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Model-based evaluation of the COVID-19 epidemiological impact on international visitors during Expo 2020

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A B S T R A C T

The impact of the COVID-19 pandemic on large events has been substantial. In this work, an evaluation of the potential impact of international arrivals due to Expo 2020 in terms of potential COVID-19 infections from October 1st, 2021, until the end of April 2022 in the United Arab Emirates is presented. Our simulation results indicate that: (i) the vaccination status of the visitors appears to have a small impact on cases, this is expected as the small numbers of temporary visitors with respect to the total population contribute little to the herd immunity status; and (ii) the number of infected arrivals is the major factor of impact potentially causing a surge in cases countrywide with the subsequent hospitalisations and fatalities. These results indicate that the prevention of infected arrivals should take all precedence priority to mitigate the impact of international visitors with their vaccination status being of less relevance.

1. Introduction

The COVID-19 pandemic has had a huge social and economic impact, including changing the daily life of individuals. It has caused more than 230 million cases and almost five million deaths globally by October 2021 (JHCRC, 2021). The rapid development and deployment of vaccines have been paramount for the prevention of fatalities (Agrawal et al., 2021; Moghadas et al., 2021). Despite widespread vaccination, most developed countries (e.g. Israel, United States, France, Spain, Germany, UK) have suffered steep increases in new cases across successive infection waves from mid-2021 to early 2022

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(Cacciapaglia, Cot, & Sannino, 2021). This seemed to occur due to the waning immunity of the vaccines in combination with the appearance of new SARS-CoV-2 variants such as the delta or the omicron variants (Bar-On et al., 2021; Fowlkes, 2021; Pouwels et al., 2021; Tartof et al., 2021). The existence of new variants of concern over two years suggests the disease probably will not disappear. It appears that COVID-19 will eventually become endemic in many regions throughout the world, especially if vaccines remain distributed unequally (Hyder, Hyder, Nasir, & Ndebele, 2021; Sawal et al., 2021).

The tourism industry has been massively affected by the COVID-19 pandemic (Sigala, 2020). Major international events were either postponed or cancelled, while other major public events occurred under the limitation of attendance in the venues (e.g. Formula 1 races, football games, etc.). The main conundrum that countries face is when and under which interventions (e.g. masks, testing, and/or vaccination), if any, to reopen. The fast transmission of COVID-19, often via superspreader events (Chen, Koopmans, Fisman, & Gu, 2021; Majra, Benson, Pitts, & Stebbing, 2021) poses a challenge, especially if the lift of restrictions appears to be too quick (Han et al., 2020). On the other hand, to ensure economic recovery, countries need to adapt to host mass gathering events such as concerts, international competitions (e.g. World Cup, Olympics), religious gatherings, and large exhibitions (e.g. Congresses, Expo). An essential part of these large events is international travel, which has recovered part of its lost volume in early 2022. International travel pre-COVID levels however are not expected to recover until 2023–2024 (Aviation Intelligence Unit (Eurocontrol) (2022).

Epidemiological models are tools that have been used to evaluate the impact of COVID-19. Several models have been published focusing on (i) the evaluation of interventions against the spread of the COVID-19 disease (Davies et al., 2020; Flaxman et al., 2020; Giordano et al., 2020; Rodríguez, Patón, Uratani, & Acuña, 2021), (ii) the evaluation of the transmission of the COVID-19 disease (Chinazzi et al., 2020; Kucharski et al., 2020) or (iii) the impact of different vaccination strategies to prevent several impacts of COVID-19 (Bubar et al., 2021; Buckner, Chowell, & Springborn, 2021; Jentsch, Anand, & Bauch, 2021; Matrajt, Eaton, Leung, & Brown, 2021; Moghadas et al., 2021). To the best of our knowledge, few works have focused on addressing the impact of people traveling to attend large events.

This paper presents an epidemiological model that has been used to evaluate the impact of international visitors to the United Arab Emirates (UAE) for Expo 2020 on the COVID-19 pandemic. This impact is evaluated in terms of the number of visitors arriving over time as well as the average length of visit, the proportion of infected arrivals, and their vaccination status. The model was used to estimate under which scenarios the impact of visitors for Expo 2020 in terms of COVID-19 infections was low as well as to guide the formulation of mitigation strategies. We foresee this type of model as an important tool to support planning efforts for future large events of international significance, for both COVID-19 and other communicable diseases.

