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Original Research Article

Minimizing disease spread on a quarantined cruise ship: A model of COVID-19 with asymptomatic infections[☆]

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ABSTRACT

On February 5 the Japanese government ordered the passengers and crew on the Diamond Princess to start a two week quarantine after a former passenger tested positive for COVID-19. During the quarantine the virus spread rapidly throughout the ship. By February 20, there were 651 cases. We model this quarantine with a SEIR model including asymptomatic infections with differentiated shipboard roles for crew and passengers. The study includes the derivation of the basic reproduction number and simulation studies showing the effect of quarantine with COVID-19 or influenza on the total infection numbers. We show that quarantine on a ship with COVID-19 will lead to significant disease spread if asymptomatic infections are not identified. However, if the majority of the crew and passengers are immune or vaccinated to COVID-19, then quarantine would slow the spread. We also show that a disease similar to influenza, even with a ship with a fully susceptible crew and passengers, could be contained through quarantine measures.

1. Introduction

Cruise ships bring diverse populations together in enclosed quarters for multiple days, creating an environment perfect for the spread of respiratory diseases. This was seen on the Diamond Princess cruise ship. A passenger disembarked on January 25 in Hong Kong, and later tested positive for COVID-19. The Japanese government ordered the passengers and crew to start a two week quarantine on February 5, during which the virus spread rapidly throughout the ship. By February 20, there were 651 cases [1]. On February 24th, the last of the passengers were allowed to disembark with the remaining crew allowed to disembark on March 1st. By March 1st among 3,711 Diamond Princess passengers and crew, 567 passengers and 145 crew members for a total of 712 (19.2%) had positive test results for SARS-CoV-2, the virus responsible for COVID-19 [2,3]. Of these, 331 (46.5%) were asymptomatic at the time of testing [2,3].

Disease outbreaks in closed environments like cruise ships, nursing homes, military barracks, and college dormitories (see for example [4–6]) frequently occur. Cruises are well known for norovirus (very contagious viruses that cause vomiting and diarrhea) outbreaks, and studies have been done to prove and prevent the pervasive route of transmission [6–8]. During norovirus outbreaks, cruises often go into quarantines until they can isolate the source to stop the spread. For outbreaks of respiratory diseases, even with a vaccinated population [9], a bigger concern is to stop the spread between people than to find the source. Outbreaks in contained environments full of older individuals, such as cruise ships and nursing homes, create a problem of heightened transmission rates and severe cases, and modeling them can show us the best way to mitigate an outbreak in a closed environment.

For large scale outbreaks, the most effective measures of containment are social isolation and quarantine (for mathematical examples see [10,11] among others). Quarantine serves to separate those infected from the susceptible population while social isolation keeps susceptible and potentially asymptomatic populations separate. This is especially important for COVID-19 since asymptomatic carriers are thought to hold the same degree of transmission as symptomatic carriers [12]. Most regional governments in the US have implemented social distancing protocols, but it is important to know the effectiveness of these protocols. In the 1918 Flu pandemic, social isolation was shown to be the most effective method for flattening the curve in cities [13]. Isolation and quarantine are our current best methods for flattening the curve before a treatment and/or vaccine is developed, but quarantine may not be the most effective in closed environments like cruise ships and nursing homes. Shared air systems, people in close proximity and poorly cleaned surfaces increase transmission rates [7,14]. In addition to these uncontrollable factors, the average age of passengers plus the possibility of insufficient disease transmission protocols due to a lack of training by crew only serve to increase the number of cases [3].

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However, there are ways to decrease the interactions between staff and the infected in such an environment. Soldiers from the U.S.S. Theodore Roosevelt experienced a massive outbreak and docked in Guam, where they were housed in a hotel-turned-quarantine-quarters. They received laundry service once a week and all their meals for the day at once in order to decrease the interactions with the staff serving them [15]. However, given the age of the sailors and their subsequent self-sufficiency, this level of quarantine is unsustainable in a nursing home whose occupants may need assistance with toileting, bathing, dressing, and eating. Cruise ship passengers are in between abilities, but have the limitations of significantly reduced space in their quarters.

Some of the questions our model attempts to address reflect the political decisions involved in allowing a cruise ship to disembark infected and potentially infected passengers. In retrospect, one can see that the quarantine of COVID-19 infected passengers on the ship increased the spread of disease. The data collected by the Japanese Ministry [2] indicates that on February 4th, the first day the Diamond Princess was under quarantine, 10 people out of 3711 passengers and crew tested positive for the virus. By February 8th, that number had modestly increased to 16. By February 17th however, that number had galloped to 454. By February 19th, when quarantine ended, and patients without the virus could disembark, at least 621 individuals linked to the ship had tested positive for the virus [1,2]. At that time, the Diamond Princess had the most cases outside of mainland China, showing that infections were being exacerbated by staying on the ship [16].

In this paper we show that quarantine on a ship with COVID-19, even with a majority of crew and passengers having immunity, either acquired or through vaccination, will lead to disease spread. However, we also show that a disease similar to influenza, even with a ship with a fully susceptible crew and passengers, could be contained through quarantine measures. The goal of this paper is to highlight preventive and quarantine measures for a disease with a less pervasive spread that may not lead to an explosion of cases. The simulations and sensitivity studies in this paper should be a starting point for discussions and further studies on quarantines in closed systems, especially regarding the role of uninfected care givers. We address the idea of reduction of disease spread through a minimization of contact between potentially infected passengers and crew members. Appropriate means to reduce this contact without compromising care will still need to be addressed, but we hope to bring forth discussions of airdropping sufficient personal protective gear or following the lead of the quarantine of exposed sailors in Guam with minimal interactions with self sufficient quarantined people. In addition, we address the issue of how quarantine might be successful if we could accurately determine infectious individuals who are not expressing outward symptoms and/or immune individuals through appropriate tests and contact tracing.

Recently, the outbreak of SARS-COV-2 on cruise ships has been modeled [17], but without the separation of asymptomatic and symptomatic cases. Retrospective reviews have been completed to see the comparison of mild to severe cases on the Diamond Princess, as well as statistical analyses to estimate the number of asymptomatic passengers [18,19]. There is also evidence that asymptomatic people can transmit the disease to others [20] and that 17.8% of the infected Diamond Princess passengers and crew members were asymptomatic and did not develop any symptoms [21].

We highlight the importance of a multi tiered model containing two classes: crew members and passengers. In our model, we calculate the reproductive number using data from the Diamond Princess, as well as complete a sensitivity analysis to determine which factors have the biggest impact on the spread of COVID-19 on a cruise. We present a $S-E-I-R$ model divided between passengers and crew members since the interactions of the groups are different both before and after a docked quarantine. We have ten categories of individuals that this model addresses consisting of five infection stages each for crew members and cruise ship passengers. The infection stages are susceptible (S), exposed (E), asymptomatic infectious (I^A), symptomatic infectious (I^S), and recovered with temporary or permanent immunity (R).

