

# MODELLING SINGAPORE'S COVID-19 PANDEMIC USING HYBRID SEIRQV MODELS

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## Abstract

In this paper, we aim to simulate the Covid-19 spread in Singapore using a SEIRQV model. It is a modified SEIR model that includes quarantining, provision of vaccines (with waning efficacy), and booster shots. To address issues caused by the many assumptions made to run a numerical simulation, we decided to utilise Kalman Filter (KF) for a simpler SIR model for data assimilation as it is less sensitive to imperfections in input data and model assumptions. It is coupled with the hybrid AI model (using LSTM, or Long Short-Term Memory, a recurrent neural network) and causal-numerical model, to show how Singapore's Safe Management Measures have delayed and greatly ameliorated the spread of Covid-19 while allowing our economy to reopen. Moreover, like other compartmental models, we have shown that this novel SEIRQV model can be hybridised with LSTM and KF, with both being much better than the non-hybrid SEIRQV model, and the latter shown to achieve a significantly better performance than that of SEIR.

## Introduction

As the pandemic situation evolved, an increase in Covid-19 variants and information regarding waning vaccine effectiveness<sup>[31,32]</sup> have surfaced. These variants have brought around greater concerns of vaccine breakthrough infections. Singapore's unprecedentedly high vaccination rate has led to the pressing need for a specialised epidemiological model.

Based on the SEIR model, we propose a SEIRQV model that represents Singapore's government's major measures such as lockdown, vaccinations, boosters, and quarantine. We also include waning vaccine efficacy and provision of booster shots.

## Literature Review

Ever since the start of the Covid-19 pandemic, researchers around the world have taken to model the spread of the virus to forecast the epidemic's spread, magnitude, and duration, via estimating various epidemiological parameters such as the reproductive number. Most Covid-19 prediction models build upon the basic SIR (Susceptible-Infectious-Removed)<sup>[1]</sup> or SEIR compartmental model with the addition of the "Exposed" compartment<sup>[12]</sup>, which is more useful due to the dormant period before becoming infectious, as is the case in most diseases.

### Hybrid modelling

Compartmental models are often used among epidemiologists, especially during the current Covid-19 pandemic, to model disease transmission in a population under certain scenarios and are a widely used tool to carry out counterfactual analysis. Thus, hybridising it with a good data assimilation method allows for better visualisation of the positive impact brought by Covid-19 mitigation measures (CMMs), which spans mobility restrictions, mask donning, vaccine jabs, quarantining of travellers, contact tracing operations to social distancing.

### AI model

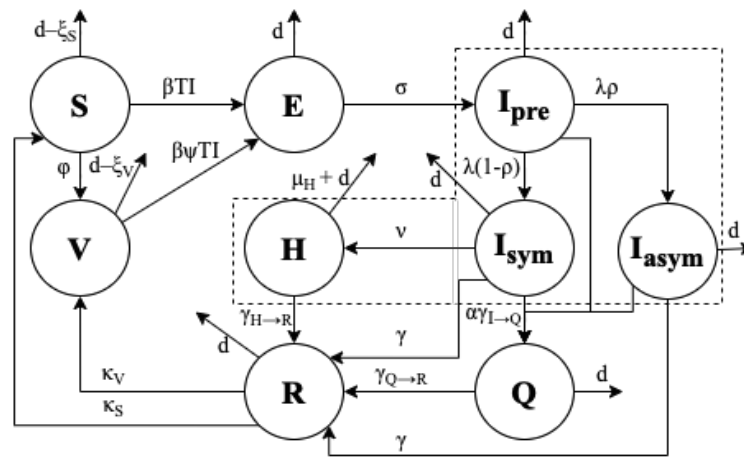
The use of AI is also being actively explored to improve models<sup>[4,13]</sup>. AI is mainly used to approximate unknown values<sup>[3,5]</sup>, extrapolate a time series<sup>[8,14]</sup>, or consider other environmental conditions<sup>[14]</sup>.

### Causal model

Ansah et al 2021, via the usage of counterfactual analysis and a modified SIR model (that differentiates diagnosed and undiagnosed cases), revealed that the Singapore government's strict measures have been extremely effective in containing the spread of Covid-19, reducing the caseload by a factor of 10.