2. Methodology

2.1. Model description

2.1.1. Definition of compartments

A modification of a previous SEIRD model published (Rodríguez, Patón, & Acuña, 2021; Rodríguez, Patón, Uratani, & Acuña, 2021) was implemented to evaluate the impact of visitors traveling into the UAE for Expo 2020. For the full description of the equations used for this model, please refer to the Supplementary Material.

Similarly, to other SEIR models, individuals from the population are allocated to disease severity stage compartments. Those compartments are also subsequently segregated by age, gender, and working group (Fig. 1).

A case study was defined to evaluate the impact of the visitors to the United Arab Emirates (UAE). The population was segregated based on the age distribution from publicly available data (World Bank Data, 2021). This segregation was based on meaningful epidemiological differences, due to the highest mortality observed for COVID-19 for elder people compared to younger people. In addition, behavioural or activity traits per age group in terms of number of contacts with other people groups appears to be substantial (Mossong et al., 2008), which might affect subsequently their risk of infection. Specific groups have been further defined to reflect the characteristics of the UAE population such as a low percentage of national citizens among residents (approximately 10–15%), while the majority of the residents are expatriates that work in the country. Based on their type of community, accommodation, and lifestyle, expatriate workers were classified into two groups, namely white-collar and blue-collar. Those two groups were defined as per the following characteristics:

i) White-collar expatriates: higher-income working individuals accompanied by their resident families and interacting with the community and leisure activities to a large degree.
ii) Blue-collar expatriates: lower-income working individuals not accompanied by their families and typically living in shared accommodations and interacting less with the rest of the community and in leisure activities.

This differentiation was important due to the nature and type of interactions that the two groups have with themselves and the rest of the community. In addition, separate groups for female blue-collar expatriates have been adopted due to their very different living arrangements, many working as domestic helpers and in childcare living within other families. Using the above definitions of expatriate workers and age groups, the group definitions adopted consisted of the following:

