Update #8 as of March 14, 2022

Modelling the fifth wave of COVID-19 in Hong Kong

D^{2}4H@HKSTP and HKU WHO Collaborating Centre on Infectious Disease Epidemiology and Modelling

Version 1: September 18, 2021 (assuming a Delta wave)
Version 2: January 6, 2022
Version 3: February 10, 2022
Version 4: February 21, 2022
Version 5: February 28, 2022
Version 6: March 5, 2022
Version 7: March 7, 2022
Version 8: March 14, 2022

Findings Highlights

Situational awareness:

The fifth wave has peaked on March 4 (same as previous updates). The number of people already infected by March 14 is estimated to be around 3.6 million (CrI: 2.3 – 4.6 million). Assuming no change in public health and social measures nor population behaviour and mixing, we anticipate that the number of infections, thus reported cases, will start dropping more significantly towards the end of March. The number of daily infections is expected to fall below 1,000 by end April and to below 100 by mid May.

We predict the final size of the fifth wave to be around 4.5 million (CrI: 4.2 – 4.8) infections and 5,102 (CrI: 4,337 – 5,954) deaths.

Of import, we are beginning to detect a slight uptick in population mobility, as indicated by the Octopus index this past weekend. (Figure 3). This could well portend a fundamental change in transmission dynamics that would render our assumptions inaccurate, thus underestimating the forward burden of the fifth wave.

In this 8th update, we have further adjusted the nowcast/forecast model, as follows:

1) From the data of 37 deaths with dates of symptom onset, we estimate that the onset-to-death interval is 8.0 days (95% CrI: 4.4 – 18.5) among seniors aged 70 or above who are living in the RCHEs and 10.5 days (95% CrI: 5.3 – 16.8) among seniors of the same age groups in general.
2) We have revised the assumption about the population size of RCHE residents: we previously assumed that 59,000 seniors aged 65 or above reside in RCHEs (https://www.lwb.gov.hk/tc/blog/post_05092021.html). We have now revised it to 74,678 seniors from all age groups according to the latest available data (https://www.swd.gov.hk/en/index/site_pubsvc/page_elderly/sub_residentia/id_overviewon/).
3) Our model also accounts for the increased risk of infection and mortality among residents of RCHEs: as of March 11, 91% of RCHEs have reported outbreaks, 31% of residents have been

confirmed with infections, and deaths reported from RCHEs are 58.9% of the total number of deaths in this wave.

4) We assume 90% of the RCHE residents would receive at least one dose of vaccine by March 18 and 90% of the RCHE residents would receive Sinovac vaccine as the first dose after March 4.
5) Two novel antiviral drugs, Molnupiravir and Paxlovid, have become available beginning the weeks of March 7 – 13 and March 14 – 20 respectively. They are expected to reduce hospitalisations and deaths by 30% and 89% respectively, if administered early after symptom onset or first test positivity. We optimistically assume the stated antiviral efficacies are the same for both unvaccinated and vaccinated patients (ie multiplicative with vaccine protection). However, the clinical trials of both antivirals were conducted among unvaccinated patients only, and their efficacy among vaccinees should be closely monitored.
6) The number of acute hospital beds for COVID patients in HA hospitals are increased to 25% of the total number of beds by March 14 and 50% by the end of March (https://news.rthk.hk/rthk/ch/component/k2/1638811-20220314.htm).

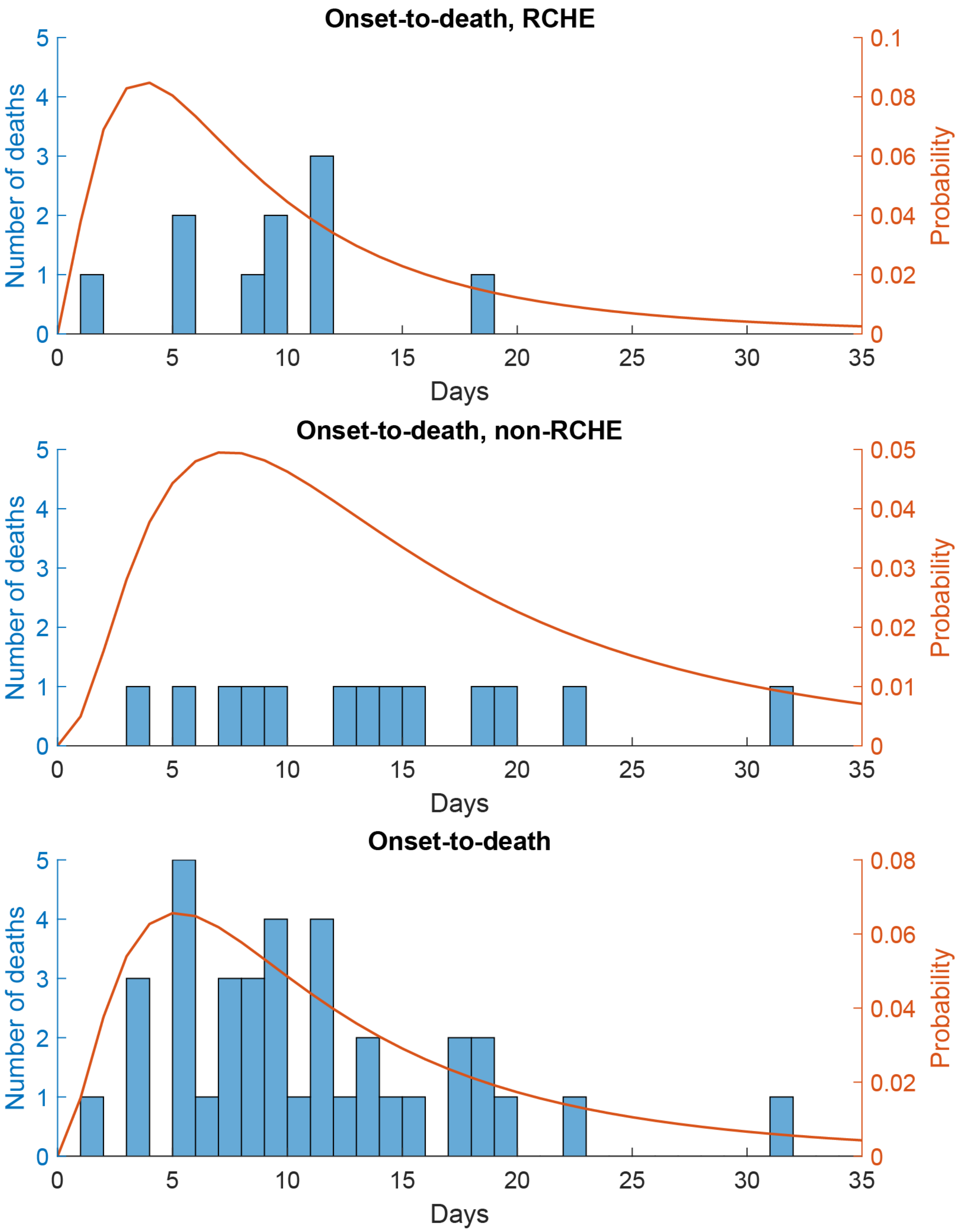


Figure 1. The onset-to-death intervals of RCHE deaths (N = 10), non-RCHE deaths (N = 13) and deaths with dates of symptom onset (N = 37) reported by March 8. Assuming the onset-to-death intervals are lognormal distributed, we estimate that the onset-to-death intervals are 8.0 days (SD 2.2) among RCHE deaths, 14.1 days (SD 2.1) among non-RCHE deaths, and 10.5 days (SD 2.2) among all deaths with dates of symptom onset. Given the small number of observed onset-to-death intervals among RCHE deaths, alternatively we estimate the mean onset-to-death interval is 7.9 days, considering that 58.6% of all deaths were from RCHE (i.e., (10.5-(1-0.586)*14.1)/0.586 = 7.9).

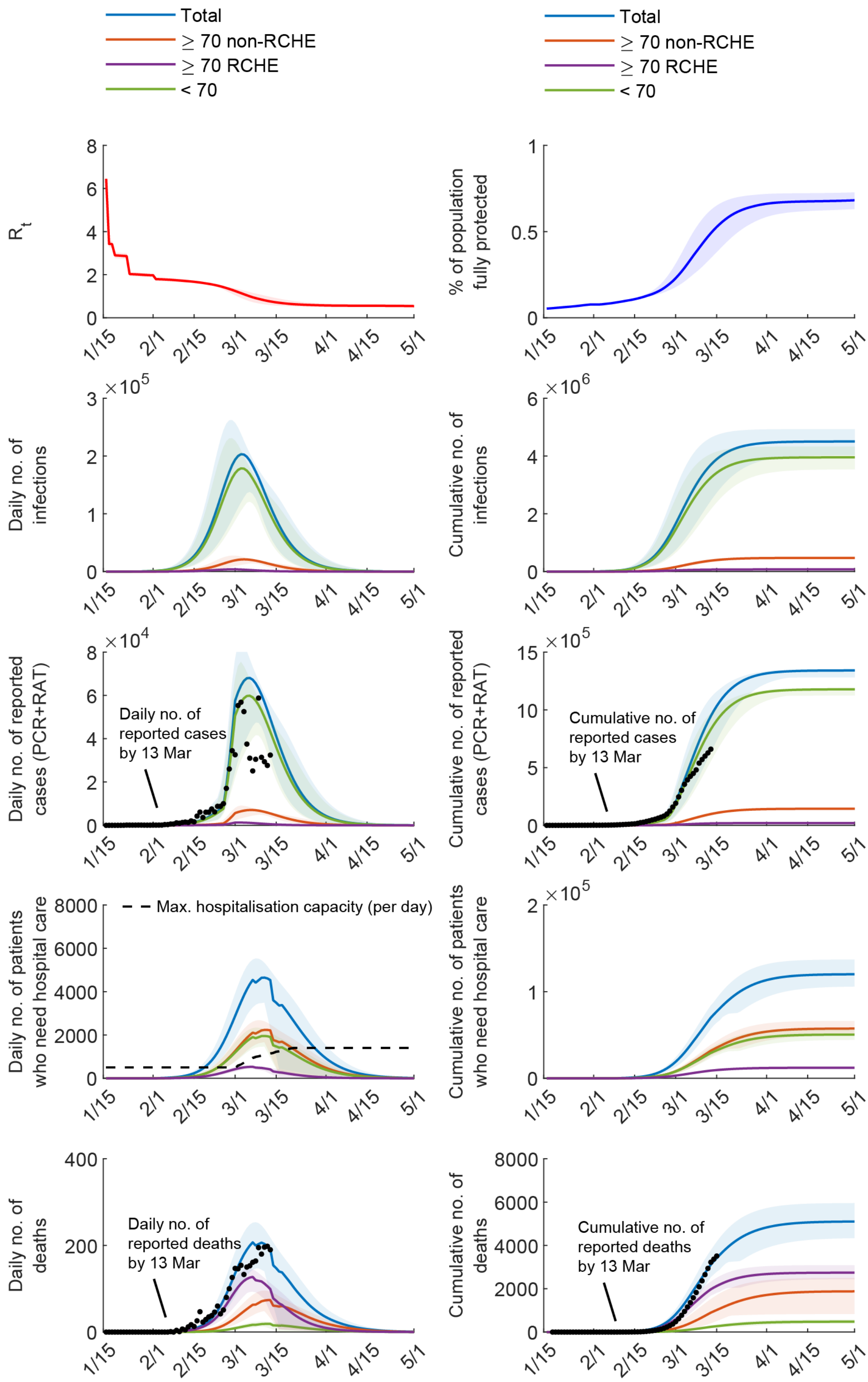


Figure 2. Daily and cumulative number of infections, reported cases, hospitalizations, and deaths, under interventions at status quo. The estimated cumulative number of deaths by May 1 is 5,102 (4,337 – 5,954). We assume the onset-to-death interval for RCHE and non-RCHE deaths are 8.0 days (SD 2.2) and 10.5 days (SD 2.2), respectively.

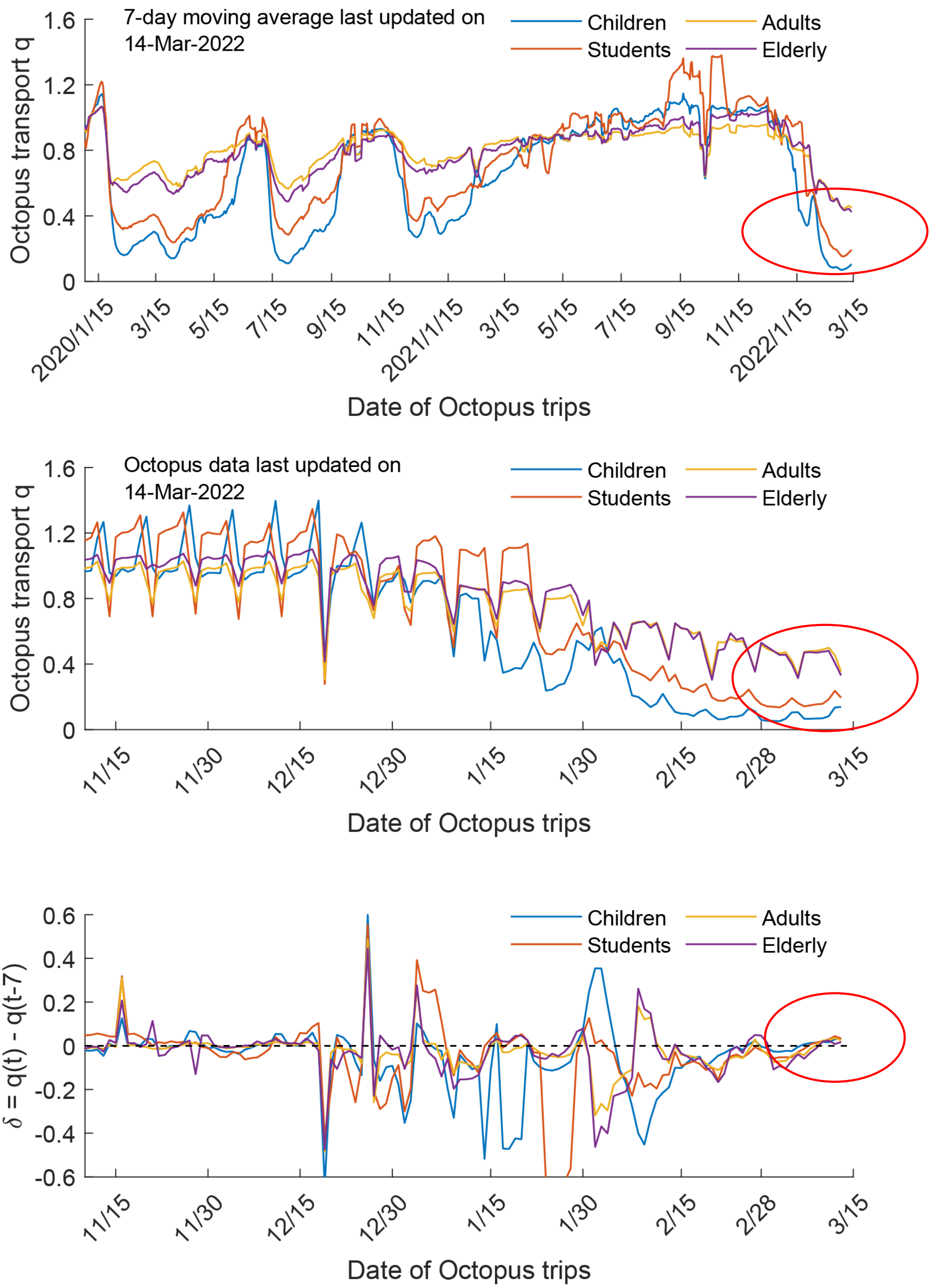


Figure 3. Mobility trends indicated by usage of Octopus cards in public transportation. (A) Seven-day moving average of the usage of Octopus cards by card types (i.e. children, students, adults and elders) since 1 January 2020. We assume the mobility levels are 100% on 1 January 2020. (B) The usage of Octopus cards since November 2021. (C) The difference in usage of Octopus cards compared with seven days ago. We detect a slight uptick in population mobility, as indicated by the Octopus card usage this past weekend (i.e., circled in red).

Update #7 as of March 7, 2022

Modelling the fifth wave of COVID-19 in Hong Kong

D^{2}4H@HKSTP and HKU WHO Collaborating Centre on Infectious Disease Epidemiology and Modelling

Version 1: September 18, 2021 (assuming a Delta wave)
Version 2: January 6, 2022
Version 3: February 10, 2022
Version 4: February 21, 2022
Version 5: February 28, 2022
Version 6: March 5, 2022
Version 7: March 7, 2022

Findings Highlights

We further assess the different impacts of scaling up the number of available inpatient acute care beds. Specifically, we assume that the number of Tier 1 (negative pressure ICU beds) and Tier 2 (acute medical ward) beds could be increased over 7 to 21 days to 20%, 25%, 30%, 50% of hospital beds operated by Hospital Authority hospitals, or to the "ideal" level of 25,000 beds that would be able to accommodate all needy patients at the peak of the fifth wave (Figure 1). We also assume that infection fatality risks (IFRs) track the number of patients who require hospital care: IFRs would increase by 10%, 20%, 30%, 40% and 50% when need outstrips supply of available beds by a ratio of 1-2, 2-3, 3-4, 4-5 and >5 to 1.

Table 1 shows that if the number of Tier 1 and Tier 2 beds were to reach 115 and 6,932 by March 7, the total number of deaths would decrease from 5,008 to 4,292; if the number of beds further increase to 115 and 11,555 by the same date, the total number of deaths would total 3,989; in the ideal case, if the number of beds were to reach 115 and 25,000, the total number of deaths would substantially come down to 3,702, which is a 25% reduction compared with status quo. With the rapid evolution of the fifth wave, the faster the increase of hospital beds (necessarily with the associated medical and nursing personnel), the more lives that could be saved. . If these modelled capacity expansions of could be achieved by March 7 instead of March 21, 3.5-6.0% more COVID-19 related deaths could be averted.

