Group 43 project report

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Problem Statement

Covid-19 is a disease that first appeared in December 2019 in Wuhan, China (WHO, 2020c). The virus responsible for the Covid-19 disease is called SARS-Cov-2, but it is mostly known as the Coronavirus. In nearly a year, this illness has ravaged the whole world. It has affected billions of humans in every aspect of their lives. Although coronavirus might be not the deadliest disease that ever existed (World Economic Forum, 2020a), the speed at which the virus spread, with over 60 million people infected, makes it a global pandemic (European Center for Disease Prevention and Control, 2020a). Thus, for now, it is the biggest crisis humans have to face in the 21st century. Countries have enforced social distancing, mask-wearing policies, limitations on events and limitations on entering some public buildings to control Covid-19 spread (European Center for Disease Prevention and Control, 2020b). However, those measures have started taking a toll on the economy (World Economic Forum, 2020b) and people's mental health (O'Connor et al., 2020). Since SARS-Cov-2 is a virus, it cannot be treated by antibiotics. The most essential way to control the virus, and go back to a normal life, depends on the invention and implementation of a vaccine (WHO, 2020b).

We created a theoretical model, in which a vaccine exists and it can be distributed among all the agents. Therefore, we can find out what the most efficient way is to distributed the vaccine in a society.

Model Description

Our model simulates the spread of the disease in a closed population with the introduction of a vaccine. Individuals wander around the world in a random motion. There are five groups of individuals: healthy, infected, ill, death, and immune (Figure 1). Healthy individuals can contract the disease and become infected. Infected people are those who already have the virus in their body but do not show any or just mild symptoms. They can become healthy again or change into the ill category if their conditions get worse. Ill patients do not move, because they are isolating themselves to

rest. They can recover or perish. When they recover, they become healthy or immune. They are immune to the virus, if a certain amount of time has passed where they were ill. Each tick, agents wander around the area randomly, and a day is over after 24 ticks. Healthy individuals have a chance to contract the virus if they are in the infection radius of infected agents. This radius can be changed. Ill patients will not infect anybody because they are quarantined. A certain amount of vaccines will be made each day. That is the amount of agents that can come to one of the distribution places to get the vaccine. Only healthy and infected individuals can get a vaccination, but the vaccine only affects healthy individuals. Infected people can still take the vaccination because they do not know they have the disease yet, but they can still become ill, because the vaccination might not work. Ill people are quarantined, so they can not move and therefore not get vaccinated. For some vaccinations that exist right now, like the cervical cancer vaccination, it takes several doses to become immune. We do not know if that is the case with the coronavirus, so it is possible to change the amount of doses needed. Figure 2 illustrates the model implemented in NetLogo along with its variables. The first plot shows the cumulative population of each group, and the second plot illustrates the number of agents in each group. Here is a summary of some of the variables:

- how-many-vaccination-places: The number of vaccination places spawned at random locations (1 - 20).

- max-vaccination-at-the-time: How many vaccines can be distributed each day per vaccine place (1 - 5).

- infect-range: Infect radius for infected people.

- infect-chance: The probability that an healthy person gets infected after having been in contact with an infected individual.

- after-how-many-days-can-you-become-ill: The least amount of days that a person is infected before getting ill.

- getting-ill-chance: The probability that an infected person becomes ill, after the first required infection days are over.

- chance-to-die and chance-to-recover: the chance for ill individuals to perish or to recover and become healthy or immune.

