Investigating vaccination roll out strategies for COVID-19 in Ireland

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Contents

1 Abstract

We examine the effects of inoculating the Irish population against COVID-19 by developing a SEIR-type mathematical model. The model will be an extension of the current efforts of the Irish Epidemiological Modelling Advisory Group to chart the evolution of COVID-19 in Ireland from the onset of the pandemic up to May 2021. We distinguish between distinct age cohorts in the population as well as vaccination status. We apply optimisation techniques to fit our model against epidemiological data for COVID-19 in the early months of 2021. We investigate the extent to which the effective reproductive number of the disease is reduced through vaccination as well as adjusting our vaccination rates within the model to reflect a range of different strategies in vaccinating the population in search for an optimal strategy which minimises further cases and deaths of COVID-19 in the near future.

2 Introduction

In the eighteen months following the emergence of the SARS-CoV-2 virus, there have been more than 183 million confirmed cases and 3.9 million deaths recorded globally as of July 2021 [1]. In order to ease the significant strain placed upon global healthcare systems by the COVID-19 pandemic, there is an urgency to develop and deploy effective vaccines which reduce the virulence of the disease. Development of vaccines against SARS-CoV-2 began shortly after the onset of the pandemic in early 2020, and as of July 2021, there are four vaccines which have been authorised by the European Medicines Agency for widespread use in the European Union: Comirnaty ("Phizer-BioNTech"), Spikevax ("Moderna"), Vaxzevria ("AstraZeneca") and Janssen [2]. All four have been shown to be effective against the disease, with clinical trials indicating efficacies as high as 95% in preventing symptomatic infection [3]. There are four additional vaccines currently under rolling review by the European Medicines Agency, thus it is expected that there will be an adequate number of vaccines to inoculate the entire population of the European Union by the end of 2021. Administration of vaccines is complicated by the varying dynamics of COVID-19 across a given population. The risk of severe disease and mortality from COVID-19 increases with age, and the risk of infection is highest among those with the highest contact rates and individuals in contact with infected patients, such as healthcare workers. Since the mass vaccination program against SARS-CoV-2 in Ireland is expected to take several months, subsequent waves of infections are to be expected and it is vital for Ireland to have implemented a vaccination strategy which will minimise deaths in the long term. Reducing deaths may arise from vaccinating the most vulnerable individuals as soon as possible, or vaccinating those most at risk to infection in order to keep the overall number of cases low. Our current vaccination strategy has been largely age-dependent, however the recent emergence of variants, such as the B.1.617.2 variant of SARS-CoV-2 (the "Delta variant"), has led to concern over the lack of vaccine coverage in the younger populations, who possess the highest contact rates.

The aim of this report is to compare our current vaccination strategy and rate of vaccination

across different age groups against other plausible strategies which may instead have been implemented at the end of 2020. A single population model will not effectively capture the differences in infectiousness and severity of COVID-19 across different age bands, and so we extended a SEIR-type model [4] implemented by the Irish Epidemiological Modelling Advisory Group (IEMAG) in the early stages of the pandemic to account for vaccinations in the populations at varying rates across the age cohorts. The model will be fitted to data in the January - May 2021 period, after which the rates of vaccination will be adjusted to reflect different vaccination strategies. Finally, we wish to determine which strategy is optimal by simulating the various vaccination strategies forward in time under set assumptions and identifying the strategy which leads to the fewest cases and deaths of COVID-19 in the near future.

3 Methods

3.1 IEMAG models

Two SEIR models published by the Irish Epidemiological Modelling Advisory Group (IEMAG) provide the foundation of the vaccination model utilised in this report. The first model [5], published in April 2020 ("Design v0.2") provides the formulation for extending a single population model into a model which distinguishes between multiple populations. The second model [4], published in November 2020 ("IEMAG population-level") is the model used by IEMAG to chart the evolution of the COVID-19 pandemic in Ireland and present their findings and trajectories to the National Public Health Emergency Team (NPHET). The governing equations of the IEMAG population-level model are shown in Appendix A, with all compartments and parameters interpreted as defined in [4]. The source code formulating the IEMAG population-level model and its calibration algorithm are both publicly available, and can be implemented in R [6]. In the calibration algorithm, a sample for the time-dependent transmission rate $\beta(t)$ is generated from over 1000 posterior realizations of a negative binomial generalized additive model (GAM) fitting procedure, a procedure outlined in detail in the original technical notes [4].

Calibration of the IEMAG population-level model served as the first step to familiarise ourselves with the model and its dynamics. As a starting point, we simulated the IEMAG population-level model in R from the onset of the pandemic to May 14th 2021, over which the model parameters were drawn from a uniform distribution and 1000 realizations of $\beta(t)$ were generated. From these realizations, we obtained an estimate of the time-dependent transmission rate $\beta(t)$ by taking its mean value over its sample. Next, we rewrote the code in Python over the same time period. We used the `odeint` function from the scipy package in Python for the IEMAG simulation and for all simulations of the vaccination model henceforth. Likewise, all computation of our vaccination model carried out hereafter was implemented in Python. We simulated the code with the estimated transmission rate $\beta(t)$ and confirmed that it provided an adequate fit to the COVID-19 case data available in the January-May period.

