Modeling of COVID-19 dynamics and path to herd immunity by vaccination

Françoise Kemp

4.03.2021
Coronavirus around the world

Total deaths
2.5 million

Total confirmed cases
115 million
Situation in Europe

14-day COVID-19 case notification rate per 100,000 weeks 07 - 08

- No cases reported
- <25.0
- 25.0 - 49.9
- 50.0 - 149.9
- 150.0 - 499.9
- ≥500.0

Regions not visible in the main map extent:
- Azores
- Guadeloupe and Saint Martin
- La Réunion
- Martinique

Countries not visible in the main map extent:
- Malta
- Liechtenstein

Administrative boundaries: © EuroGeographics (C) UN-FAO (C) Takemap (C)Arbebia (C) Instituto Nacional de Estatística (C) Statistiek Nederland (C) Statistiques Portugal.
The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union. ECDC. Map produced 01 04 2021.
## Situation in Luxembourg

<table>
<thead>
<tr>
<th>Total deaths</th>
<th>Total confirmed cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>648</td>
<td>56110  (9%)</td>
</tr>
</tbody>
</table>

**Latest daily figure**

<table>
<thead>
<tr>
<th>new deaths</th>
<th>new cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>206</td>
</tr>
</tbody>
</table>
Modeling and forecasting

• disease forecast could aid public health responses by informing key preparation and mitigation efforts
• major tool to understand its diffusion
• fit the observed data well can be simulated forward in time to make predictions about the future state of the system, a task known as forecasting
• modeling and forecasting the spread of COVID-19 remains a challenge
Motivation of the model

• Being confronted with soaring numbers of infections, sickness and dead
• Puts a major constraint on hospital logistics
• Simulate ICU and hospital bed needs in the upcoming week
Basic SEIR Model

- Formulated by Kermack and McKendrick in 1927
- Compartment model
Scheme of extended SEIR model for ICU/hospital

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_n$</td>
<td>social distancing ($n = 0, \ldots, 14$)</td>
<td>adim.</td>
</tr>
<tr>
<td>$\beta$</td>
<td>average contact rate</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>(mean incubation period)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>(mean time in $I$)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>(mean time in $Q$)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>(mean time in $H$)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_4$</td>
<td>(mean time in ICU)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_5$</td>
<td>(mean time in $HI$)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_6$</td>
<td>(mean time in AICU)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_7$</td>
<td>(mean time in $NI$)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_8$</td>
<td>(mean time in $AI$)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$\tau_9$</td>
<td>(mean time in NII)$^{-1}$</td>
<td>days$^{-1}$</td>
</tr>
<tr>
<td>$p_1$</td>
<td>probability of $E \rightarrow I$</td>
<td>adim.</td>
</tr>
<tr>
<td>$p_2$</td>
<td>probability of $Q \rightarrow H$</td>
<td>adim.</td>
</tr>
<tr>
<td>$p_3$</td>
<td>probability of $H \rightarrow HI$</td>
<td>adim.</td>
</tr>
<tr>
<td>$p_4$</td>
<td>probability of ICU $\rightarrow$ AICU</td>
<td>adim.</td>
</tr>
<tr>
<td>$p_5$</td>
<td>probability of $HI \rightarrow R_{II}$</td>
<td>adim.</td>
</tr>
<tr>
<td>$p_6$</td>
<td>probability of AICU $\rightarrow$ R_{II}</td>
<td>adim.</td>
</tr>
<tr>
<td>$p_7$</td>
<td>probability of $N_{I} \rightarrow R_{II}$</td>
<td>adim.</td>
</tr>
<tr>
<td>$p_9$</td>
<td>probability of NII $\rightarrow R_A$</td>
<td>adim.</td>
</tr>
</tbody>
</table>
Scheme of extended SEIR model for ICU/hospital

