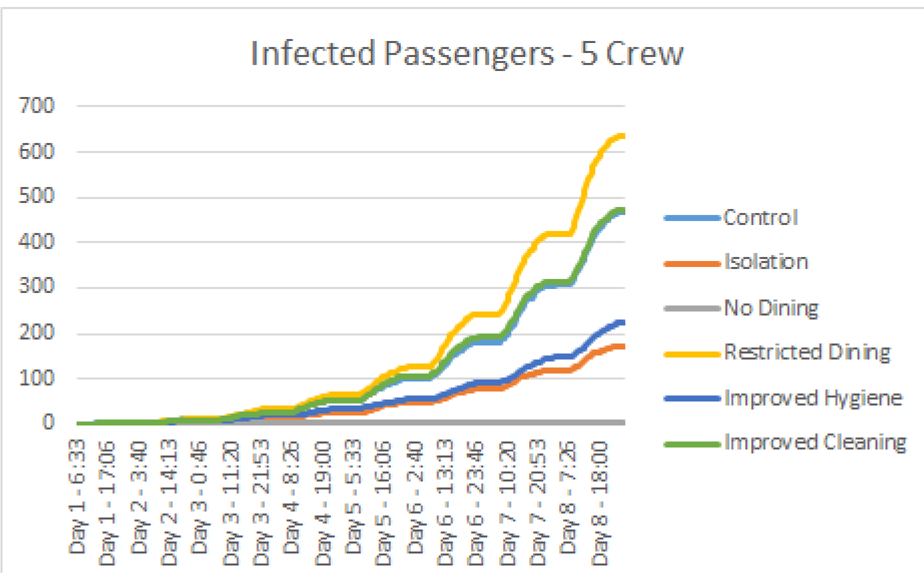

Appendix N8. Passenger Average Infections for 5C Cases



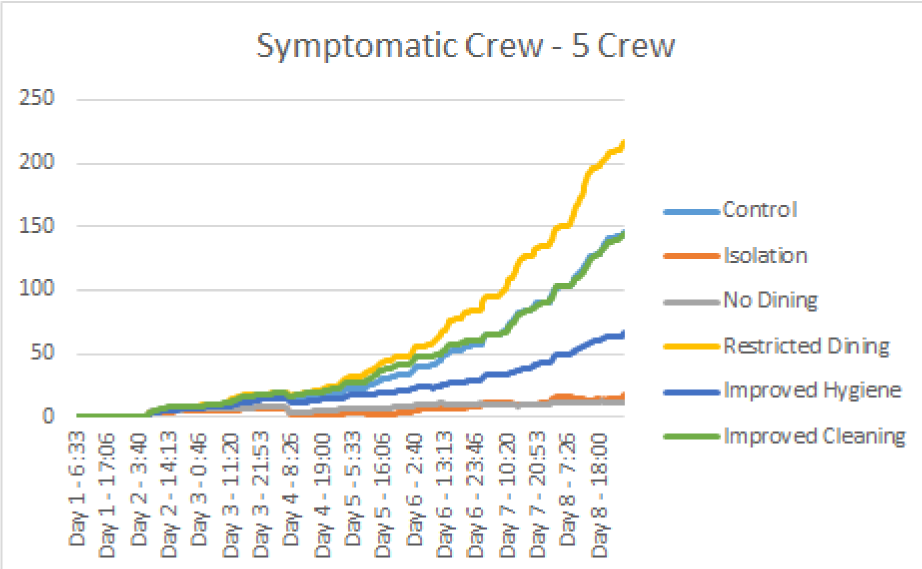
Appendix N9. Passenger Average Recovered for 5C Cases