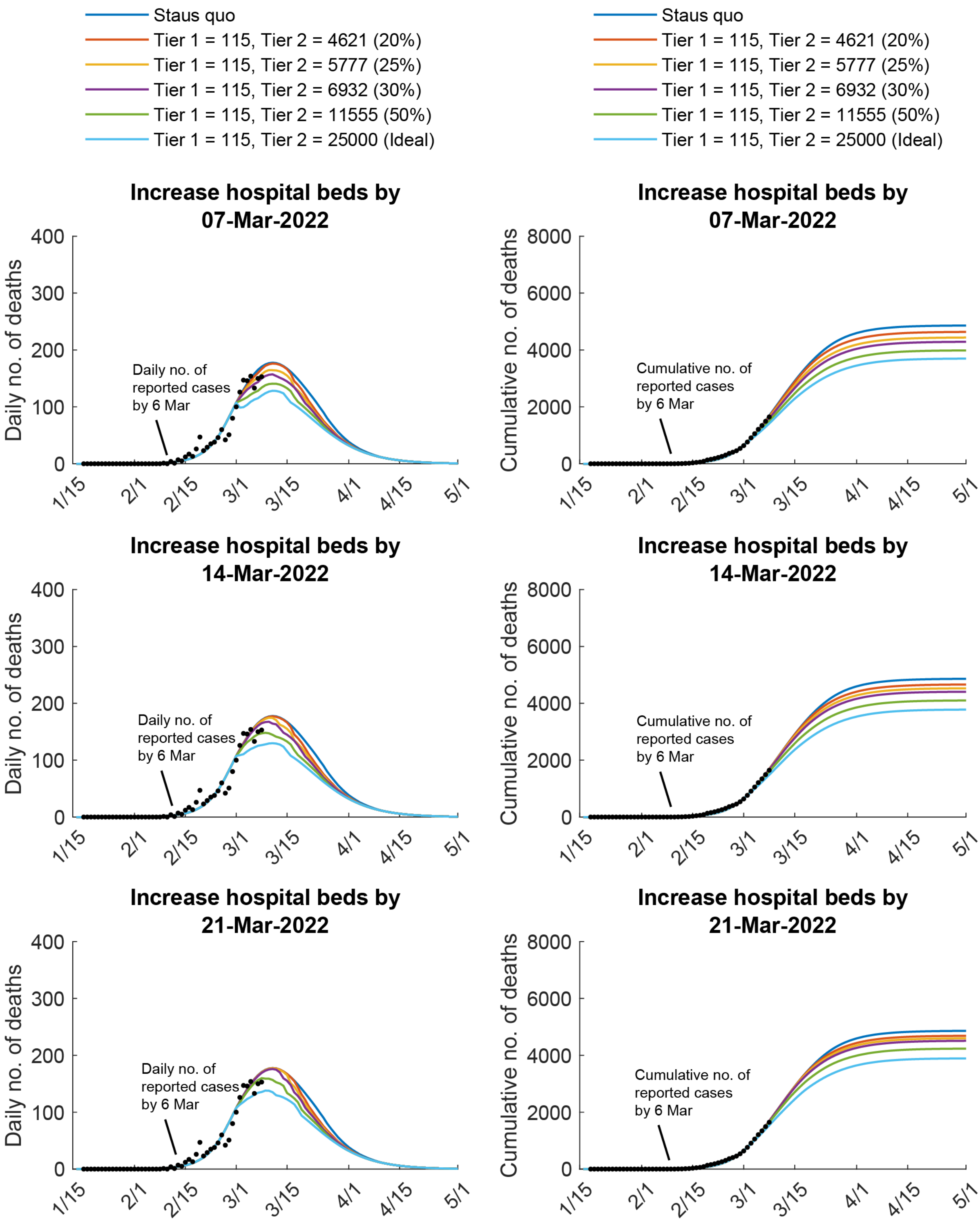


Figure 1. Scaling up the number of Tier 1 and Tier 2 hospital beds rapidly would reduce mortality. The estimated number of deaths by May 1 under status quo is 5,008. See Table 1 for the estimated number of deaths by May 1 by hospital capacities and rates of scaling up. We assume hospital capacity is scaled up linearly between March 1 and the specified date to 20%, 25%, 30%, 50% of hospital beds in public hospitals managed by Hospital Authority, or to an ideal level of 25,000 beds. Confidence intervals are not shown for easier comparison.

Table 1. **Estimated number of deaths by May 1 by hospital capacities and rates of scaling up**

Increase beds by	Tier 1 = 115 Tier 2 = 4,621	Tier 1 = 115 Tier 2 = 5,777	Tier 1 = 115 Tier 2 = 6,932	Tier 1 = 115 Tier 2 = 11,555	Tier 1 = 115 Tier 2 = 25,000
Mar 7	4,640	4,442	4,292	3,989	3,702
Mar 14	4,665	4,531	4,411	4,104	3,782
Mar 21	4,691	4,601	4,514	4,239	3,896

Update #6 as of March 5, 2022

Modelling the fifth wave of COVID-19 in Hong Kong

D^{2}4H@HKSTP and HKU WHO Collaborating Centre on Infectious Disease Epidemiology and Modelling

Version 1: September 18, 2021 (assuming a Delta wave)
Version 2: January 6, 2022
Version 3: February 10, 2022
Version 4: February 21, 2022
Version 5: February 28, 2022
Version 6: March 5, 2022

Findings Highlights

1. If there are no changes in transmission dynamics and interventions for the rest of the fifth wave, the estimated cumulative number of COVID-19 deaths by May 1 is 5,008 (4,491 - 5,430).
2. Given the overriding priority to minimise serious morbidity and mortality at this current stage of the fifth wave when community transmission is already widespread, we modelled 4 plausible interventions and their combinations:
    a. Scaling up the number of available public hospital acute care beds to achieve more optimal patient outcomes;
    b. Widely deploying novel antivirals (ie Paxlovid and/or Molnupiravir) in all high-risk patients (eg institutionalised elderly and disabled persons, 70+ age group, those immunocompromised);
    c. Rapidly increasing vaccine coverage in residents of resident care homes for elderly (RCHEs);
    d. Imposing further public health and social measures (PHSMs).
3. Although increasing the number of hospital beds and associated health care workers (eg via integrative resource allocation among HA, leveraging private hospitals resources and various other temporary treatment and isolation facilities; more effective triage; shortening of bed turnover time) can reduce mortality, the impact is likely to be limited in the near term unless the current demand-supply ratio (which exceeds 10) can be substantially lowered within the coming week. As such, increasing hospital surge capacity alone will only have a limited effect on deaths (<6% reduction).
4. Paxlovid and Molnupiravir have been shown to reduce the risk of hospitalization and death among high-risk groups by 90% and 30%, respectively, if these novel antivirals are administered soon after symptom onset. We found that wide deployment of antivirals could immediately and substantially reduce the number of new COVID-19 hospitalizations and deaths (8-25% reduction depending on delivery schedules of the antivirals, with the additional indirect benefit of improved outcomes through reducing the burden on hospital surge capacity).
5. Although vaccination remains the most effective mid- to long-term strategy for reducing COVID-19 hospitalizations and deaths, the short-term impact of ramping up coverage on mortality would be relatively modest (<5% reduction), because it takes at least 2 weeks to mount an adequate

serological and cell-mediated immune response after inoculation. Nonetheless, expeditious vaccination of high-risk groups, especially those in RCHEs, remains a top priority because building population immunity is a pre-requisite for resurgence prevention and reopening as PHSMs are progressively lifted towards the end of the fifth wave.

6. Further restricting social mixing and mobility (eg limiting frequency of grocery and daily supplies shopping to once a week, imposing across-the-board WFH arrangements except for those in critical sectors, no in-person dining throughout the day, banning cross-district/neighbourhood movements etc) may "flatten the curve" somewhat, thus allowing the surge capacity of hospitals to better cope with patient inflow. However, the exact choice of specific PHSMs should take reference from mobility patterns as indicated by the Octopus card index in terms of target age groups and their daily activities.
7. Therefore, the imminent imperative of saving lives could best be achieved by simultaneously implementing combinations of at least three of the four strategies modelled, i.e. expanding hospital care capacities, reducing the risk of severe diseases among high-risk cases with novel antivirals, and ramping up durable immunity among high-risk groups with vaccines (29% reduction in overall COVID-19 mortality).
8. Current PHSMs (Level 4) have reduced social mixing by 71% compared to pre-5th-wave baseline level. If further measures can enhance the reduction to 80%, daily hospitalization and deaths will be reduced by around 30% after around one week. This effect will only last as long as the additional measures remain in place, with a latency fadeout of again around one week. Simultaneous implementation of the previous three strategies and 14-day lockdown would reduce overall COVID-19 mortality by 33%.
9. If PSHMs drift from level 4 to 2 shortly after the peak (due to pandemic fatigue or premature relaxation), transmissibility is expected to increase by 55% at that point, hence substantial resurgence of cases and deaths would again ensue. As such, PSHMs should not be lifted until at least 95% of high-risk groups have received two or three doses of vaccination.

Methodological revisions

In this 6th update, we have adjusted the methods of our nowcast/forecast as follows:

1. Given the over-representation of cases from RCHEs in the death count, we extended our model to explicitly simulate the number of RCHEs that have reported confirmed cases of COVID-19 during the fifth wave. The data stream for this extension is provided by CHP (Figure S1). Briefly, around 59,000 individuals aged 70 years or above reside in 1,055 RCHEs. In the absence of more granular data at the moment, we assumed that all RCHEs have the same number of residents. Let $I(t)$ be community prevalence and $x(t)$ be the number of RCHEs that have had no outbreaks up to time *t*. We assumed that the hazard rate of reporting a first case in an RCHE is proportional to the community prevalence, i.e $x(t) = x(0)\exp\left(-\alpha \int_0^t I(u)du\right)$ where α is a scaling parameter subject to model calibration. Let $y_t = x(t) - x(t+1)$ be the daily number of RCHEs with new outbreaks. We used an ordinary SIR model, in which the within-facility basic reproductive number is R_0^{RCHE}, to simulate the number of deaths in an RCHE outbreak. Let d_u be the cumulative number of deaths in an RCHE *u* days after an outbreak has begun (using RCHE-specific onset-to-death interval). The number of deaths from all RCHEs on day *t* is therefore $D_t = \sum_{u=1}^{t} y_{t-u} d_u$. We included y_t and D_t as targets for model calibration by inferring α and R_0^{RCHE} .

2. We included the daily viral load detected in sewage surveillance (operated by the Enivornmental Protection Department) over the course of the 5th wave (i.e. since mid-January) in our model calibration. See Figure S2 for this data stream.
3. We have initiated a weekly population-level prevalence survey with rapid antigen tests (RAT). In our first round of survey, 27 of 298 subjects were RAT-positive on 3-4 March 2022 which corresponds to an an age-standardised positivity rate of around 9% (6%-13%). We included the data from this prevalence survey in our model calibration.

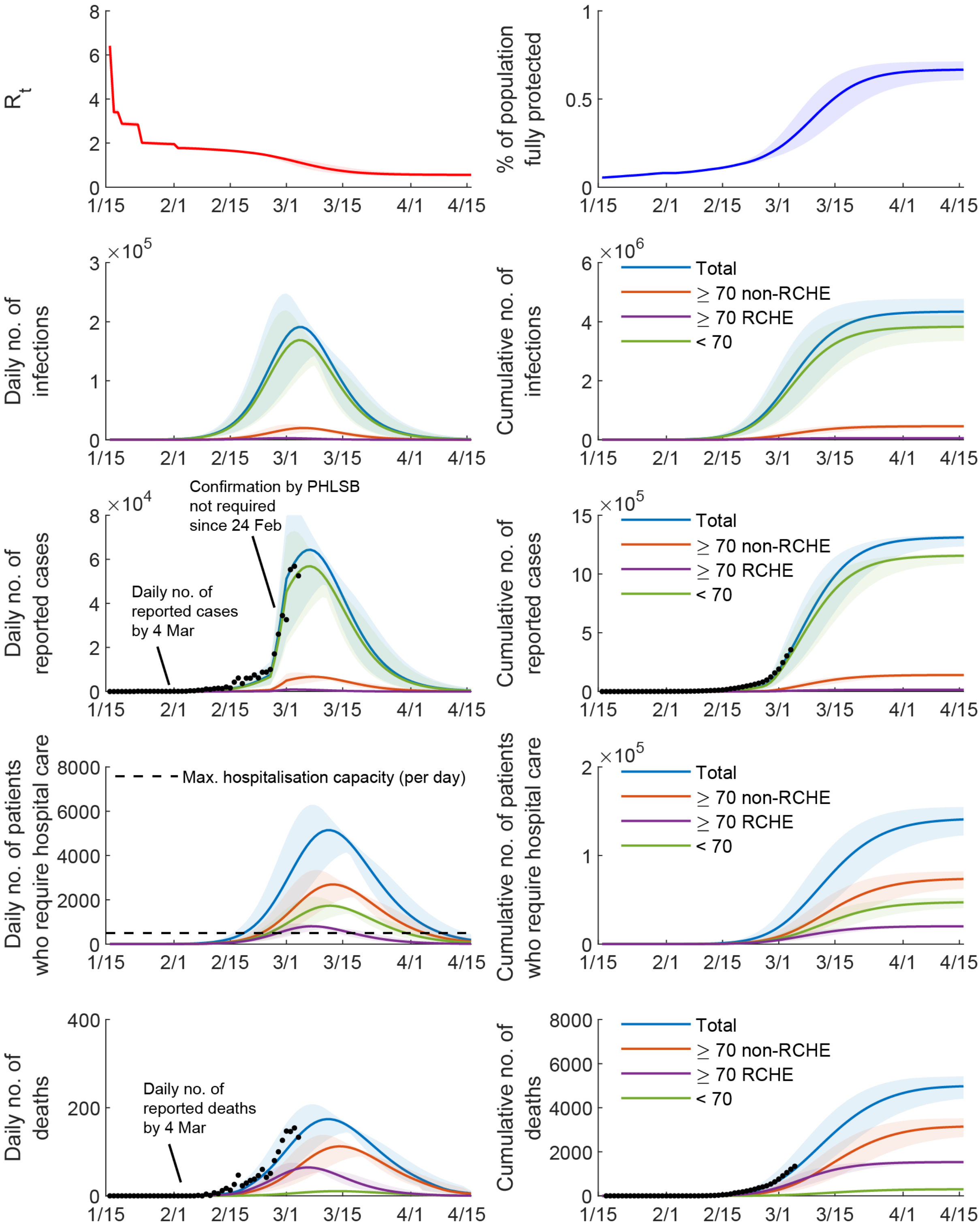


Figure 1. Daily and cumulative number of infections, reported cases, hospitalizations, and deaths, under interventions at status quo. The estimated cumulative number of deaths by May 1 is 5,008 (4,491 - 5,430).

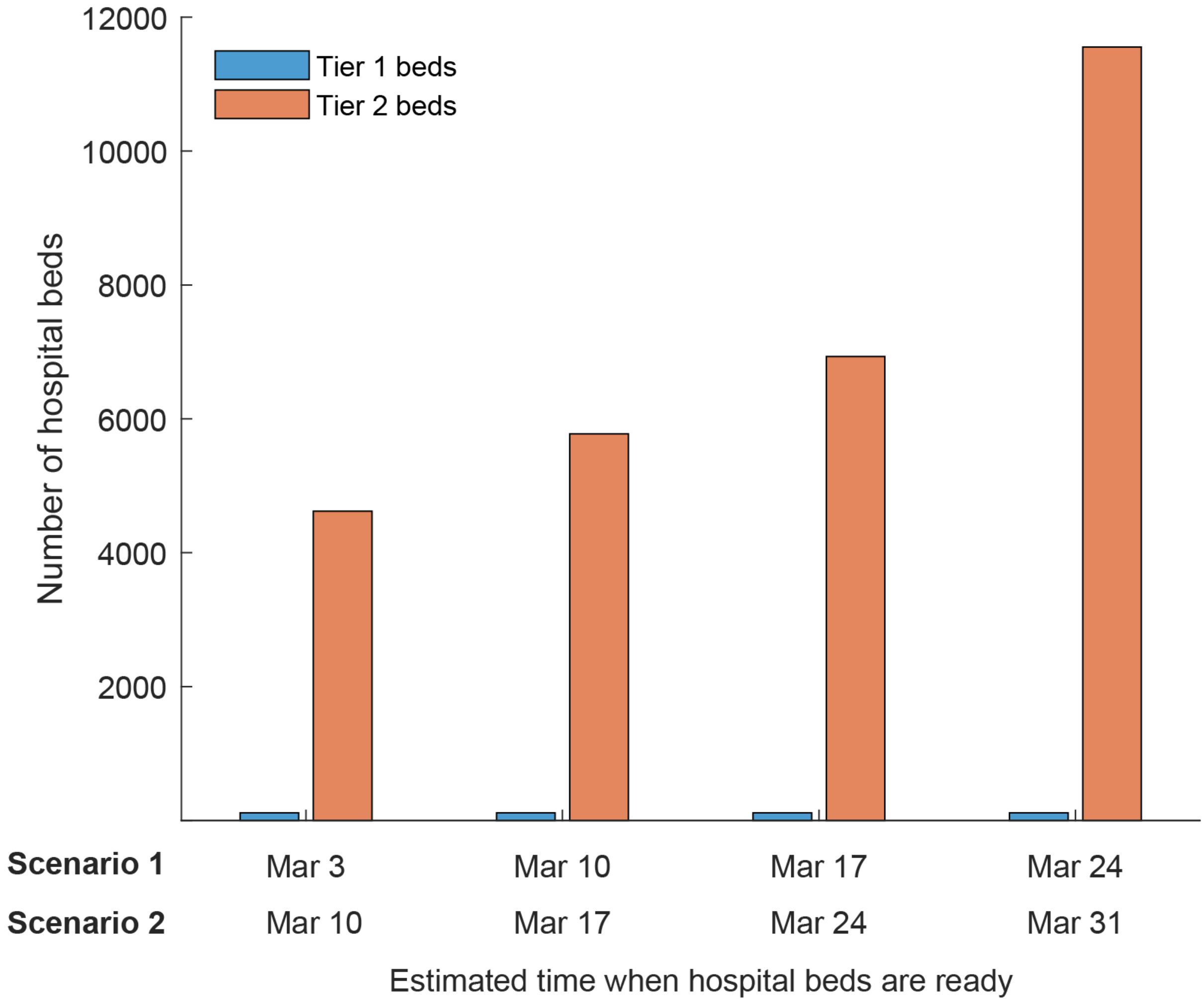


Figure 2. Estimated number of Tier 1 and Tier 2 hospital beds from Hospital Authority's public hospitals in March, 2022.