In the model we can assume that the disease behaves nearly the same in the crew members and passengers, modeled with the shared parameter values, in order to capture the difference in disease spread by shipboard role. Since the average passenger, age 70, being older than the average crew member, age 40, has a weakened immune system we do the asymptomatic passengers develop symptoms faster [22,23]. Some asymptomatic individuals never develop symptoms and are hidden disease spreaders while others can develop symptoms and join the symptomatic class. With this model, we hope to examine isolation and quarantine in a closed system in order to find the conditions to reduce transmission rates. In the model we assume that symptomatic passengers and crew members are confined in their quarters, although with a mean of 1.98 passengers per cabin and 1.73 crew members per cabin [3] they are not truly isolated. The system we examine is not entirely closed, since we allow seriously ill passengers to be evacuated.

In this paper we explore the spread of COVID-19 and an influenza-like illness in relation to different isolation and quarantine levels on a cruise ship. We have chosen to compare COVID-19 to H1N1 since the recent pandemics: 2009–2010 swine flu and 1918 flu were strains of H1N1. In addition, both COVID-19 and H1N1 are known to be infectious before symptoms develop. The contagious period for H1N1 infected adults begins 1 day before symptoms appear and lasts around 5–7 days after symptoms develop [24]. The high viral load during the early phase of COVID-19 suggests that patients could be most infectious during this period [25]. An important factor in the transmissibility of COVID-19 is the high level of SARS-CoV-2 shedding in the upper respiratory tract, even among infected individuals before symptoms appear [26]. A comparison between SARS-CoV-2 (the virus that causes COVID-19), MERS-CoV, and SARS-CoV-1 was not used as the period of the peak viral loads appears to be quite different. For SARS-CoV-1, replication occurs mainly in the lower respiratory tract [27]. The peak viral load of patients with MERS-CoV and SARS-CoV-1 infections occurs at around 7–10 days after symptom onset [28–30]. Unlike with patients infected with MERS-COV and SARS-CoV-1, patients infected with COVID-19 had the highest viral load near symptom onset [31]. Hence quarantine and isolation of persons with symptoms are extremely effective in keeping MERS-CoV and SARS-CoV-1 from becoming pandemics. With H1N1, asymptomatic infections average 16% [32,33] and pre-symptomatic spreading indicate that quarantine and isolation of people with symptoms is not necessarily sufficient to keep the virus from spreading.

In Section 2 we discuss the ODE system examining the transmission of the virus in two populations, the crew and passengers, while separating the infected populations into symptomatic and asymptomatic. We calculate the basic reproduction number, $\mathcal{R}_0$ for COVID-19 and influenza. In Sections 2.2 and 2.3 we discuss the data parameters used for our models of COVID-19 and influenza (H1N1). In Section 3 we perform a sensitivity analysis of the model in order to determine the relative significance of parameters to the disease transmission in the ship. We compare the effective reproduction number values and infection levels depending on different levels of isolation and quarantine. Last, in Section 4 we tie in our results and to isolation and quarantine decisions.

2. Methods and materials

2.1. Model

In the cruise ship model, there are two populations, crew members and passengers. These groups have different roles in a ship quarantine. When passengers are restricted to their rooms, the crew is still responsible for serving the passengers, and in the absence of tests to distinguish between exposed and infectious individuals, they initially are only quarantined after expressing symptoms. Once accurate tests are made available then crew members can be similarly quarantined after testing positive. Due to this difference in shipboard roles, we separate the inhabitants of the ship into the two groups. Within each group, there are susceptible (S), exposed (E), asymptomatic (I^A), symptomatic (I^S), and recovered (R) classes. These terms are defined in Table 1.

While it is true that not all crew members interact with the same frequency with the passengers, we do not have sufficient information to break down infections by crew role. From [22,23] we have the roles of 20 crew members who tested positive by February 9th out of 79 tested crew members. We do not have any information on infection status for the rest of the crew. We also do not have information on infection or test status for the crew versus passengers for February 10th–20th. Unfortunately there is a lack of consistency between reports [1,23] for the division of positive test status of crew and passengers for February 4th–9th. Table 5 in Appendix has the infection data for the Diamond Princess cruise ship with the results for the passengers and crew members combined [1] for February 5–20, 2020. Table 6, also in Appendix, has the test results for February 4–9, 2020 with the passengers and crew separated [23]. In addition, the labeling of 245 crew member roles as "food service (restaurant)", does not distinguish between servers and food preparation team members. Out of a total of 1068 crew members, 533 members have a workplace designated as "other" [23]. It is noted that 5 of the 20 infected food service workers worked in the kitchen away from passengers and 16 of the 20 were housed in cabins on a common deck [22]. This indicates that the spread was must likely crew–crew in that cluster. However, we do not know more about the primary contact that spread the infection into that cluster. Given the uncertainty in passenger–crew interaction by role, it seems justified to maintain a simple model that breaks the individuals on the ship into just two categories represented by an average crew member and average passenger.

To describe the interactions between the passengers and crew, we have the following assumptions:

- Before isolation and quarantine, all ship passengers and crew members mix uniformly.
- Symptomatic passengers and crew members are immediately restricted to their cabin.
- Before quarantine is instituted on the ship, only symptomatic passengers and crew are restricted to their cabin.
- All crew members have the same number of contacts with passengers and crew, regardless of their shipboard role.
- All passengers have the same number of contacts with passengers and crew.
- Cabin restricted crew members and passengers only interact with their cabin mates and crew who come to service the cabin with food and housekeeping services.
- Complete isolation is not possible on the ship. The mean number of passengers per cabin and crew members per cabin are both over 1.
- In order to account for social isolation, all passengers cease interaction with other passengers outside their cabins once quarantine is started.
- Recovered crew and passengers cannot be reinfected.
- The cruise ship voyage is short enough that no one dies of natural death while on board.
- Crew and passengers have the same rate of developing an initially symptomatic case, recovery rate, evacuation rate, and fraction of the population having asymptomatic cases.
- There are no deaths on the ship, however, seriously ill individuals are evacuated to the hospital.

Since only interactions with infected individuals spread the disease, we model just these contacts. In Fig. 1 we illustrate the interactions with infected individuals with dashed lines and the transmission rate listed by the dashed lines. In Table 2 we define the parameters, where β is the transmission probability per contact, ξ is the reduction for asymptomatic infectiousness as compared to symptomatic, and κ_{XY} represents the interaction rate of population X with population Y. Fig. 1 shows that the susceptible passengers can be infected through interactions with asymptomatic crew and other passengers. The susceptible passengers can be infected by symptomatic passengers through shared quarters. The susceptible crew members have additional infection routes since they interact with both asymptomatic and symptomatic passengers and crew members.