We consulted existing knowledge to set up our default parameters, to make them be as close to reality as possible. Phucharoen, Sangkaew, and Stosic (2020) says "It was found that the infection probability per se of a contact was 36% before quarantine, and 29% after the quarantine". We speculated that even with a vaccine people may still take some measure to protect themselves (e.g., washing hands regularly, avoid other people, wear a mask, etc). We want to model the current situation (after we all were quarantined in March), so we chose the infect chance to be 29% as our default and set the infect chance to 15% in a scenario where people take extreme social-distancing measures. After 4 days of illness, people have a change to recover. After 10 days, ill people have a chance of becoming immune, because it usually takes at least 10 days after having the first symptoms to develop immunity (To et al., 2020). The time it takes for symptoms to appear, on average, is 5 to 6 days. So infected individuals in our model need at least 6 days to become ill (WHO, 2020a). On 30/11/2020, the Netherlands has in total accumulated 523,478 confirmed cases and a death count of 9,376. The mortality rate is on this day approximately 1.8%, so it is also the mortality rate of our model. Finally, the number of doses needed to become immune is two because the newest Pfizer vaccine, and most other vaccines, also require two doses. (Pfizer, 2020).

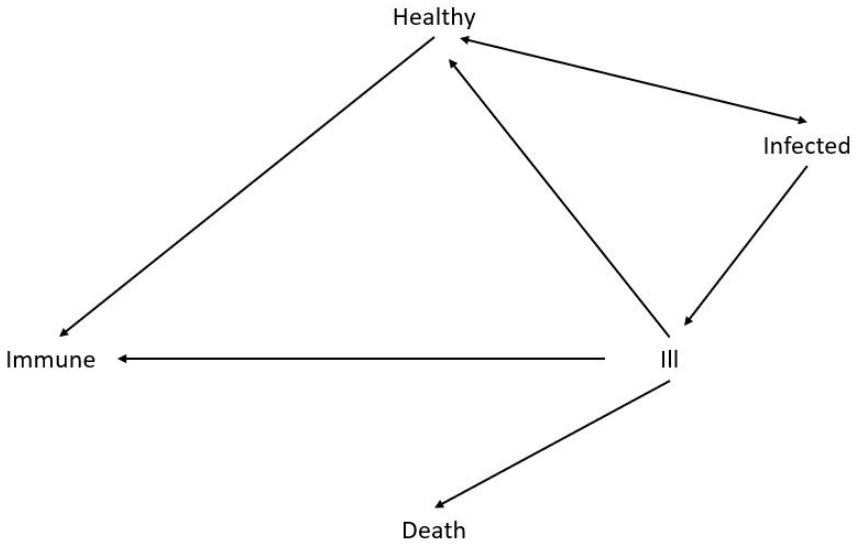

Figure 1. 5 groups of individuals

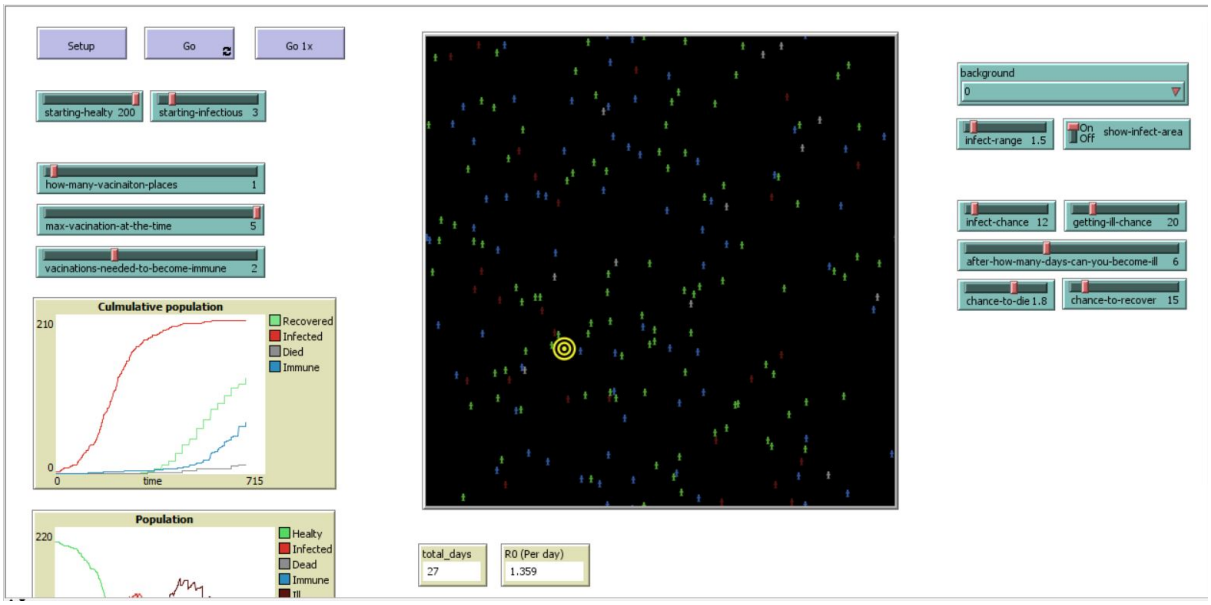