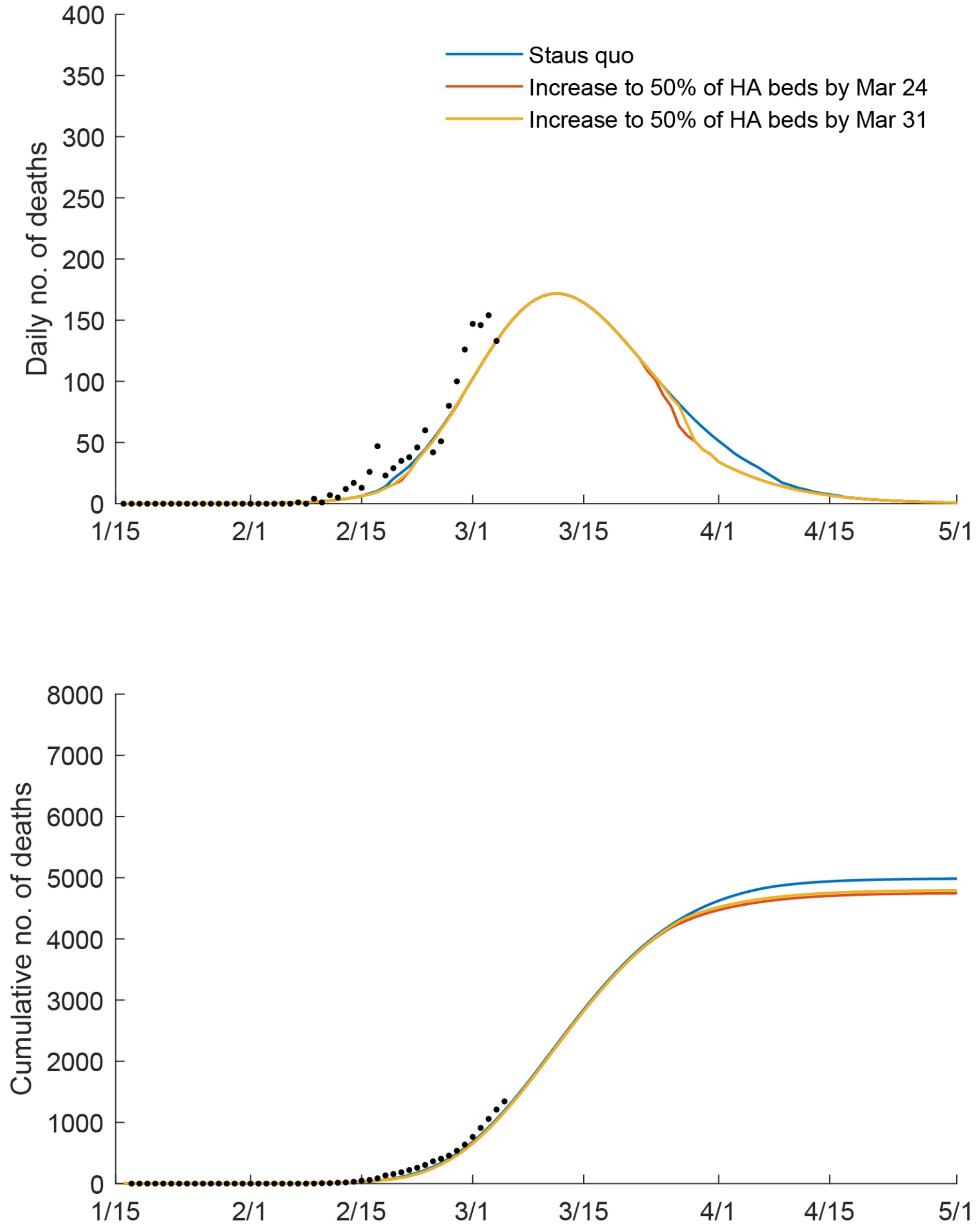


Figure 3. Increasing the number of hospital beds only (according to the schedule in Figure 2) has minimal impact on mortality. The cumulative number of deaths by May 1 would be reduced from 5,008 to 4,748 and 4,794 in Scenario 1 and 2, respectively. Confidence intervals are not shown for easier comparison.

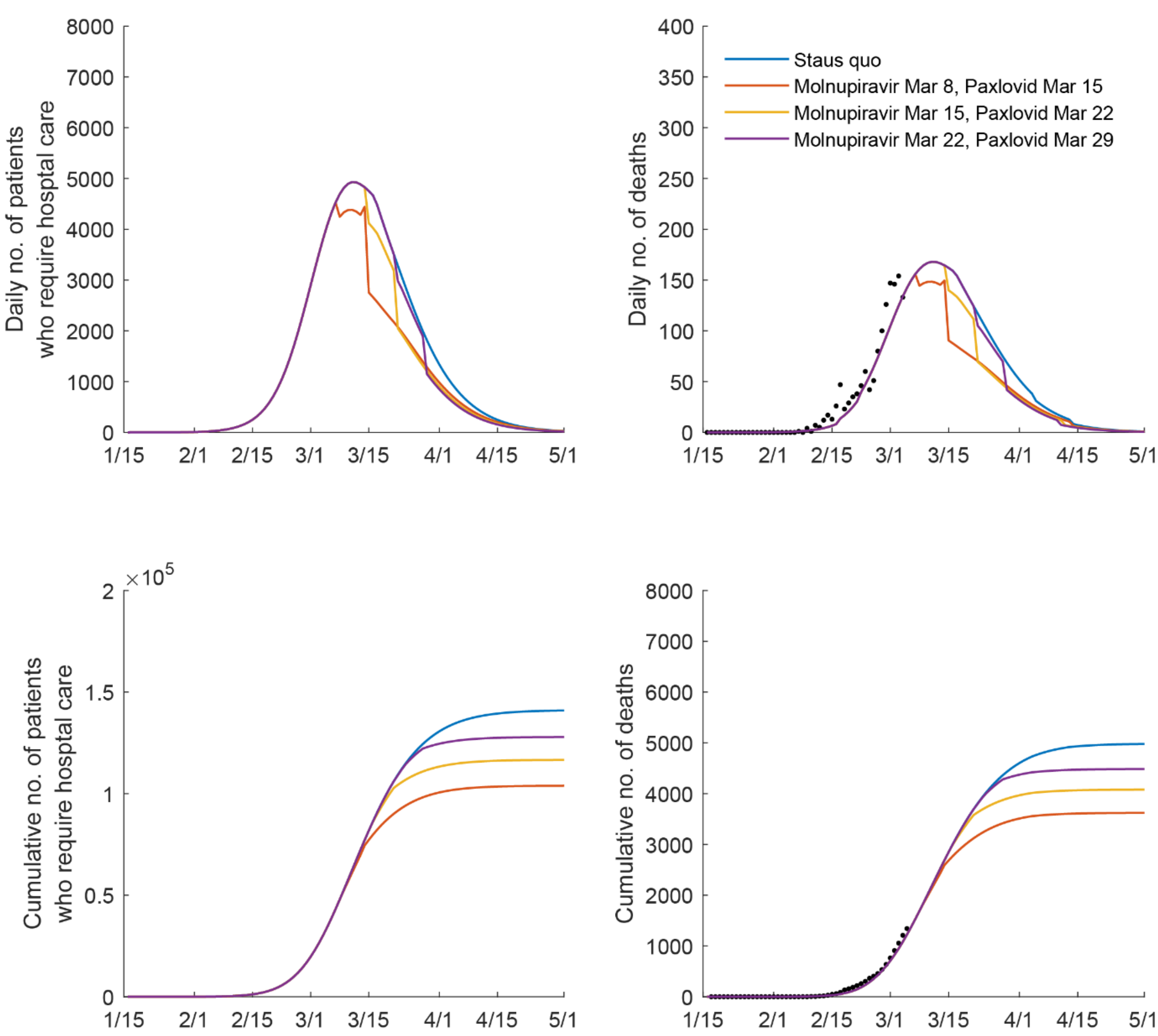
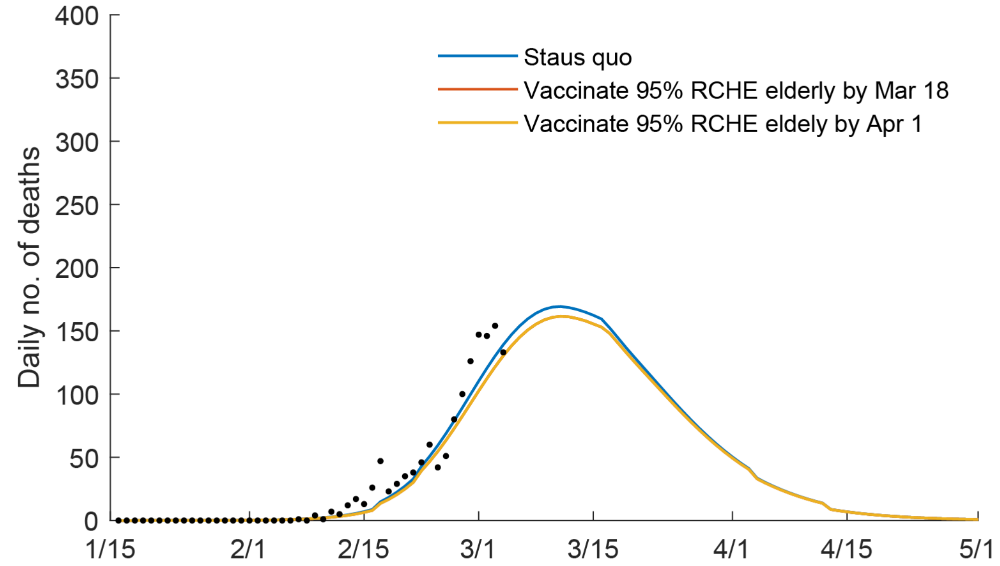


Figure 4. Immediate availability of antivirals would substantially reduce the hospitalisations and deaths. According to our communications with Hospital Authority, there should be enough antivirals for all patients who need them. We assume that delivery schedules of the two antivirals are as follows: 1) MSD Molnupiravir: 2,000 courses in stock now; then another 3,000 courses available in the week of March 7-13; and then another 95,000 courses delivered by mid-Mar; 2) Pfizer Paxlovid: 8,000 courses available in the week of March 14-20; then another 152,000 courses available before the end of March; and then another 90,000 courses available in April. Delivery of both antiviral drugs on March 15, 22, and 29 would reduce deaths from 5,008 to 3,749, 4,229 and 4,622 respectively. Confidence intervals are not shown for easier comparison.



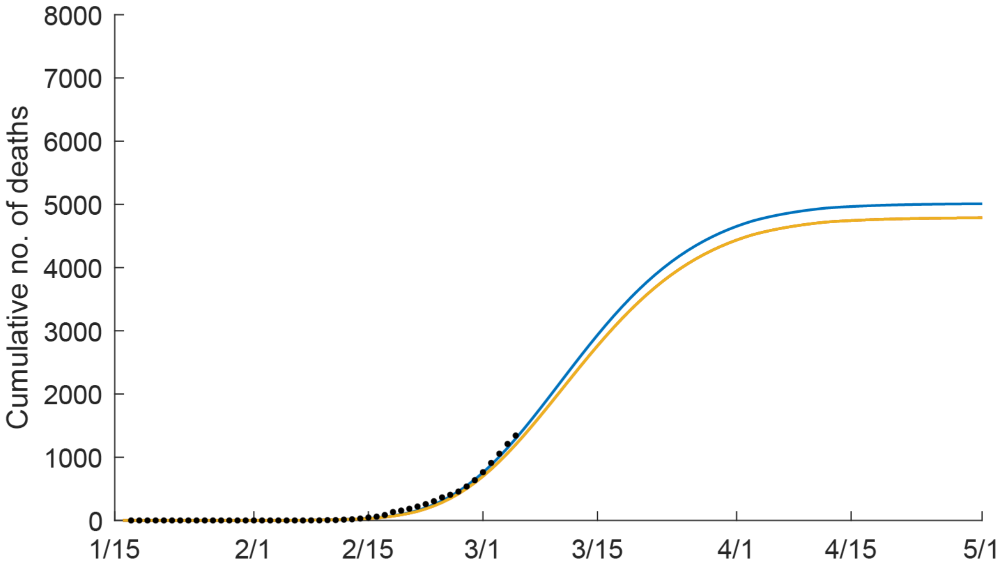


Figure 5. Increasing vaccine uptake has minimal impact on mortality. We assume that the first dose of either Sinovac or BioNTech vaccine would reduce the risk of death by 20% on or after Day 14 of vaccination. The cumulative number of deaths by May 1 would be reduced from 5,008 to 4,788 if 95% of elderly residents are vaccinated with at least one dose of vaccine by March 18 or April 1. Confidence intervals are not shown for easier comparison.

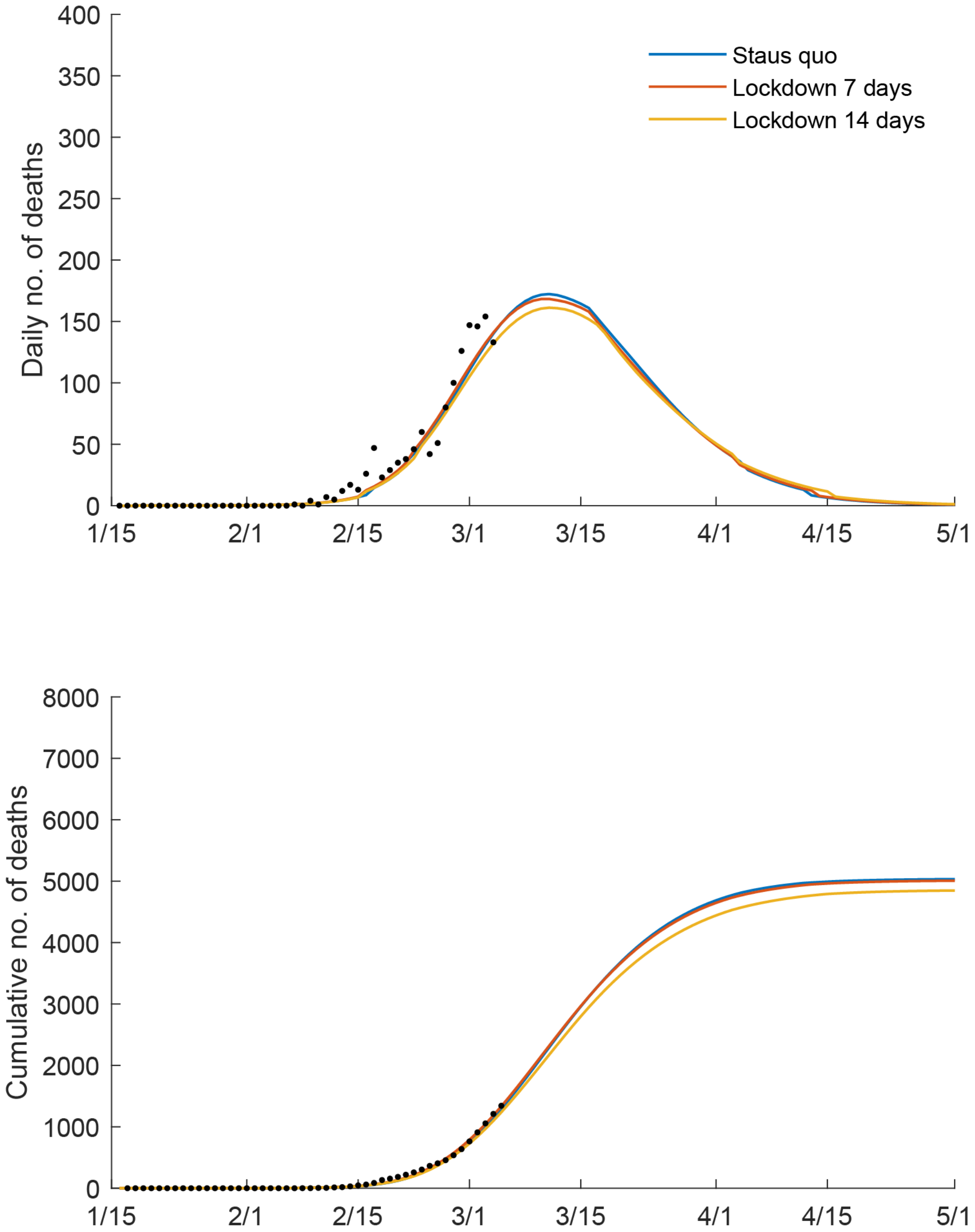


Figure 6. Implementing further PHSMs such as lockdown (Sydney style) for 7 or 14 days would have minimal impacts on the reduction of deaths. We assume the lockdown would reduce Rt by 80%. The cumulative number of deaths by May 1 would be reduced from 5,008 to 4,847 if a 14-day lockdown were implemented on March 14. Confidence intervals are not shown for easier comparison.