## The Model

Based on the susceptible-exposed-infected-removed (SEIR) compartmental model, we included quarantine and vaccinated compartments to improve the accuracy of pandemic modelling. An individual can be in one of each state, susceptible (**S**), exposed (**E**), infectious (**I**), recovered (**R**), dead (**D**), vaccinated (**V**), and quarantined (**Q**). Below shows a flowchart summarizing the model. Due to the high rate of asymptomatic Covid-19 cases, the **I** compartment includes not just the hospitalised (**H**) subcategory, but also pre-symptomatic (**I<sub>pre</sub>**), asymptomatic (**I<sub>asym</sub>**), and symptomatic infected (**I<sub>sym</sub>**). Each compartment represents a fraction of the total population,  $N$ . The parameters on the arrows in the figure shown indicate the proportion of individuals from one compartment entering another.



Mathematically, the dynamic process of SEIRQV can be described as such:

$$\begin{aligned} \dot{S} &= -\beta TSI + \kappa_S R - (\phi + d - \xi_S)S \\ \dot{E} &= \beta T(S + \psi V)I - (\sigma + d)E \\ \dot{I} &= \sigma E - (\alpha \gamma_{I \rightarrow Q} + \mu + (1 - \alpha)\gamma + d)I = \sigma E - C_I I \\ \dot{Q} &= \alpha \gamma_{I \rightarrow Q} I - (\gamma_{Q \rightarrow R} + d)Q = \alpha I - C_Q Q \\ \dot{R} &= \gamma_{Q \rightarrow R} Q + (1 - \alpha)\gamma I - (\kappa + d)R \\ \dot{V} &= \phi S - \psi \beta TVI + \kappa_V R - (d - \xi_V)V \end{aligned}$$

$(1 - \psi_V)$ , denotes the protection against infection after being doubly vaccinated. Every individual that are newly vaccinated/ received a booster shot is assumed to have a vaccine efficacy “half-life” of 300 and 500 days respectively, such that  $\psi_{V,i} = 1 - (1 - \psi_{V,i}) \left(\frac{t}{2}\right)^{\frac{1}{300}}$ .

To take booster shots into account, we use  $\psi$  to denote net vaccine non-protection, where:

$$\psi = \sum_{i=t_V}^{t \geq t_V} (\psi_{V,i}(V(i) - B(i)) + \psi_{B,i}B(i)) \text{ and } B = \phi_B \max\left(0, \min\left(t_B + \frac{V}{\phi_B}, t\right) - t_B\right).$$

### Table of expressions:

Symbol	Represents:
$\phi, \phi_B$	Those getting fully vaccinated or booster shots per day as a fraction of $S$ and $V$ respectively
$\psi$	Net vaccination non-protection against infection
$\kappa$	The rate needed for recovered individuals to become vulnerable to infection (assume it is very small) Note: $\kappa_S = \frac{S}{S+\psi V} \kappa, \kappa_V = \kappa - \kappa_S$
$\sigma$	Reciprocal of the incubation period, $\sigma_{og} = \frac{1}{\tau_{inc}}^{29}$
$B$	Total number of individuals who had booster shots (were previously vaccinated) as a fraction of $V$
$\alpha$	Net proportion of infected individuals quarantined, assumed as 78.4% , (Appendix)
$\rho$	Proportion of asymptomatic individuals, about 42.5%
$\gamma$	$\frac{1}{\tau_{inf}}$ , reciprocal of infectious period (Note: $\frac{1}{\gamma_{I \rightarrow Q}} + \frac{1}{\gamma_{Q \rightarrow R}} = \frac{1}{\gamma_{I \rightarrow H}} + \frac{1}{\gamma_{H \rightarrow R}} = \frac{1}{\gamma} \approx 10 \text{ days}^{27}$ )
$\mu$	Rate of death among infected individuals <b>per day</b> , about $4.1 \times 10^{-6}$ as of January 2022
$\beta$	Contact rate, usually multiplied with <b>transmissibility rate</b> , $T = (1 + (\eta - 1)\rho)T_{Covid}$
$t_V, t_B$	Relative date (from $t_0$ ) when vaccine/ booster shots become available
$d$	Daily deaths (in 2019), about $1.36 \times 10^{-5}$ <sup>33</sup>
$\eta$	Relative transmissibility of asymptomatic individuals with respect to symptomatic, about 50%,
$\lambda$	Reciprocal of the pre-symptomatic infectious period, about $\frac{1}{5} \text{ days}^{-1}$
$\xi_S, \xi_V$	Sum of births ( $S$ ) and overall immigration as a fraction of $S/V$ per day, $\xi$ totals to $-3.382 \times 10^{-5}$

In this paper, we aim to:

1. Simulate Covid-19 spread in Singapore solely using this SEIRQV model (utilising Kalman filter or KF) and thus estimate key parameters ( $\gamma$ ,  $\beta$  and  $T$ )
2. Simulate Covid-19 spread in Singapore using a hybrid AI model (using SIR model)
3. Analyse the effects of pandemic interventions on Covid-19 spread locally
4. Prove or disprove our hypothesis that government interventions cause a great decrease in Covid-19 caseload.