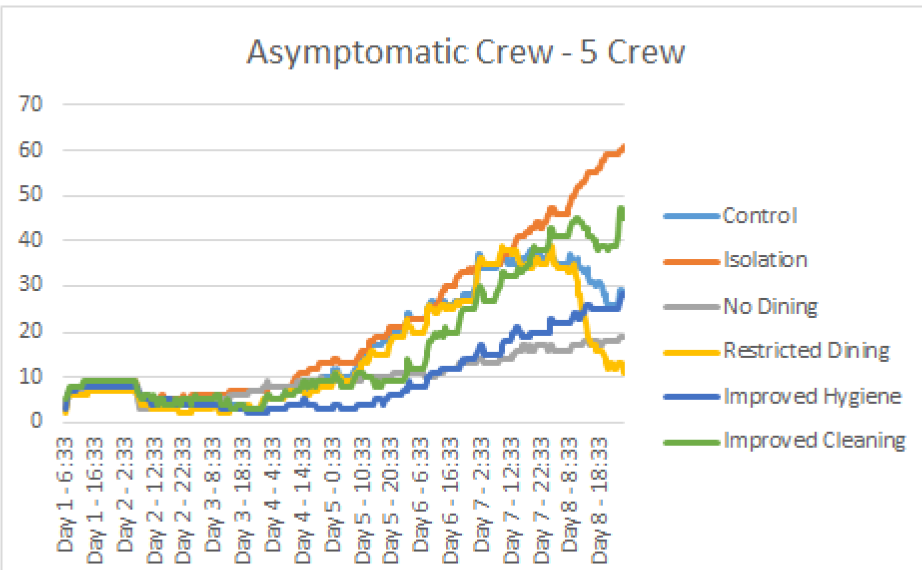

Appendix N10. Passenger Average Infections for 5C Cases



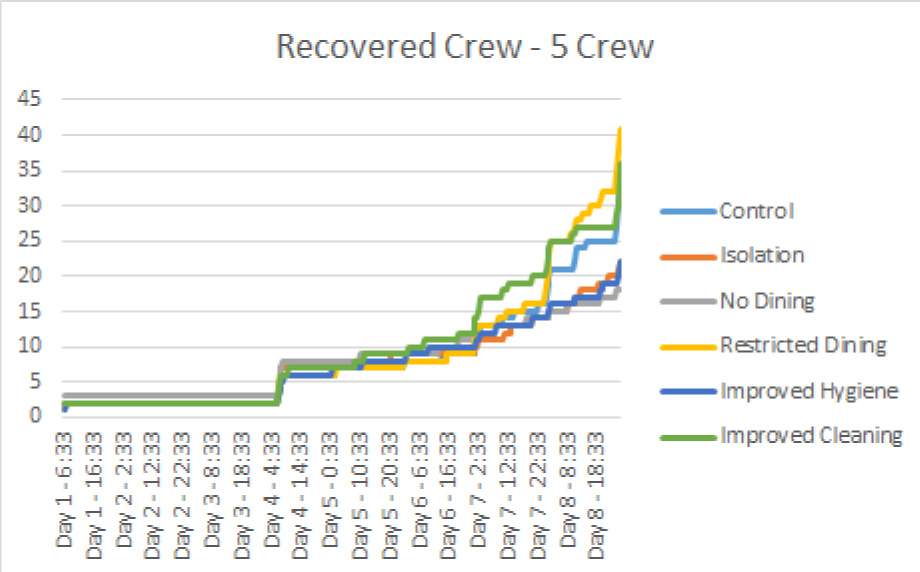
Appendix N11. Crew Average Symptomatic for 5C Cases