3.2 Vaccination Model

3.2.1 Compartments and Parameters

The vaccination model used in simulations forward from January 2021 is an extension of a SEIR-type age cohort model designed by IEMAG. It consists of twelve states, $\{S_0, S_1, S_2, E, IP, IA, IS, IT, R, Ailing, D, Cases\}$ = {Fully susceptible, Susceptible (one dose), Susceptible (two doses), Exposed, Infected (presymptomatic), Infected (asymptomatic), Infected (symptomatic), Infected (awaiting test), Recovered, Ailing, Dead, Cases}. For each state, there are three age cohorts denoted by i = {youth (aged 0-24), adult (aged 25-64), seniors (aged 65+)}. This results in a model with 36 compartments in total. Since this is a multi-population model, there are a total of nine contact rates differing by the class in which the exposed individual and infected individual belong to. The contact rates can be represented by the following matrix,

$$\begin{pmatrix} \beta_{CC} & \beta_{CA} & \beta_{CS} \\ \beta_{AC} & \beta_{AA} & \beta_{AS} \\ \beta_{SC} & \beta_{SA} & \beta_{SS} \end{pmatrix} \tag{1}$$

where {C, A, S} = {youth, adult, senior} and the (i, j) entry denotes the contact rate that population i holds with an infected individual from population j.

Symbol	Biological Description	Lower Bound	Upper Bound	Value
L	latent period	3.9	5.9	4.12
C	incubation period	$max(L, 4.8)$	6.8	6.05
D	infectious period	$max(C - L, 5.0)$	9.0	5.99
h	reduction in β from asymptomatic compartment	0.01	0.5	0.36
f	proportion asymptomatic	0.18	0.82	0.20
T	time from symptoms to test result	1	5	3.54
g	proportion of symptomatic tested	0.5	1.0	0.62
q	proportion of symptomatic who fail to self-isolate	g	1	0.555
η	reduction in infectiousness due to two doses	0	0.4	0.20
ω	reduction in infectiousness due to one dose	0.2	0.52	0.36
κ	time between vaccine doses	21	84	56
N_{youth}	youth population	N/A	N/A	1635207
N_{adult}	adult population	N/A	N/A	2605632
N_{senior}	senior population	N/A	N/A	723600
δ_{youth}	youth IFR	N/A	N/A	0.00005
δ_{adult}	adult IFR	N/A	N/A	0.00200
δ_{senior}	senior IFR	N/A	N/A	0.09466
t_d	time spent in ailing class	10	30	14.03

Table 1: Value of parameters featured in both vaccination model and IEMAG population-level model, including their respective upper and lower bounds.

The vaccination rates $\nu_i(t)$ are piecewise functions of time, inferred from vaccination data available for Ireland [7]. Population figures are fixed and vaccination and fatality rates are inferred from actual rates from January 10th - May 11th, 2021.

3.2.2 Assumptions of the model

1. COVID-19 is not yet treated as an endemic disease. Hence, this model will neglect all births and natural deaths. The total population figures will remain constant for each respective age cohort and there will be no transfer of individuals from one age cohort to another. Further, there is no movement in/out of the population as a result of immigration/emigration.

2. We have taken all parameters in Table 1 to be constant across the age cohorts unless denoted otherwise.

3. Recovery from the disease is associated with full immunity from further infection. Reinfection does occur, however, its risk is unclear and is considered to be rare.

4. While there are four distinct vaccines being deployed in Ireland, only one type of vaccine is modelled. It is assumed that two doses from this vaccine are required for maximum efficacy, to be taken over a uniform time interval. The rates $\nu(t)$, as well as the parameters ω, η and κ are chosen to reflect the average dynamics of all vaccines present in Ireland.

5. The vaccines are assumed to have a non-perfect efficacy, meaning that it is possible for an individual to become infected despite being vaccinated. The efficacy parameters ω and η are the sole measurements of the effectiveness of the vaccine in the model. When a vaccinated individual becomes infected, we treat them the same as all infected individuals and are assumed to have equal likelihood of symptomatic infection and death as an individual who was fully susceptible prior to infection. There is evidence, however, that vaccinated individuals are less likely to be symptomatically infected [8].

6. Given an efficacy rate $\sigma \in \{0.6, 1\}$, the reduction in infectiousness due to two doses η is given by $\eta = 1 - \sigma$. Based upon the work of Moore *et al.* [9], the relative efficacy between one and two doses of the vaccine is estimated to be 0.8 and so ω is modelled as $\omega = 1 - 0.8\sigma$.

3.2.3 Model Equations

For i, j ={youth, adult, senior},

$$
\begin{aligned}
\frac{dS_{0i}}{dt} &= -\frac{S_{0i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right) - \nu_i(t) \\
\frac{dS_{1i}}{dt} &= \nu_i(t) - \omega\frac{S_{1i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right) - \frac{S_{1i}}{\kappa} \\
\frac{dS_{2i}}{dt} &= \frac{S_{1i}}{\kappa} - \eta\frac{S_{2i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right) \\
\frac{dE_i}{dt} &= -\frac{S_{0i} + \omega S_{1i} + \eta S_{2i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right) - \frac{E_i}{L} \\
\frac{dIP_i}{dt} &= \frac{E_i}{L} - \frac{IP_i}{C-L} \\
\frac{dIA_i}{dt} &= f\frac{IP_i}{C-L} - \frac{IA_i}{D-C+L} \\
\frac{dIS_i}{dt} &= (1-f)\frac{IP_i}{C-L} - \frac{IS_i}{D-C+L} \\
\frac{dIT_i}{dt} &= g(1-f)\frac{IP_i}{C-L} - \frac{IT_i}{T} \\
\frac{dR_i}{dt} &= \frac{IA_i}{D-C+L} + (1-\delta_i)\frac{IS_i}{D-C+L} \\
\frac{d(Ailing_i)}{dt} &= \delta_i\frac{IS_i}{D-C+L} - \frac{Ailing_i}{t_d} \\
\frac{dD_i}{dt} &= \frac{Ailing_i}{t_d} \\
\frac{d(Cases_i)}{dt} &= \frac{IT_i}{T}
\end{aligned}
\tag{2}
$$