### The hybrid AI model

It is a cyclic process which progressively improves the accuracy of critical values  $\beta, \gamma, R_0$ . Our hybrid model is bond on a SIR hybrid model done in the paper [3]. Our improvement on the model is adding compartments for exposed (E) and vaccinated (V) populations. From the existing data, a time trend of  $\beta$  is determined. To extrapolate data, a long-short-term memory (LSTM) neural network is trained on the time trend of  $\beta$  and predicts the future trend. The data source originates from Our World in Data [35] and Worldometer [34].

### Mathematical approach to predicting pandemic trajectory

As the SEIRQV model is a system of non-homogenous linear differential equations, where:

$$\mathbf{y}' = \mathbf{U}(t)\mathbf{y}(t)$$

We can express the system (excluding Deaths) as such:

$$\begin{pmatrix} \dot{S} \\ \dot{E} \\ \dot{I} \\ \dot{Q} \\ \dot{R} \\ \dot{V} \end{pmatrix} = \begin{pmatrix} -\phi - d + \xi_S & 0 & -\beta TS & 0 & \kappa_S & 0 & S \\ 0 & -\sigma - d & \beta TS & 0 & 0 & \beta T I \psi & E \\ 0 & \sigma & -C_I & 0 & 0 & 0 & I \\ 0 & 0 & \alpha \gamma_{I \rightarrow Q} & -C_Q & 0 & 0 & Q \\ 0 & 0 & (1 - \alpha) \gamma & \gamma_{Q \rightarrow R} & -\kappa - d & 0 & R \\ \phi & 0 & 0 & 0 & \kappa_V & -\beta T I \psi - d + \xi_V & V \end{pmatrix}$$

Unfortunately, since  $U$ 's eigenvalues are extremely complex (refer to Appendix), we decided to simplify the matrix to greatly reduce its complexity and obtain more useful expressions.

### Observing dynamics of extended SEIR model

Thus, we can approximate the solution when  $\dot{V} \approx 0$ , (valid for short-term predictions)

$$\begin{pmatrix} \dot{S} \\ \dot{E} \\ \dot{I} \\ \dot{Q} \\ \dot{R} \end{pmatrix} = \begin{pmatrix} -\phi - d + \xi_S & 0 & -\beta TS & 0 & \kappa_S & S \\ 0 & -\sigma - d & \beta T(S + V\psi) & 0 & 0 & E \\ 0 & \sigma & -C_I & 0 & 0 & I \\ 0 & 0 & \alpha \gamma_{I \rightarrow Q} & -C_Q & 0 & Q \\ 0 & 0 & (1 - \alpha) \gamma & \gamma_{Q \rightarrow R} & -\kappa - d & R \end{pmatrix}$$

The eigenvalues are  $-d - \phi$ ,  $-C_Q$ ,  $-d - \kappa$ ,  $\frac{-(\sigma + C_I + d) - \sqrt{\Delta}}{2}$ ,  $\frac{-(\sigma + C_I + d) + \sqrt{\Delta}}{2}$ , assuming  $\xi_S = 0$ .

The determinant,  $\Delta = (\sigma + C_I + d)^2 - 4((d + \sigma)C_I - \sigma\beta T(\psi V + S))$  (solution in A3)

Finally, we arrive at the solution (where each eigenvector,  $X_n$ , is positive):

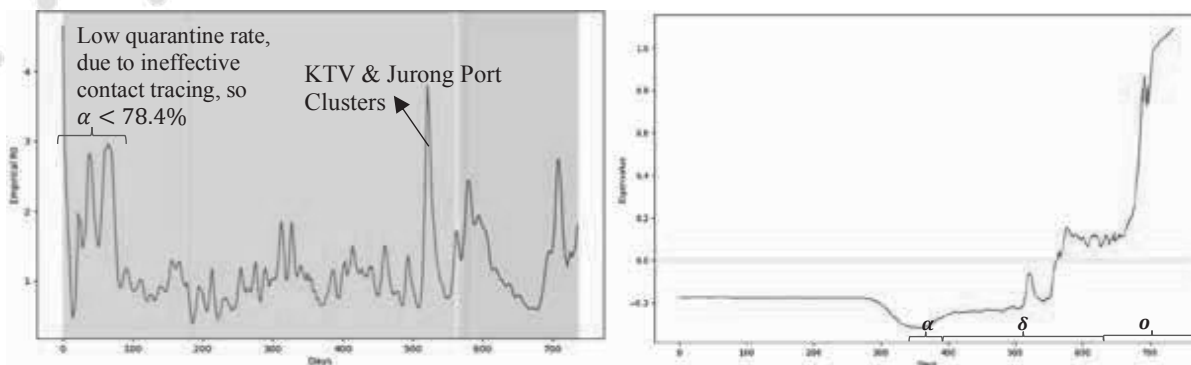
$$\begin{pmatrix} S \\ E \\ I \\ Q \\ R \end{pmatrix} = \sum_{n=1}^5 c_n e^{\lambda_n t} X_n, \text{ for } c_n \text{ such that } \sum_{n=1}^5 c_n X_n = \begin{pmatrix} S(0) \\ E(0) \\ I(0) \\ Q(0) \\ R(0) \end{pmatrix}$$