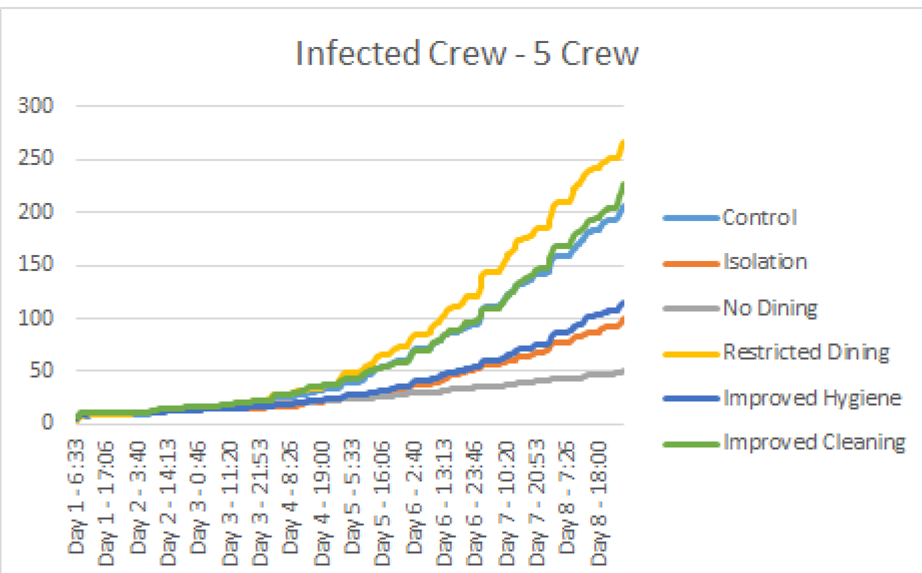

Appendix N12. Crew Average Asymptomatic for 5C Cases



Appendix N13. Crew Average Recovered for 5C Cases

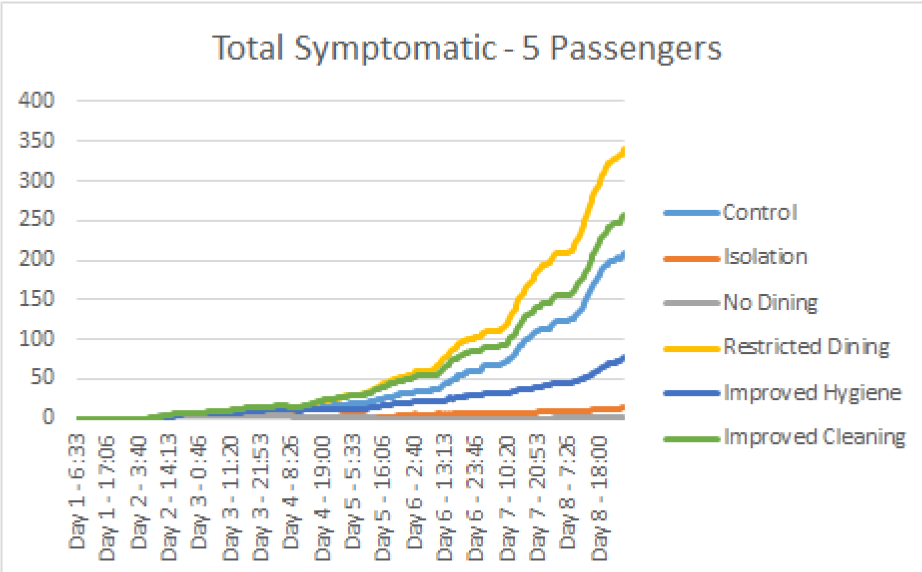



Appendix N14. Crew Average Infections for 5C Cases

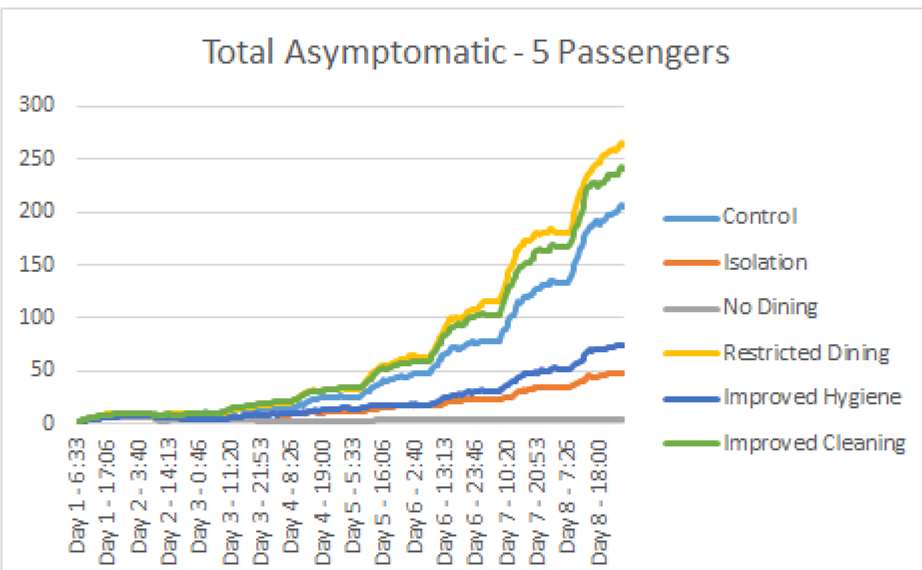


# Appendix O. Combined Charts for 5P Case

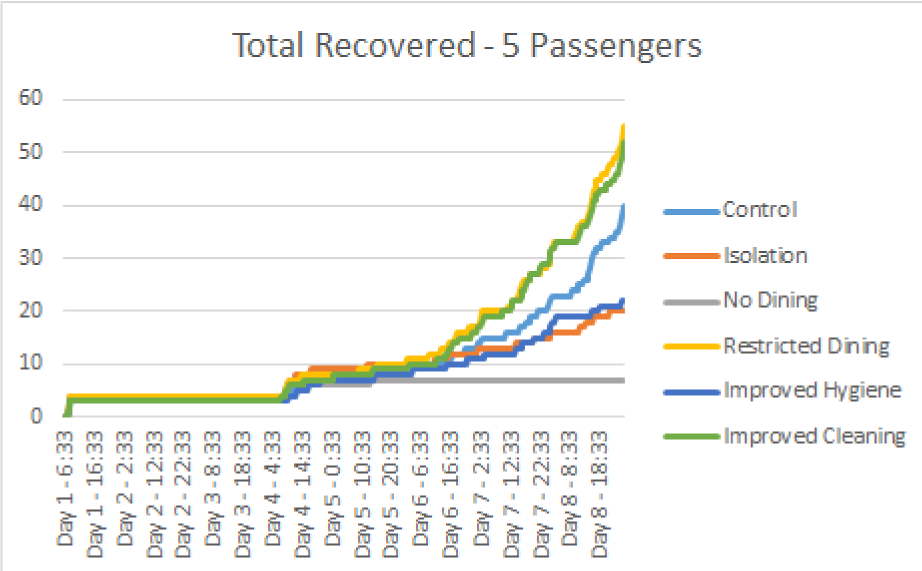
## Appendix O1. Total Average Symptomatic for 5P Cases



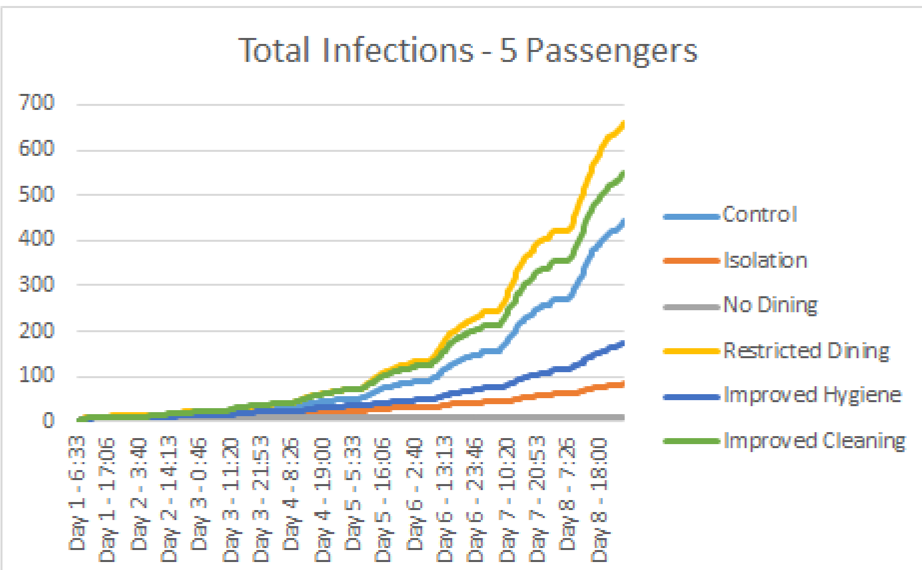

## Appendix O2. Total Average Asymptomatic for 5P Cases



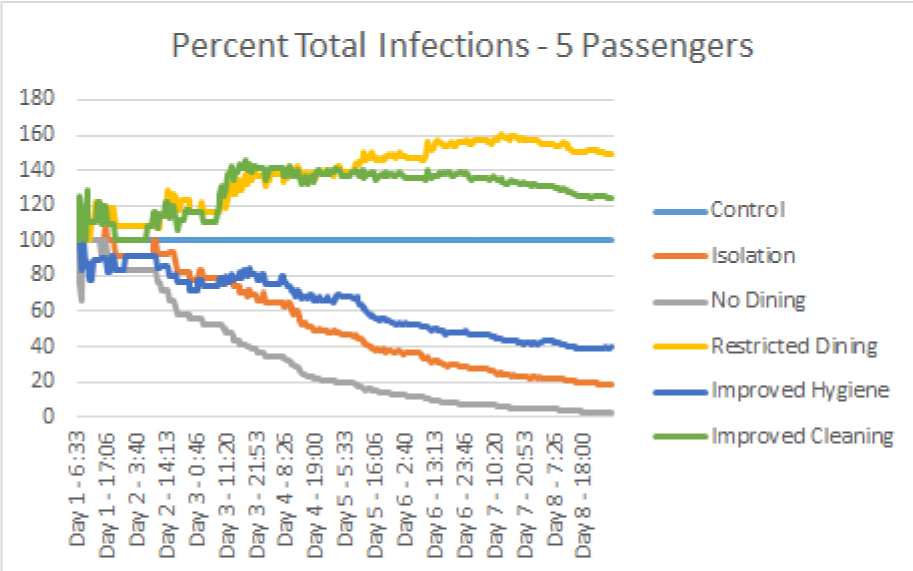
Appendix O3. Total Average Recovered for 5P Cases