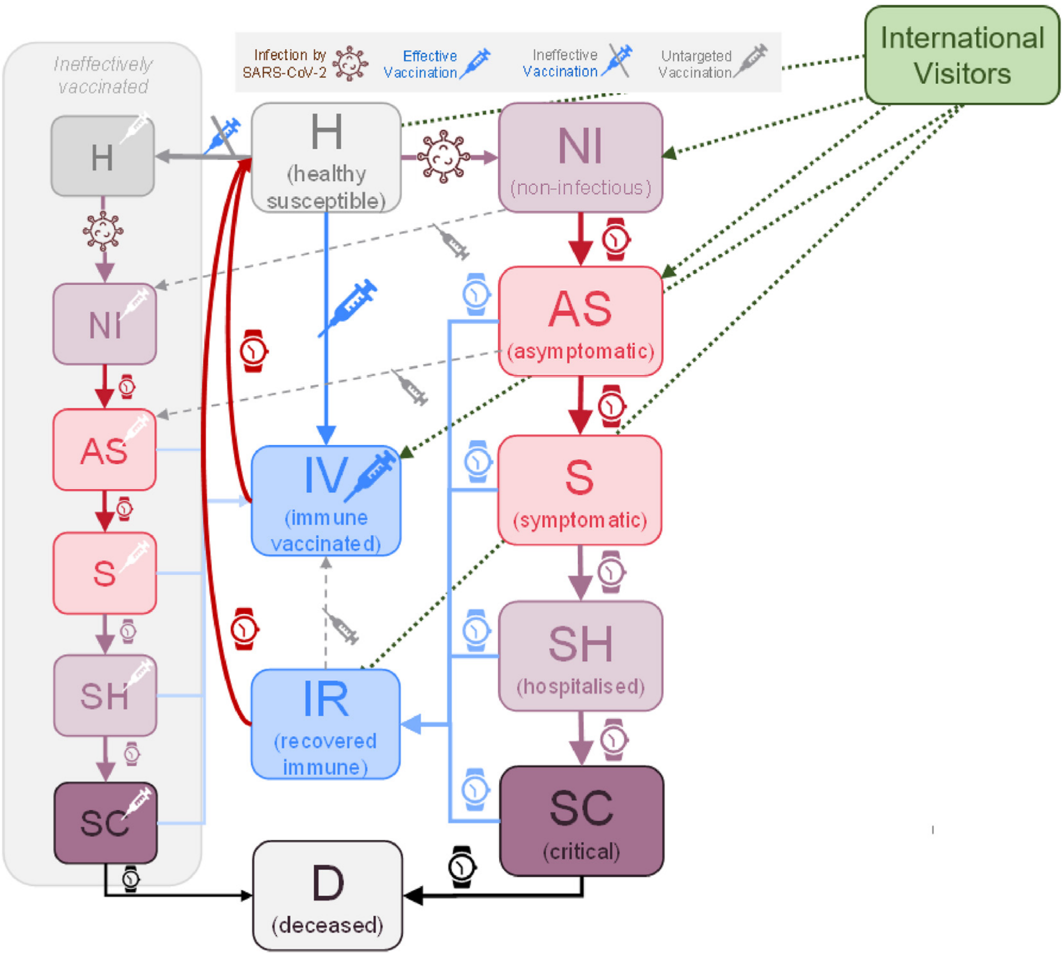

Fig. 1. Schematic representation of the model compartments in terms of infection and disease severity stages. Infection can only occur by contact of healthy susceptible individuals with infectious either asymptomatic or symptomatic individuals (red boxes). Individuals spend in each stage an average amount of time depending on their transition path towards recovery or increased severity. Vaccination, if effective, avoids infection and transmission and places individuals at the immune-vaccinated stage. Ineffective vaccination maintains individuals in their disease stage although accounted separately as already vaccinated. International visitors are allocated (green arrows) to the healthy susceptible, non-infectious, asymptomatic, recovered immune, or immune vaccinated compartment according to their status on arrival as input to the model.

- Preschool children (ages 0–4)
- School children and teenagers (ages 5–19)
- Young workers white-collar (ages 20–49)
- Mature workers white-collar (ages 50–59)
- Senior workers white-collar (ages 60–69)
- Young workers blue-collar male (ages 20–49 male)
- Young workers blue-collar female (ages 20–49 female)
- Mature workers blue-collar (ages 50–59)
- Senior workers blue-collar (ages 60–69)
- Retired (ages 70–79)
- Elderly (ages 80+)

For modelling purposes, individuals never leave the population group to which they belong (Rodríguez, Patón, Uratani, & Acuña, 2021). At a given time throughout the simulation, they sit on and may transition through the different compartments of infection, which correspond to disease severity stages (Fig. 1). These compartments are defined in terms of infectiousness and severity of symptoms as described in our previous model (Rodríguez, Patón, Uratani, & Acuña, 2021), namely: *healthy susceptible* (H); *infected non-symptomatic non-infectious* (NI); *asymptomatic infectious* (AS); *symptomatic infectious* (S); *in need of hospitalisation* (SH); *in need of critical care* (SC); *recovered immune* (R) and *deceased* (D). In addition, those effectively vaccinated become *immune vaccinated* (IV). Individuals ineffectively vaccinated (i.e., the vaccine does not immunise them against infection, severity nor transmission) maintain their current stage and they are simply accounted for separately as already vaccinated (see Fig. 1). Vaccinated individuals are considered those who are fully vaccinated as per the CDC criteria (CDC, 2022).

2.1.2. Modelling the impact of visitors

To evaluate the impact of visitors, the balance equations of the model were modified to allow for the incorporation of visitors over time. The visitors entering the country at any given time were allocated to any of the indicated compartments in Fig. 2 (segregated by age and activity group). As outlined in Fig. 2, only certain individuals that belong to a certain compartment are eligible to travel (either into the country and/or to depart the country). Those compartments are: (i) *healthy susceptible* or individuals that have not been infected nor fully vaccinated; (ii) *non-infectious* or infected people in the incubation period in which the virus is not transmitted; (iii) *asymptomatic* or infected people in the incubation period in which the virus can be transmitted; (iv) *recovered* or people that have overcome the disease but have not been vaccinated or (v) *vaccinated* or people that have received the full complete two doses for the vaccine. *Symptomatic*, *hospitalised*, and *critical* people were considered unable to travel. For simplicity purposes, no visitors were allocated to any of the ineffectively vaccinated compartments. In addition, an important consideration is that no visitors were not assigned to the groups defined as blue-collar individuals.