Currently,  $\gamma_{I \rightarrow Q} \approx \frac{1}{4+1} = \frac{1}{5}$ <sup>18,19,22</sup>, and assuming  $\alpha = 78.4\%$  as rationalised in the appendix, allowing us to obtain  $C_I \approx 0.8056$ . From this, we can estimate the boundary conditions needed to for a growth or decline in caseload, where  $R_0 = 1$ . As the largest eigenvalue (and thus rate-determining exponent) is  $\lambda_5$  (since other eigenvalues are always negative), it allows us to predict Covid-19 trends by checking its sign (This criterion is only valid when quarantine is a very commonly followed procedure, especially when it is enforced by quarantine orders for close contacts, which is no longer done after October 11<sup>th</sup>, 2021):

$R_0$	$\lambda_5$	Requirement (valid until Oct 11 <sup>th</sup> , 2021 <sup>[45]</sup> )	Caseload
$R_0 > 1$	$\lambda_5 > 0$	$\sqrt{\Delta} > 0.8056 + \sigma$	exponential growth
$R_0 = 1$	$\lambda_5 = 0$	$\sqrt{\Delta} \approx 0.8056 + \sigma$	approximately constant
$R_0 < 1$	$\lambda_5 < 0$	$\sqrt{\Delta} < 0.8056 + \sigma$	exponential decrease

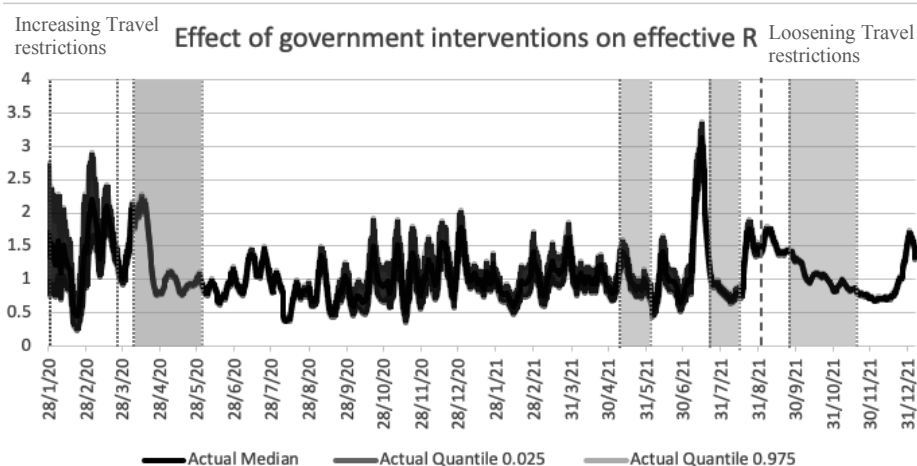
This is further verified by Diekmann et al, 1990, which proved that  $\lambda + 1 = R_0$ , where  $\lambda$  is the largest eigenvalue. Thus, this eigenvalue criterion can help us to quickly approximate the

trend of the epidemic based on just one datapoint. The graphs below show the accuracies of the graphs:



From the graphs, it is evident that the criterion is highly insensitive, but at least accurately showed that Singapore’s Covid-19 spread is kept in bay till about 5 August 2021 onwards, when it began growing exponentially, despite a decrease in November to December. This is likely due to the sharp increase in transmissibility of Covid-19 due to Omicron variant dominating Delta, so the dip in active cases only causes a very small decrease in eigenvalue in the right-side graph.