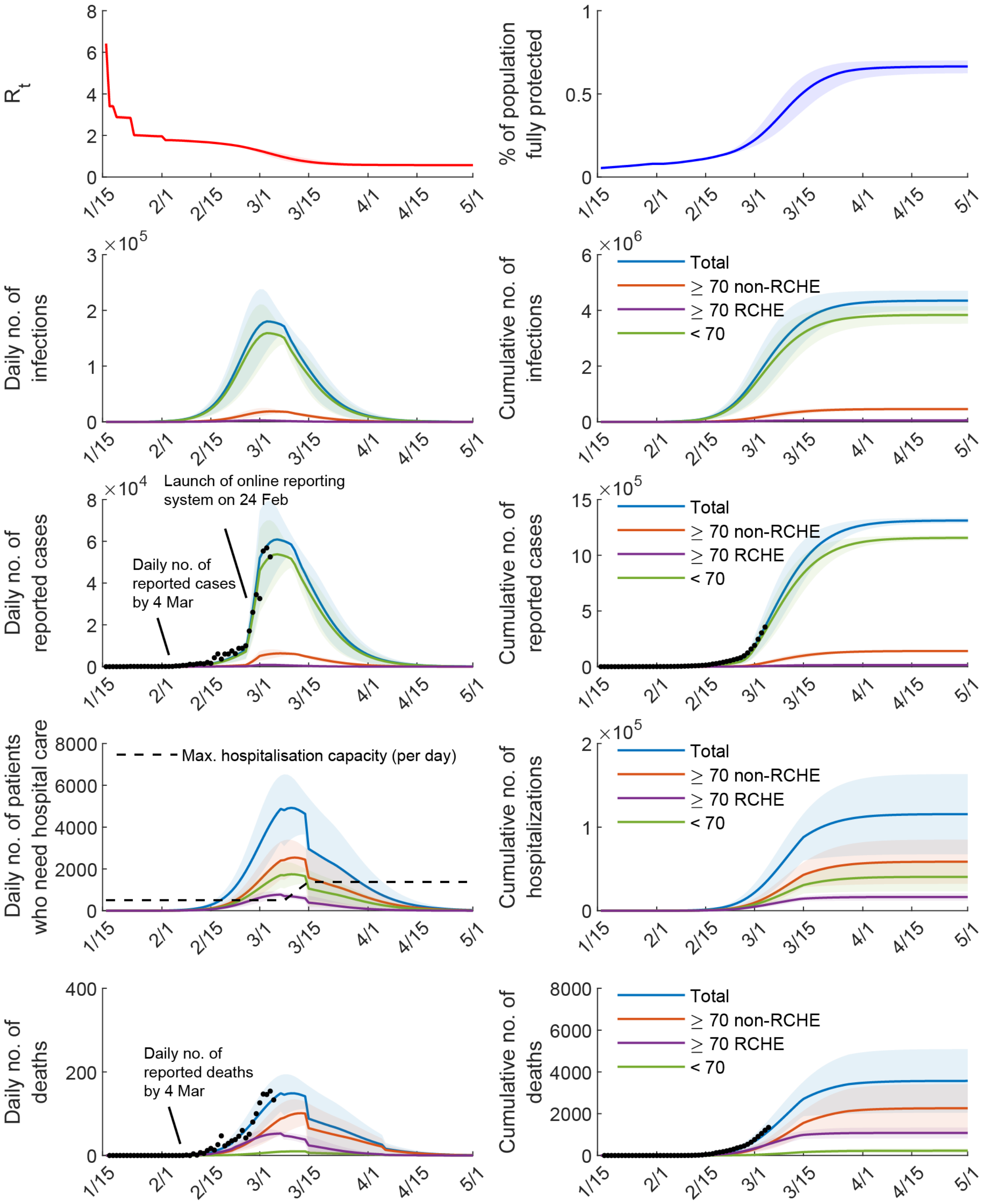


Figure 7. Daily and cumulative number of infections, reported cases, hospitalizations, and deaths, with rapid vaccination of RCHE residents, immediate availability of antivirals and fast increase of hospital beds. We assume Molnupiravir and Paxlovid would be widely available by March 8 and March 15 respectively. The number of Tier 2 beds would increase from about 2,500 to 7,000 between March 8 and March 15. We assume that all RCHE residents would receive at least one dose of vaccine (mostly Sinovac) by March 18 and the vaccine effectiveness in reducing deaths is 20% 14 days after vaccination. Other parameters are the same as Figure 1. **The estimated cumulative number of deaths by May 1 is 3,569 (2,052 - 5,086).**

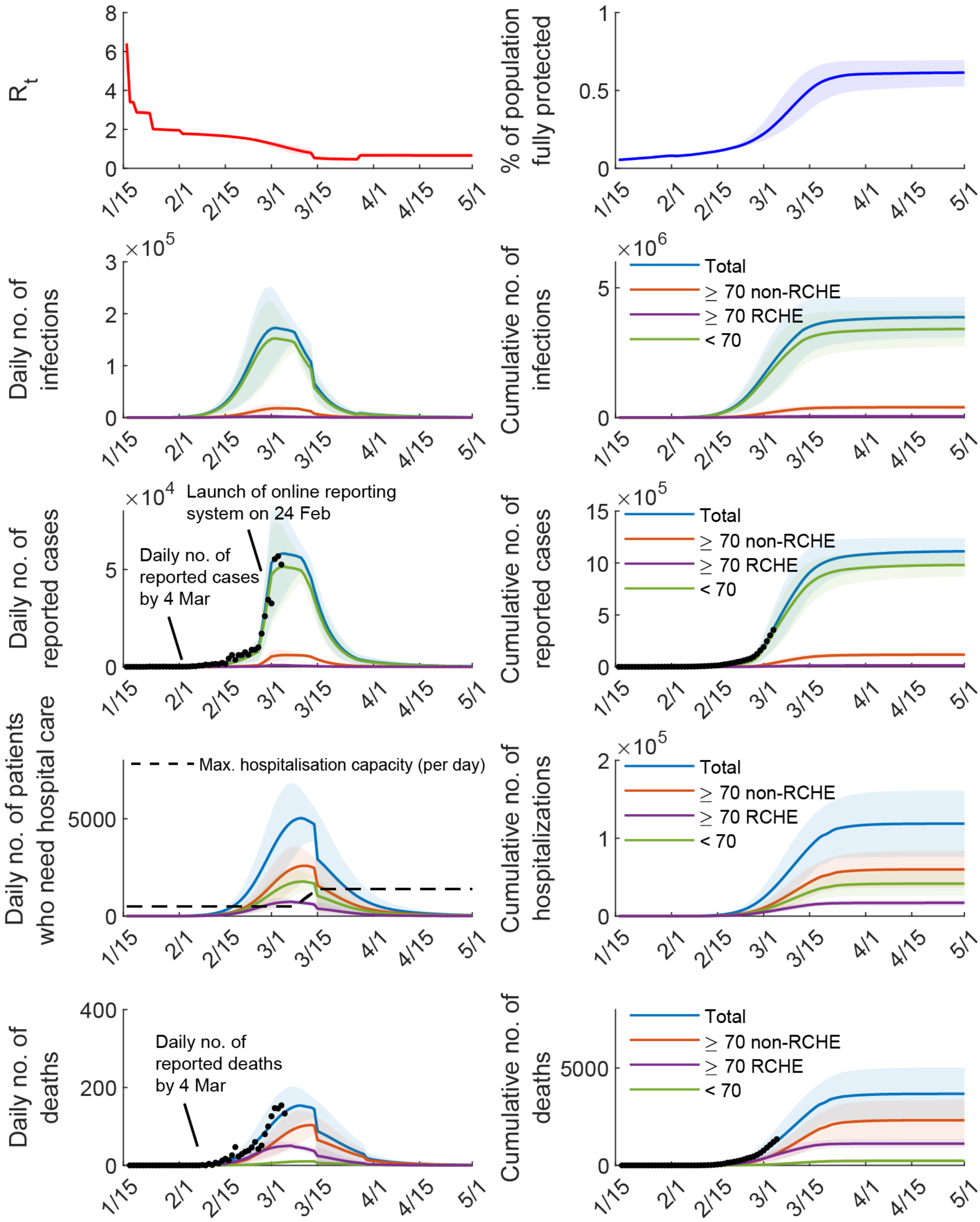


Figure 8. **Daily and cumulative number of infections, reported cases, hospitalizations, and deaths, with rapid vaccination of RCHE residents, immediate availability of antivirals, fast increase of hospital beds and 14-day lockdown.** We assume the lockdown would reduce Rt by 80% and is implemented between March 14 and 27. Other parameters are the same as Figure 6. **The estimated cumulative number of deaths by May 1 is 3,352 (2,098 - 5,015).**

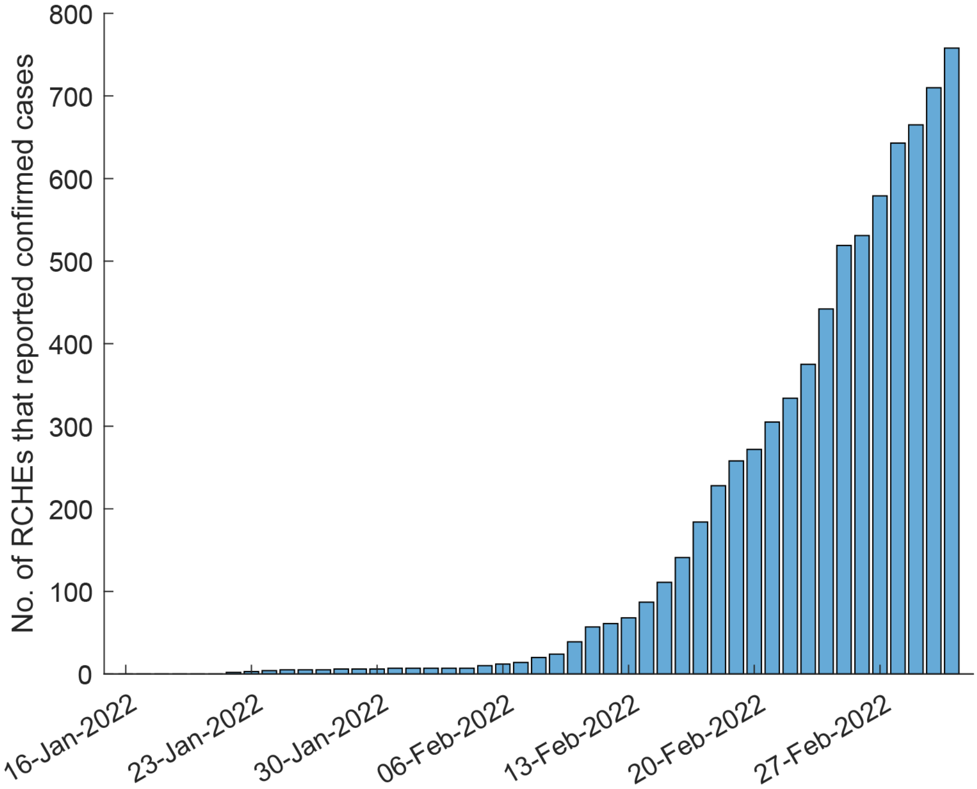


Figure S1. Daily number of RCHEs that reported confirmed cases.

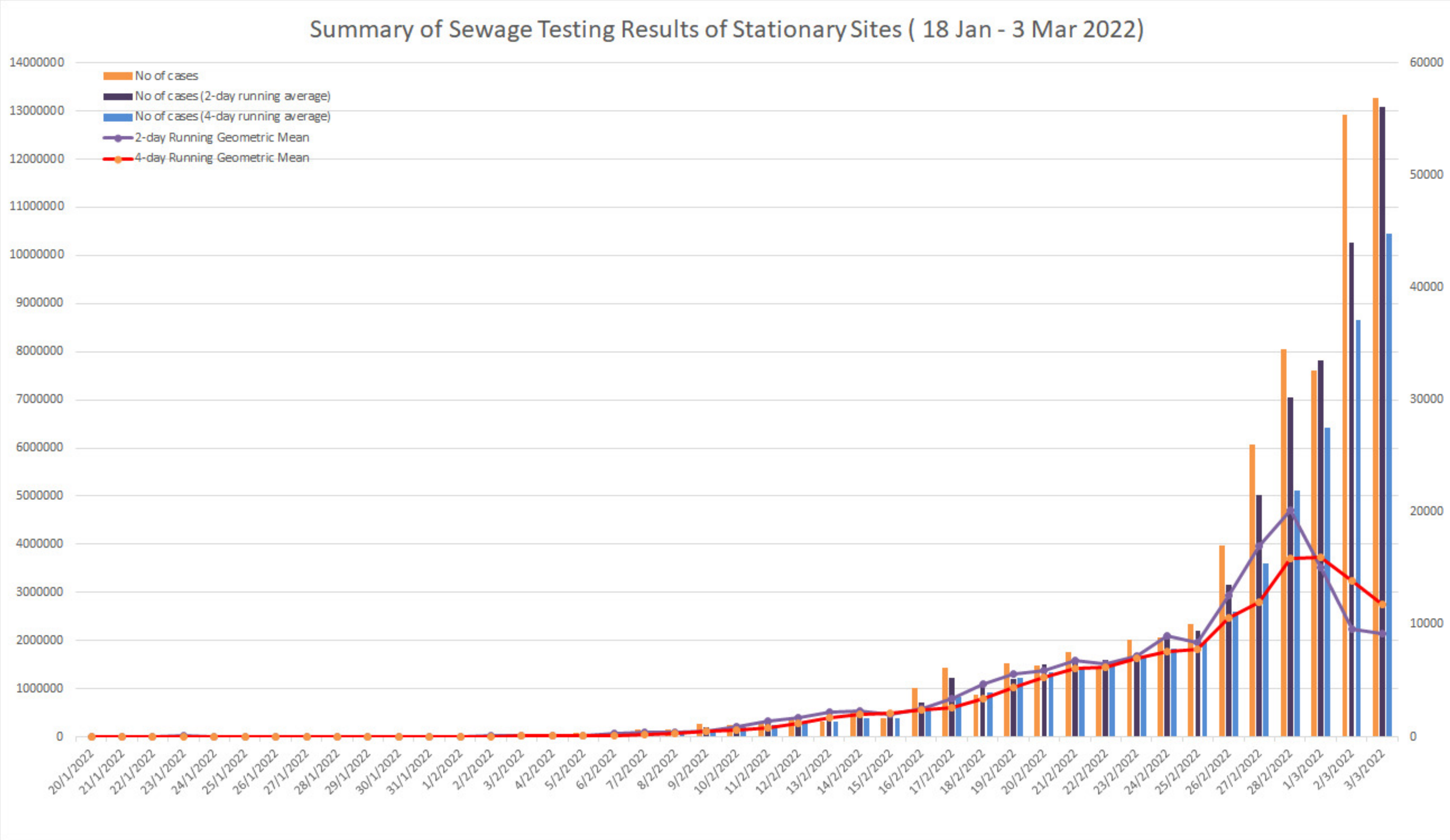


Figure S2. Estimated daily number of viral copies in the population covered by sewage surveillance.

Update #5 as of February 28, 2022

Modelling the fifth wave of COVID-19 in Hong Kong

D^{2}4H@HKSTP and HKU WHO Collaborating Centre on Infectious Disease Epidemiology and Modelling

Version 1: September 18, 2021 (assuming a Delta wave)
Version 2: January 6, 2022
Version 3: February 10, 2022
Version 4: February 21, 2022
Version 5: February 28, 2022

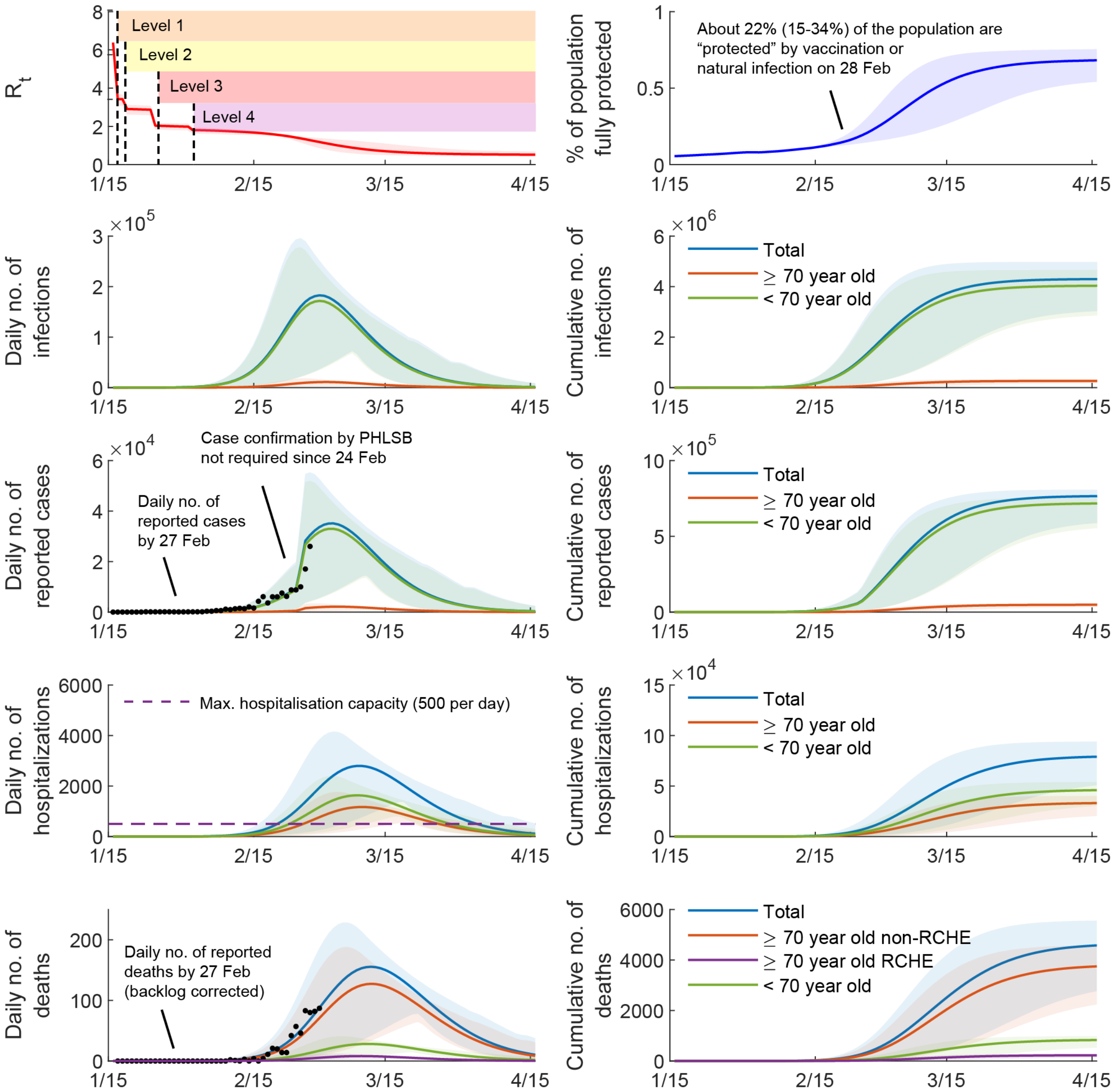
Findings highlights

- Cumulatively since the beginning of the 5th wave, there have been about 1.7 (0.32 – 2.86) million people already infected by COVID-19 as of February 28, 2022.
- This wave is expected to peak in the coming week or so, at 182,738 (36,794 – 263,300) new *infections* per day or 35,121 (9,985 – 46,091) newly *reported cases* per day.
- The lagged daily number of deaths is projected to peak around 156 (46 – 184) by mid-March and the cumulative number of deaths by the end of April could be around 4,645 (3,143 – 5,568); assuming 1) that our health system surge capacity continues to be overwhelmed, 2) that there is no dramatic and rapid improvement in vaccine coverage amongst the institutionalised elderly, and 3) in the absence of the immediate and widespread availability of novel antivirals (e.g. Paxlovid or molnupiravir).
- **As with all models in a rapidly evolving epidemic with incomplete up-to-date information, there remains much uncertainty (as shown in the credible intervals in brackets above and the shaded areas in Updated Figure 1 below) in these estimates and they should be interpreted accordingly.**
- Disease spread will speed up if public health and social measures (PHSMs) were to be relaxed before April (e.g. due to pandemic fatigue or other socioeconomic considerations). If the virus is not ***locally eliminated*** by late-April, ongoing PHSMs with at least 35% reduction in social mixing would be needed in order to prevent case numbers from resurging albeit unlikely at currently observed levels.
- Therefore, if compulsory universal testing (CUT) were to be implemented pursuant to the "dynamic zero-covid policy", it should be deployed towards mid- to late-April when case numbers are anticipated to already be at very low levels in order to maximise its utility in achieving true elimination, or "zero covid". Doing so earlier, especially when case numbers will still be too high to properly and appropriately isolate and care for, paying particular attention to population mental and emotional wellbeing in HK's unique context, would not be recommended.