In Fig. 2 we show the progression of the infection from susceptible S, to exposed E, to infectious, either asymptomatic I^A or symptomatic I^S, and then recovered, R. The infection rates λ_P and λ_C combine the disease transmissions shown in Fig. 1. These rates are explicitly defined in the system (1). Once the passenger or crew member becomes infected at the rate λ_P or λ_C, they remain in the exposed category until they are infectious. Once the individual becomes infectious, they move out of the exposed category at a rate ℓ. A fraction σ of the infectious individuals move to the asymptomatic category I^A and the remainder, $(1-\sigma)$ move to the symptomatic category I^S. Individuals may recover from an asymptomatic infection at a rate γ and develop symptoms at the rate α_P or α_C. We assume that the average passenger, age 70, being older than the average crew member, age 40, has a weaker immune system and develops symptoms faster [22,23]. From the symptomatic population, I^S, an individual may recover at a rate ρ or be evacuated from the ship at a rate μ. Although on average passengers are significantly older than crew members and thus are more likely to become seriously ill, remain infectious longer, and perhaps more likely to be symptomatic, we do not capture these details in our model since the publicly available data does not reflect whether the infected individual is a passenger or crew member. The ship-wide infection model as described here is defined in the ordinary differential equations for system (1).

$$\frac{dS_P}{dt} = -\beta_P \frac{S_P}{N_P}\left(\xi\kappa_{PC}I_C^A + \xi\kappa_{PP}I_P^A + \kappa_{PS}I_P^S\right) = -\lambda_P\frac{S_P}{N_P}$$
$$\frac{dE_P}{dt} = \beta_P \frac{S_P}{N_P}\left(\xi\kappa_{PC}I_C^A + \xi\kappa_{PP}I_P^A + \kappa_{PS}I_P^S\right) - \ell E_P$$

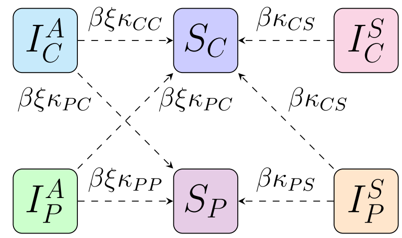


Fig. 1. Disease transmission routes for susceptible passengers and crew. Dashed lines indicate infection routes. Passengers are infected by asymptomatic crew, asymptomatic passengers, and symptomatic passengers through a shared cabin. Since the crew interacts with all people on the ship, they can get the disease from all infected individuals.

Table 1
List of dependent variables.

Notation	Definition
$S_P(t)$	Number of susceptible passengers at time t
$E_P(t)$	Number of exposed passengers at time t
$I_P^A(t)$	Number of infected asymptomatic passengers at time t
$I_P^S(t)$	Number of infected symptomatic passengers at time t
$R_P(t)$	Number of recovered passengers at time t
$S_C(t)$	Number of susceptible crew members at time t
$E_C(t)$	Number of exposed crew members at time t
$I_C^A(t)$	Number of infected asymptomatic crew members at time t
$I_C^S(t)$	Number of infected symptomatic crew members at time t
$R_C(t)$	Number of recovered crew members at time t

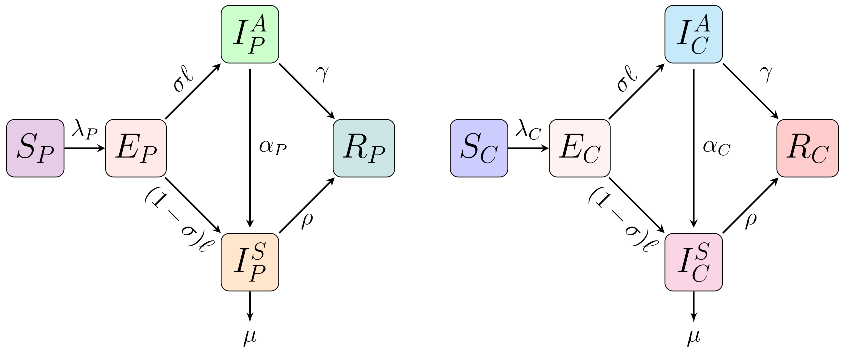


Fig. 2. The progression of infection for the passengers and crew from susceptible S, to exposed E, to infectious, either asymptomatic I^A or symptomatic I^S, and then to recovered R. The subscript reflects crew or passenger. The infection rates λ_P and λ_C combine the disease transmissions shown in Fig. 1. Exposed passengers and crew become infectious at the rate ℓ with or without symptoms. Initially asymptomatic individuals may develop symptoms at the rate α_C, α_P, or recover at the rate γ. Symptomatic individuals either recover at the rate ρ or are evacuated from the ship at a rate μ.

Table 2
List of parameters.

Notation	Description
β	Transmission probability
ξ	Reduction of infectiousness for asymptomatic individual compared to symptomatic
κ_{PP}	Contact rate between passengers
κ_{PC}	Contact rate between passengers and crew
κ_{CC}	Contact rate between crew
κ_{CS}	Contact rate between crew and symptomatic individuals
κ_{PS}	Contact rate between passenger and symptomatic individuals
ℓ	Rate to become infectious
α	Rate of developing symptoms
γ	Rate of recovering from asymptomatic stage
μ	Rate of removal of severely infected individuals from ship
ρ	Rate of recovery of symptomatic individuals
σ	Fraction of infected individuals who are asymptomatic

$$
\begin{aligned}
\frac{dI_P^A}{dt} &= \sigma\ell E_P - (\alpha_P+\gamma)I_P^A \\
\frac{dI_P^S}{dt} &= (1-\sigma)\ell E_P + \alpha_P I_P^A - (\mu+\rho)I_P^S \\
\frac{dR_P}{dt} &= \gamma I_P^A + \rho I_P^S \\
\frac{dS_C}{dt} &= -\beta_C\frac{S_C}{N_C}\left[\xi\kappa_{PC}I_P^A + \kappa_{CS}(I_P^S+I_C^S) + \xi\kappa_{CC}I_C^A\right] = -\lambda_C\frac{S_C}{N_C} \\
\frac{dE_C}{dt} &= \beta_C\frac{S_C}{N_C}\left[\xi\kappa_{PC}I_P^A + \kappa_{CS}(I_P^S+I_C^S) + \xi\kappa_{CC}I_C^A\right] - \ell E_C \\
\frac{dI_C^A}{dt} &= \sigma\ell E_C - (\alpha_C+\gamma)I_C^A \\
\frac{dI_C^S}{dt} &= (1-\sigma)\ell E_C + \alpha_C I_C^A - (\mu+\rho)I_C^S \\
\frac{dR_C}{dt} &= \gamma I_C^A + \rho I_C^S
\end{aligned} \tag{1}
$$

2.2. Calculating β and contact rates

In this section we describe our calculations for parameter values from data and discuss the values that we have gathered from reliable sources for COVID-19 and influenza. Since the COVID-19 pandemic is still in its early stages, most of the parameter values are estimated from publicly available data.

To approximate a value for the transmission probability β for COVID-19, we used data from Guangzhou, China [34], South Korean [35,36], and New York City [37]. We employed the idea from [38] to approximate $\beta\kappa$, where κ is the number of contacts per day. Jahedi and Yorke [38] employ a simple exponential model for the beginning of the pandemic in each location. Since initially no one had immunity to SARS-CoV-2 we can approximate the total number of susceptible individuals to be the total population when using data from initial infections in Guangzhou, China, South Korea, and New York city. With this assumption one can use the exponential model

$$I_{n+1} = \beta\kappa I_n, \tag{2}$$

to calculate $\beta\kappa$ by using data values for I_n and I_{n+1}.

