Exploring the Effectiveness of Compartmental Models to Predict Epidemiological Trends

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The Coronavirus Pandemic & The Omicron Oscillation Problem

COVID-19:

- In 2020, an Imperial College study used compartmental models to predict that an unhindered COVID-19 pandemic could kill over half a million UK residents [1].
- Their findings provided key scientific advice to the British government to aid in enforcing public guidance and social restrictions with the aim to lower mortality and reduce pressure on the National Health Service (NHS).
- This shows the importance of modelling the spread of epidemics such that we can act quickly to intervene and reduce preventable fatalities and other global impacts.

Omicron Oscillation Problem:

- Data gathered by WHO displays a clear set of sustained oscillations in COVID-19 Omicron infections and fatalities between June 2022 and 2023 (Fig 1) [2] .
- The weekly cases show a damped oscillation whereas fatalities hold consistent in their amplitudes.
- The decrease in the amplitude of cases can be attributed to a decrease in testing frequency when the public was required to pay for LFTs (Free Lateral Flow Testing ended in April 2022) [3]. Officially registered deaths do not have this issue and thus stay constant.
- The fundamental aim of this project is to attempt to reproduce this trend through the implementation of a series of compartmental models thus underlining their effectiveness.

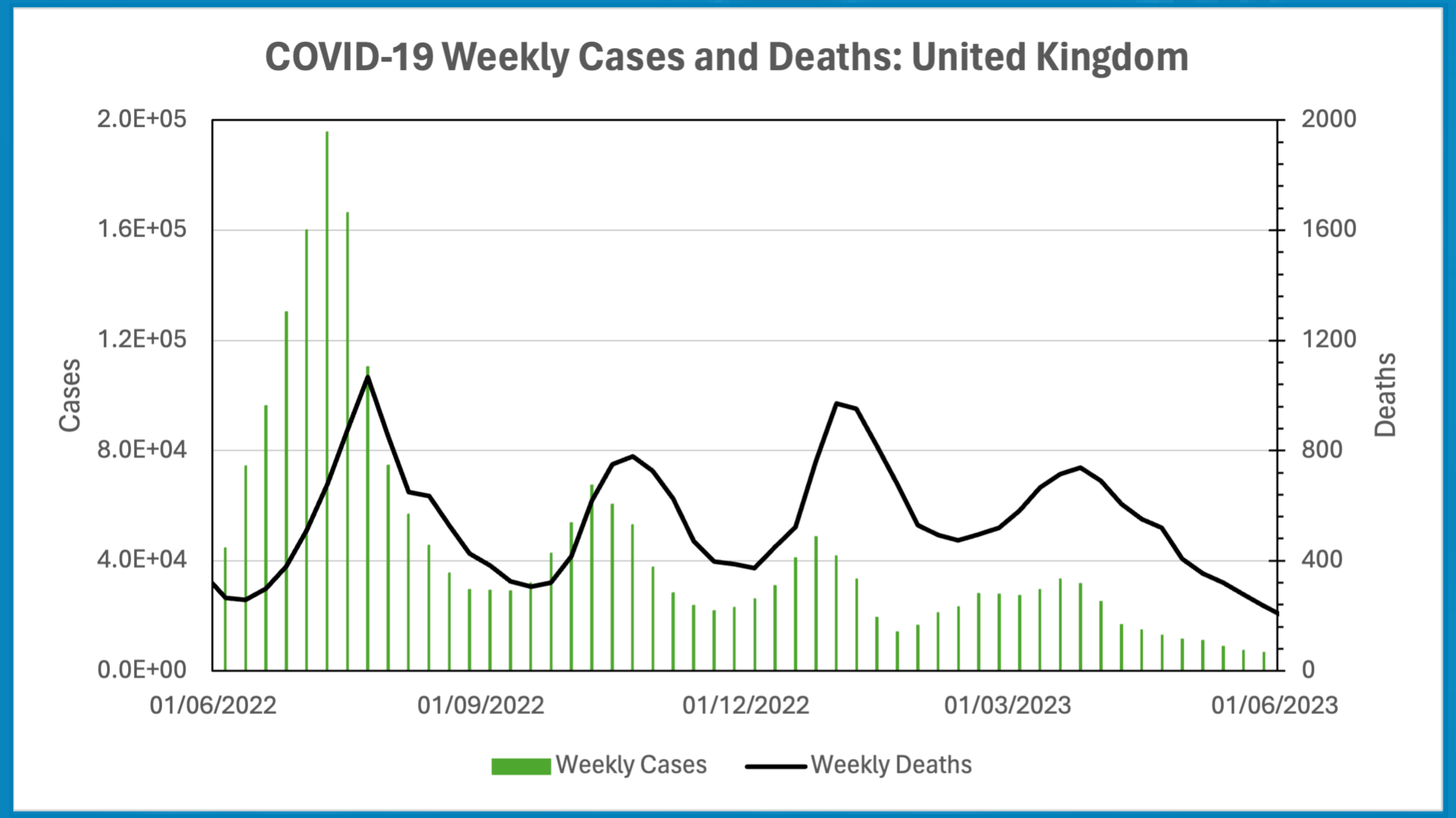