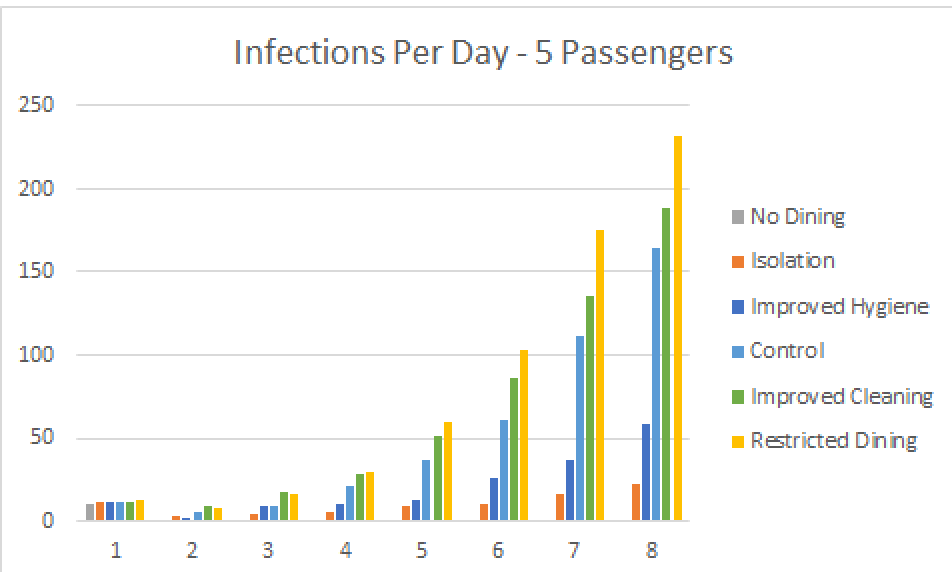

Appendix O4. Total Average Infections for 5P Cases



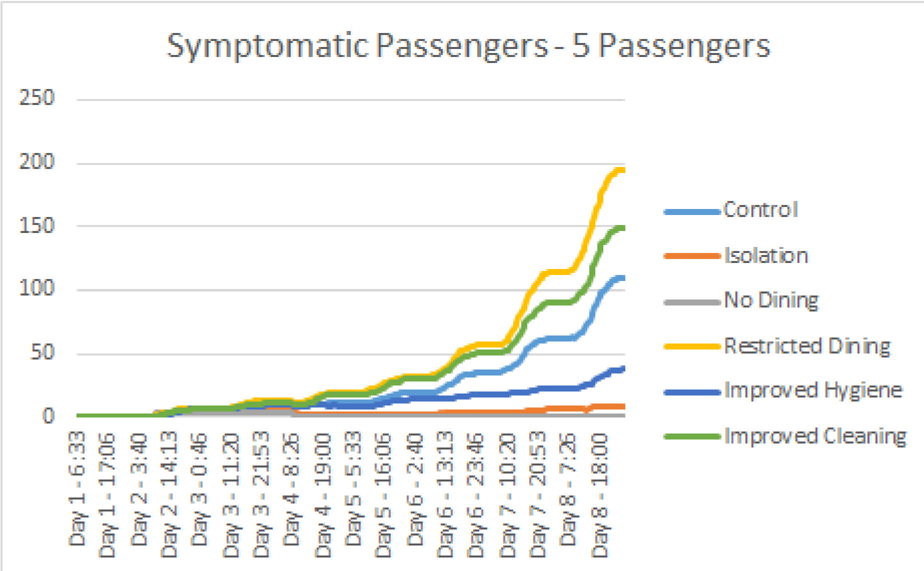
Appendix O5. Percentage of Control Infections for 5P Cases