Methodological revisions

In this 5th update, we have adjusted the methods of our nowcast/forecast by:

1. Shortening the onset-to-death interval among those aged above 70 years from 18.8 days to 6-9 days. Since the beginning of the fifth wave in Hong Kong, COVID-19 cases have been confirmed in more than 580 residential care homes for the elderly (RCHEs). The death counts over the past week increased more rapidly than what we had previously projected, at least in part because about 90% of these deaths were in very frail, unvaccinated older adults with substantial chronic diseases or comorbidities living in RCHEs. Limited preliminary linelist data from CHP indicates that the symptom onset-to-death interval in this most vulnerable group is shorter than 7 days, i.e., much shorter than the 18.8 days that we had assumed in our previous reports (which was in turn based on the 213 deaths during the first four waves of the ancestral strains in Hong Kong). To account for this new observation (the complete and updated line-list of COVID-19 death cases is not yet available), we split the 70+ age group into RCHE vs non-RCHE (or community dwelling) residents and revised their onset-to-death interval to be 6 and 9 days, respectively. We also account for the much lower vaccine uptake in the RCHE group (two-dose uptake 15% in RCHE vs 45% in non-RCHE group) to reflect their higher IFR and hence overrepresentation in the fifth wave death counts.
2. Upward adjusting all age-specific IFRs since 21 February by 1.5 times which was based on fitting the model (with the revised onset-to-death interval) to the total number of daily death counts. This is consistent with our previous assumption that IFR would be increased by 50% when hospital surge capacity is overwhelmed which has indeed been the case since 21 February.
3. We replace our projections of "daily number of symptomatic cases" with "daily number of reported cases" because previously defined "preliminary PCR-positive" cases by commercial laboratories (that had been providing the majority of all PCR tests done) are now officially accepted as confirmed cases and reported as such, without double confirmation by the government Public Health Laboratory Services Branch. The number of reported cases is also a much more directly comparable and easily understood metric, as it is the number announced each day by government.
4. As more detailed and timely line list (epidemiological) and clinical data become available, we will be able to further revise the model for higher fidelity to reality.



Updated Figure 1. Daily and cumulative number of infections, reported cases, hospitalizations, and deaths given the vaccine uptake and vaccine rollout in Hong Kong, with an Omicron outbreak seeded on 16 January 2022, under Level 4 control measures. We simulate an epidemic caused by one importation of Omicron variant on 16 January 2022 (i.e., the superspreading event in Kwai Chung Estate). We estimate that Level 1-4 measures reduce R_t by 47%, 55%, 69% and 71%. (A) R_t between 16 January and 15 April. (B) Proportion of the population fully protected from infection. (C, E, G, I) Daily number of infections, reported cases, hospitalisations, and deaths. (D, F, H, J) Cumulative number of infections, symptomatic cases, hospitalisations, and deaths. We assume that 8% and 20% of infected individuals were confirmed and reported before and after 24 February. We assume that the mean onset-to-death interval is shortened from 18.8 days to 6 days for residents of RCHEs and 9 days for others, and IFRs are increased by 50% when the health system is overwhelmed.

Updated Table 1. **Point estimates of daily and cumulative incidence of infections, reported cases, hospitalisations, and deaths (for credible ranges of these point estimates please refer to the shaded areas as shown in Updated Figure 1)**

Date	Infections		Reported cases		Hospitalisation		Death (IFR increased by 50% after 21 Feb)	
	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative
Feb 28	181035	1697825	32274	166425	1749	11566	78	573
Mar 3	178530	2240980	35102	269822	2274	17884	107	895
Mar 7	149314	2888051	32857	406470	2723	28219	140	1439
Mar 15	74431	3736117	19098	609890	2487	49822	150	2658
Mar 23	29049	4104718	8115	708976	1523	65470	106	3630
Mar 31	9983	4239120	2928	747537	732	73851	57	4200
Apr 8	3324	4284240	984	760876	302	77561	26	4473
Apr 15	1299	4298294	381	765018	129	78906	12	4578
Apr 22	536	4303930	153	766648	53	79469	5	4624
Apr 30	211	4306538	58	767379	19	79720	2	4645

Updated Table 2. **Point estimates of the prevalence of infected individuals being isolated, and prevalence of close contacts being quarantined (for the scenario as per the Updated Figure 1)**

Date	In the scenario shown in Figure 1 Isolated		In the scenario shown in Figure 1 Quarantined	
	7-day	14-day	7-day	14-day
Feb 28	577349	855438	1732048	2566314
Mar 3	622168	1041206	1866504	3123619
Mar 7	573642	1150991	1720926	3452974
Mar 15	322585	870254	967755	2610762
Mar 23	133765	426304	401294	1278911
Mar 31	47573	165917	142719	497751
Apr 8	15875	57405	47626	172216
Apr 15	6149	22024	18447	66073
Apr 22	2484	8633	7453	25900
Apr 30	950	3144	2851	9431

Update #4 as of February 21, 2022

Modelling the fifth wave of COVID-19 in Hong Kong

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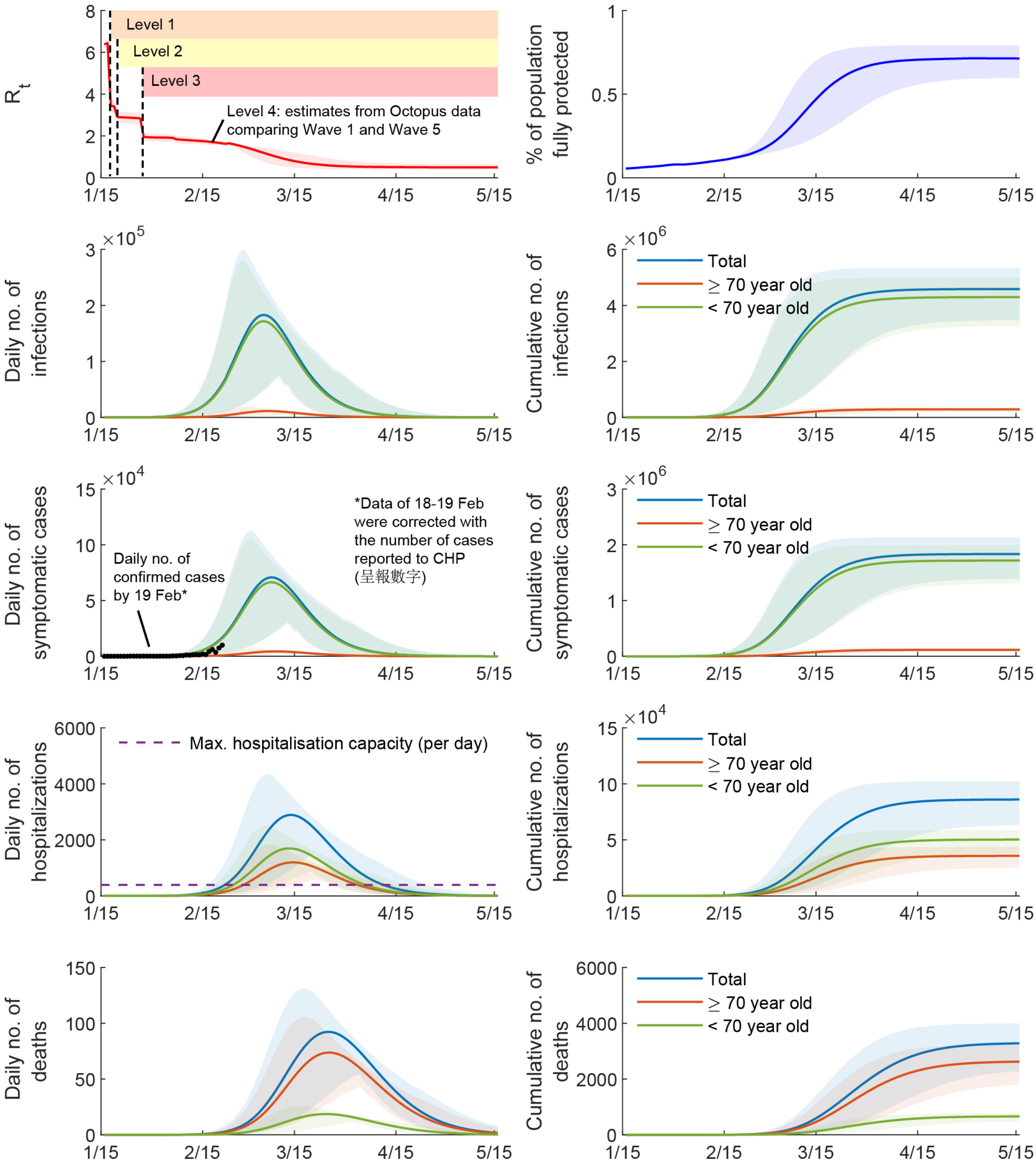
Version 1: September 18, 2021 (assuming a Delta wave)
Version 2: January 6, 2022
Version 3: February 10, 2022
Version 4: February 21, 2022

Summary

In the previous version of our 5th wave projection dated February 10, 2022, we assumed that Level 4 control measures introduced on February 10 would reduce R_t by 77% -- i.e. the effectiveness of Level 4 is midway between that of Level 3 and city-wide lockdown. This was an arbitrary but necessary assumption made in the absence of empirical data in order to make scenario projections. Incident case numbers (despite clear testing capacity constraints) and death counts since 10 February 2022 suggest that this assumption overestimates the effectiveness of Level 4 measures thus underestimates R_t (Updated Figure 1). Using Octopus data and the case numbers from 10-20 February 2022 (esp. reported cases or 呈報數字, https://www.news.gov.hk/chi/2022/02/20220220/20220220_175422_202.html), we revise our estimate of the effectiveness of currently implemented Level 4 measures downward to 71% which corresponds to R_t = 1.9 (Updated Figure 1). The observed trajectory of the fifth wave is now closer to our epidemic projection in Scenario 2 of our Feb 10 original report.

In this scenario, the daily number of infections, symptomatic cases, and hospitalisations (i.e., patients who require in-hospital care in a Tier 1/2 acute care bed) would peak at around 182,923, 70,798, and 2,893 in early- to mid-March. The daily number of deaths would peak at nearly 100 by late-March and the cumulative number of deaths by the mid-May would be around 3,206. In the absence of much more intensive PHSMs (akin to a "lockdown"), the trajectory of the fifth wave is unlikely to change substantially from its current course. Substantial disruption of societal functions is anticipated: at peak, the point prevalence of infected individuals in 7-day isolation could reach 625,377 and the prevalence of close contacts in 7-day quarantine could reach 1,876,139.

Real-time estimation of R_t based on daily number of confirmed cases is becoming increasingly unreliable due to radically changing testing behaviour and capacity over time as well as the delay in case confirmation (https://www.news.gov.hk/chi/2022/02/20220220/20220220_175422_202.html). Real-time prevalence estimates based on (i) large-scale serial cross-sectional or longitudinal viral testing surveys and/or (ii) wastewater SARS-CoV-2 viral load should be urgently considered and implemented.



Updated Figure 1. Daily and cumulative number of infections, symptomatic cases, hospitalizations, and deaths given the vaccine uptake and vaccine rollout in Hong Kong, with an Omicron outbreak seeded on 16 January 2022, under Level 4 control measures. We simulate an epidemic caused by one importation of Omicron variant on 16 January 2022 (i.e., the superspreading event in Kwai Chung Estate). **We estimate that Level 1-4 measures reduce R_t by 47%, 55%, 69% and 71%.** (A) R_t between 16 January and 15 June. (B) Proportion of the population fully protected from infection. (C, E, G, I) Daily number of infections, symptomatic cases, hospitalisations, and deaths. (D, F, H, J) Cumulative number of infections, symptomatic cases, hospitalisations, and deaths. The effectiveness of Level 4 control measures is estimated from the Octopus data and the case numbers from 10-20 February 2022 (esp. reported cases or 呈報數字, https://www.news.gov.hk/chi/2022/02/20220220/20220220_175422_202.html).

Updated Table 1. Daily and cumulative incidence of infections, symptomatic cases, hospitalisations, and deaths (as shown in Updated Figure 1)

Date	Infections		Symptomatic cases		Hospitalisation		Death		Death (IFRs increased by 50% when > max. capacity)	
	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative
Feb 28	147417	1106435	47030	324407	1119	6929	10	54	14	73
Mar 7	181097	2334510	70350	763985	2328	19618	30	193	45	282
Mar 15	118812	3537831	55961	1285285	2880	41698	66	593	100	882
Mar 23	53711	4174774	28445	1605507	2180	62119	91	1252	136	1871
Mar 31	20341	4435462	11465	1748575	1209	75082	85	1973	127	2951
Apr 8	7322	4531098	4200	1803100	554	81555	61	2553	81	3777
Apr 15	2983	4562789	1715	1821305	255	84122	39	2888	44	4186
Apr 30	1223	4575743	701	1828738	112	85274	22	3088	23	4399
May 15	443	4581506	254	1832038	42	85813	10	3206	10	4520

Updated Table 2. Prevalence of infected individuals being isolated, and prevalence of close contacts being quarantined (Updated Figure 1 Scenario)

Date	In the scenario shown in Figure 1		In the scenario shown in Figure 1	
	Isolated		Quarantined	
	7-day	14-day	7-day	14-day
Feb 28	380830	511557	1142491	1534670
Mar 7	614038	994868	1842114	2984605
Mar 15	513007	1136448	1539022	3409343
Mar 23	263865	745588	791595	2236763
Mar 31	106415	344312	319246	1032936
Apr 8	38868	132981	116604	398944
Apr 15	15845	54713	47536	164140
Apr 30	6477	22322	19431	66967
May 15	2343	8045	7028	24136

Update #3 as of February 10, 2022

Modelling the fifth wave of COVID-19 in Hong Kong

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February 10, 2022

Summary

Omicron is at least three times more transmissible than the ancestral strains that caused the previous COVID-19 waves in Hong Kong. Assuming R_0 = 7.2 for Omicron, the current level of population immunity in Hong Kong (conferred by an overall 80% vaccine uptake of at least one dose) would only push the effective reproductive number R_t to 6.4 in the absence of public health and social measures (PHSMs) which roughly corresponds to an epidemic doubling time of 1 day. The latest PHSMs (effective today) would only reduce R_t to 1.3-2.0 which roughly corresponds to an epidemic doubling time of 4-9 days. In this scenario, the daily number of infections, symptomatic cases, and hospitalisations (i.e., patients who require in-hospital care in a Tier 1/2 acute care bed) would peak at around 28,000, 11,165, and 468 in mid- to late-March. The daily number of deaths would peak in the high teens by mid-April and the cumulative number of deaths by the end of June would be around 954. In the absence of a city-wide lockdown, the fifth wave is unlikely to be containable even with the current most stringent PHSMs. Substantial disruption of societal functions is anticipated: at peak, the point prevalence of infected individuals in 7-day isolation could reach 97,852 and the prevalence of close contacts in 7-day quarantine could reach 293,556.

If the effectiveness of the latest PHSMs wanes due to pandemic fatigue or other socioeconomic considerations and reverts to the levels seen during the previous waves, the outcome of the fifth wave would be far more dire with 3,027-5,013 deaths by mid-June. The infection fatality risk may increase by 50% when the healthcare system becomes overburdened, in which case the cumulative number of deaths could further increase to 4,231-6,993. Given that both BioNTech and Sinovac vaccines are highly effective in reducing hospitalisations and deaths within 120 days after the second or third dose, expeditiously increasing vaccine uptake among high-risk groups (e.g., the elderly, especially for those who have chronic illnesses and/or reside in long-term care facilities) is the most (and probably the only) effective way to reduce the morbidity and mortality associated with the fifth wave.

The Omicron-dominant COVID-19 epidemic in Hong Kong has been growing exponentially with geographical expansion since mid-January 2022 despite progressive ramp-up of public health and social measures (PHSMs). In this report, we provide epidemic projections of the fifth wave of COVID-19 in Hong Kong across several plausible scenarios.

Omicron is at least three times more transmissible than the ancestral strains that caused the previous COVID-19 waves in Hong Kong [1]. As such, we assume R_0 = 7.2 for the fifth wave. The current age-specific vaccine uptake in Hong Kong (as of February 8) would push the effective reproductive number R_t to 6.4 in the absence of PHSMs which roughly corresponds to an epidemic doubling time of 1 day. The current vaccine-induced population immunity against Omicron infection is very limited because for both BioNTech and Sinovac, vaccine effectiveness (VE) of two-dose vaccination in reducing susceptibility to Omicron infection is low and becomes negligible 90 days after the second dose (See Supplementary Information for details).

Based on the observed impact of PHSMs on the case counts during previous COVID-19 waves in Hong Kong, we estimate that progressive ramp-up of PHSMs from Level 1 to 5 measures reduces the R_t by 47%, 55%, 69%, 77% and 85%, respectively (See Supplementary Information for details).

Although Level 3 has been sufficient for containing the previous waves, **R_t would remain at 1.9 when Level 3 measures are in effect** because Omicron is inherently more transmissible than the previous strains. **Ramping up to Level 4 would push R_t down to only 1.5**. That is, despite their unprecedented stringency, Level 4 measures would not be able to push R_t below the critical threshold of 1. **Therefore, the current fifth wave of Omicron is unlikely to be containable with the current PHSMs.**

Scenario 1: In the absence of mainland-style city-wide lockdown, the fifth wave is unlikely to be containable with the present Level 4 measures

Given the age-specific vaccine uptake as of early February 2022, we simulate the current Omicron-dominant COVID-19 epidemic in Hong Kong with Level 4 measures in place. In this scenario, the daily number of infections, symptomatic cases and hospitalisations would peak at around 28,000, 11,165, and 468 in mid- or late-March. The daily number of deaths would peak in the high teens in mid-April (**Figure 1**). The cumulative number of deaths by end of June, when the fifth wave ends, would be around 954.