The total number of visitors at any given time was distributed proportionally (P_i) following these criteria:

- Infected people were allocated into the non-infectious ($P_{inf,ni}$, Eq. (1)) and the asymptomatic ($P_{inf,as}$, Eq. (2)) compartments based on their transition times from each stage onto the next disease or severity stage (non-infectious to asymptomatic and asymptomatic to symptomatic).
- The proportion of people vaccinated and immune ($P_{Vis,Imm}$, Eq. (3)) was estimated as the product of the proportion of people vaccinated and the estimated vaccine effectiveness.
- The proportion of visitors recovered and not vaccinated ($P_{Vis,\ RecUnvac}$, Eq. (4)) was calculated as the percentage of people that recovered ($P_{Recovered}$, based on an estimated seroprevalence for visitors of 20% obtained from (Arora et al., 2021) and based on previous seroprevalence studies) multiplied by the proportion of people not vaccinated according to the defined vaccination coverage.
- The proportion of visitors allocated to the healthy susceptible compartment ($P_{Vis,h}$, Eq. (5)) was then calculated by difference from the rest of the proportions calculated.

$$P_{Inf,ni} = t_{as,ni} \cdot \Big/ \left(t_{as,ni} + t_{s,as}\right) \tag{Eq. 1}$$

$$P_{Inf,as} = t_{s,as} \cdot \Big/ \left(t_{as,ni} + t_{s,as}\right) \tag{Eq. 2}$$

$$P_{Vis,Imm} = vacCov \cdot vacEff \tag{Eq. 3}$$

$$P_{Vis,RecUnvac} = (1 - vacCov) \cdot P_{Recovered} \tag{Eq. 4}$$

$$P_{Vis,h} = 1 - P_{Vis,Inf} - P_{Vis,Imm} - P_{Vis,RecUnvac} \tag{Eq. 5}$$

Once the proportion for each compartment for the visitors has been calculated, the balance of each compartment was updated. The addition of the visitors in the compartment is made by adding a rate of arrival and a rate of departure for each of the eligible compartments.

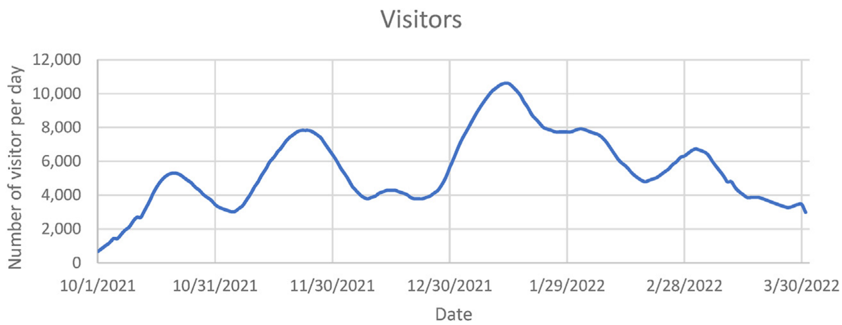

Fig. 2. Estimated number of visitor arrivals per day into the country.

A profile of visitors expected to visit the UAE for the duration of the Expo 2020 (October 2021–March 2022) was projected as depicted in Fig. 2. The rate of departure (r_{Dep}) is equal to the rate of arrival (r_{Arr}) 10 days prior (e.g. the rate of departure on October 11th corresponds to the rate of arrival on October 1st). The visitors are incorporated into the balance equations of the compartments (see Supplementary Material). Fig. 2 shows the example profile for visitor arrivals used.

The total number of visitors shown in Fig. 2 is based on a total of 1 million visitors. Different scenarios for a total number of visitors were evaluated by applying a multiplier to match the expected total amount of visitors.

Visitors were incorporated into each age group following the age distribution of the world population (see Supplementary Material). In addition, visitors were allocated to the white-collar age group for those age groups in which segregation for the working category was defined (e.g. 20–49).

2.2. Model assumptions

The baseline scenario was selected with the following initial conditions and assumptions. All parameter values are based on current COVID-19 surveillance data and scientific knowledge. For the full list of parameters used and their sources, please refer to the supplementary material.

- A total population of 10 million was considered.
- An initial percentage of 80% of the population was assumed to be vaccinated. From these, 55% were assumed to be effectively vaccinated and therefore fully immunised. This was applied both to the population of the country and to the visitors.
- The initial number of recovered individuals (R) was set at 20% of the population. This estimation was based on the results from the seroprevalence study in the UAE (Alsuwaidi et al., 2021).
- The initial 14-day incidence rate was set at 150 active cases per 100,000 population. These number of cases were distributed into different compartments (between non-infectious (NI), asymptomatic (AS), and symptomatic (S)) based on the proportion of transition per age group and the transition times.
- All other individuals were initially considered as healthy susceptible (H).