Fig 1: Weekly COVID-19 infection and fatality data among the UK population between June 2022 and 2023. A clear oscillation pattern arises in both sets of data with death tolls peaking roughly two weeks after infections as expected (people do not pass away immediately). The period of these oscillations is 3 months (~ 90 days). Data acquired from [2].

Compartmental Models

SIR Model:

- As seen from the study by Imperial College [1], Compartmental models are a key mechanism in predicting the effects of epidemics.
- The foundation is the Susceptible, Infected & Resistant model, commonly known as SIR. The model is comprised of the following ODEs:

$$\frac{\partial S}{\partial t} = -\beta S I \qquad \frac{\partial I}{\partial t} = \beta S I - \gamma I \qquad \frac{\partial R}{\partial t} = \gamma I$$

Where β & γ are the infection and recovery rates associated with the virus.

SEIR, SIRS & SEIRS:

- A key feature of compartmental models is that they can always be expanded to resemble more complex systems.
- The SEIR model adds an "Exposed" section effectively splitting the infection compartment in two to signify that people can be carrying the disease prior to feeling sick.
- The SIRS variant importantly allows individuals to lose their immunity and return to the susceptible stage over time.
- SEIRS is the next stage in evolution combining the key features from both of the previous models.

Spatial SIRS:

- One key feature that the other approaches lack is a spatial component, this method uses the concepts of cellular automata to implement a spatial version of the SIRS model
- The model is implemented stochastically such that on each iteration a random node is selected and its four nearest neighbours are assessed on whether they are infected. The system repeats this process routinely updating each node using transition parameters defined upon initialisation.