The daily number of new hospitalisations (as defined on an absolute need basis drawing on overseas experience) may exceed the maximum capacity of the local health system between late-March and mid-April (i.e., 400 hospital admissions per day which is equivalent to 1/5 of the total number of relevant available beds in public hospitals, assuming a 5-day stay in a Tier 1 or Tier 2 acute hospital bed when the combined total for both types of beds is 2,000). The infection fatality risk will likely increase when ICUs and acute hospital beds become overburdened. In 2020, we estimated that the case-fatality ratio in Wuhan was 1.5-3 times higher than cities outside Hubei [2,3]. If we assume that the infection fatality ratio increases by 50% (i.e., at the lowest end of the 2020 mainland experience) when the daily numbers of new hospitalisations exceed 400, the estimated number of deaths by end of June would be around 1,107 (**Table 1**).

If we assume that x proportion of infected individuals would undergo 7-day or 14-day isolation at home, the number of infected individuals being isolated would peak at around 195,704x (e.g., 97,852 when x = 0.5) on 25 March and 384,932x (e.g., 192,466 when x = 0.5) on 28 March, respectively

(**Table 2**). Note that the parameter x is determined not only by the natural history of Omicron (e.g., asymptomatic proportion) but also testing behaviour and capacity. For example, $x = 0.5$ means 50% of infections would be isolated which would be the case if testing capacity is unlimited and all the symptomatic cases and their close contacts could be tested, thus identified, with PCR or rapid antigen tests.

Similarly, if we assume that each isolated case would have 3 close contacts to be quarantined by 7 or 14 days, the number of close contacts being quarantined would peak at around 293,556 (when $x = 0.5$) on 25 March and 577,398 (when $x = 0.5$) on 28 March, respectively (**Table 3**). Note that these levels of quarantine prevalence may be overestimates because (i) quarantine is not necessary for contacts who have recovered from previously confirmed infection; and (ii) linked cases likely have overlapping close contacts.

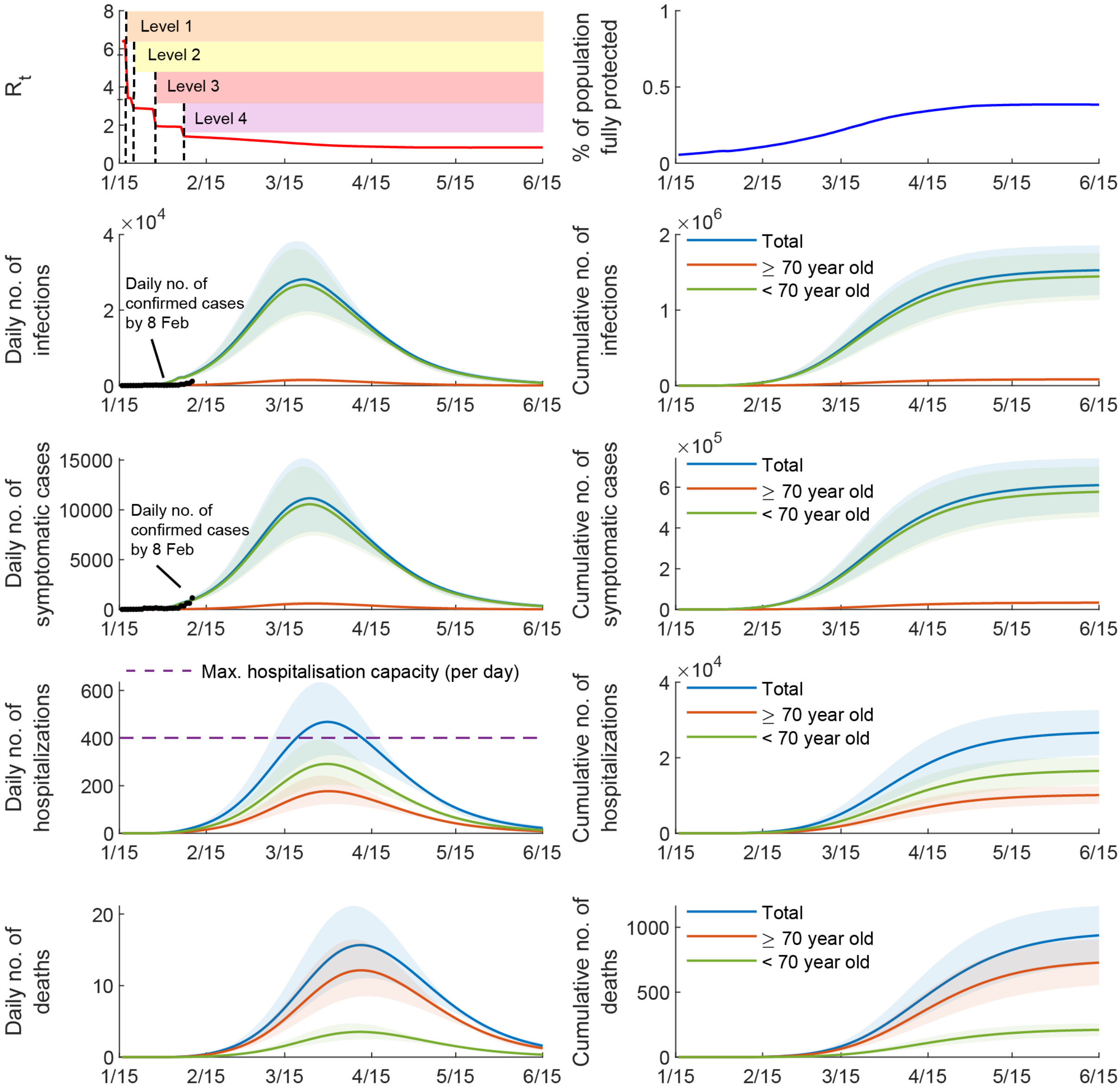

Figure 1. Daily and cumulative number of infections, symptomatic cases, hospitalizations, and deaths given the vaccine uptake and vaccine rollout in Hong Kong, with an Omicron outbreak seeded on 16 January 2022, under Level 4 control measures. We simulate an epidemic caused by one importation of Omicron variant on 16 January 2022 (i.e., the superspreading event in Kwai Chung

Estate). **We estimate that Level 1-4 measures reduce R_t by 47%, 55%, 69% and 77%.** We estimate that the maximum daily number of COVID-19 hospitalizations that the local health system could manage is 400 (Table S5). (A) R_t between 16 January and 15 June. (B) Proportion of the population fully protected from infection. (C, E, G, I) Daily number of infections, symptomatic cases, hospitalisations, and deaths. (D, F, H, J) Cumulative number of infections, symptomatic cases, hospitalisations, and deaths.

Table 1. Daily and cumulative incidence of infections, symptomatic cases, hospitalisations, and deaths (in the scenario shown in Figure 1)

Date	Infections		Symptomatic cases		Hospitalisation		Death		Death (IFRs increased by 50% when > max. capacity)	
	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative	Daily	Cumulative
Feb 8	2475	16303	793	4528	17	83	0	0	0	0
Feb 28	14180	166933	4883	54728	141	1440	2	18	2	18
Mar 15	26497	485446	9980	170012	346	5135	7	83	7	83
Mar 31	25083	920879	10464	343541	468	12033	14	254	21	323
Apr 15	15654	1222432	6866	472863	368	18419	15	482	15	634
Apr 30	7897	1391348	3584	548189	216	22705	12	688	12	841
May 15	3661	1471961	1669	584900	107	25002	7	825	7	978
May 31	1614	1510890	735	602646	48	26149	3	903	3	1056
Jun 15	763	1527474	346	610183	22	26637	2	938	2	1090
Jun 30	369	1535400	167	613771	11	26867	1	954	1	1107

Table 2. Prevalence of infected individuals being isolated

Date	In the scenario shown in Figure 1		In the scenario shown in Figure 2		In the scenario shown in Figure 3	
	Isolated		Isolated		Isolated	
	7-day	14-day	7-day	14-day	7-day	14-day
Feb 8	6405	7950	6409	7955	6412	7959
Feb 28	40846	64373	71161	94706	174180	197741
Mar 15	85971	151641	497867	747363	1203318	2497871
Mar 31	92654	190487	319748	856137	26833	192831
Apr 15	61399	138492	50471	177530	499	3718
Apr 30	32273	76930	6160	22838	9	68
May 15	15040	36573	716	2663	0	1
May 31	6620	16089	74	273	0	0
Jun 15	3118	7536	9	33	0	0
Jun 30	1502	3607	1	4	0	0

* We assumed 50% of infections would be isolated, assuming all the symptomatic cases would test themselves and their close contacts with rapid antigen tests.

Table 3. Prevalence of close contacts being quarantined

Date	In the scenario shown in Figure 1		In the scenario shown in Figure 2		In the scenario shown in Figure 3	
	Quarantined		Quarantined		Quarantined	
	7-day	14-day	7-day	14-day	7-day	14-day
Feb 8	19215	23851	19226	23864	19236	23876
Feb 28	122537	193120	213482	284119	522539	593223
Mar 15	257913	454924	1493601	2242090	3609954	7493612
Mar 31	277963	571462	959243	2568410	80500	578493
Apr 15	184196	415477	151414	532591	1497	11154
Apr 30	96819	230790	18481	68513	27	204
May 15	45120	109719	2147	7990	0	4
May 31	19861	48267	223	820	0	0
Jun 15	9354	22609	27	100	0	0
Jun 30	4506	10822	3	12	0	0

* We assumed 50% of infections would be isolated, and each of them would have 3 close contacts to be quarantined.

Scenario 2: A worse fifth wave of Omicron considering pandemic fatigue and other socioeconomic considerations (de facto relaxed to Level 3 after Feb 23)

We consider a second scenario where Level 4 control measures are sustainable for only a couple of weeks due to pandemic fatigue or other socioeconomic considerations. In this scenario, Level 4 control measures are maintained for 16 days between February 8 and 23, and the PHSMs would subsequently revert to, by policy fiat or de facto, Level 3 after the introduction of the "vaccine pass" (**Figure 2**). In this case, a large Omicron outbreak would result with 3,027 deaths by mid-June. If we assume that the infection fatality ratio increases by 50% when the healthcare system is overburdened, the cumulative number of deaths could increase to 4,231.

If we assume that a proportion x of infected individuals would undergo 7-day or 14-day isolation at home, the maximum number of infected individuals being isolated would reach 1,167,186x (e.g., 583,593 when $x = 0.5$) on 20 March and 2,173,114x (e.g., 1,086,557 when $x = 0.5$) on 24 March, respectively (**Table 2**). The maximum number of individuals under 7- or 14-day quarantine would be over 1.7 and 3.2 million respectively (**Table 3**).

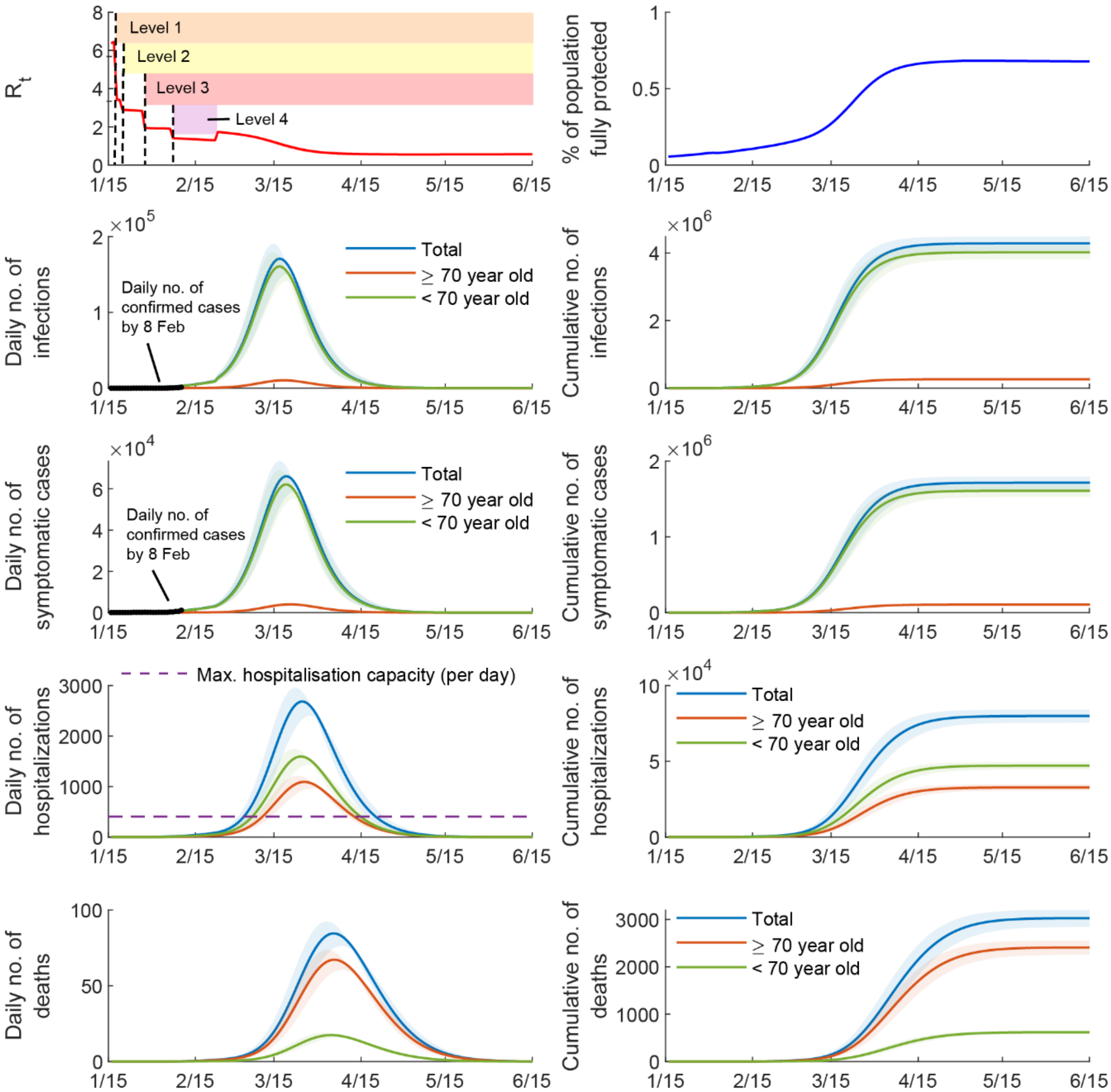

Figure 2. Same as Figure 1 under Scenario 2.

Scenario 3: A dire fifth wave of Omicron considering pandemic fatigue and other socioeconomic considerations (de facto relaxed to Level 2 after Feb 23)

We consider a third scenario which is the same as Scenario 2 except that PHSMs reverts to Level 2 instead of Level 3 after February 23 (**Figure 3**). In this case, a very large Omicron outbreak would result with 5,005 deaths by mid-June. If we assume that the infection fatality ratio increases by 50% when the healthcare system is overburdened, the cumulative number of deaths could increase to 6,993.

If we assume that a proportion x of infected individuals would undergo 7-day or 14-day isolation at home, the maximum number of infected individuals being isolated would reach 3,166,640x (e.g., 1,583,320 when x = 0.5) on 11 March and 4,995,742x (e.g., 2,497,871 when x =0.5) on 15 March, respectively (**Table 2**). The maximum number of individuals under 7- or 14-day quarantine would be over 3.6 and 7.4 million respectively (**Table 3**).

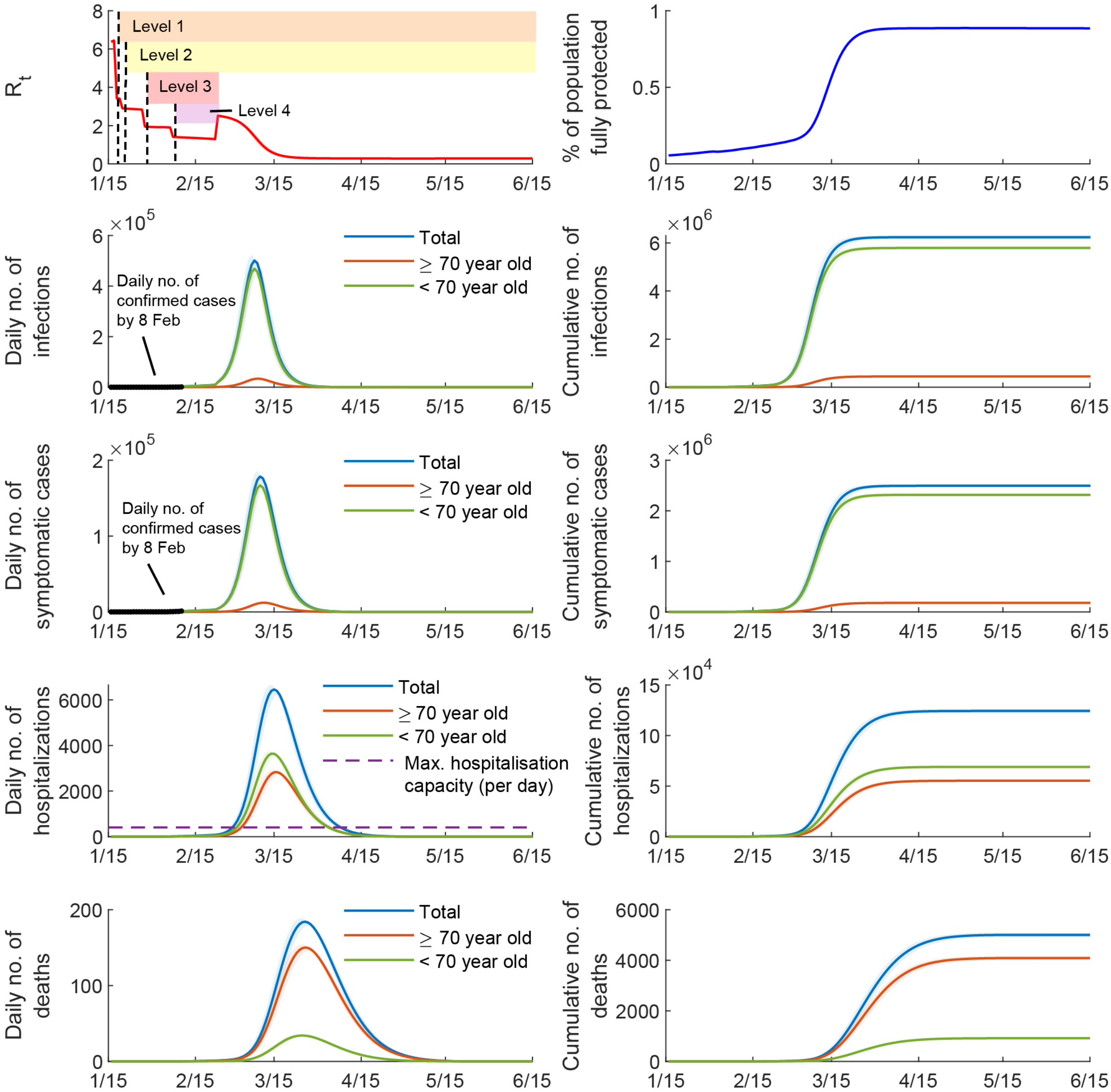

Figure 3. Same as Figure 1 under Scenario 3.