To evaluate the impact of visitors traveling to a large event, the following assumptions were considered:

- The age-group segregation for visitors was set as per the world age-group distribution.
- Vaccination coverage for visitors (proportion of visitors that are vaccinated). This parameter is then corrected to account for the vaccine effectiveness (Eq. (3)) to calculate the number of immune-vaccinated visitors. Three values of vaccine coverage were used:
  - o 50% vaccine coverage (equivalent to 27.5% visitors immune)
  - o 100% vaccine coverage (equivalent to 55% visitors immune)
  - o 0% vaccine coverage (equivalent to 0% visitors immune)
- The total number of visitors into the country for the six months of Expo 2020 was set at:
  - o 2 million
  - o 7 million
  - o 15 million
- Percentage of people infected entering the country: a range from 0 to 5% was evaluated.
- Two different scenarios for variants were evaluated:
  - o Scenario A: No new variant develops over the next three months.
    Scenario B: A new variant resistant to vaccines was considered to emerge on December 1st, 2021. This variant was considered to decrease the immunity of the vaccinated and recovered individuals by 50% and became predominant in three weeks.

3. Results and discussion

In this section, the results of the simulations described in the methodology section are presented. All simulations conducted were evaluated in terms of:

- Number of new daily cases
- Number of people hospitalised (total beds occupied per day including both acute and critical beds)
- Number of people in critical beds (total critical beds occupied per day)
- Total number of fatalities (cumulative)

3.1. Scenario A: No new emerging variant

The simulations evaluated the two scenarios for variants described in the methodology section (Scenario A without a new variant and Scenario B with a new emerging variant). As described in the model assumptions section, simulations were run for three scenarios of total visitors into de country and three vaccination coverage for the visitors. For each one of the 9 possible combinations, a range of visitors infected was evaluated.Scenario A: No new emerging variant.

The results in terms of new cases, hospitalised, critical beds, and deaths when there is no new emerging variant are shown in Fig. 3:

Fig. 3 shows that the new daily cases increase proportionally to the number of visitors to the country. In particular, the peaks of new daily cases are much higher proportionally for the scenarios with a large proportion of infected arrivals. The results clearly show the very important impact of infected arrivals to the country, triggering a lot of new cases within the country.

The vaccination status of the individuals entering the country did however show none to negligible impact on the total number of cases per day (data shown in Supplementary Material). This is expected but numerically shown here as the small proportion of visitors has a small impact on the herd immunity due to their numbers in comparison to the population already in the country, irrespective of their vaccination and immunity status. Therefore, it is expected to see similar dynamics of the pandemic in a population of 10 million or in a population of 10.5 million (assuming that other factors remain constant for the