3.2.4 Optimisation

We calibrated the vaccination model above by optimising the model against actual COVID-19 cases and deaths data in three stages. To establish a relationship between the contact rates, the first stage optimises the rates from June 15th to July 15th, 2020. We chose this particular period of time because the growth of cases in this period was minimal and the contact rates can be assumed to be near-constant. The cost function Δ to be minimised by the optimisation

algorithm is the following L^2 norm,

$$\begin{aligned}\Delta = &\sum_{j=0}^{n} \Big(\ln|Cases_{model}(t_j)| - \ln|Cases_{data}(t_j)| \Big)^2 \Big|_{youth} \\ &+ \sum_{j=0}^{n} \Big(\ln|Cases_{model}(t_j)| - \ln|Cases_{data}(t_j)| \Big)^2 \Big|_{adult} \\ &+ \sum_{j=0}^{n} \Big(\ln|Cases_{model}(t_j)| - \ln|Cases_{data}(t_j)| \Big)^2 \Big|_{senior}\end{aligned} \tag{3}$$

where $n = 30$ and t_j denotes the cumulative number of cases on day j, with $j = 0$ corresponding to June 15th. We did not consider deaths for optimisation at this stage as the increase in deaths in the data in this time period was low and likely corresponded to backlogged deaths from the peak of infections in April. The optimisation algorithm which we used was the `minimize` function from the scipy.optimize package, applying the powell method [10]. To save computational effort, the parameters that we sought to optimise were the six upper-triangular entries in the contact matrix (1). The remaining three lower-triangular contact rates can be solved via the relation

$$\beta_{ij} = \frac{N_j}{N_i}\beta_{ji} \tag{4}$$

Our second stage of calibration was to optimise the model fit to daily cases from January 10th to May 11th, 2021. We used the same cost function seen above in (3), for $n = 122$ and $j = 0$ corresponding to January 10th. In this period, we assumed that the contact rates increase linearly as vaccines are administered and restrictions are gradually eased from early March. The parameters which we introduced into the model to be optimised were an "intercept" parameter, setting the contact rates for the beginning of the simulation, followed by fifteen "slope" parameters which allow the contact rates to linearly increase through early 2021. The computational effort is more costly for the second stage of optimisation, thus we used the `differential_evolution` function from the scipy.optimize package [10]. The `differential_evolution` function attains a global minimum for the cost function within a given set of bounds, whereas the `minimize` function attains a local minimum for all of its methods, relying on an estimate for the minimum.

Finally, we added the ailing and death compartments to the model and we optimised the model to attain the best fit against data on COVID-19 deaths from January 10th to May 11th, 2021. The parameters which we sought to optimise were t_d and a "factor" parameter ρ which represents the ratio between the case fatality rate and the symptomatically-infected fatality rate based on data available in the January-May period. The cost function Ω to be minimised

was the following L^2 norm,

$$\begin{aligned}\Omega = &\sum_{j=0}^{n} \Big(\ln|D_{model}(t_j)| - \ln|D_{data}(t_j)| \Big)^2 \Big|_{youth} \\ &+ \sum_{j=0}^{n} \Big(\ln|D_{model}(t_j)| - \ln|D_{data}(t_j)| \Big)^2 \Big|_{adult} \\ &+ \sum_{j=0}^{n} \Big(\ln|D_{model}(t_j)| - \ln|D_{data}(t_j)| \Big)^2 \Big|_{senior}\end{aligned} \tag{5}$$

where D_{model} represents the total deaths recorded in the model across all age categories, $n = 122$ and $j = 0$ corresponding to January 10th. We used the powell method from the `minimize` function as the optimisation algorithm. Prior to all stages of optimisation, we smoothed the data using the `nonparametric.lowess` function from the statsmodels.api package [11]. The source of our data was the HPSC COVID statistics profile open data set [12], which had been updated daily until the HSE cyber attack on May 14th.

3.2.5 Vaccination Strategies

After we had inferred all remaining parameters through optimisation of the model, we adjusted the vaccination parameters over numerous simulations in order to reflect different vaccination strategies which Ireland may have implemented from the onset of the vaccination program. We left the evolution of contact rates unchanged in all cases. Further, we simulated a scenario in which no vaccines were administered as a means of comparison, although this simulation cannot be taken to be entirely reasonable as it would not have been safe to allow for the easing of restrictions at the rate in which they occurred in the absence of vaccine coverage. The scenarios explored in the analysis of vaccination strategies are as follows,

1. The Current Model - Ireland's vaccine roll-out in the early months of 2021 was set around a priority list of "cohorts" of the population [13]. It prioritised a mix of those vulnerable to the severity of the disease (long-term care residents and the elderly) as well as those who are most exposed to acquiring the disease from infected COVID-19 patients (frontline healthcare workers).

2. Seniors First - The senior population are entirely vaccinated, before moving to the adult population and the remaining population aged over 18.

3. Youth First - Those aged 18-24 are prioritised in order to drive down transmission, before vaccinating the remaining adult population, followed by the senior population.

4. Contact Based - The adult population is the largest cohort in terms of size and number of contacts. They are prioritised before the youth and senior populations are vaccinated respectively.