__Scenario 4: A fifth wave of Omicron with city-wide lockdown__

We consider a fourth scenario where Level 5 control measures with city-wide lockdown could be implemented and sustained for two to three months (**Figure 4**). Based on the empirical effectiveness of the city-wide lockdown as observed in Shanghai during the 2020 spring national lockdown, we assume that Level 5 measures would virtually eliminate all non-within-household transmissions and decrease R_t by 85%. In this case, the epidemic size of the Omicron outbreak would be limited with only 115 deaths by mid-June. The daily number of hospitalisations would remain well below the maximum capacity of the local health system. However, if prevalence is non-zero when the lockdown is lifted, the epidemic will resurge. Population immunity against infection at that point would only be around 20% higher than that before lockdown.

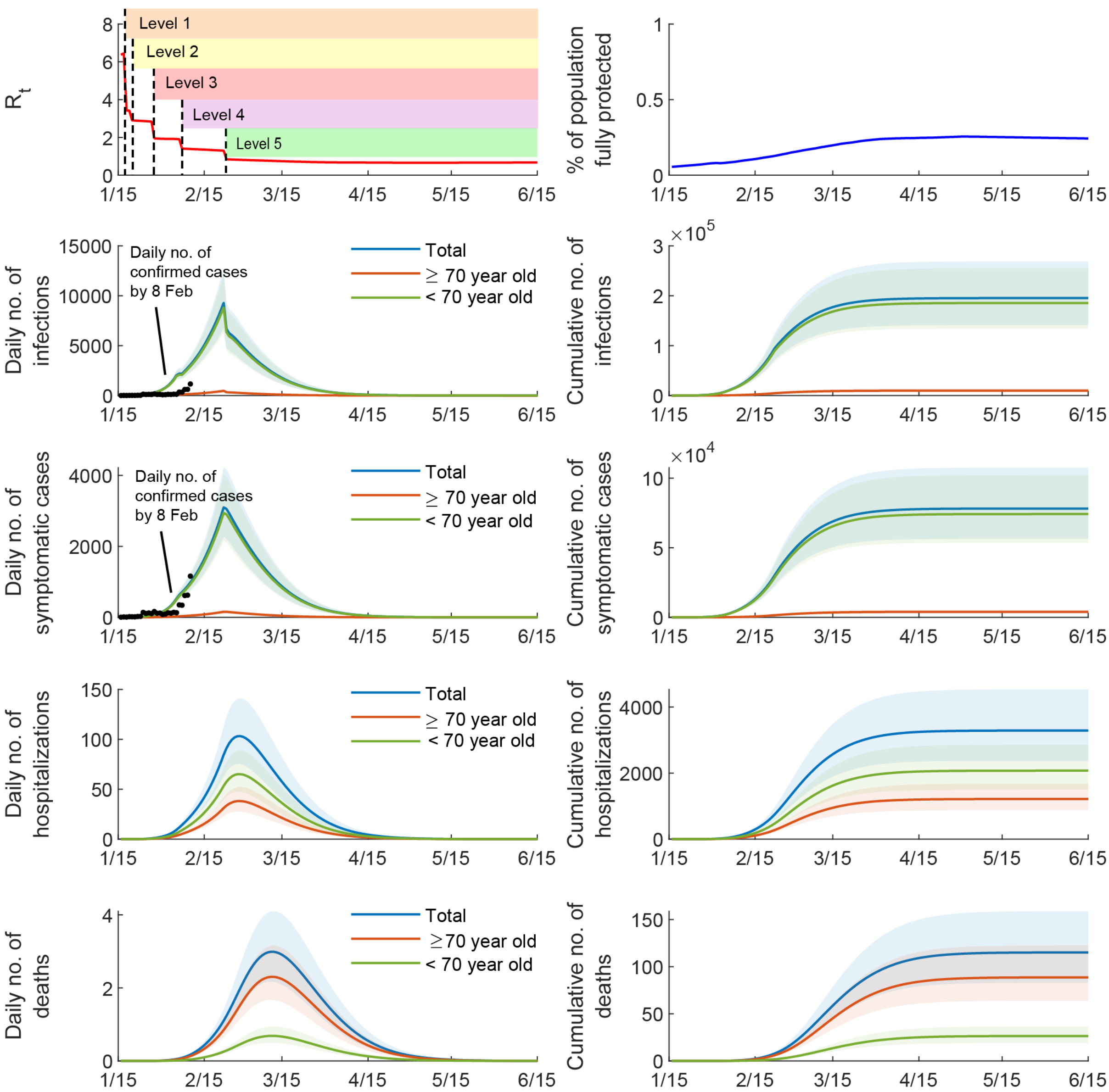

Figure 4. Same as Figure 1 under Scenario 4.

Scenario 5: A fifth wave of Omicron with faster rollout of vaccination programme

We consider a fifth scenario which is the same as the baseline scenario, but the daily vaccination rate would increase from 73,000 to100,000 doses per day over the next few months (**Figure 5**). Such accelerated vaccination would have minimal impact on the trajectory of the fifth wave (**Figure 5 vs. Figure 1**), because VE in reducing susceptibility to Omicron infection is limited and short-lived even for two-dose vaccination. Nevertheless, we emphasize here again that a faster rollout of vaccination would significantly reduce the number of hospitalisations and deaths because VE of two-dose vaccination in reducing severe clinical outcomes is high and more long-lasting for both BioNTech and Sinovac [4].

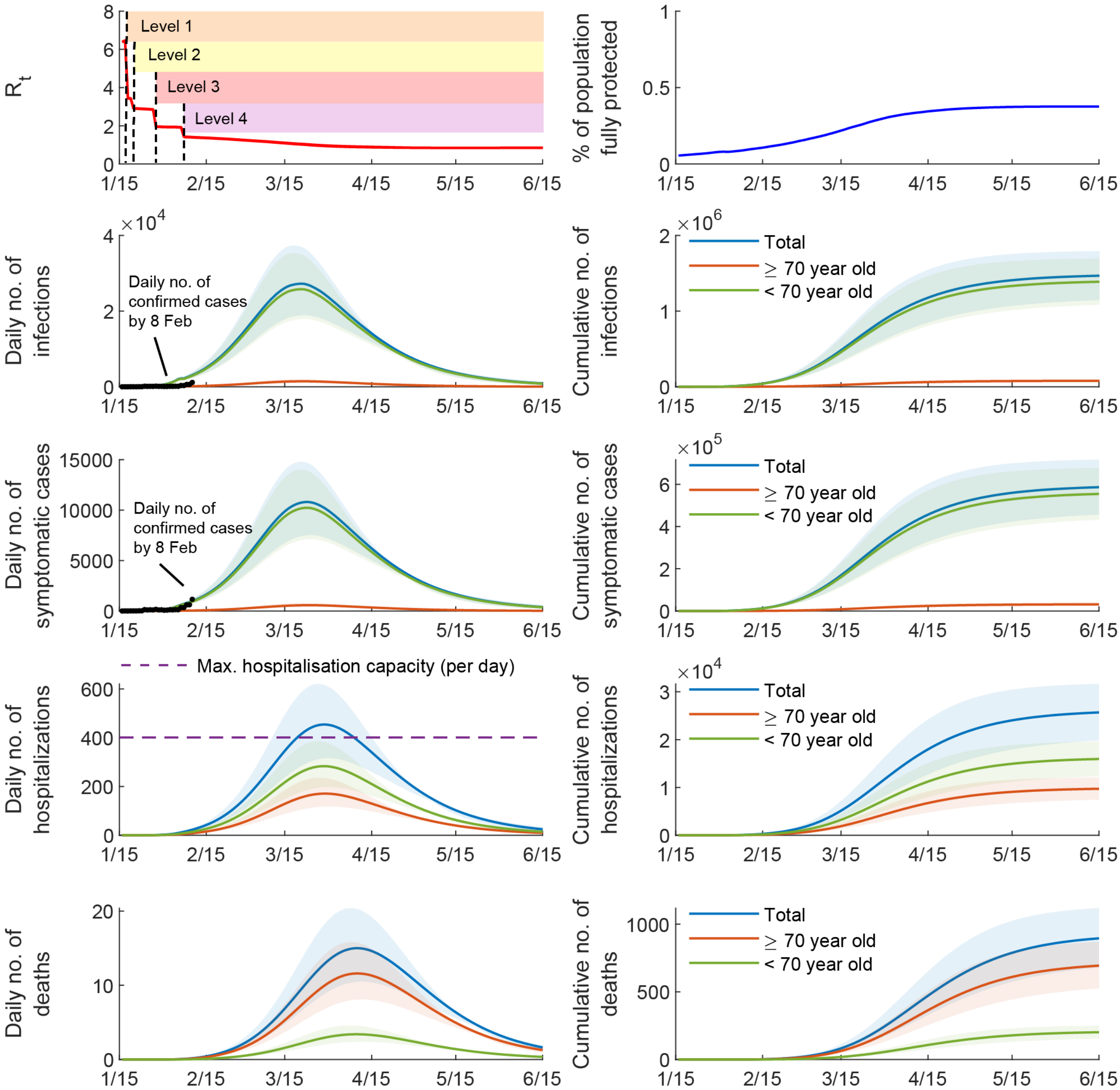

Figure 5. Same as Figure 1 under Scenario 5.

Supplementary information

Estimating the effects of control measures from the past waves of COVID-19 outbreaks

We analyse the epidemic curve of laboratory-confirmed local cases for the first four waves of COVID-19 outbreaks to estimate the daily effective reproductive number (R_t) and infer the impact of public health, and social measures (PHSMs) on R_t. During each wave, PHSMs were progressively tightened commensurate with the size of the outbreak. Using the time when civil servants were mandated to work from home (WFH) as the reference point, we group these PHSMs into the following three levels:

1) **Level 1:** PHSMs announced or implemented before civil servants WFH, which usually include tightened social distancing measures in restaurants and indoor leisure facilities, and closure of kindergartens and primary schools of P1-P3/4.
2) **Level 2:** PHSMs announced or implemented together with civil servants WFH, which often include closure of most indoor leisure facilities, closure of all schools, no dine-in in restaurants after 9 pm.
3) **Level 3:** PHSMs announced or implemented after civil servants WFH, which include more stringent control measures of restaurants, such as no dine-in after 6 pm or all day.

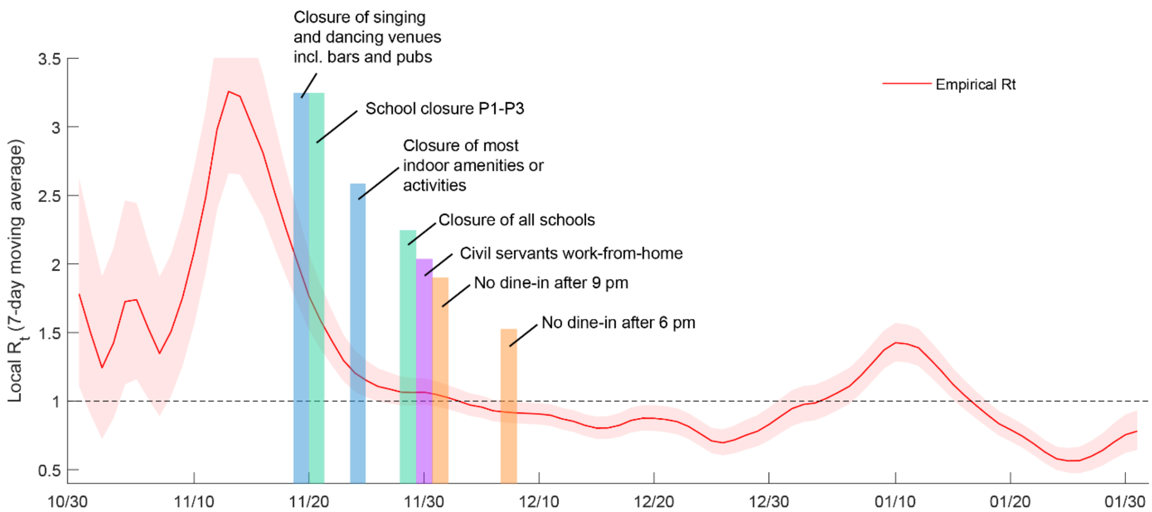

Figure S1. R_t and public health and social measures (PHSMs) implemented during the fourth wave. R_t is estimated from deconvoluted time series of daily number of cases in the EpiEstim model[3].

Table S1. Effects of PHSMs in reducing empirical R_t in the fourth wave

PHSM	Type	Date	Reduction in R_t	Level of control
School closure (P1-P3, kindergarten)	School closure	Nov 20	47%	1
Closure of singing and dancing venues incl. pubs and clubs	Leisure	Nov 20		
Closure of most indoor amenities	Leisure	Nov 24		
Closure of all schools	School closure	Nov 29	55%	2
Civil servants work-from-home	WFH	Nov 30		
No dine-in after 9 pm	Restaurant	Nov 30		
No dine-in after 6 pm	Restaurant	Dec 2	69%	3

Given that Omicron is at least three times more transmissible than the ancestral strains in the previous waves, we further considered more stringent PHSMs that have not been implemented in Hong Kong before:

4) **Level 4:** PHSMs as announced on 8 February 2022, which include those in Level 3 and additional stringent PHSMs (e.g., prohibiting more than two households from gathering in private premises and lowering the maximum number of people permitted for group gatherings in public places from four to two).
5) **Level 5:** PHSMs similar to the regional lockdowns implemented in mainland Chinese cities in response to outbreaks of Delta, such as lockdowns of Guangzhou in June, Nanjing in July, Yangzhou in August, Xiamen in September, Dongguan, and Xi'an in December 2021.

We assume that the effectiveness of PHSMs during the fifth wave would be the same as that during the fourth wave (**Table S1**). We assume that Level 1, 2 and 3 control measures reduce R_t by **47%**, **55%** and **69%**, respectively. Based on estimates of reduction in daily contacts in Shanghai during city-wide lockdown between January to February 2020, we assume that Level 5 control would reduce R_t by **85%**[5] and that the effectiveness of Level 4 is midway between that of Levels 3 and 5 (i.e. reduce R_t by **77%).** Note that around 10-15% of daily contacts are contacts among household members which would inevitably happen even in full city lockdown similar to Wuhan/Hubei in early 2020.

Data and assumptions about waning of COVID-19 vaccine effectiveness

Vaccine effectiveness in reducing susceptibility and infectiousness

Vaccine effectiveness (VE) is estimated from the titre distributions of 50% plaque reduction neutralisation test (PRNT50), with the following data and assumptions (**Figure S2**):

a) The distributions of neutralising antibody (Ab) titres of BioNTech and Sinovac vaccinees are estimated from the data presented in Mok et al [6].
b) We assume that Ab titres after the second dose decreases by 3.5 folds over a 6-month period [7,8].
c) We assume that vaccine-induced Ab titres against Omicron is 12 folds lower than that against the ancestral strain [9].
d) A third dose of vaccine would increase Ab titres against Omicron by 12 and 5 folds for BioNTech and Sinovac vaccine, respectively [9,10].
e) There are limited data about waning of immunity after the third dose. We assume that the rate of Ab waning after the third dose is the same as that after the second dose, i.e., decreases by 3.5 folds over a 6-month period. However, preliminary data show that Abs wane more slowly after the third dose due to immunological memory [11]. Thus, the assumption here slightly underestimates the durability of vaccine protection from the third dose.

The VEs in reducing susceptibility and infectiousness are then estimated from the distribution of neutralising Ab titres [12].

Table S2. Estimates of vaccine effectiveness in reducing susceptibility by time since the second or third dose

VE in reducing susceptibility		Time since 2nd or 3rd dose		
Virus	**Vaccine**	**14 days**	**90 days**	**180 days**
Omicron 1 dose	BioNTech × 1	0	0	0
	Sinovac × 1	0	0	0
Omicron 2 doses	BioNTech × 2	0.20	0.05	0.01
	Sinovac × 2	0.03	0.01	0.01
Omicron 3 doses	BioNTech × 3	0.89	0.86	0.77
	BioNTech × 2 + Sinovac	0.81	0.67	0.44
	Sinovac × 2 + BioNTech	0.64	0.47	0.29
	Sinovac × 3	0.36	0.19	0.08

We estimate that **VE of two-dose vaccination in reducing susceptibility** to infections is markedly reduced against Omicron (**Table S2**). A third dose of vaccine would substantially increase the **VE in reducing susceptibility** to infections.

a) There is limited data about Ab titres against Omicron after one dose of any vaccine. To avoid overestimating the VEs, we assume that VEs in reducing susceptibility were 0% after the first dose of any vaccine.
b) For two doses of BioNTech vaccines, VEs in reducing susceptibility is 20%, 5% and 1% on day 14, 90 and 180 after the second dose. These VE estimates are consistent with observed data in the UK: i) 24% among recent second dose recipients and 7% for those received the second dose 5 months ago from Figure 4 of Willett et al, *medRxiv,* 2021 [13]; and ii) about 10% for those received the second dose 6 months ago from Figure 2 of the UKHSA report published on 31 Dec 2021.
c) For two doses of Sinovac vaccines, VEs in reducing susceptibility is 3%, 1% and 1% on day 14, 90 and 180 after the second dose, respectively.
d) A three-dose course of BioNTech vaccines would increase VEs in reducing susceptibility to 77-89% within 180 days after the third dose. Our VE estimates are slightly more optimistic than the UK data (Figure 4 of Willet et al and Figure 2 of UKHSA report), but the UK might have underestimated the VEs due to the limited testing capacity recently.
e) A third dose of BioNTech is recommended for recipients of either vaccine as the first two doses. Our estimates of PRNT50 titres are consistent with the results from Brazilian Phase 4 trial RHH-001 [14] and results from Iwasaki et al about Sinovac vaccines in Dominic Republican [9].