First we need to approximate the average number of contacts per day, κ, for an infected individual for each of those cities. Jing et al. [34] determined the secondary attack rate (SAR) in Guangzhou from 195 unrelated clusters with 212 primary cases and 137 secondary or tertiary cases with the tracing of 1938 uninfected close contacts. Jing et al. defined a close contact as an individual who had unprotected contact within 1 meter with a confirmed positive individual within 2 days either before symptom onset or testing. Close contacts were quarantined under observation and followed for 14 days. The household SAR, the secondary attack rate on those living at the same address, was 19.3% and the non-household SAR was 3.06%. This information indicates the 2075 contacts could be divided into 452.6 household contacts and 1622.4 non-household contacts for the 212 primary cases. Assuming that the primary case interacted with the household contacts each day and the non-household contacts only once in those two days, we have on average 5.9 contacts per day for a primary case. Jing et al. did note that the quarantine and isolation policy reduced the spread of COVID-19 by 30%, so we could assume that without this policy the contact rate would be 30% higher, or $\kappa = 7.7$.

With the number of positive tests in South Korea from February 15–25 and in New York City from March 9–19, as shown in Table 7 in Appendix, we can calculate $\beta\kappa$. For South Korea we find an average $\beta\kappa$ of 1.125. If we assume each South Korean had 7.7 contacts per day, then $\beta = 0.187$. We note that this calculated value for COVID-19 β might be lower than what would be expected on a cruise ship environment due the average age of the Korean population being around seven years lower than what you would expect to find on a cruise ship [39,40]. We also would expect the daily contact rate to be higher on a cruise ship. Next we considered New York City, which has a high density that should attribute to a higher contact rate. With the New York City data, we have $\beta\kappa = 1.712$, which if we assume that $\beta = 0.187$, then the average number of contacts for a New Yorker is 9.1. This increase in contact number to match the average $\beta\kappa$ calculated from data gives us confidence that our estimates are reasonable.

Now that we have established an estimate for an average β, we need to take this average transmission probability and divide it into asymptomatic and symptomatic transmission rates. Currently it is believed that asymptomatic transmissions are 75% as infectious as symptomatic transmissions and that 40% of the transmissions are asymptomatic [20]. To find the value for symptomatic transmission we evaluate

$$0.40(0.75)x + 0.60x = 0.187, \tag{3}$$

Table 3
Estimated parameter values: Before and after quarantine.

Parameter	Before, $(d = 0)$	After, $(d = 1)$
κ_{PP}	14/day	2/day
κ_{PC}	2/day	2/day
κ_{CC}	5/day	3/day
κ_{CS}	2/day	1/day
κ_{PS}	2/day	2/day
μ (COVID-19)	0.1/day	0.25/day

where x represents the symptomatic transmission probability. Therefore our symptomatic transmission probability is $\beta = 0.208$ and asymptomatic transmission probability is $\xi\beta = 0.156$, with ξ equal to 75%.

Now that we have established an estimate for β, we find contact rates for the passengers and crew members. On the Diamond Princess there were a mean of 1.98 passengers per cabin and 1.73 crew members per cabin [3]. However, all the other information about contact rates is unknown. Hence, all the contact rates need to be estimated. Although there is one other person in a room for a passenger on average, passengers had interactions with others during their walks on deck and when passengers across the hall would open their balconies and doors to allow their neighbors to get fresh air [41]. Thus, the passenger–passenger contact rate is greater than 1 during full quarantine. To include the exact means in our contact numbers would give a false air, so we have rounded those precise numbers to 2 to define κ_{PP} for after quarantine, κ_{PS}, and κ_{CS}. We estimate that aboard a cruise ship, there are a large number of contacts between passengers with other passengers, κ_{PP}, and crew with other crew, κ_{CC}. With 2666 passengers and 1045 crew members on board, we assume there is an average contact rate of 2 per day between passengers and crew, κ_{PC}. Using the exponential model in (2) and Table 5 in Appendix with positive test results for February 4–9th, we have a median contact rate for all individuals on the ship of 16.8. With this information we assume the passengers have twice as many close contacts as they would in New York City, which sets $\kappa_{PP} = 14$. Then, to maintain our average ship-board contact rate we have $\kappa_{CC} = 5$.

Once the ship went into quarantine, the passenger–passenger contacts were limited to within the cabin (and balconies) as the passengers were isolated. News reports [41] indicate that thrice daily meal delivery and hospitality services were continued so we assume that the passenger–crew contact rate remained unchanged. We assume that the crew was able to minimize contact with each other and reduced the crew–crew contact rate from 5 to 3. We also assume that the crew-seriously ill individuals contact rate, κ_{CS} was halved by use of protective gear. Setting $d = 0$ before quarantine and $d = 1$ during quarantine, we thus have the passenger–passenger interaction rates are captured by $\kappa_{PP} = 2 + (1 - d)12$, crew–crew interaction rate by $\kappa_{CC} = 3 + (1 - d)2$ and crew-symptomatic individuals interaction rate by $\kappa_{CS} = 1 + (1 - d)1$. We assume that with the minimum quarantine (when d=0), the crew will regularly interact with passengers through laundry, ship activities, and meal services. As the quarantine increases, more passengers are restricted to their rooms, and the crew uses protective equipment, leading to the smallest number interactions when d=1. These rates are given in Table 3.

We calculated the transmission probability, β of influenza (H1N1) similarly by averaging the household transmission rates by different age categories [33] and dividing by 3 interactions daily.

2.3. Calculating the rest of our parameters

By the CDC count of US infections between February 12 and March 16, 2020 [42] 12.3% of all COVID-19 positive identified individuals needed hospitalization, with the highest rates in persons 65 years and older (38.7 per 100,000) and 50–64 years (20.7 per 100,000). The evacuation rate of the Diamond Princess ship was slightly lower than this percentage at 10% at the start of quarantine [1]. Once quarantine started, shipboard evacuations were increased to 25% of the total infections [1]. Hence we define $\mu = 0.25 - (1 - d)0.15$ where $d = 0$ before quarantine and $d = 1$ during quarantine for COVID-19. Table 3 has the values for μ before and after quarantine. Influenza has a daily hospitalization and death rate of $0.005\% = 1/\mu$ [32,33].

The baseline parameter values that we use in our analysis of system (1) are given in Table 4. The ranges reflect either a variation in data values or the uncertainty in the true values for COVID-19.

Both the CDC and WHO state that on average it takes between 2 and 14 days for symptoms to appear in symptomatic COVID-19 patients. Recent studies [43] show that the incubation period before symptoms start is 5.1 days on average [43]. However, actual infectiousness starts before then with a range of 24–72 h before symptoms appear [21]. We assume infectiousness begins an average of 2 days before symptoms and thus calculate an exposed and noninfectious period of $1/\ell = 3.1$ days for COVID-19. Influenza has a shorter exposed and not yet infectious period on the average of 1.9 days [33].

While the clinical recovery rate is assumed to be 2 weeks for a mild case and 3–6 weeks for a more severe case [45], the actual infectious period is undetermined. One virological assessment of mild to moderate patients [26] indicates that peak infectiousness was on day 4 of illness, but SARS-CoV-2 RNA could be detected for 20 days or longer in a third of patients, and one patient had SARS-CoV-2 RNA detected for 25 days. The study measured the highest salivary viral load during the first week after symptom onset with subsequent decline with time [26]. The high viral load during the early phase of illness suggests that patients could be most infectious during this period [25]. So keeping in mind the early peak of infectiousness, for the mild and severe cases we are assuming that asymptomatic individuals lose infectiousness on average in 7 days and symptomatic individuals in 14 days. This corresponds to $\gamma = 1/7$ and $\rho = 1/14$ for COVID-19. Influenza has a faster recovery from mild and severe cases averaging at 4.1 days [32,33].