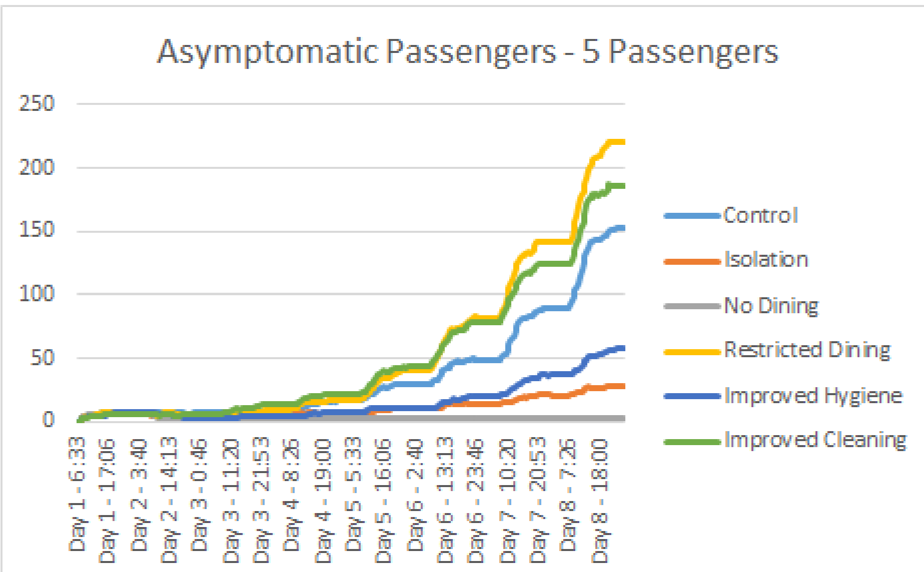

Appendix O6. Total Infections Per Day for 5P Cases



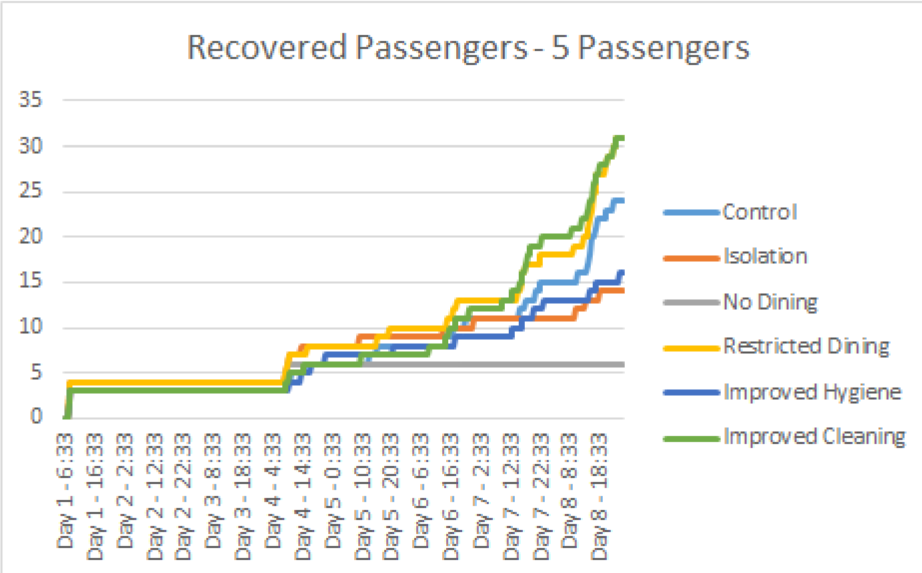
Appendix O7. Passenger Average Recovered for 5P Cases



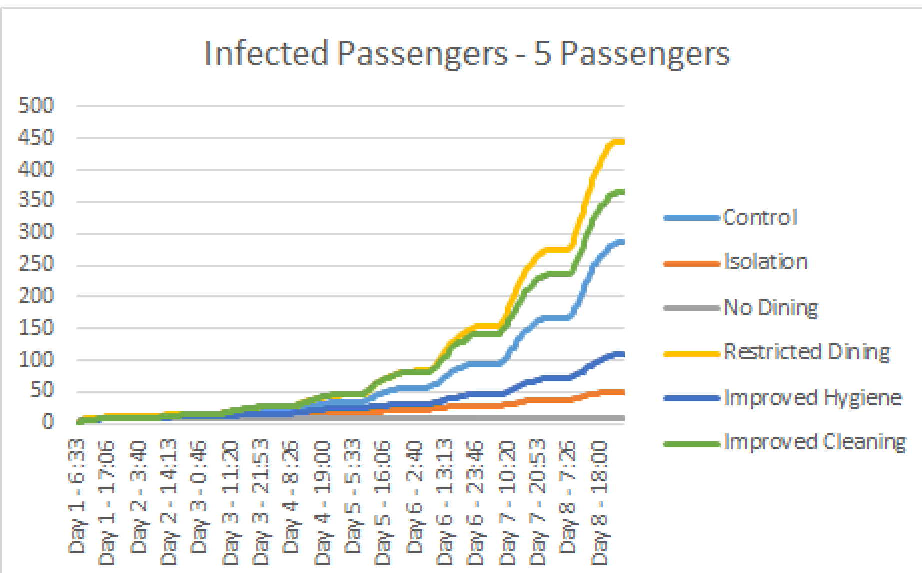

Appendix O8. Passenger Average Infections for 5P Cases



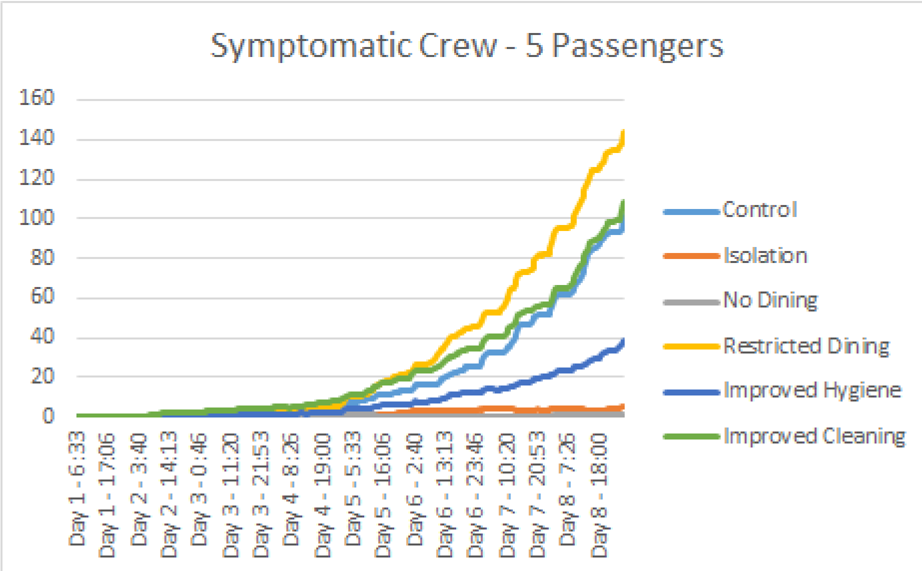
Appendix O9. Passenger Average Recovered for 5P Cases