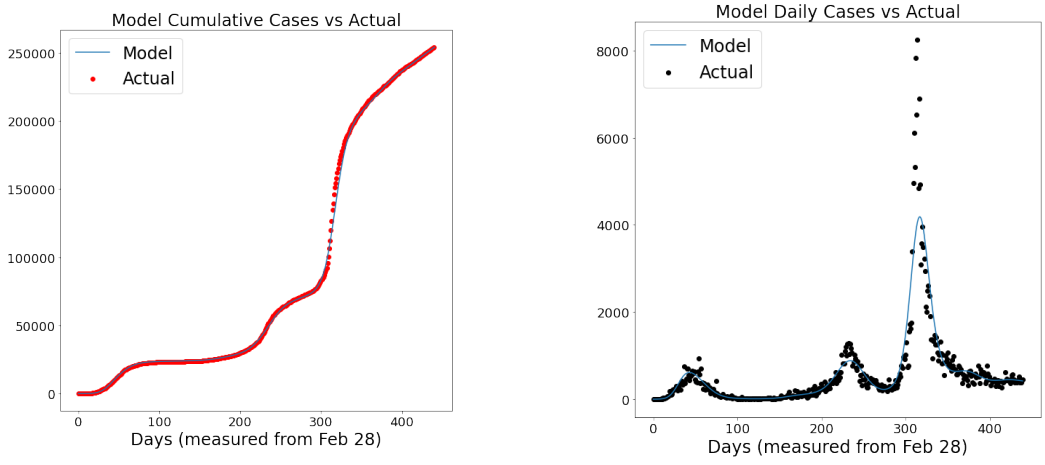
5. Randomised - With respect to vaccination, the population is essentially homogenised and the vaccination rates reflect the size of the cohorts. All cohorts undergo vaccination over the same time period at the same relative rate.

It is important to note that as of July 12th 2021, the National Immunisation Advisory Committee (NIAC) have not yet recommended COVID-19 vaccination to those under the age of 18, with the exception of Phizer-BioNTech [14]. This policy may be subject to change as more countries in the European Union begin administration of the Phizer-BioNTech vaccine to those aged 12 years and older. We mirror this assumption in all scenarios, resulting in a substantial proportion of the youth population who are fully susceptible to the disease despite the vaccination program having been completed.

4 Results

4.1 Calibration of IEMAG Population-level Model

Figure 1 below shows the simulation of the IEMAG population-level model (see Appendix A) from the onset of the pandemic (Day 0 correlating to February 28th 2020) to May 14th 2021. The initial conditions on this date are taken to be $\{S(0), E(0), I_p(0), I_a(0), I_i(0), I_{t1}(0), I_{t2}(0), I_n(0), R(0), Cases(0)\} = \{N-1, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0\}$. A 7 day offset is applied in fitting the simulation to the data due to the delay between the first infected person entering the population and the first confirmed case. Figure 1 shows an extremely close model fit to the data, which can be expected as the $\beta(t)$ curve is constructed from the mean contact rate from 1000 realizations for each day of data. The period of largest inaccuracy in the simulation is during the peak of the "third wave" in early January 2021. This can be expected due to the delay in reporting of cases as the testing system was overwhelmed by demand.



(a) Cumulative Cases

(b) Daily Cases

Figure 1: Simulation of the IEMAG population-level model

4.2 Vaccination Rates

Before we were able to simulate our vaccination model in any period after the beginning of vaccine administration in Ireland, it was necessary for us to construct our time-dependent vaccination functions according to data available from January 10th 2021. The vaccination functions are structured as time-dependent constant rates inferred through linear regression of vaccination data filtered by age cohort using the `LINEST` command in Excel. The vaccination functions are as follows,

$$\nu_{youth}(t) = 571.28 \qquad \forall t \in \{0, 121\} \tag{6}$$

$$\nu_{adult}(t) = \begin{cases} 3118.96 & t \in \{0, 42\} \\ 4603.97 & t \in \{42, 91\} \\ 6650.02 & t \in \{91, 105\} \\ 14755.53 & t \in \{105, 121\} \end{cases} \tag{7}$$

$$\nu_{senior}(t) = \begin{cases} 1081.60 & t \in \{0, 42\} \\ 5380.60 & t \in \{42, 91\} \\ 11303.75 & t \in \{91, 120\} \\ 0 & t \in \{120, 121\} \end{cases} \tag{8}$$

where t is time measured in days after January 10th 2021 and the function values represent the average number of people receiving a first dose of any vaccine in Ireland per day.

4.3 Optimisation

4.3.1 Stage 1

The initial stage of optimising the vaccination model was to simulate the model over a period with (relatively) constant contact rates among the populations to capture a relationship between the inter-population contact rates. The cost function Δ in (3) was minimized to 1.62×10^{-4} by the following contact rates,

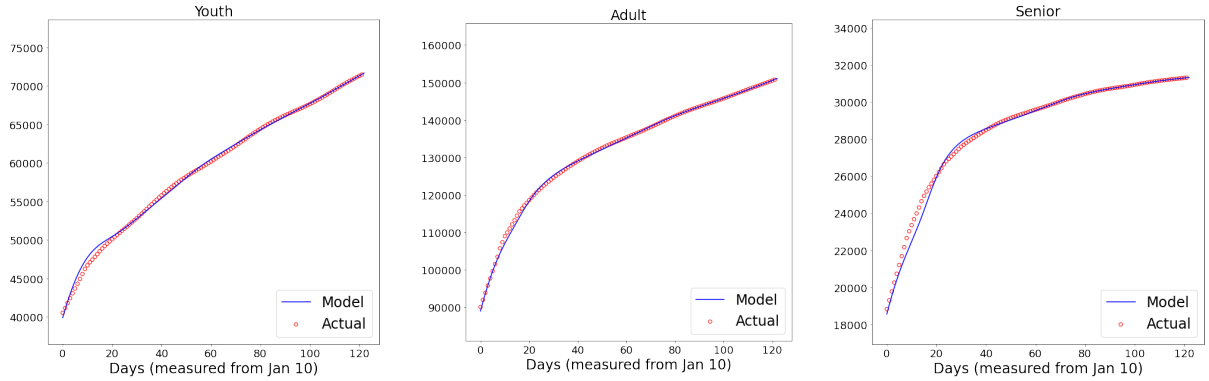
$$\begin{pmatrix} \beta_{CC} & \beta_{CA} & \beta_{CS} \\ \beta_{AC} & \beta_{AA} & \beta_{AS} \\ \beta_{SC} & \beta_{SA} & \beta_{SS} \end{pmatrix} = \begin{pmatrix} 0.3682 & 0.0206 & 0.0070 \\ 0.0128 & 0.2553 & 0.0051 \\ 0.0173 & 0.0202 & 0.0051 \end{pmatrix} \tag{9}$$