- Susceptible (S)
  - Exposed (E)
    - Detected (I)
    - Quarantined (Q)
      - Hospital (H)
      - Recovering at home (NI)
    - Undetected (A)
  - Vaccinated (V)

Parameters:
- $\rho$ (infection rate)
- $\beta$ (transmission rate)
- $\tau_{vac}$ (vaccination rate)
- $\alpha$ (recovery rate)
- $p_1$ (probability of being detected)
- $p_2$ (probability of being quarantined)
- $\tau_1$ (quarantine period)
- $\tau_2$ (hospital period)

Equations:
1. $S' = -\rho S E + \alpha(1 - p_1) A$
2. $E' = \rho S E - \rho E + \beta I E - \beta E E - \tau_{vac} E$
3. $I' = \beta E I - \alpha(1 - p_1) A - \alpha I$
4. $Q' = \alpha(1 - p_1) A - \tau_1 Q$
5. $H' = \tau_1 Q - \tau_2 p_2 H$
6. $NI' = \tau_2 (1 - p_2) Q - \alpha(1 - p_1) A - \alpha NI$
7. $A' = \alpha(1 - p_1) A - \alpha A$
Scheme of extended SEIR model for ICU/hospital
Scheme of extended SEIR model for ICU/hospital

- Susceptible (S)
  - Exposed (E)
    - Detected (I)
    - Quarantined (Q)
      - Hospital (H)
        - Longer stay hospital (H1)
          - Recovering at home (N1)
            - Recovered (R1)
  - Undetected (A)
    - Recover at home (NII)
      - Recovered (R4)
  - Vaccinated (V)
    - Detect (I)
      - Recover (R)
        - Dead (D)
          - Back to hosp. after ICU (AI/ICU)
            - ICU (ICU)
              - Died (D)
                - Recovered (R)
                  - Dead (D)
                    - Recovered (R)
                      - Dead (D)
Scheme of extended SEIR model for ICU/hospital

- System of 18 ODE
- 22 parameters
- 18 variables
Social interaction is the driver of the epidemic

- Social distancing key in order to reduce the spread
- Implemented as a piecewise constant function of time

$$\frac{dS}{dt} = -\rho \beta (A + I) S - \tau_{vac}$$

$$\frac{dE}{dt} = \rho \beta (A + I) S - \alpha E$$
Change of rho for Luxembourg
Projections for Luxembourg

9% of population had a detected COVID-19 infection

Done by Stefano Magni
Projections for Luxembourg

Hospitals Occupancy (Considering only residents)

- Simulation, Social Distancing as October
- Simulation, 99% Social Distancing October
- Simulation, 89% Social Distancing October
- Simulation, 79% Social Distancing October
- Simulation, 69% Social Distancing October
- Simulation, 59% October as FULL LOCKDOWN
- Simulation from SEIR-ICU Model, Fit 4 March Data until 3 March (reported 4 March)
- 7-Days Moving Average of Data
- Critical Hospital threshold
- Max Hospital bed capacity
- Uncertainty, 50% Credible Interval

ICU Occupancy (Considering only Residents)

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Done by Stefano Magni
Schematic MCMC

INPUT

DATA

OUTPUT

MCMC

DATA

MODEL

SAMPLER

PRIORS

COMPUTATION

POSTERIOR
Changes in the parameter

- Very close either to the maximum or the mean posteriori estimate
- Fully consistent with our manually calibrated set
Fold changes between the different waves

- Changes observed by different fitting methods
- $p_2$ decreased between the subsequent waves
Basic reproduction

- signifying the average number of cases each infected person will cause, if no action is taken.