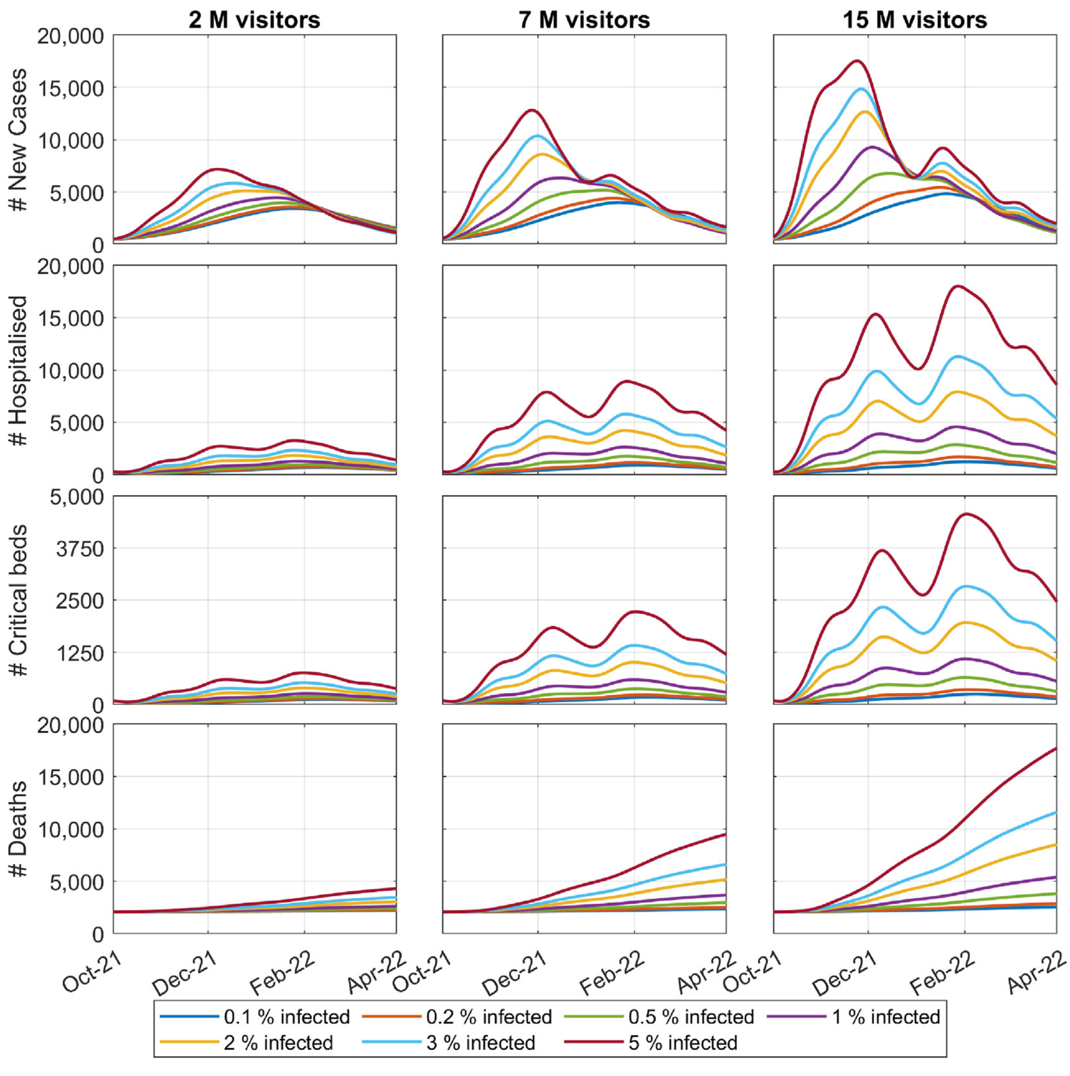

Fig. 3. New daily cases for a different number of total visitors, the proportion of vaccinated visitors at different proportions of visitors infected. Under this scenario, no new variant emerges throughout the whole simulation.

same time). As described in other works, the impact of vaccination is indeed relevant in proportion to the entire population within the country (Bubar et al., 2021; Buckner et al., 2021; Hogan et al., 2021; Matrajt et al., 2021; Moghadas et al., 2021).

In terms of new hospitalisations in Fig. 3, the peaks are higher in the scenarios in which visitors come with a high proportion of people infected. Analogously to new cases and hospitalisations, the number of people in critical beds and the total fatalities increase with the infection proportion of the visitors. In addition, the number of deaths increases significantly with the number of visitors, particularly with higher proportions of visitors infected.

3.2. Scenario B: New emerging variant mildly resistant to vaccines

The results in terms of new cases, hospitalised, critical beds, and deaths under the scenario of a new variant emerging on November 19th are shown in Fig. 4.

Fig. 4 shows a similar trend for the new daily cases in comparison to the scenario without an emerging variant. The peaks are substantially higher, however, both at a high number of visitors (circa 20,000 vs. circa 5000 new daily cases (Fig. 3) with 5% visitors infected in early January) and at a low number of visitors (circa 11,000 vs. circa 5000 new daily cases (Fig. 3) with 5% visitors infected).

As observed in the number of cases per day, the number of hospitalised people also increases with the new emerging variant on November 19th (circa 20,000 hospitalised people with the new variant vs. circa 18,000 hospitalised without a new emerging variant). As expected, the higher the number of new cases, the more people will be eventually hospitalised.