where the six upper-triangular entries of the contact matrix were optimised using the powell method and the three remaining lower-triangular matrices were computed according to the relation in equation (4). We can clearly see that the highest contact rates are the intra-population rates β_{CC} and β_{AA}. This is expected as adults mix mainly with other adults and young people mix primarily with other young people. The exception is visible when analysing the bottom row of the matrix. The inter-population rates for the senior population exceed its intra-population rate. An explanation for this may be the fact that many over

70s were still cocooning and limiting contacts at this stage of the pandemic, limiting contact especially with other members of the senior population due to their vulnerability to the disease. Those aged over 70 were likely seeing their grandchildren more so than each other. Initial conditions for the exposed-infected classes when solving were estimated by examining the numerical solution of the IEMAG population-level model and calculating a ratio between the number of individuals in the unknown classes against the cumulative number of cases in each age cohort as of June 15th 2020.

4.3.2 Stage 2

The second stage of optimisation involved simulating the vaccination model from January 10th - May 11th, 2021. Regarding the evolution of contact rates, we assumed that each row in the contact rate matrix increased linearly at distinct rates (per day), with these rates changing at four distinct points in the simulation until May. The starting contact matrix is determined by the "intercept" parameter, representing a ratio between the contact matrices from January 10th against the contact matrix (9) from Stage 1 of the optimisation process. We chose the dates for changes in the rate of increase in contact rates to be days 14, 47, 67 & 107 (January 24th, February 26th, March 18th & April 27th) of the simulation. The first date was chosen to curb the initial surge in cases in the early January period which may reflect discrepancies in the case data such as delayed testing. The latter two dates represent the reopening of schools across March and the reopening of outdoor sports facilities and museums respectively. The "intercept" and "slope" parameters which minimise the cost function (3) to 2.66×10^{-2} are as presented in Appendix B.



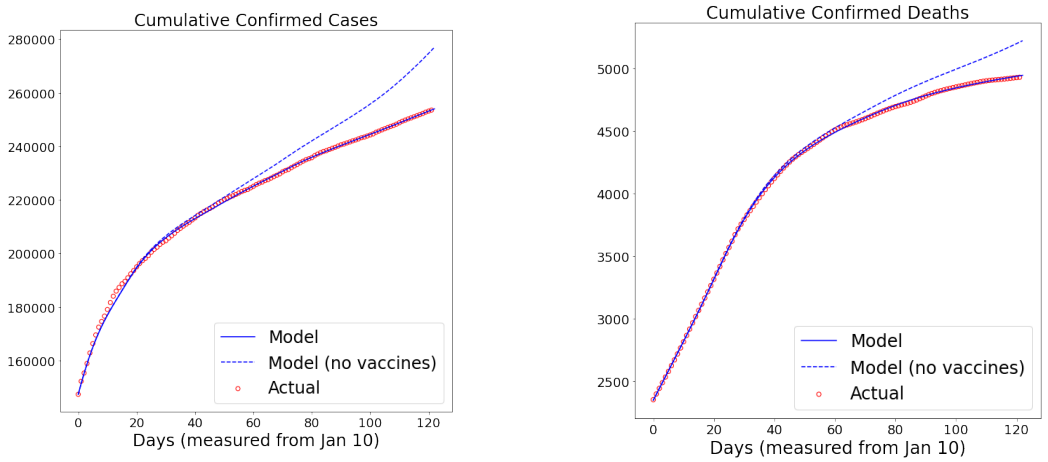
(a) Youths (aged 0-24) (b) Adults (aged 25-64) (c) Seniors (aged 65+)

Figure 2: Cumulative confirmed cases among the three age cohorts from January 10th - May 11th, 2021 upon optimisation.

4.3.3 Stage 3

We sought to fit the model to COVID-19 deaths data upon adding the ailing and dead compartments to the vaccination model for our final stage of optimisation. The t_d parameter

was optimised alongside a "factor" parameter ρ which represented the relationship between a symptomatically-infected fatality rate against the case fatality rates recorded for each age cohort in the data period. The values which optimized the cost function Ω to 4.24×10^{-4} were $(t_d, \rho) = (14.03, 0.5169)$. The fit that the optimal parameters produced is visible in Figure 3 below. The dashed line represents the model simulation in the absence of vaccination with the exact same parameters otherwise, which demonstrates that vaccines are beginning to take effect from early-mid March.



(a) Cumulative Cases

(b) Cumulative Deaths

Figure 3: Simulation of the vaccination model from January 10th - May 11th, 2021 after all optimisation steps had been taken.