The proportion of true asymptomatic cases on the Diamond Princess cruise was calculated at 17.8% [1]. However, we use the CDC [20] estimate of $\sigma = 40\%$ for COVID-19 and use 16% for asymptomatic influenza cases [44] to include people who do develop symptoms. The rate of infectious but initially asymptomatic individuals to show symptoms is not yet known for COVID-19. We have chosen to set the rate that the asymptomatic passengers develop symptoms, with average age 70, $\alpha_P = 1/1.5$ since this is on the shorter timeline for developing symptoms. We set the rate that the asymptomatic crew members develop symptoms, average age 40, α_C to be 1/4. For influenza we use the data that it takes 1.5 days, on average to show symptoms [32,33] so we set $\alpha_P = 1.5$ and use the longer range of symptoms onset for the crew, $\alpha_C = 1/3$.

3. Results

The motivation for developing mathematical models of infection in a closed system such as a nursing home or cruise ship is to evaluate possible control strategies that may be put in place in case of an emergency. First and foremost, one would choose to enforce preventative measures to keep infection from entering the system. Once infection is in the system, all that is left is control measures: isolation of infected individuals and quarantine of potential contacts along with social distancing. Unfortunately, on a cruise ship, as well as in a nursing home with all double occupancy rooms, total isolation is not possible. However, social distancing is possible by keeping cabin mates confined together and apart from others.

3.1. Basic reproduction number $\mathcal{R}_0$

The basic reproduction number $\mathcal{R}_0$ is the reproduction number when there is no immunity from past exposures or vaccination, nor any deliberate intervention in disease transmission. The basic reproduction number, $\mathcal{R}_0$, provides a condition for establishment of a single virus infection. If $\mathcal{R}_0 < 0$, the disease will die out, if $\mathcal{R}_0 > 0$, the disease will

Table 4
Parameter values for COVID-19 and H1N1 that remain unchanged for isolation and quarantine.

	COVID-19		H1N1	
	Baseline	Range	Baseline	Range
β	0.208 Calculated	0.1-0.4 Estimated	0.144 [33]	0.064–0.400 [33]
ξ	75% [20]	25%–100% [20]	75% Estimate	25%–100% Estimate
$1/\ell$	3.1 days [43]	2.5-3.8 days [43]	1.9 days [33]	1–3 days [32,33]
$1/\gamma$	7 days Estimated	10–14 days Estimated	4.1 days [32,33]	3–6 days [32,33]
$1/\rho$	14 days Estimated	7–25 days Estimated	4.1 days [33]	3–6 days [33]
σ	40% [20]	10%–70% [20]	16% [44]	4%–28% [44]
μ	0.1/day [1]	0–0.25/day Estimated	0.0005/day [32]	0–0.001/day Estimated
α_P	1/(1.5 days) [21,43]	0–1/(4 days) [21,43]	1/(1.5 days) [32,33]	1/3–1/day [32,33]
α_C	1/(4 days) [21,43]	0–1/(4 days) [21,43]	1/(3 days) [32,33]	1/3–1/day [32,33]

persist. We calculate $\mathcal{R}_0$ using the Next Generation Method (see [46] for a thorough discussion of this technique). Due to the complexity of the system we only present numerical results for $\mathcal{R}_0$.

By using sensitivity analysis, we estimated which parameters had the most impact in affecting the value of our $\mathcal{R}_0$. We use our results to determine the importance of each parameters in achieving disease free equilibrium on the ship. In our case, we use sensitivity analysis to point out the highest impact on the transmission of COVID-19 in which could be used to help determine strategies for preventative and quarantine measures. Sensitivity indices measure the percentage change of a key quantity, such as the reproduction number, in response to a percentage change of a parameter in that quantity. The normalized forward sensitivity index of $\mathcal{R}_0$ relative to a differentiable parameter p is defined as follows [47]:

$$\Upsilon_p^{\mathcal{R}_0} = \frac{\partial \mathcal{R}_0}{\partial p} \times \frac{p}{\mathcal{R}_0}. \tag{4}$$

The value of the normalized forward sensitivity index determines whether each parameter is sensitive (quite responsive), unit sensitive, or insensitive (not very responsive). A sensitive parameter is one where a given change in the parameter will cause a large change in the reproductive number. Insensitive parameter can be defined analogously. A unitary sensitivity conveys that a given change in a parameter leads to an equal change in quantity demanded or supplied. Sensitivity values can be positive or negative. A positive value represents the increase of a parameter creates an increase in $\mathcal{R}_0$, while a negative value represents the increase of a parameter creates a decrease in $\mathcal{R}_0$.

The sensitivity of the reproduction number to each of the parameters is given in Fig. 3 for influenza in (a) and COVID-19 in (b) before quarantine was imposed. Once quarantine conditions are established on the cruise ship, the reproduction number of the disease is described by the effective reproduction number. The forward sensitivity of the reproduction number to the parameters reflects a local sensitivity, so as the parameter values change, so does the sensitivity.

As shown in Fig. 3(a) the most sensitive parameters for the reproduction number for influenza (H1N1) before quarantine are β, ξ, ρ, and κ_{CS}. Secondary sensitivity belongs to σ, μ, and κ_{PS}. While β is fixed for each disease, measures can be taken to reduce $\mathcal{R}_0$ for each of the other parameters. When ρ is increased, $\mathcal{R}_0$ decreases. This means that decreasing the recovery time in the symptomatic stage for H1N1 will decrease infections. This can be achieved with influenza by prompt testing and administering of antivirals such as Tamiflu in the first 48 h of illness. The parameter σ represents the fraction of infectious individuals who are asymptomatic. When σ gets larger, so does the reproduction number. While σ itself cannot be changed for the disease, its effect can be reduced by contact tracing and quarantining all close contacts. This will reduce the spread by asymptomatic individuals. There is still a limitation in that isolation cannot be achieved on a cruise ship, but certainly, quarantining should limit the number of contacts. The parameters κ_{CS} and κ_{PS} represent the number of crew to symptomatic contacts and the number of passengers to symptomatic contacts. Decreasing the number of these contacts to a minimum, using personal protection equipment as masks and gloves, will reduce the reproduction number. To reduce κ_{PS}, symptomatic passengers need given separate quarters from their healthy passenger companions.

The reproduction number for COVID-19 before quarantine, see Fig. 3(b), is most sensitive to the parameters β, ξ, γ, σ, and κ_{PP}. Unfortunately as there is currently no cure or drug that has been proven to shorten the length of infection for COVID-19, the parameter γ cannot be affected. It is clear that identifying asymptomatic cases is very important to reducing the reproduction number, as shown by the sensitivity of $\mathcal{R}_0$ to ξ and σ. This affirms that testing and contact tracing to identify these individuals followed by isolating these contacts is truly necessary to reduce the spread of COVID-19 on the ship. Furthermore, when comparing the case of COVID-19 on the ship to influenza, it is noted that ρ does not have a significant impact on the reproduction number either before quarantine. This means that the rate of recovery of symptomatic individuals is not as important to curbing the spread of COVID-19 as identifying the asymptomatic infectious individuals.