The impact on critical beds (circa 5000 new cases vs. circa 4,00 new cases with 5% visitors infected) and deaths (~17,000 for the worst-case scenario with and without variant) appears to be lower than for hospitalisations and new cases. This is due to

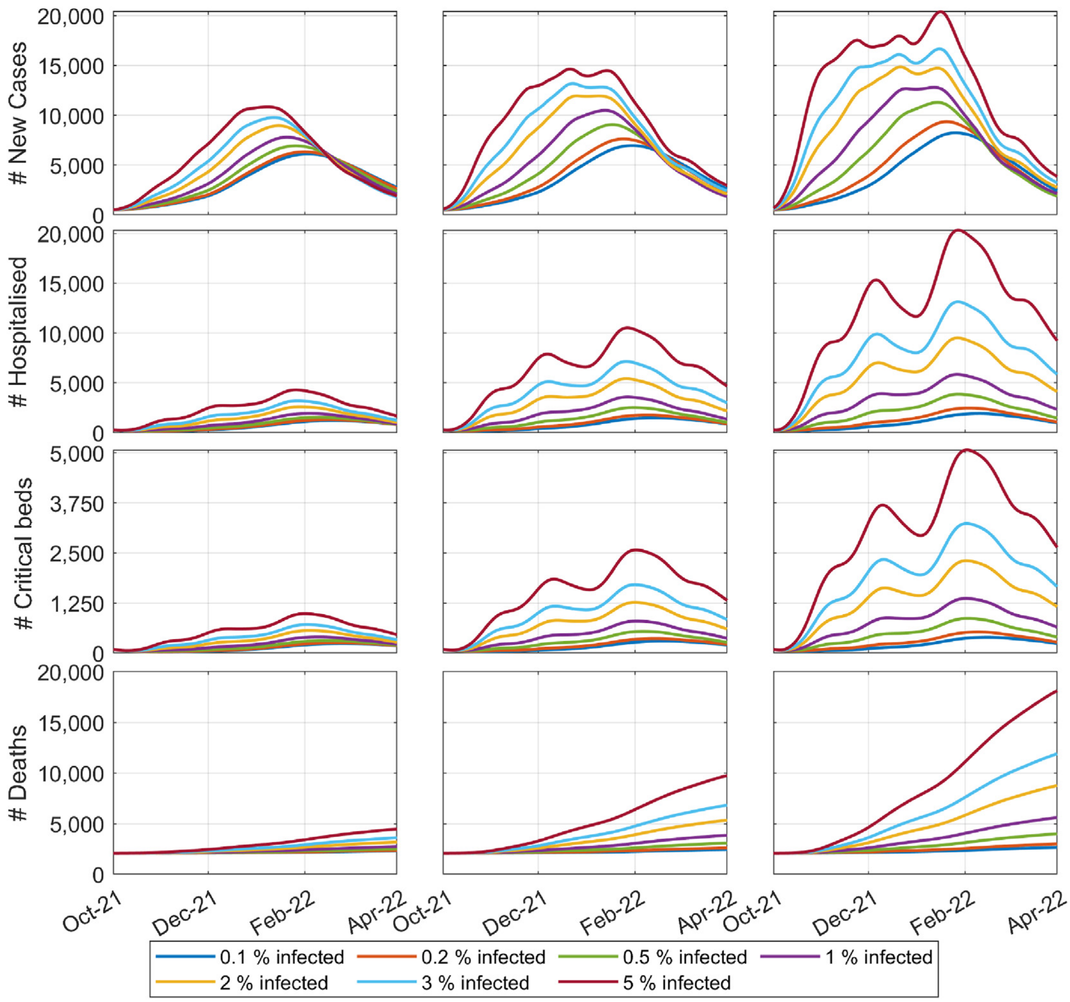

Fig. 4. New daily cases for a different number of total visitors, the proportion of vaccinated visitors at different proportions of visitors infected. Under this scenario, a new variant emerges on November 19th.

the same reason for the impact on hospitalised people being lower than for the number of new daily cases: a lower proportion of people hospitalised transitions into critical care and eventually to death.

4. Conclusions

The use of mathematical models can provide new, useful insights for public health response as the COVID-19 pandemic evolves and more data becomes available regarding the factors that affect outbreak dynamics. The following conclusions can be extracted from the simulations:

The proportion of infected visitors has a major impact on the evolution of the pandemic. A high number of infected visitors appears to increase substantially the number of cases (and subsequently hospitalised, critical care, and deaths).

The vaccination status of the visitors appears to be of negligible impact in comparison to the number of infected arrivals. This is expected as the visitors account for a low proportion of the people in the country. The vaccination status of the country receiving visitors is what is most important in terms of its resilience when receiving international visitors.

A new variant appearing can potentially result in a high number of cases. However, if the mortality rate of the new variant does not increase, a major impact in terms of fatalities or people in critical beds is not expected.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2022.08.003.

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