Figure 2. Netlogo model implementation

Results

Experiment set up

We set up the experiment in three different ways, with three different settings. Firstly, a control scenario with no vaccine and a 29% infect chance per contact. Secondly, we varied the number of vaccination stations from 1 to 20, with each station

distributing 5 vaccines per day. Finally, we modelled a second simulation with the infect chance of 15%.

Immunity, Death, and R0.

200 healthy and 3 infected individuals were first initialized. Although our model could measure many variables. We chose to measure total immunity, total death, and R0. Total immunity could provide insight into the efficiency of the vaccine. The total death count could let us know if we succeeded in protecting vulnerable individuals. R0 reflects the estimation of the reproduction rate, or in other words the average number of secondary infections that arise form an infected individual. The calculation for R0 is shown below in equation 1 with N as the initial total population and S(t) as the number of healthy/susceptible people at time t.

$$N * ln(\frac{S(0)/S(t)}{N - S(t)}) \tag{1}$$

Analyzing the results

In our control setting, we set the infect chance to 29% and ran it 10 times. Figure 3 to 5 show the results. The means and deviations of R0 tend to be consistent throughout the 10 runs. However, sometimes there were outliers with the total death count($M = 17.9, SD = 1.79$) and with the immunity ($M = 38, SD = 5.61$). It showed that those two parameters can be affected considerably by chance alone.