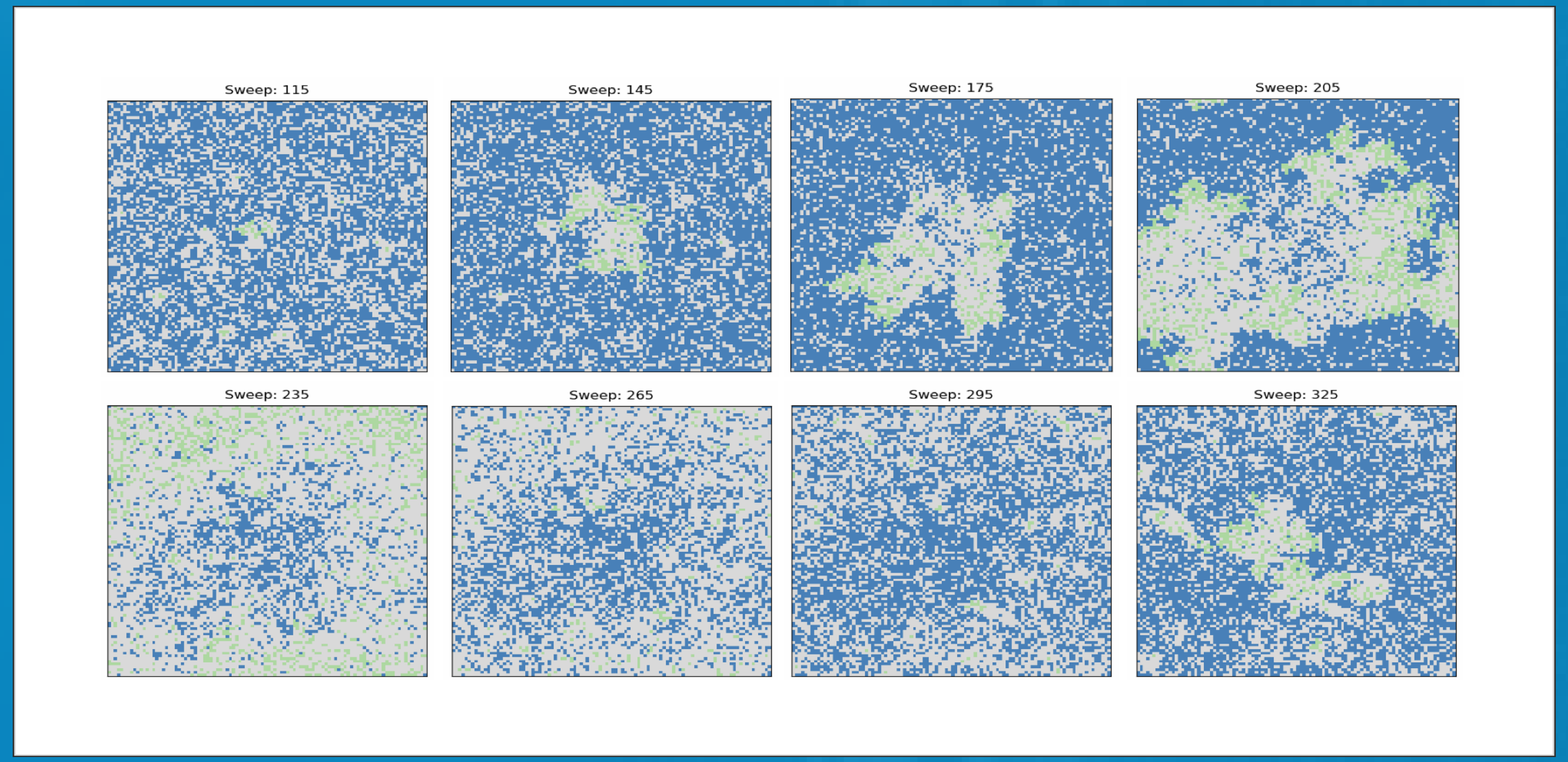

Fig 3: The plots show the stages of a single wave of infection spreading through a system in a spatial SIRS model. The blue, green and grey nodes represent Susceptible, Infected and Resistant individuals respectively.

Results & Conclusions

Results:

- The spatial SIRS model proved to be the most effective approach in producing sustained oscillations in infection numbers as shown in Fig 3.
- Fig 3 shows the mean period of oscillations for R_0 = 3, to be 237.5 days with infection peaks reaching an average value of 9.7(7)% of the population.
- Here R_0 is the basic reproduction number referring to the number of secondary infections generated by an individual at the beginning of an epidemic.
- The Omicron data in Fig 1 shows a consistent period of 90 days affecting between 3-8% of the population at a time. However, the upper boundary likely provides a better representation of the real behaviour due to reduced testing frequency and consistency [3].
- Thus the R_0 = 3 results lie within 2.38σ of the expected result for peak infected fraction, the oscillatory period is however 2.64x larger than expected.
- Further simulations with varied R_0 values found an inverse correlation with the period, although it is likely that the period also relates strongly to the geometric setup of the system. Thus, improved model and parameter optimisation could reduce the discrepancy in results.