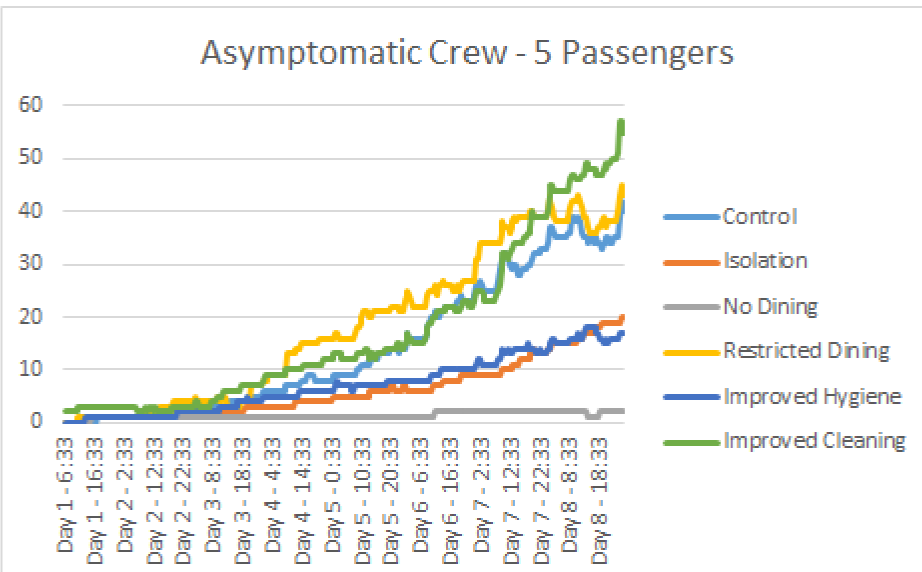

Appendix O10. Passenger Average Infections for 5P Cases



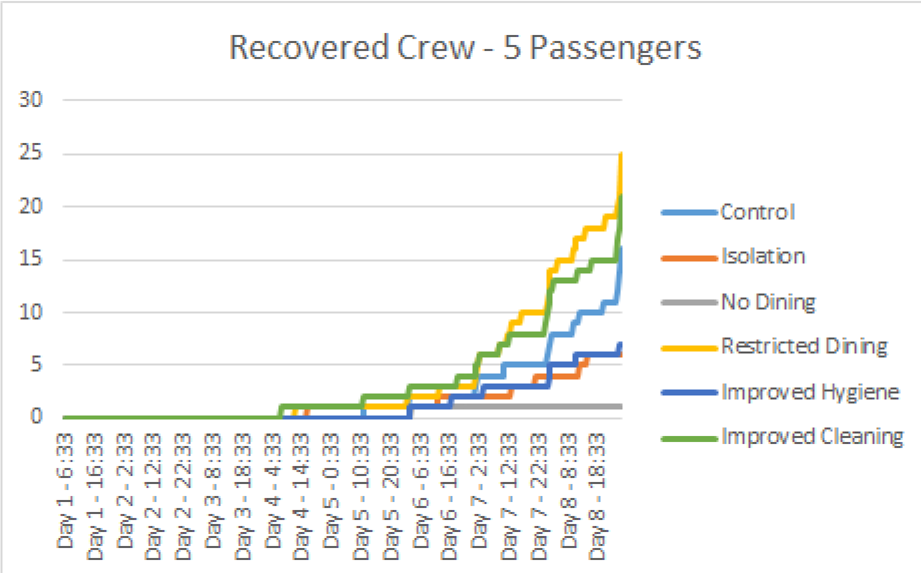
Appendix O11. Crew Average Symptomatic for 5P Cases