Since the criterion is theoretical and is based on many idealistic assumptions (which has been shown to be inaccurate), thus we must resort to using data assimilation hybrid models like KF-SEIR and LSTM-SEIR models to accurately predict how a pandemic will progress. In the following graph, R is determined by taking the 7 days average of daily Covid-19 cases, and comparing it with the 7-day average a week ago, adjusted for changes in susceptible populations as shown below:  $R_t = \frac{\beta_i S_i I_{avg,i}}{\beta_{i-7} S_{i-7} I_{avg,i-7}}$  The graph below illustrates how significant government interventions have been on reducing  $R_t$ .



This illustrates how government interventions are strongly associated with a sharp decrease in  $R_t$ , as seen by the effect of the progressive implementation of CMMs since 29<sup>th</sup> January, the

Circuit breaker (4<sup>th</sup> April to 1<sup>st</sup> June), and each subsequent tightening up of CMMs during May, July and October, which help to stabilise and gradually lower infection rate. This allows us to hypothesize that government measures is highly effective at reducing Covid-19 spread.

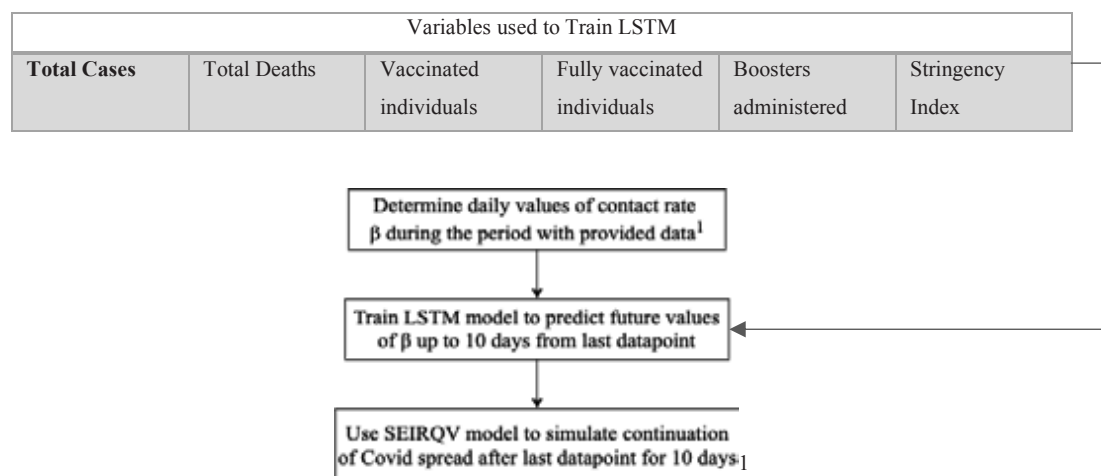
## Methodology

### SEIRQVD + KF model

As mentioned above, we used a SEIRQV model to simulate Covid-19 spread in Singapore. The Python library SciPy is used to numerically integrate the differential equations governing the system to get a time series of the SEIRQVD compartments. The KF model takes in data of active cases, recovered cases and deaths. State vectors of SIRD compartments and parameters  $\beta$ ,  $\gamma$  and  $\mu$  are used with the matrix update equations seen in KF models to get a series of the parameters over time.

### Hybrid AI model

The flow of the hybrid model is vastly different from the pure math SEIRQV model. Rather than start with an initial state, this model utilises actual data of Covid-19 spread in Singapore. The model also used other factors such as stringency index and booster shots to better model the changes in parameters  $\beta$ ,  $\gamma$ ,  $\phi$ .



The figure above shows how the hybrid AI model is implemented. In the 2<sup>nd</sup> step, value of  $\beta$  on a certain day is calculated by rearranging the SEIR differential equations, as shown:

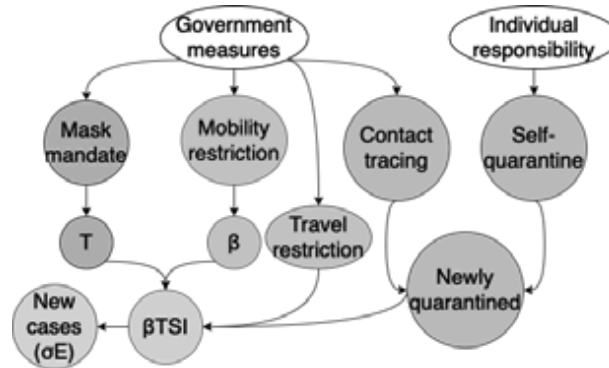
$$S_{t+1} = S_t - \frac{\beta I_t S_t}{N}$$

$$\beta = \frac{N}{I_t} \left( \frac{S_t - S_{t+1}}{S_t} \right)$$

<sup>1</sup> (15 Feb 2020 – 17 Dec 2021); Model is adapted from Ossa et. al, 2021's Neuro-hybrid Covid-19 model<sup>[26]</sup>