Conclusion:

- Analysis of the spatial SIRS model was able to accurately reproduce the real trends in epidemiological data and thereby was able to conclude an estimate for the value of R_0 for the Omicron variant to be around 3.
- This shows the effectiveness of compartmental models to predict real situations and its use during COVID-19 allowed us to save over 250,000 UK lives, further underlining their importance in protecting society.

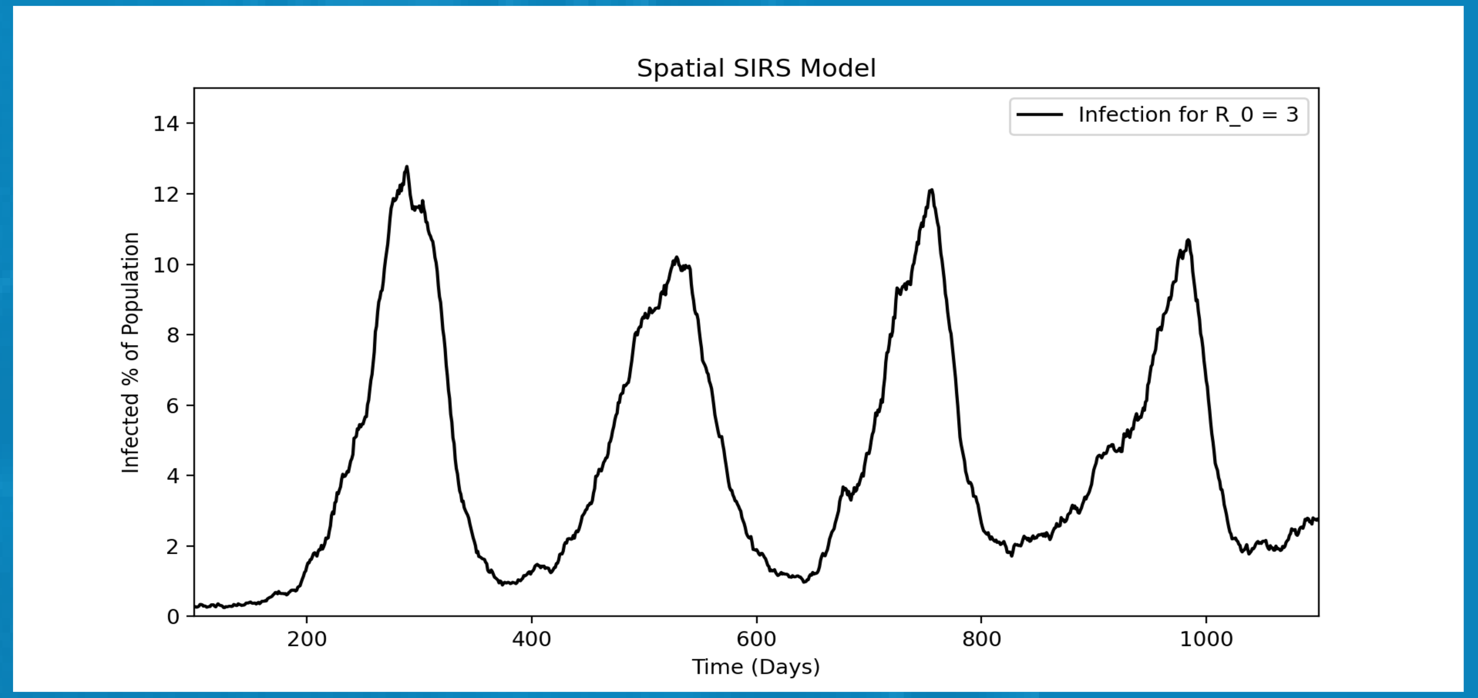

Fig 3: The plot shows the results of the spatial SIRS model for R_0 = 3 using estimated COVID-19 recovery and immunity periods of 10 and 100 days respectively.

References

1. Neil M. Ferguson et al. Report 9: Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand. *Imperial College London*, 2020
2. World Health Organization 2023. WHO Coronavirus (COVID-19) dashboard. Date Accessed: 15th March 2024
3. UK Health Security Agency. Guidance COVID-19: testing from 1 April 2024, 2024

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