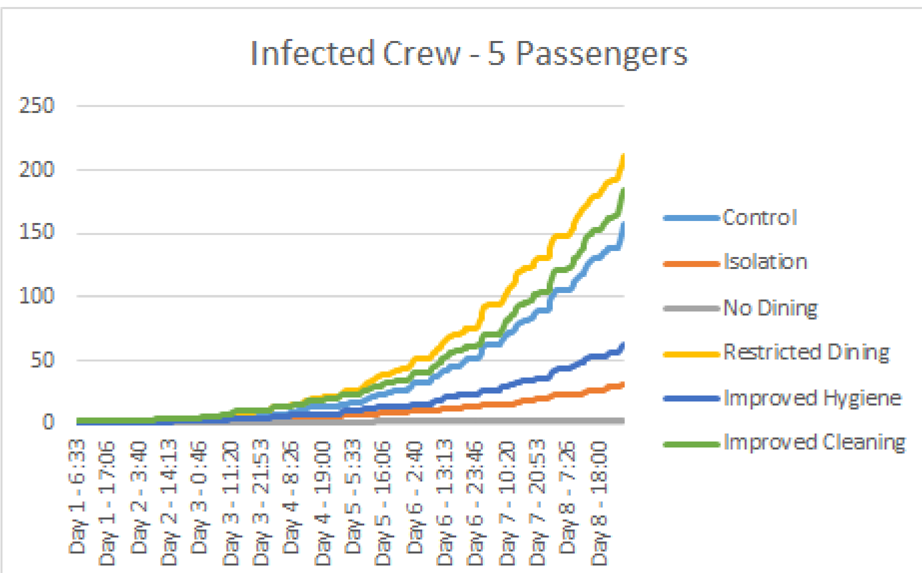

Appendix O12. Crew Average Asymptomatic for 5P Cases



Appendix O13. Crew Average Recovered for 5P Cases

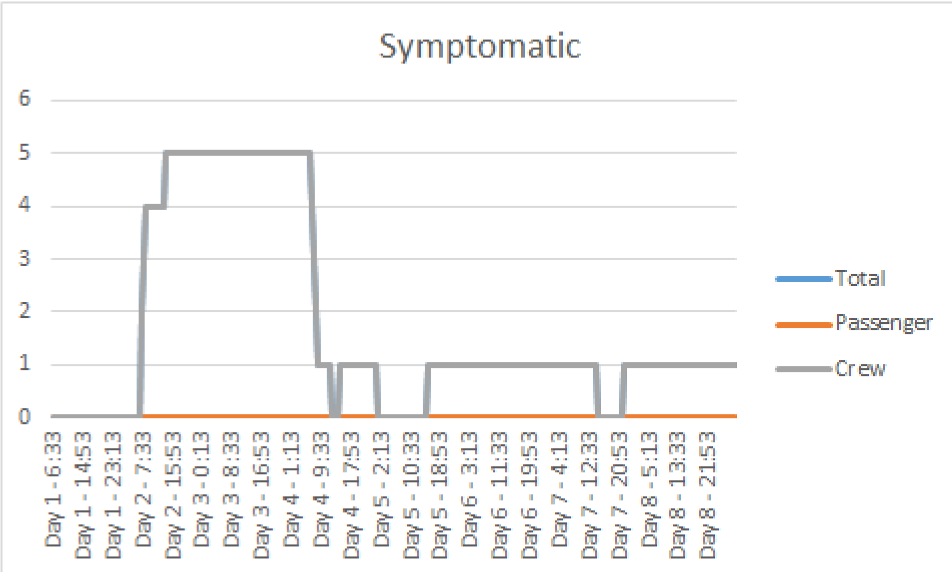



Appendix O14. Crew Average Infections for 5P Cases

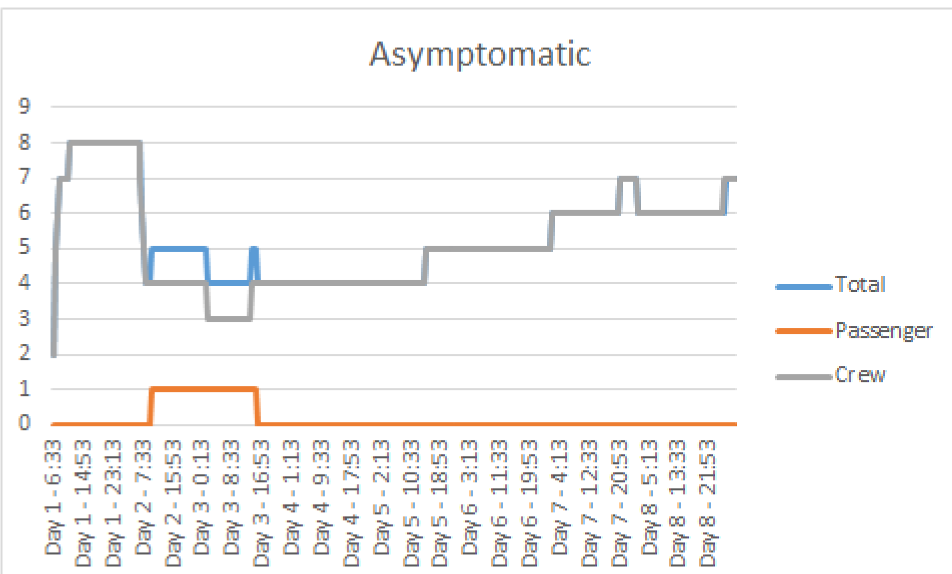


# Appendix P. Combined Simulations for 5C - Graph Data

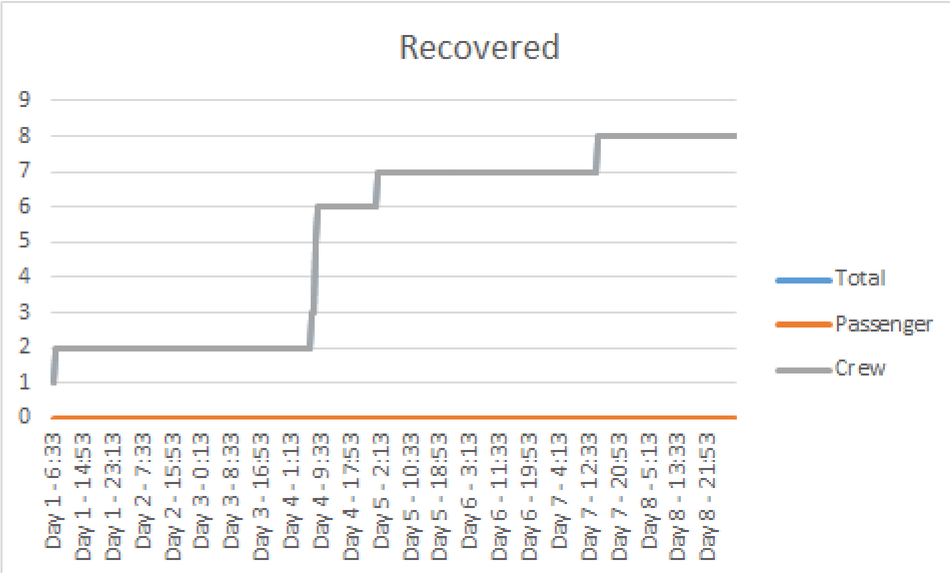
## Appendix P1. Average Symptomatic for 5C Combined - 5 Simulations