4.4 The Effective Reproductive Number

In infectious disease modelling, the reproductive number $\mathcal{R}$ of a disease is the average number of secondary infections stemming per infected case. In the case of the IEMAG population-level model, it can be derived analytically from the maximum eigenvalue of the next-generation matrix [4],

$$\begin{aligned} \frac{\mathcal{R}_0}{\beta} &= (f-1)((i-1)q(C-L) + (j-1)\tau(C-L+T)) \\ &\quad + D(f(h-iq-j\tau+q+\tau-1) + (i-1)q + (j-1)\tau + 1) \end{aligned} \tag{10}$$

In the case of our vaccination model, we chose to infer a crude estimate for $\mathcal{R}$ from the growth rate of cases in our model. Keeling *et al.* [15] estimate the effective reproductive rate $\mathcal{R}_{eff}$ by calculating the growth rate r of daily cases on a logarithmic scale. The reproductive rate can then be estimated by

$$\mathcal{R}_{eff}(r) = \Big(1 + r(D - C + L)\Big)\Big(1 + \frac{rL}{M}\Big)^M \tag{11}$$

where M is defined as the number of latent compartments in the model. For the vaccination model, there is one exposed class for each age cohort, so we have that $M = 3$.
If we wished to take vaccinations into account, we work backwards to solve for $\mathcal{R}_0$ in the absence of vaccinations by applying the following formula,

$$\mathcal{R}_0(r) = \frac{\mathcal{R}_{eff}(r)}{1 - ((1-\omega)P_{onedose} + (1-\eta)P_{twodoses})} \tag{12}$$

where $P_{onedose}$ and $P_{twodoses}$ are the proportions of the population which have received one and two doses of the vaccine respectively. The growth rate r for each day of the January - May simulation was solved by fitting the logarithmic curve $a + b\log(x)$ over the previous 7 daily cases curve in the model using the `curve_fit` function from the scipy.optimize library. In Figure 4 below, we can see that $\mathcal{R}_{eff}$ is kept more or less below 1 from simulating our model, whereas in the absence of vaccinations $\mathcal{R}_{eff}$ would have been firmly above 1 from late March.

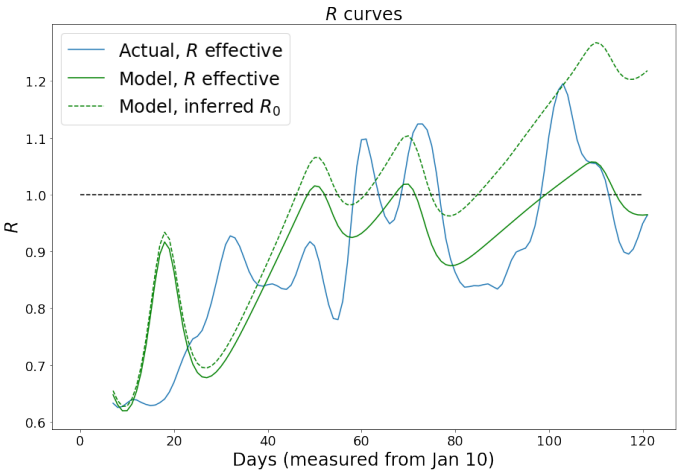
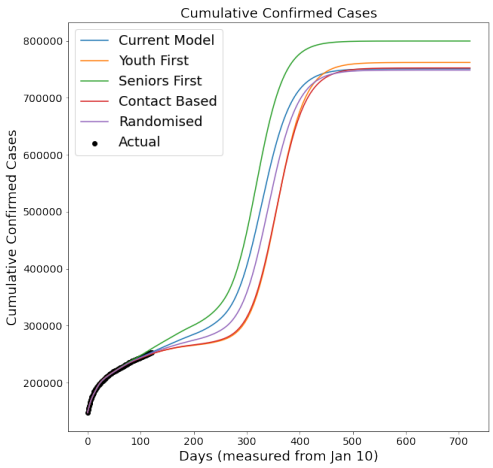


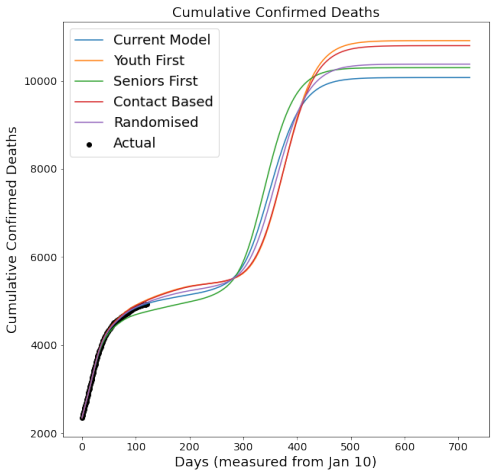
Figure 4: Estimation of $\mathcal{R}_{eff}$ inferred from 7 day growth rate r and applying equation (11). The dashed line represents $\mathcal{R}_0$ taking vaccinations into account through (12). From investigating the dashed green line we can see a linear increase in $\mathcal{R}_0$ from late January 2021, matching our assumption of linearly increasing contact rates.