### Causal model

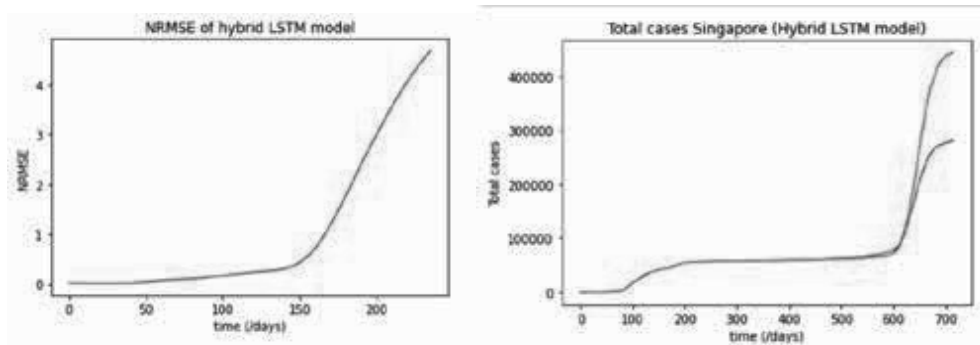
To obtain more meaningful and in-depth understanding of how relevant factors affect Covid spread, we decided to use a comprehensive directed acyclic graph (DAG) to not only illustrate the multifarious causes affecting Covid-19 spread but also attempt to find the resulting SEIRQV and new cases graphs given certain scenarios. Below shows the causal DAG:



## Results and Discussion

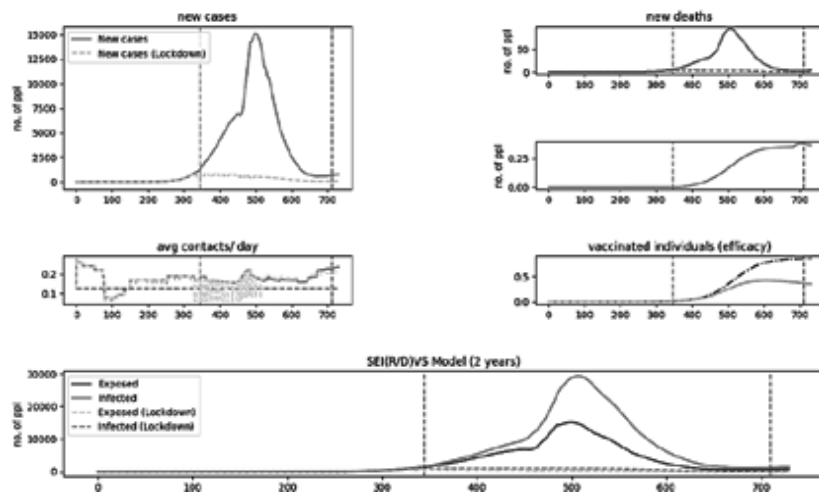
### SIR-LSTM hybrid AI model

The following graph shows the comparison of the LSTM model's prediction from day 400 to 700 compared with the actual data, showing that the initial 150 days rather accurately models the rise in cumulative cases, which is not the case afterwards, as they diverge sharply. The graph on the left shows the normalised root mean squared error (NRMSE) of the model while the one on the right shows the total cases predicted by the hybrid AI model vs the actual cases (begins prediction at Day 500 after 23 January 2020)



### SEIRQV model simulation

This SEIRQV model shows the likely possible result when no government restrictions are put in place to mitigate the pandemic (i.e.,  $\alpha = 0$ ) as compared to when  $\alpha = 1$ :

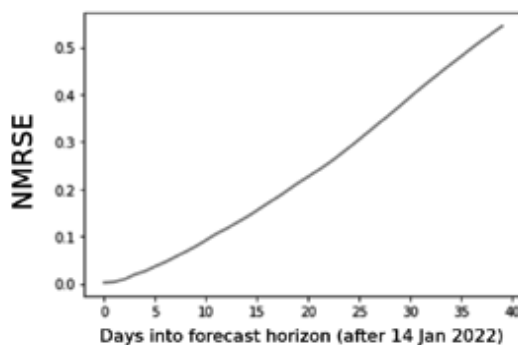


This comparison (despite not matching caseloads in reality) manages to show that the second Delta wave would have arrived much sooner and severely, suggesting that government SMM measures have managed to push it back a month and avert an even worse upsurge in cases. Via counterfactual analysis, we found that the cumulative number of cases in a no-quarantine scenario, or  $\alpha = 0$ , is 10.42 times that of in a 100%-quarantine scenario, or  $\alpha = 1$ .