“0” refers to “time zero” (beginning) of the epidemic.

\[ R_0 = \frac{\beta}{\gamma} \]

- \( R_0 < 1 \) the disease cannot invade the population
- \( R_0 > 1 \) invasion is possible and infection can spread
- obtained by next generation matrix method
- \( R_0 \) is one of the eigenvalues

\[ R_0 = \beta\left[\frac{(1 - p_1)}{\tau_8} + \frac{p_1}{\tau_1}\right] \]

<table>
<thead>
<tr>
<th>How quickly does it spread?</th>
<th>Basic reproduction value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mers</td>
<td>0.7</td>
</tr>
<tr>
<td>Ebola</td>
<td>1.7</td>
</tr>
<tr>
<td>Smallpox</td>
<td>7</td>
</tr>
<tr>
<td>Measles</td>
<td>17</td>
</tr>
</tbody>
</table>

Source: ECDC, UMICH, Lancet
Effective reproduction number

- Re calculated at different time points during the epidemic, i.e. the average number of expected infected persons by a primary case in a population of susceptible and infected individuals

\[ R_{\text{eff}} = \rho(t)\beta\left[\frac{1 - p_1}{\tau_8} + \frac{p_1}{\tau_1}\right]\frac{S(t)}{N} \]
R-effective
Herd immunity

• also known as 'population immunity'
• a population is immune either through vaccination or immunity developed through previous infection
• vaccines train our immune systems to create proteins that fight disease
Vaccination in Luxembourg

<table>
<thead>
<tr>
<th></th>
<th>Journée du 02.03.2021</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnes vaccinées - Dose 1</td>
<td>817</td>
<td>28 476</td>
</tr>
<tr>
<td>Personnes vaccinées - Dose 2</td>
<td>525</td>
<td>11 984</td>
</tr>
<tr>
<td>Total des doses administrées</td>
<td>1 342</td>
<td>40 460</td>
</tr>
</tbody>
</table>

1.95% fully vaccinated Luxembourgish population
203 doses per day
Herd immunity by April

- The interplay between the vaccination dynamics and social interaction
- 3 potential vaccination strategies (6 months, 1 year and 1.5 years)
- Estimate for herd immunity:
  \[ p_c = 1 - \frac{1}{R_0} \]
- 70% of population needing to be immune
Herd immunity for 2021

- All three vaccination strategies might lead to herd immunity in 2021
Corona in Austria
5.64% of population had a detected COVID-19 infection
Projections of Austria
Herd immunity for 2021 in Austria

- 68% of population needing to be immune
Corona in Sweden
Time-dependent probabilities of detection and hospitalization

- Different strategies and experienced a different epidemic dynamics

A. Exponential Fit
   - Gompertz Fit
   - Linear Fit
   - Prevalence Data

B. Estimate of $p_3$ from Linear Fit
   - Estimate of $p_3$ from Gompertz Fit
   - Estimate of $p_3$ from Exponential Fit
   - $I(t)$ Assumed for the model
   - Time when Prevalence was measured

C. Cases Detected Daily (Data)
   - People Entering ICU (Data)

D. People Entering Hospital / Daily Detected Cases (2 days before)
   - $H(t)$ Assumed for the model
Projections of Sweden

Total cases

- Data until 2 March
- 7-Days Moving Average of Data
- Simulation Manual Fit
- Optimistic Projection (as March)
- Pessimistic Projection (as October)
- Projection if No Further Change
- Undetected Cases (No change scenario)

Daily new cases

6.8% of population had a detected COVID-19 infection
Herd immunity for 2021 in Sweden

• 75% of population needing to be immune
Summary of the talk

• model which describes all the stages of COVID-19
• Allows to describe the situation in Luxembourg, Austria and Sweden
• provides data-based estimations of the interplay between social measures and vaccination rollouts
• Luxembourg has the highest fraction of infected
Thanks for your attention

Supported
By
Task Force WP6:

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R. Balling
C. Ley
J. Goncalves
A. Skupin
I built another Covid exposure model to help me limit my risk.

Any new insights?

Yeah: “If you spend all day debugging models, you don’t have close contact with a lot of people.”

Well, I guess it worked. According to my meta-model, the end of the pandemic is only four more models away.

So close!