4.5 Analysis of Vaccination Strategies

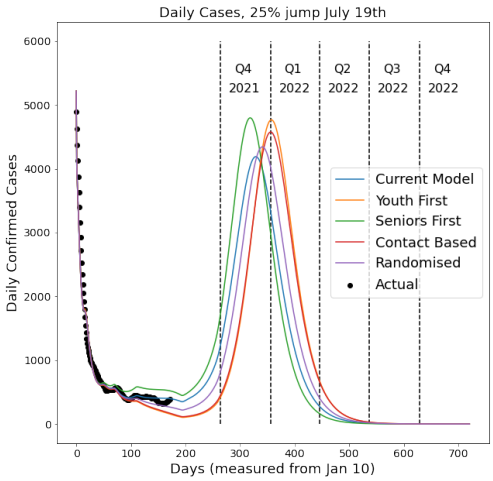
The final step in our results compares the current vaccine rollout in Ireland against the vaccination strategies detailed in Section 3.2.5. We simulated all five strategies from January 10th, 2021. To hypothesize an incoming "fourth wave" of infections as a result of loosening restrictions and the arrival of the Delta variant, we simulated the model forward to the end of 2022, including an immediate 25% increase in contact rates on July 19th. We chose this particular date for a step-increase in the contact rates as it reflected the return of non-essential travel in the European Union. Figure 5 charts the evolution of cases and deaths for all five strategies, with numerical tallies of cumulative cases and deaths arising from each simulation detailed in Table 2. While the strategy with the lowest number of cumulative deaths at the end of the simulation is the most obvious measure for the optimal vaccination strategy, a procedure which results in a significant excess of cases should also be avoided. Excess cases increase the likelihood of further mutation in COVID-19, which leads to an increased risk in the emergence of variants which may be more transmissible or even vaccine-evasive.



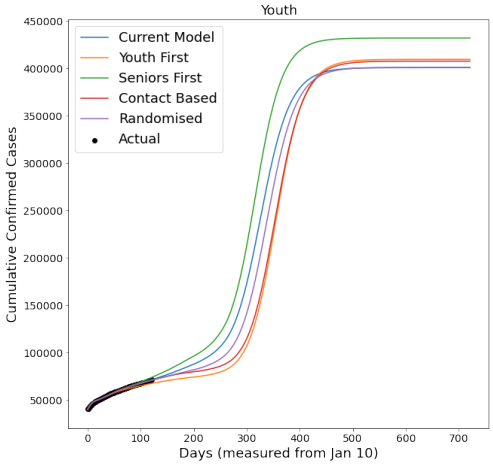
(a) Cumulative Cases



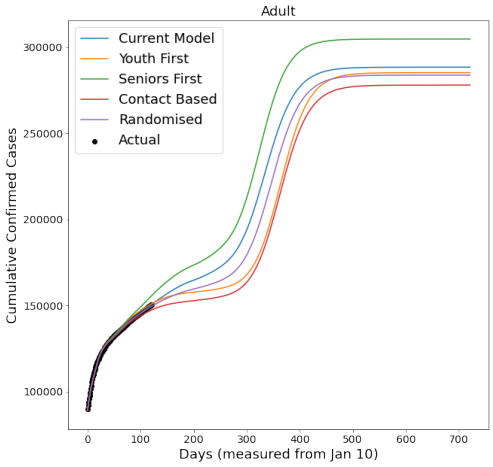
(b) Cumulative Deaths



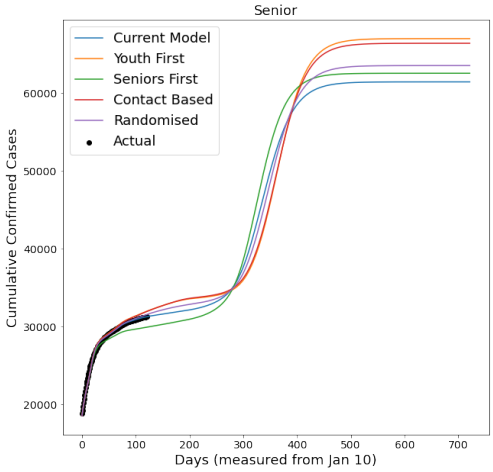
(c) Daily Cases



(d) Youths (aged 0-24)



(e) Adults (aged 25-64)



(f) Seniors (aged 65+)

Figure 5: Simulation of vaccine strategies to the end of year 2022, accounting for 25% increase in contact rates on July 19th 2021.

Strategy	Cases May 11th 2021	Deaths May 11th 2021	Cases December 31st 2022	Deaths December 31st 2022
Current Model	253,960	4,947	750,856	10,073
Youth First	251,083	5,036	761,967	10,912
Seniors First	260,312	4,768	799,553	10,298
Contact Based	250,871	5,021	752,287	10,797
Randomised	252,547	4,975	748,576	10,378

Table 2: Numerical results of cumulative cases and deaths for each vaccine strategy of the simulation in Figure 5.

5 Conclusion

Our report sought to assess Ireland's current vaccination strategy against other potential strategies to determine whether our current rollout will be effective in minimising further cases and deaths of COVID-19. As a starting point, we began by reviewing the work of IEMAG in charting the epidemiology of COVID-19 in Ireland for the entirety of the pandemic. We implemented their model into Python, gaining insight into the methods which they employ in their mathematical model of the disease. From there, we constructed a SEIR-type model for COVID-19 in Ireland, which takes into account vaccination rates in 2021 across various age categories in our population. After various stages of optimisation, we could use this model to chart the growth of the disease in the early months of 2021, before adjusting our vaccination rates to model different vaccination strategies which Ireland may have chosen to implement at the onset of our vaccine campaign. The results detailed in Section 4.5 indicate that our current vaccine rollout is optimal in minimising total deaths, predicting 750,856 cumulative cases and 10,073 deaths in the simulation to December 2022. While the seniors first strategy is among the lowest in terms of cumulative deaths, it results in 799,553 cumulative cases by the end of 2022. When the senior population is prioritised for vaccination, the lack of vaccine coverage amongst younger populations allows the disease to continue to spread, leaving this strategy at enhanced risk to virus mutation. The optimal strategy would in fact minimise a weighted combination of cases and deaths. Having resulted in less than 2,000 excess cases over the strategy with the lowest cumulative cases by the end of 2022 (the randomised strategy) the current vaccine rollout is our selection for the optimal strategy of vaccinating Ireland's population against COVID-19. This strategy likely wins out due to the fact that it prioritises vaccinating the most vulnerable population without entirely neglecting the age cohorts with the highest contact rates. Lastly, it is important to note that all five strategies experience significant waves of infection in the final quarter of 2021, all peaking at 4,000-5,000 daily cases. This suggests that we fail to achieve herd immunity by inoculating our 18+ population alone, and it would be necessary to vaccinate further into the youth age cohort to acquire a more substantial immunity coverage in our population. We solved the current model separately and allowed for the population aged 12-18 to be vaccinated from early September. The enhanced immunity coverage decreased the "peak" of the fourth wave of infection to 1,120 daily cases and a total of 474,534 cases and 7,169 deaths were recorded by the end of year 2022. Furthermore, increasing the efficacy of the vaccine to 90% $(\eta, \omega) = (0.1, 0.28)$