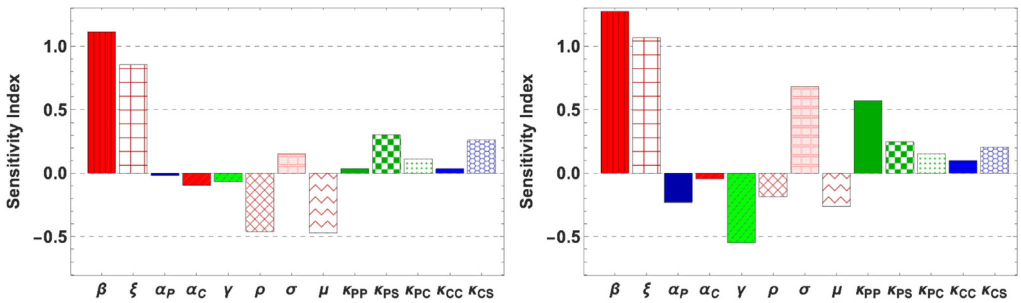
3.2. Dependence of $\mathcal{R}_e$ on isolation practices in quarantine and COVID-19 characteristics

Once we establish quarantine conditions on the cruise ship, we change the reproduction number of the disease accordingly. We will refer to $\mathcal{R}_e$ as an effective reproduction number when there is some immunity or some intervention measures are in place. To model the isolation and quarantine situation on the cruise ship we enforce the isolation by the parameter d. When $d = 0$, all non-symptomatic passengers are free to move about the ship and the disease spread is described by $\mathcal{R}_0$. When d=1, all the passengers are isolated their quarters and $\mathcal{R}_e$ describes the disease spread. The daily interactions (contact number) κ_{PP}, κ_{CC}, κ_{CS} as well as the evacuation rate of the severely ill individuals, μ (for COVID-19 only), depend on a function of d. The passenger–crew contact rate, κ_{PC}, passenger to symptomatic passenger contact rate, κ_{PS}, remain the same before and after quarantine. These contact rates would only decrease if the cruise ships adopted a service model similar to that of the quarantined sailors in Guam [15] and provided separate quarters for symptomatic passengers.

The sensitivity of the effective reproduction number, $\mathcal{R}_e$, to each of the parameters is given in Fig. 4 for influenza (a) and COVID-19 (b) at the values after quarantine was imposed.

Once quarantine begins, see Fig. 4(a), the sensitivity of the reproduction number for H1N1 to asymptomatic infections decreases since asymptomatic passengers are now confined to quarters. The sensitivity to decreasing the recovery time in the symptomatic stage, ρ lessens, but increasing the removal of ill passengers and crew from the ship, μ, becomes more important. We see that the need to lessen contact between crew to symptomatic passengers and crew, κ_{CS}, becomes more important in a quarantine situation.

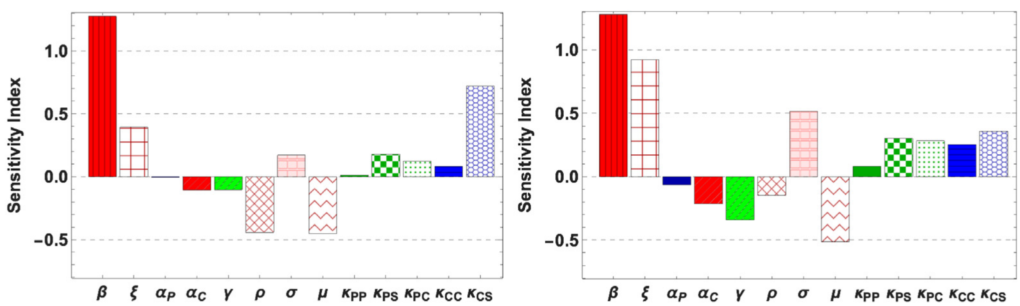
Once quarantine on the ship has been established, the sensitivity of $\mathcal{R}_e$ for COVID-19, see Fig. 4(b), to the number of asymptomatic infections, σ, and the reduction of infectiousness of these asymptomatic



(a) Flu, Before Quarantine

(b) COVID-19, Before Quarantine

Fig. 3. Sensitivity Analysis for reproduction number for (a) influenza and (b) COVID-19 evaluated at the baseline parameter values in Table 4 and pre-quarantine values in Table 3.



(a) Flu, After Quarantine

(b) COVID-19, After Quarantine

Fig. 4. Sensitivity Analysis for the effective reproduction number for (a) influenza and (b) COVID-19 evaluated at the baseline parameter values in Table 4 and quarantine values in Table 3.

infections, ξ, is decreased. The effective reproduction number is insensitive to the contact rate of passenger–passenger interactions, κ_{PP}, once quarantine is in effect. The key to reducing $\mathcal{R}_e$ by parameters currently under our control is increasing the removal of ill passengers and crew from the ship, μ, just as with influenza. The effective reproduction number is less sensitive for COVID-19 as compared to H1N1 to a reduction in the crew to symptomatic passengers and crew contact, κ_{CS}.

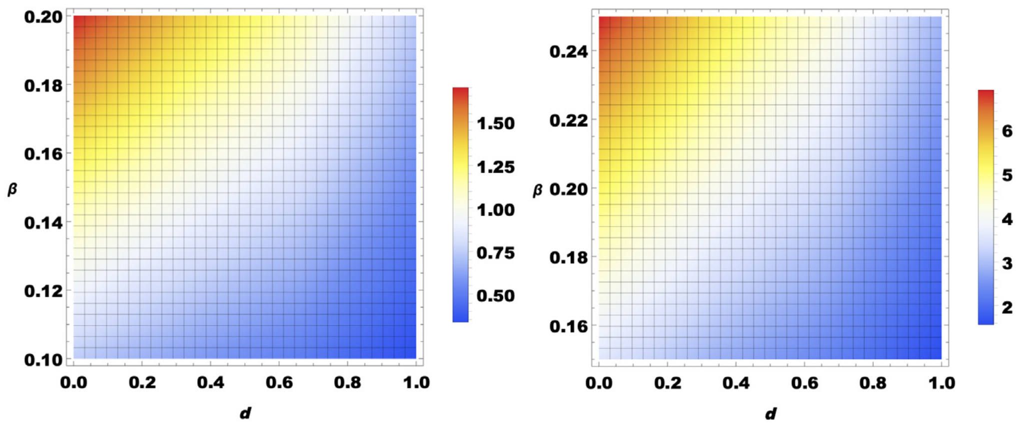
Furthermore, when comparing the case of COVID-19 on the ship to influenza, it is noted that ρ does not have a significant impact on the reproduction number either before or after quarantine. This means that the rate of recovery of symptomatic individuals is not as important to curbing the spread of COVID-19 as identifying the asymptomatic infectious individuals.