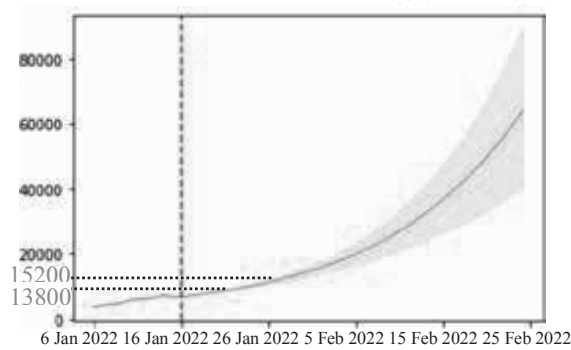
This model based on the following constants for each time:

Variant name	Transmission rate (unvaccinated) / $\sigma$	Transition period
Original	$0.075^{[23,28]} / \frac{1}{5.2} \text{ days}^{-1} [41]$	mid-Feb 2021
Alpha	$0.1305^{[24]} / \frac{1}{3} \text{ days}^{-1} [43]$	mid-May 2021
Delta	$0.196^{[25]} / \frac{1}{4} \text{ days}^{-1} [44]$	mid-Dec 2021
Omicron	$0.402^{[38]} / \frac{1}{3} \text{ days}^{-1} [42]$	—

SIR-KF model



Using the SIR-KF model, we can predict Singapore's active cases for the next 40 days (assuming no government intervention, based on data from Jan 23<sup>rd</sup>, 2020 to Jan 16<sup>th</sup>, 2022):



The numbers in orange (actual 7-day average of active cases <sup>[34]</sup> for each date 21<sup>st</sup> and 27<sup>th</sup> January 2022, to dampen the impact of outliers), thus the KF predictions are rather accurately. The upper and lower bounds of this graph represent the 95% confidence interval, showing that the uncertainty of predicted active cases increases at an exponential rate. As we think the Singapore Government would not allow such a surge in Covid-19 cases, assuming the prediction is accurate, a tightening of restrictions during mid-February may be necessary.

### Limitations

The model overgeneralizes the movement of individuals and treats the parameters as discrete variables rather than distributions. Thus, we are unable to account for super-spreader events in our model, as  $\beta$  varies a lot per person, as shown by the superclusters during mid to end of July 2021. In addition, due to our inability to account for reporting rate of Covid-19 infection in Singapore, we can only assume that there is no underreporting of cases. Also, we could have made the model more comprehensive such as by separating the Infected compartment into categories like asymptomatic, mild, and severe <sup>[2,9,15,16]</sup> instead of merging them together. Additional depth in compartments can also account for social interactions between and within groups, by creating multiple SEIR compartments for different demographics of people <sup>[7]</sup>.

### Conclusion

From the results, we have clearly showed that the presence of government restrictions has very effectively reduced the spread of Covid-19.

### Future work:

Due to the overgeneralisations as aforementioned, further research can be done on models where parameters are not discrete but rather distributions, where  $\beta, \gamma$  can be modelled based on a gamma distribution while the latency rate can be modelled as a logistic distribution, all of which has been shown to accurately fit real-life data for specific  $k, \theta$  and  $\mu, s$  respectively. The model can be made more accurate by integrating models that account for the assumptions

made by the other, and processing their predictions via a weighted average where a more accurate

In conclusion, the modelling capability of the numerical SEIRQV model can be improved by using better parameter estimation and a more comprehensive compartmentalisation of the population based on public health interventions, healthcare system capacity, population distribution and vaccination rate. Our KF model could be improved with more accurate methods to estimate parameters based off crude data.

### **Acknowledgments:**

We would like to thank our school and research mentor Mrs Liu (Ye Xia Juan) for her guidance in this project.

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## Appendix

A1: Eigenvalues of 6x6 matrix: [here](#)

A2: Due to  $\alpha_{sym} = q + h$  and  $\alpha_{asym} = h$ , where  $q$  represents self-quarantine rate, assumed to be 80% for symptomatic individuals and 0% otherwise, and  $h$  represents contact-tracing effectiveness, which stands at about 60%<sup>[27]</sup> after an individual was traced just 1 day after they no longer are pre-symptomatic (can be either symptomatic or asymptomatic), thus  $\alpha = \alpha_{sym}(1 - \rho) + \alpha_{asym}\rho = 78.4\%$