while restricting vaccines to the population over 18 leads to a similar reduction in COVID-19 incidence (466,842 and 6,153 cumulative cases and deaths respectively by the end of year 2022). This scenario may reflect a prioritisation of use of only the most effective vaccines in preventing symptomatic infection.

Our approaches do not, however, come without their limitations. In our assessment of the strategies, we charted cases and deaths solely. Further understanding into the consequences of each simulation may become clearer if our model recorded other measures such as hospital admissions and ICU capacity. We chose to model only one type of vaccine in our model, a two-dose vaccine with an efficacy rate and gap between doses which reflects the range of vaccines currently being administered in Ireland. A desired next step in our approach would be to distinguish between the mRNA vaccines (Phizer-BioNTech, Moderna) and the viral vector vaccines (AstraZeneca, Janssen) in order to infer a more accurate estimate for the number of individuals immunised rather than relying on two constant efficacy rates for inoculation of one and two doses respectively. When simulating the model forward to the end of 2022, we decided upon placing upper bounds on the contact rates to prevent the contact rates rising indefinitely. These upper bounds are difficult to determine in reality, and thus we decided on halting the increase in contact rates around November 2021, a point in time where the vaccine campaign was completed and Ireland would likely remove as many restrictions as hospital/ICU capacity at the time would allow. A final consideration which we hope to explore further is the effect of a waning immunity against COVID-19. Research regarding the long-term immunity provided by our currently available vaccines is inconclusive and it is plausible that further mutations of COVID-19 could potentially arise in the future which may lead to variants which evade antibodies produced by our vaccines to a heightened extent.

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Appendices

Appendix A. Compartments and Equations of the IEMAG population-level model

The system of equations solved numerically in Python to obtain the fits observed in Figure 1 are as follows,

$$\begin{aligned}
\frac{dS}{dt} &= -\beta S(I_p + hI_a + iI_i + I_{t1} + jI_{t2} + I_n)/N \\
\frac{dE}{dt} &= \beta S(I_p + hI_a + iI_i + I_{t1} + jI_{t2} + I_n)/N - \frac{1}{L}E \\
\frac{dI_p}{dt} &= \frac{(1-f)}{L}E - \frac{1}{C-L}I_p \\
\frac{dI_a}{dt} &= \frac{f}{L}E - \frac{1}{D}I_a \\
\frac{dI_i}{dt} &= \frac{q}{C-L}I_p - \frac{1}{D-C+L}I_i \\
\frac{dI_{t1}}{dt} &= \frac{\tau}{C-L}I_p - \frac{1}{T}I_{t1} \\
\frac{dI_{t2}}{dt} &= \frac{1}{T}I_{t1} - \frac{1}{D-C+L-T}I_{t2} \\
\frac{dI_n}{dt} &= \frac{(1-q-\tau)}{C-L}I_p - \frac{1}{D-C+L}I_n \\
\frac{dR}{dt} &= \frac{1}{D}I_a + \frac{1}{D-C+L}I_i + \frac{1}{D-C+L-T}I_{t2} + \frac{1}{D-C+L}I_n
\end{aligned} \tag{13}$$

The definition of all compartments and parameters are detailed in [4]. Note that we have defined q differently in our vaccination model (2).

Appendix B. Parameters optimised in Section 4.3.2

Parameter	Description	Value
intercept	ratio between initial contact matrix against (9)	0.1020
rate_{C1}	top row rate of increase, days 0-14	0.0007
rate_{A1}	middle row rate of increase, days 0-14	0.0185
rate_{S1}	bottom row rate of increase, days 0-14	0.0069
rate_{C2}	top row rate of increase, days 14-47	0.0026
rate_{A2}	middle row rate of increase, days 14-47	0.0032
rate_{S2}	bottom row rate of increase, days 14-47	0.0005
rate_{C3}	top row rate of increase, days 47-67	0.0013
rate_{A3}	middle row rate of increase, days 47-67	0.0028
rate_{S3}	bottom row rate of increase, days 47-67	0.0005
rate_{C4}	top row rate of increase, days 67-107	0.0011
rate_{A4}	middle row rate of increase, days 67-107	0.0018
rate_{S4}	bottom row rate of increase, days 67-107	0.0002
rate_{C5}	top row rate of increase, days 107-121	0.0009
rate_{A5}	middle row rate of increase, days 107-121	0.0016
rate_{S5}	bottom row rate of increase, days 107-121	0.0002

Table 3: Value of parameters upon optimisation of cost function (3) using the `differential_evolution` function from the scipy.optimize library.