The heat maps in Fig. 5 show the dependence of the effective reproduction number, $\mathcal{R}_e$, on the transmission probability, β and quarantine levels given by d. The calculation for the $\mathcal{R}_e$ was run for each combination of β and d values. To allow for a straightforward comparison, we assume that there is no immunity or effective vaccination against the flu, so all persons on the ship are susceptible. Note that influenza and COVID-19 both have their highest $\mathcal{R}_e$ values with high transmission and low quarantine, but the highest COVID-19 $\mathcal{R}_e$ values occur for over a larger range and are far above the values for influenza. Most importantly, we note that at the mean β value for influenza, 0.14, and total passenger quarantine, $d = 1$, the effective reproduction number for influenza is less than 1, indicating that the disease will die out. On the other hand, for COVID-19 at the mean $\beta = 0.208$ value that we calculated, the disease is still spreading when $d = 1$. Also note, that the heat map shows that for $\beta = 0.15$, significantly lower than our estimate, still has a $\mathcal{R}_e > 1$ in the shipboard quarantine conditions. The takeaway is that if a disease with qualities very similar to the H1N1 is on the ship, quarantine could be effective at containing the spread of disease. However, under cruise ship quarantine conditions, the spread of COVID-19 could not be stopped.

3.3. Simulation results for influenza and COVID-19 infections with and without immunity

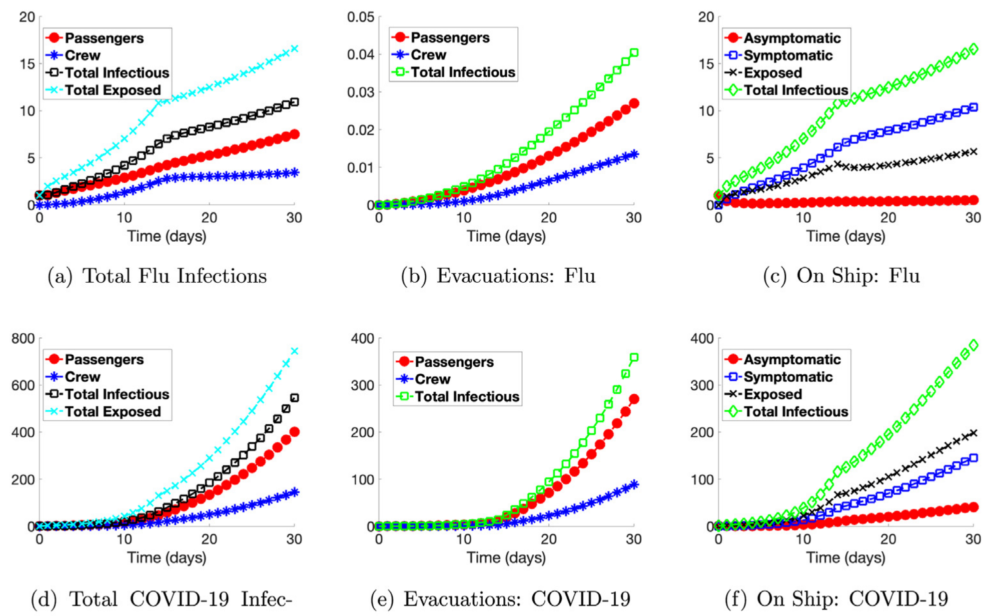
In these simulations, we model a month on a cruise ship, based on the Diamond Princess, with 2666 passengers and 1045 crew members on board. We assume the voyage begins with one asymptomatic passenger and all other crew members and passengers are susceptible (no immunity). The parameter values using these simulations are given in Tables 3 and 4. On day 14 the passengers are isolated in staterooms and the crew reduces contact. The evacuation rate increases after day 14 for COVID-19 infections to capture the procedure on the Diamond Princess.

We simulate the spread of infection for 30 days on board the Diamond Princess cruise ship. In Fig. 6 neither the crew members nor passengers have any immunity to the disease. Fig. 6(a–c) demonstrate the effects of influenza or a disease with parameters similar to influenza (H1N1). Fig. 6(d–f) show the effect of COVID-19 spread. For influenza, once quarantine is established, the exponential growth of the disease spread is stopped and the curve becomes flatter in Fig. 6(a), showing that the quarantine measures: keeping the passengers restricted to quarters and reducing crew interactions are effective, although not sufficient to completely stop disease spread. Noting the vertical axis for Fig. 6(b), we see that no single person has needed to be evacuated for medical reasons. Fig. 6(c) shows that the infectious cases are leveling off and the exposed cases are increasing at a lower rate. In contrast, Fig. 6(d) shows that quarantine measures nearly lower the rate of COVID-19 infection spread, but that the spread is still exponential.



(a) Flu (b) COVID-19

Fig. 5. This figure illustrates $\mathcal{R}_e$ values as a function of β and d. Figure (a) uses influenza parameter values and Figure (b) uses COVID-19 parameter values as listed in Tables 3 and 4. When $d = 0$, all non-symptomatic passengers are free to move about the ship. When $d = 1$, all the passengers are restricted to their quarters. The density shown is $\mathcal{R}_e$. No immunity is assumed to influenza or COVID-19.



(a) Total Flu Infections (b) Evacuations: Flu (c) On Ship: Flu

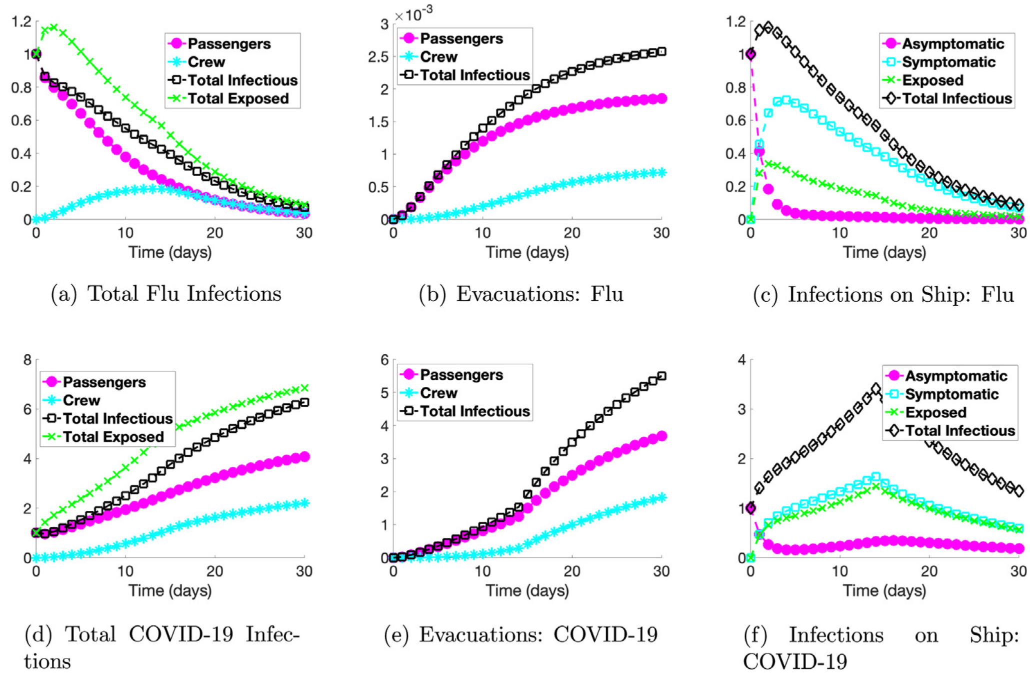
(d) Total COVID-19 Infections (e) Evacuations: COVID-19 (f) On Ship: COVID-19

Fig. 6. Comparison of influenza and COVID-19 infections on the ship **without immunity**: Figures (a–c) are for an infection matching the flu, but without any immunity on the part of the crew or passengers. Figures (d–f) are for COVID-19 infections. Figures (a) and (d) show the total number of infected crew members and passengers. Figures (b) and (e) show the rate of evacuation of individuals with serious infections. Figures (c) and (f) capture the infection type of the all the individuals remaining on the ship.