Vaccine effectiveness in reducing hospitalisations and deaths

It is believed that the immune response after vaccination, especially cellular immunity (e.g., via T cells), may provide greater protection against severe disease than mild or asymptomatic infection [12,15,16]. Therefore, we assume that VE in reducing severe disease or death would be retained against Omicron.

a) To avoid overestimating the VEs, we assume that VE in reducing severe disease or death is 0% after the first dose of any vaccine. This assumption is slightly more pessimistic than the observed VEs in the UK [4], but it is expected that in the absence of boosting, VE would wane quickly after the first dose.

b) We assume that VE of two-dose vaccination in reducing severe disease for Omicron is 75% that for the ancestral virus [16]. Under this assumption, two-dose vaccination reduces the risk of Omicron severe disease (if infected) by 60%-95%.
c) We assume VE of three-dose vaccination in reducing severe disease for Omicron is the same as VE of two-dose vaccination in reducing severe disease for the ancestral virus.
d) We assume that the third dose of vaccine would completely restore the VE in reducing severe disease for Omicron compared with the ancestral virus. Under this assumption, three-dose vaccination reduces the risk of Omicron severe disease (if infected) by 80%-95%.

Table S3. Estimates of vaccine effectiveness in reducing hospitalisation or death by time since the second or third dose

VE in reducing hospitalisation				
Virus	**Vaccine**	**14 days**	**90 days**	**180 days**
Omicron 1 dose	BioNTech × 1	0	0	0
	Sinovac × 1	0	0	0
Omicron 2 doses	BioNTech × 2	0.60	0.60	0.60
	Sinovac × 2	0.60	0.60	0.60
Omicron 3 doses	BioNTech × 3	0.95	0.95	0.94
	BioNTech × 2 + Sinovac	0.95	0.83	0.80
	Sinovac × 2 + BioNTech	0.81	0.80	0.80
	Sinovac × 3	0.80	0.80	0.80
VE in reducing death				
Virus	**Vaccine**	**14 days**	**90 days**	**180 days**
Omicron 1 dose	BioNTech × 1	0	0	0
	Sinovac × 1	0	0	0
Omicron 2 doses	BioNTech × 2	0.70	0.70	0.70
	Sinovac × 2	0.70	0.70	0.70
Omicron 3 doses	BioNTech × 3	0.95	0.95	0.95
	BioNTech × 2 + Sinovac	0.95	0.95	0.95
	Sinovac × 2 + BioNTech	0.94	0.90	0.90
	Sinovac × 3	0.90	0.90	0.90

Under the above assumptions, we estimate that **the VE of two-dose vaccination in reducing severe diseases** is largely retained against Omicron within 180 days (**Table S3**). A third dose of vaccine would further increase the **VEs in reducing severe diseases** [13].

a) For recipients of two doses of vaccines, VEs in reducing severe disease against Omicron is 70% within 180 days.
b) Three doses of BioNTech vaccines would increase VEs in reducing severe diseases to 95% within 180 days after the third dose. Our VE estimates are consistent with the UK data (Table 6 of the UKHSA report), but the confidence intervals of UK estimates are wide.
c) A recent news report suggested the UK might have underestimated the VEs because many hospital admissions recently were due to medical needs not directly caused by COVID-19 infection.

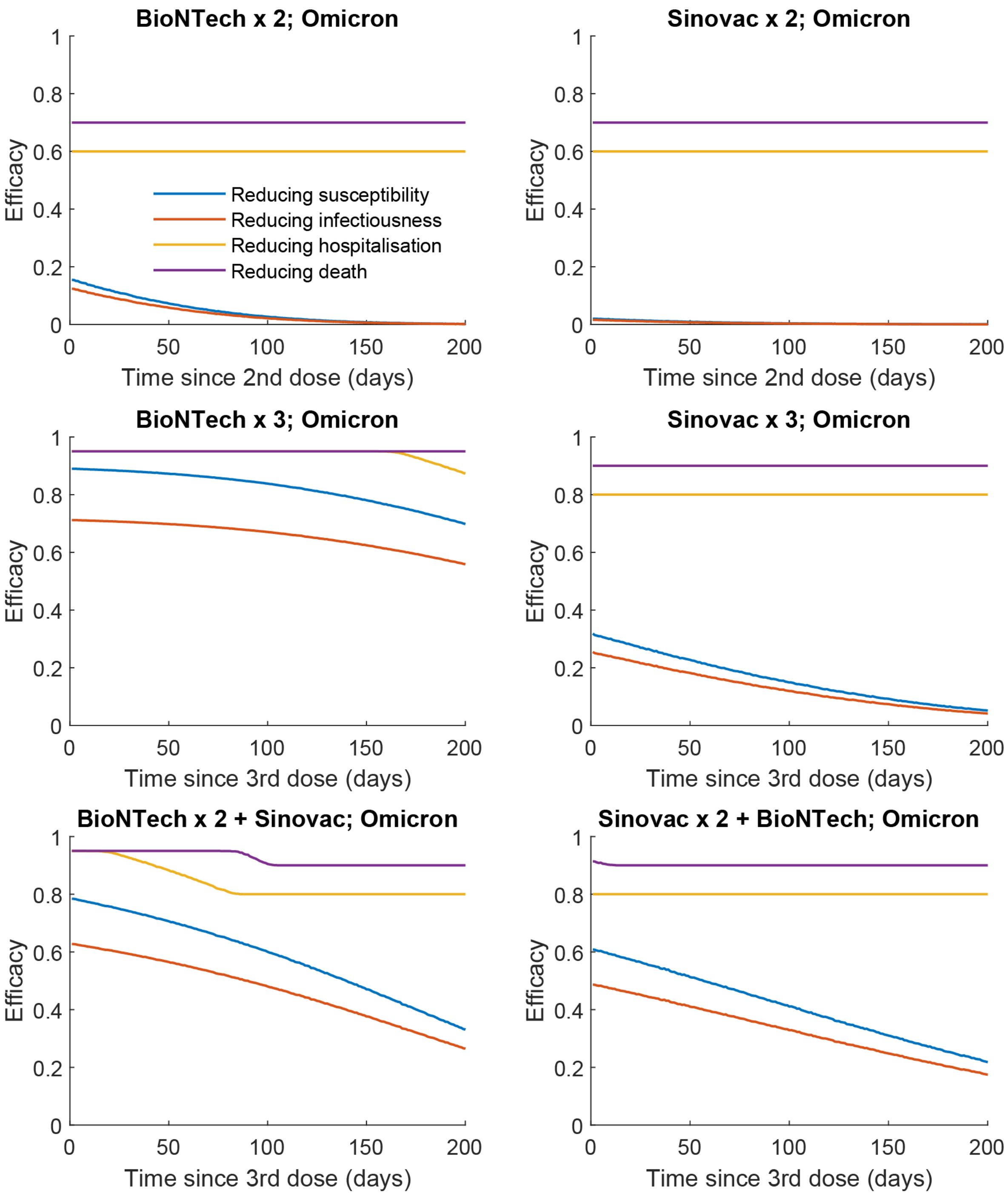

Figure S2. Estimates of vaccine effectiveness in reducing susceptibility, infectiousness, hospitalisation, and death by time since the second or third dose. The distributions of neutralising antibody titres of BioNTech and Sinovac vaccinees are estimated from the data presented in Mok et al [6]. We assume an exponential decay in neutralisation titres with a constant rate of 0.006 per day after the second dose, which corresponds to a 3.5-fold drop in titres over a 6-month period [7,8]. Similarly, we assume an exponential decay with a constant rate of 0.006 per day after the third dose, which corresponds to a 3.5-fold drop in titres over a 6-month period. We assume that Omicron variant's immune escape would result in 12-fold reduction in vaccine-induced neutralising Ab titres [9]. A third dose of BioNTech vaccine would fully restore the reduction by Omicron (i.e., 12-fold increase in neutralising Ab titres) and a third dose of Sinovac vaccine would increase the neutralising Ab titres by 5-fold [9,10].

Estimating the vaccine-induced population immunity

The impact of Hong Kong's COVID-19 vaccination programme on the epidemic trajectory of the fifth wave critically depends on (i) vaccine effectiveness of BioNTech and Sinovac vaccines against Omicron (**Figure S2**); (ii) the age-specific vaccine uptake (**Table S4**); (ii) and uptake rate of primary and booster vaccination (**Figure S3**).

Age-specific vaccine uptake

Table S4. Age-specific vaccine uptake in Hong Kong as of 7 February 2022

Age group	**1st dose**	**2nd dose**	**3rd dose**
0-4	0%	0%	0%
5-11	4.16%	0.02%	0%
12-19	86.0%	61.9%	0.7%
20-29	84.8%	79.0%	7.0%
30-39	86.2%	80.0%	14.4%
40-49	92.7%	87.2%	23.7%
50-59	87.5%	82.0%	24.8%
60-69	75.8%	68.0%	20%
70-79	61.1%	50.9%	7.7%
80 and above	32.5%	22.5%	1.7%

Assumptions about the roll-out of primary and booster vaccination programme

We model the roll-out of primary vaccination and booster vaccination programme in Hong Kong under the following assumptions (**Figure S3**):

a) The target vaccine uptake of primary vaccination, i.e., completion of two doses, is 95% for all age groups.
b) After 7 February 2022, 60% of vaccinees would choose BioNTech vaccines and 40% of vaccinees would choose Sinovac vaccines in the primary vaccination.
c) After 7 February 2022, 80% of vaccinees who have completed primary vaccination would choose the same vaccine if they were to receive a third dose, while 20% of vaccinees would choose a different vaccine.
d) The intervals between the first and second dose are 21 and 28 days for BioNTech and Sinovac vaccines respectively.
e) The interval between the second and third dose is 180 days for both vaccines.
f) The maximum daily vaccination rate is 73000, i.e., the full capacity of the mass vaccination programme now after the emergence of Omicron outbreak in Hong Kong.

Since both two- and three-dose vaccination are highly effective in reducing Omicron hospitalisations and deaths irrespective of the underlying prime-boost combinations (Table S3), assumption (b)-(c) have little impact on the projected hospitalisations and deaths.

Estimating the proportion of population protected in a "leaky" vaccine model

We used a "leaky" model to estimate the vaccine-induced population immunity conferred by the vaccination programme accounting for both increasing vaccine uptake and waning of VEs over time (**Figure S3**).

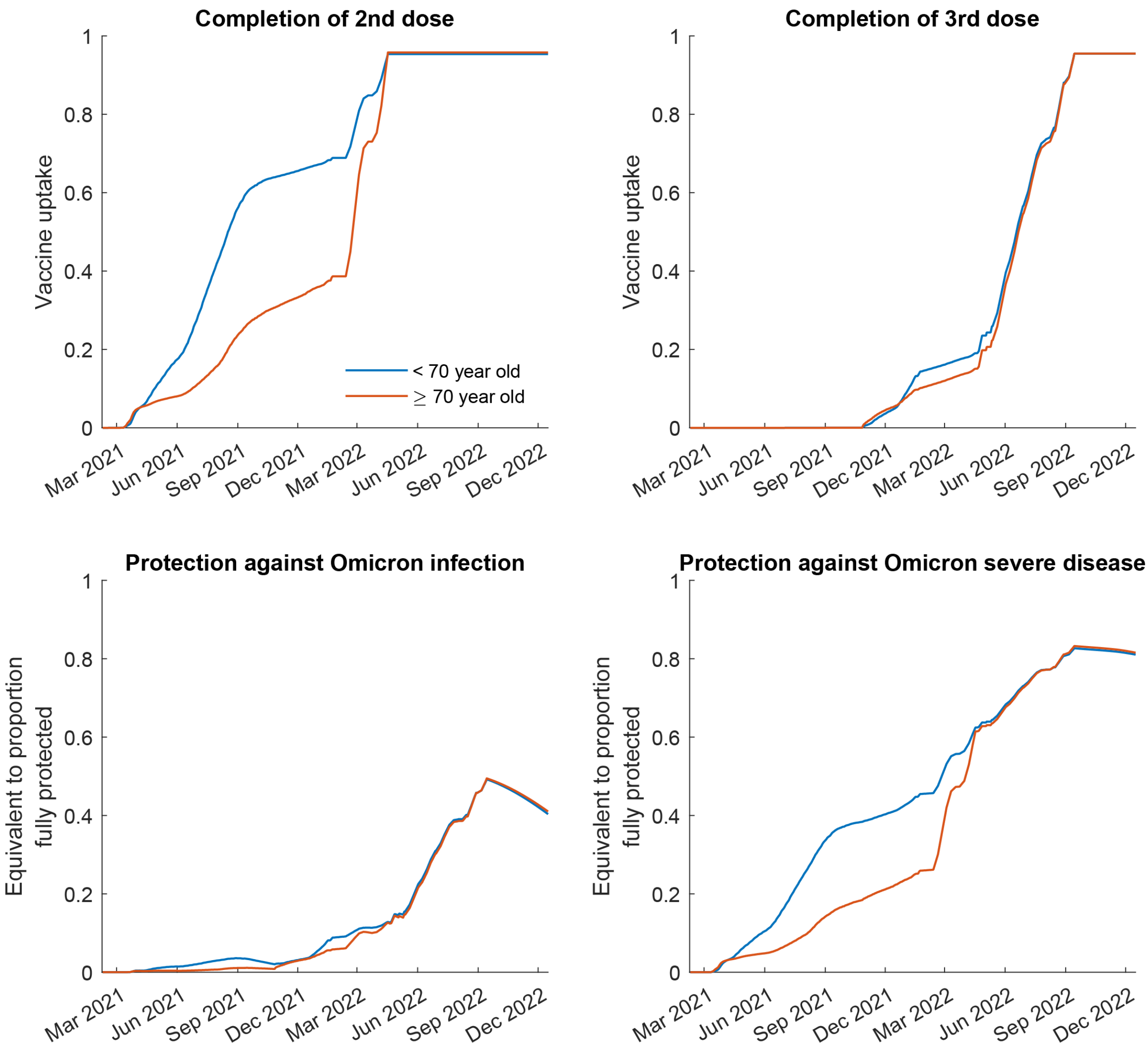

Figure S3. Estimates of vaccine uptake between January and December 2022 and the estimated proportion of population protected against Omicron infection and severe disease by vaccination. We assume that the maximum number of vaccines given per day in Hong Kong is 73000 between 7 February and end of December 2022. We calculate the proportion of population "fully" protected from Omicron infection or severe disease in a leaky model for vaccines. For example, if the VE against severe disease is 50% for a vaccine and the vaccine uptake is 68%, the protection against severe disease is equivalent to that 34% of the population are "fully" protected from severe infection (i.e., $0.68 \times 0.5 = 0.34$).

We estimate that the age-specific vaccine uptake as of 7 February is equivalent to having 43% of the total population "fully" protected against Omicron severe disease (45% and 26% for individuals aged <70 and ≥70 years).

Table S5. Other model parameters

Parameter	Description, assumption, and source	Value
R_0	Basic reproductive number	2.6 for the ancestral strain during the 4th wave 7.2 for Omicron variant [1]
T_{GT}	Mean generation time [3]	5.4 days
f_{GT}	Probability density function of generation time [3]	Gamma (4, 1.35)
σ_m	Vaccine effectiveness in reducing susceptibility	Estimated
σ_t	Vaccine effectiveness in reducing infectivity	Assumed to be $0.8 \times \sigma_m$
σ_s	Vaccine effectiveness in reducing hospitalizations or deaths	Assumed to be $1.25 \times \sigma_m$ and between 0.6 and 0.95 after the second dose and between 0.8 and 0.95 after the third dose
$p_{n,symptom}$	The probability of developing symptomatic diseases if infected, for unvaccinated individuals (estimated from preliminary data from the Hong Kong Omicron outbreak in Kwai Chung Estate)	60%
$p_{v,symptom}$	The probability of developing symptomatic diseases if infected, for vaccinated individuals (estimated from preliminary data from the Hong Kong Omicron outbreak in Kwai Chung Estate)	40%
$p_{a,death}$	Age-specific infection fatality risk of a VOC similar to the Omicron variant [17,18] among unvaccinated individuals; assuming the hazard ratio of Delta variant was 1.45 times of that of Alpha variant and the hazard ratio of Omicron variant was 0.5 times of Delta variant [4,19]	Age 0-34: 0.022% Age 35-54: 0.056% Age 55-69: 0.43% Age 70-84: 4.4% Age ≥ 85: 16.5%
$p_{a,hospitalization}$	Age-specific infection hospitalization risk of a VOC similar to the Omicron variant [17,18] among unvaccinated individuals; assuming the hazard ratio of Delta variant was 1.45 times of that of Alpha variant and the hazard ratio of Omicron variant was 0.5 times of Delta variant [4,19]; assuming these hospitalisations require care from Tier 1 Hospital Authority hospitals	Age 0-9: 0.0018% Age 10-19: 0.045% Age 20-29: 1.2% Age 30-39: 3.9% Age 40-49: 4.9% Age 50-59: 9.2% Age 60-69: 13.3% Age 70-79: 18.8% Age ≥ 80: 20.8%
$f_{incubation}$	Probability density function of incubation period [20,21]	Lognormal distribution Mean: 3.5 days SD: 2.6 days
$f_{hospitalization}$	Probability density function of the time between infection and hospitalization [22]	Gamma distribution Mean: 8 days SD: 3.6 days

f_{death}	Probability density function of the time between infection and death; estimated from $f_{incubation}$ and the probability density function of the time between onset and death (Mean 18.8 days and SD 8.46 days) from Verity et al [22];	Gamma distribution Mean: 23.0 days SD: 9.9 days
H_{max}	The maximum number of COVID-19 hospitalizations that the local health system could take care of is 400 per day: assuming hospitalisations in the context of this report require 5 days of care from Tier 1 Hospital Authority hospitals before they could be transferred to Tier 2 or Tier 3 hospitals (i.e., 2000/5 = 400). (Reference from Japan experience: https://news.rthk.hk/rthk/ch/component/k2/1632742-20220209.htm)	Tier 1 Hospital Authority hospital beds: 2700 Tier 2 800 (HKICC) Tier 3 hospital beds with minimum support: 1000 (AWE) 3500 (Penny's Bay)

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