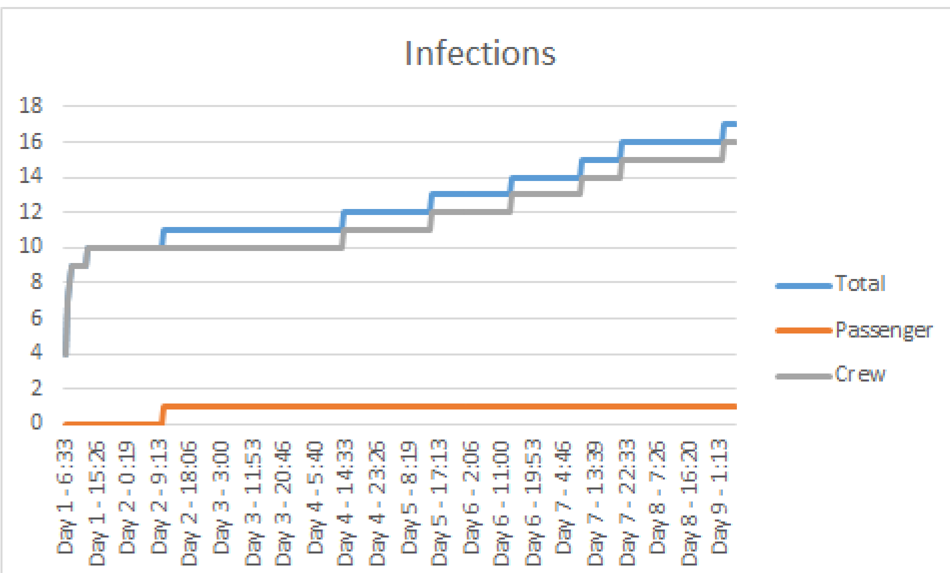

## Appendix P2. Average Asymptomatic for 5C Combined - 5 Simulations



Appendix P3. Average Recovered for 5C Combined - 5 Simulations

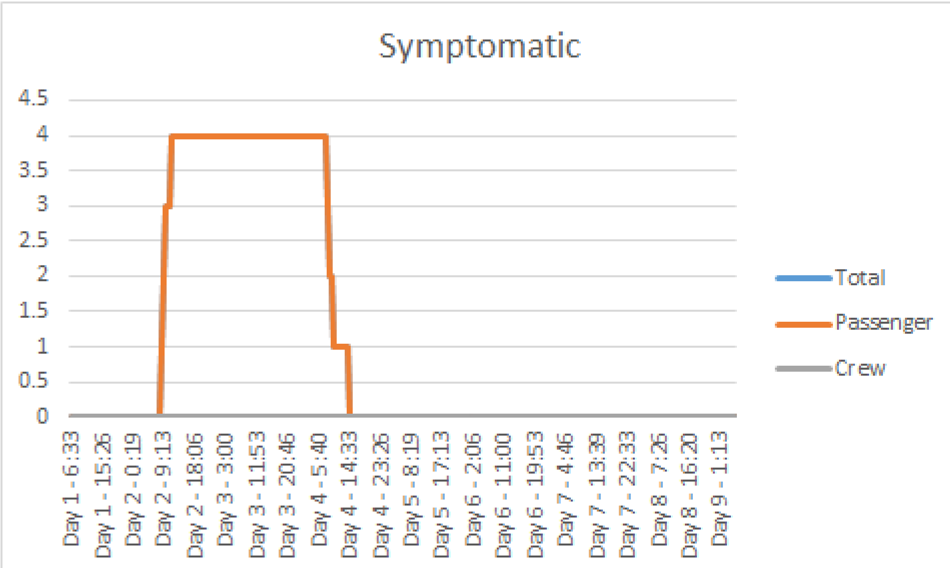



Appendix P4. Average Infections for 5C Combined - 5 Simulations

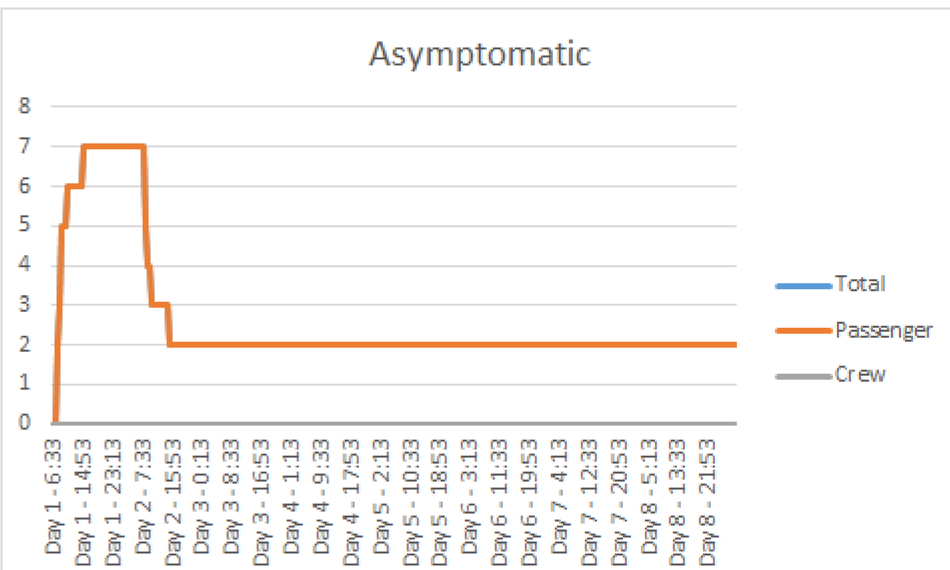


# Appendix Q. Combined Simulations for 5P - Graph Data

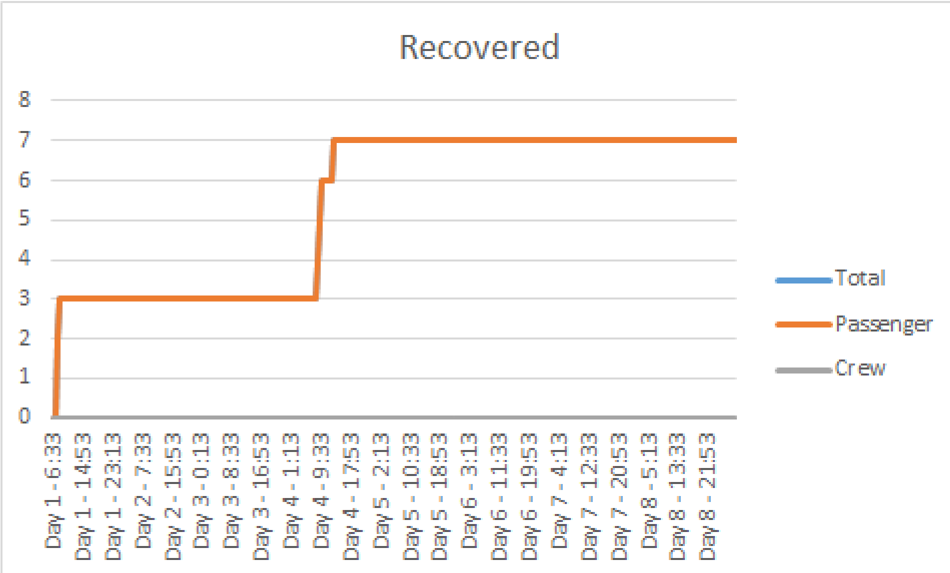
## Appendix Q1. Average Symptomatic for 5P Combined - 5 Simulations




## Appendix Q2. Average Asymptomatic for 5P Combined - 5 Simulations



Appendix Q3. Average Recovered for 5P Combined - 5 Simulations




Appendix Q4. Average Infections for 5P Combined - 5 Simulations