We also see that about 300 passengers and crew are seriously ill and need to be evacuated before the end of the month in Fig. 6(e). Even with the evacuations there are enough crew and passengers remaining on the ship to continue growing the infection. The asymptomatic, symptomatic, and exposed cases are still continuing to grow in Fig. 6(f). We note that these COVID-19 infections result in large numbers, crew and passengers, of medically necessary evacuations in Fig. 6(f). Clearly, the ship board quarantine measures are not sufficient to check the spread of COVID-19.

Next we ask, could the quarantine on the Diamond Princess worked if some of the passengers and crew members were immune either earned by surviving bouts of illness or from a vaccine? For the brief shipboard time of 30 days, we can assume that all persons boarding the ship with immunity maintained immunity. In this instance, the equations in system (1) describing disease spread remain the same, only the initial conditions are altered. Instead of the total number of crew being susceptible, at $t_0 = 0$, we have $N_C(t_0) = S_C(t_0)$, we have individuals starting in the recovered category, $N_C(t_0) = S_C(t_0) + R_C(t_0)$, similarly with the passengers. The reproduction numbers will be smaller as well as fewer susceptible persons will be on the ship.

We consider the case where 70% of passengers are vaccinated/immune and 50% of the crew are vaccinated/immune. We perform the same simulations as before with results shown in Fig. 7 to see if quarantine would be effective under this condition. In Fig. 7(a)–(c) we model influenza and see that before quarantine, the single H1N1 infected passenger would not successfully spread the disease. For COVID-19, before quarantine the cases have grown to 4 and then afterwards the growth is slowed, but not stopped. However, by evacuating



(a) Total Flu Infections (b) Evacuations: Flu (c) Infections on Ship: Flu

(d) Total COVID-19 Infections (e) Evacuations: COVID-19 (f) Infections on Ship: COVID-19

Fig. 7. Comparison of influenza and COVID-19 infections on the ship **with immunity**: 70% of passengers are vaccinated/immune and 50% of the crew are vaccinated/immune. Figures (a–c) are for an infection matching the flu with immunity. Figures (d–f) are for COVID-19 infections with immunity. Figures (a) and (d) show the total number of infected crew members and passengers. Figures (b) and (e) show the rate of evacuation of individuals with serious infections. Figures (c) and (f) capture the infection type of the all the individuals remaining on the ship.

those seriously ill passengers, the number of infected persons remaining on board the ship declines. While quarantine has not been successful in stopping disease spread, quarantine and evacuations have dampened the spread significantly.

4. Conclusion

As we consider a post-pandemic world, we must think about how we will adjust our usual activities to avoid causing more outbreaks. For a disease such as COVID-19, an on board quarantine with an inability to isolate infectious individuals will not be effective even if most of the shipboard population is vaccinated or immune. However, for a disease outbreak similar to influenza on a cruise ship, even without the majority of the population having immunity, a quarantine could halt the infection spread. The longevity of the infectious period of COVID-19, the timing of the high infectious period, as well as the high number of asymptomatic cases requires nearly complete isolation of all potentially infected individuals, a difficult task on a cruise ship or nursing home.

To minimize infection spread, it would be best to allow said ships to test and send all positive (symptomatic or not) passengers and crew to medical care off-ship and to provide appropriate isolation for the remaining crew and passengers for the quarantine period. If, however, ships are refused disembarkation and forced into quarantine, it is of paramount importance that infection control procedures be put in place to reduce infection. On the Diamond Princess, COVID-19 was still able to spread despite passengers being restricted to their quarters. Crew members for the most part, were not confined to their quarters and likely unintentionally spread the virus through movement between rooms and handling of things such as utensils. Crew members are also regularly in close proximity. These issues are not easy to overcome as these activities are part of the crew member's job description.

The factors that can decrease the reproduction number are dependent on crew contact rates, early awareness of all cases, both symptomatic and asymptomatic, and effective treatment. One way to ensure better quarantine is to do everything possible to minimize the spread of the virus. To determine the extent of the outbreak, accurate testing is necessary. Ships would require additional protective equipment, staff, and test kits delivered to them.

Understandably, governments want to prevent passengers and crew who may be COVID-19 positive from spreading it into their land territories. Although this makes sense for them, it does not mean that by allowing ships to dock, there will be widespread infections on shores of the accepting nation.

Building on this shipboard quarantine study, future mathematical investigations on border screening is the next step to determine whether it is better for a country to allow disembarkation or mandate a shipboard quarantine. While possibly politically beneficial, policies to keep ship passengers and crew disembarking and entering countries may not be effective if implemented in the middle of an outbreak [48]. Previous studies have been done studying border control methods, but mainly examining airports and not by sea. The question remains, will imposing border control methods on disembarking passengers and crew help reduce the overall infection spread in comparison to a shipboard quarantine? Which method minimizes the costs in terms of infections, deaths, and dollars? The timing of border screening is of importance. During the SARS and H1N1 pandemics in 2003 and 2009, respectively, border exit and entry screening was conducted at the wrong time to prevent the spread of such viruses, as countries did not start screening until well into an outbreak [48].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Tables 5–7.

Table 5
COVID-19 test data for Diamond Princess cruise ship for both passengers and crew for February 2020. Each positive test represents a newly diagnosed passenger or crew member.
Source: Data taken from [23].

Date	Persons onboard	New positive tests
5 Feb	3711	10
6 Feb	–	10
7 Feb	–	41
8 Feb	–	3
9 Feb	–	6
10 Feb	–	65
11 Feb	–	–
12 Feb	–	39
13 Feb	–	44
14 Feb	3451	–
15 Feb	–	67
16 Feb	–	70
17 Feb	3183	99
18 Feb	–	88
19 Feb	–	79
20 Feb	–	13

Table 6
Test results for suspected COVID-19 cases in Diamond Princess cruise ship for passengers and crew for February 4–9, 2020.
Source: Data taken from [1].

Date	Passengers Positive/tested	Crew Positive/tested
4–6 Feb	36/148	1/8
7 Feb	1/2	5/50
8 Feb	52/75	5/10
9 Feb	35/54	9/11
Total:	124/279	20/79

Table 7
Number of positive tests for South Korea for the dates February 15–25 and New York for the dates March 9–19.
Source: Seoul data from [35,36] and New York City data from [37].

Date	South Korea Positive tests	Date	New York City Positive tests
15 February	28	9 March	7
16 February	29	10 March	19
17 February	30	11 March	22
18 February	31	12 March	40
19 February	51	13 March	79
20 February	104	14 March	104
21 February	204	15 March	164
22 February	346	16 March	233
23 February	602	17 March	394
24 February	763	18 March	729
25 February	977	19 March	1166

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