A3: In observing dynamics of SEIRQV model, the detailed solution is as follows:

$$\det \mathbf{U} = (-\kappa - d - \lambda)(-\phi - d + \xi_s - \lambda)(Q(x))(-C_Q - \lambda) = 0$$

$$\text{Solve: } Q(x) = -\sigma\beta T(\psi V + S) + (d + \sigma + \lambda_{4,5})(C_I + \lambda_{4,5}) = 0$$

$$\lambda_{4,5} = \frac{-(\sigma + C_I + d) \pm \sqrt{\Delta}}{2}, \Delta = (\sigma + C_I + d)^2 - 4((d + \sigma)C_I - \sigma\beta T(\psi V + S)) > 0$$

$$(x + y)^2 \geq 4xy \Rightarrow (\sigma + d + C_I)^2 \geq 4(d + \sigma)C_I; \because 4\sigma\beta T(\psi V + S) > 0 \Rightarrow \Delta > 0 \blacksquare$$

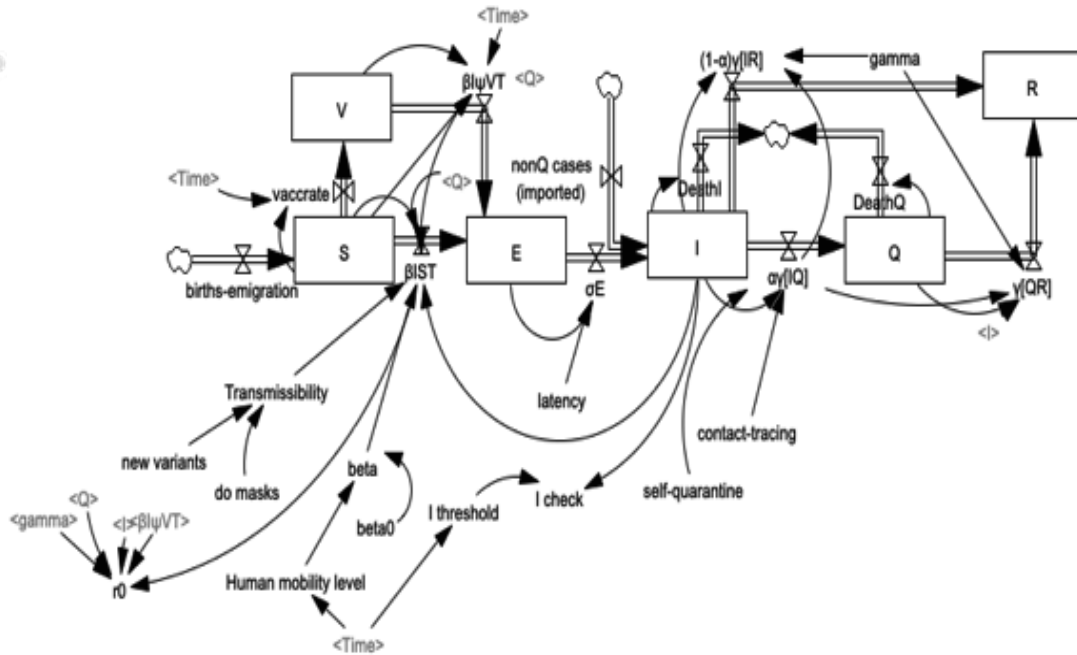
A4: We assume Singapore's pre-Covid-19 net contact rate,  $\beta_0 \approx 2.7 \text{ day}^{-1}$  (Observed median from distribution curve of a Hong Kong study<sup>20</sup>, adjusted based on average household size (Hong Kong: 2.7<sup>21</sup>; Singapore: 3.22<sup>39</sup>)).

A5: Google drive folder of all codes used in this project:

[https://drive.google.com/drive/folders/1w7XzmSNMVff8bUgqgMK2gY5d0a736JF\\_?usp=sharing](https://drive.google.com/drive/folders/1w7XzmSNMVff8bUgqgMK2gY5d0a736JF_?usp=sharing)

## Causal model

Below shows the causal diagram modelled on Vensim PLE (right)



We assume  $\beta$  varies proportionally with that of mobility changes relative to pre-Covid-19 levels using the model by the Institute of Health Metrics and Evaluation (IHME), with respect to  $\beta_0$ . Using Chu et al's estimate that masks have an average effectiveness of 67%<sup>[40]</sup>, mask usage rate is 90%, we arrive at  $T_{mask} = (1 - mp) \approx 0.397$ , we find that transmissibility is reduced to about 39.7% of the initial level. In addition, to take the rapidly evolving Covid-19 pandemic into account, we ensured the changes brought by new variants to the key parameters changed gradually via a logistic function.