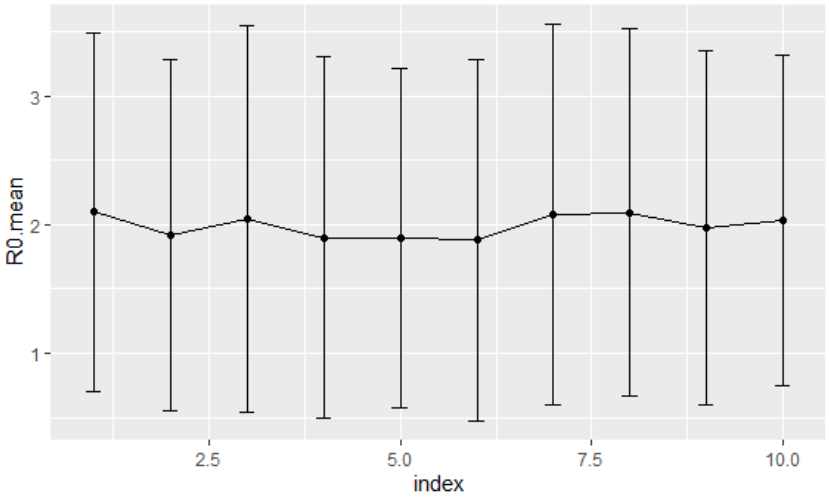

Figure 3. Control setting - R0 mean

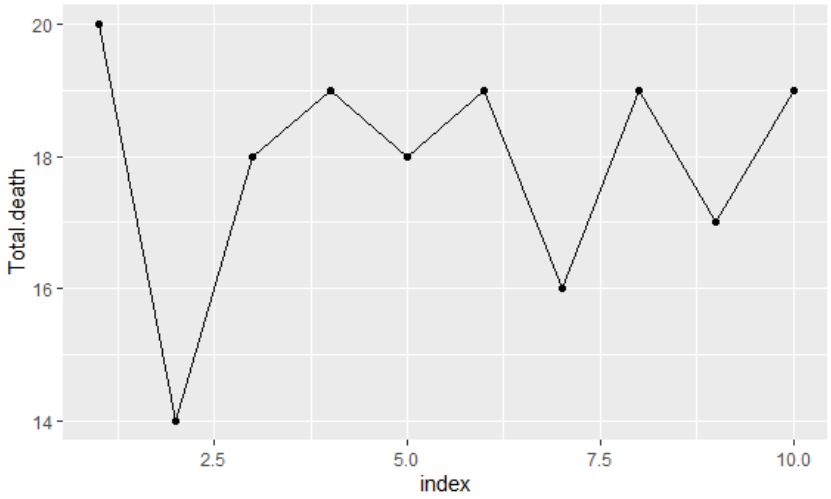

Figure 4. Control setting - Total Death

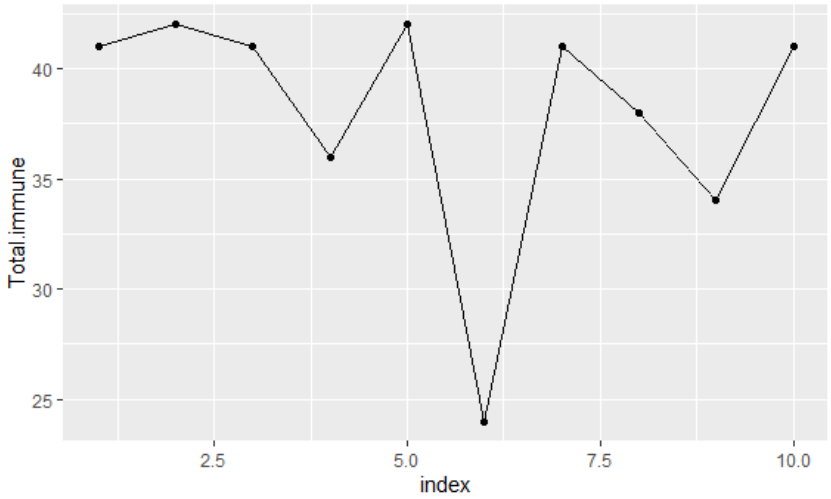

Figure 5. Control setting - Total Immunity

In the second experiment, we varied the number of vaccination places from 1 to 20. We ran a certain set-up 10 times, so in total, we had 200 runs in every experiment. With the 10 runs we could get a mean for that variable and plot it against the number of vaccination places. Figure 6 to 9 show the plots with the means and standard deviations as error bars. From figure 6 we can see that as we increase the number of vaccination station, the R0 means tend to increase as well. The R0 means all stayed above 1.0, indicating that it might be an epidemic. We theorize that the vaccination stations unintentionally act as disease spreading hubs. They attract people to gather there and give a chance for infected people to transmit the virus. The vaccine needs 2 shots to provide immunity, so healthy individuals who get their first shot might still

catch the virus before they get the chance to get the second shot. Another probable explanation is that infected people take away the chance to get the shot from healthy individuals, which makes them more susceptible to the virus. The total death rates fluctuate and the graph shows long error bars, or standard deviations. That means the death counts are quite different for each run. Particularly, the mortality mean rate when there are 4 vaccination places ($M = 18.4, SD = 3.37$) is even worse than the control condition ($M = 17.9, SD = 1.79$). It is not until we hit 12 vaccine places that the number consistently decreases. In the total immunity result (figure 8), the count increases until it levels off at 6 vaccination places. The mean number of immune individuals at 5 stations is 186.1(2.42), which accounts for 91.67% of the population. This number is enough to create the so-called group immunity, or herd immunity (Fontanet & Cauchemez, 2020). Generally, the results show that the increase in vaccine places does create group immunity in the end. However, it unintentionally helps to spread the disease and does not protect the vulnerable groups.

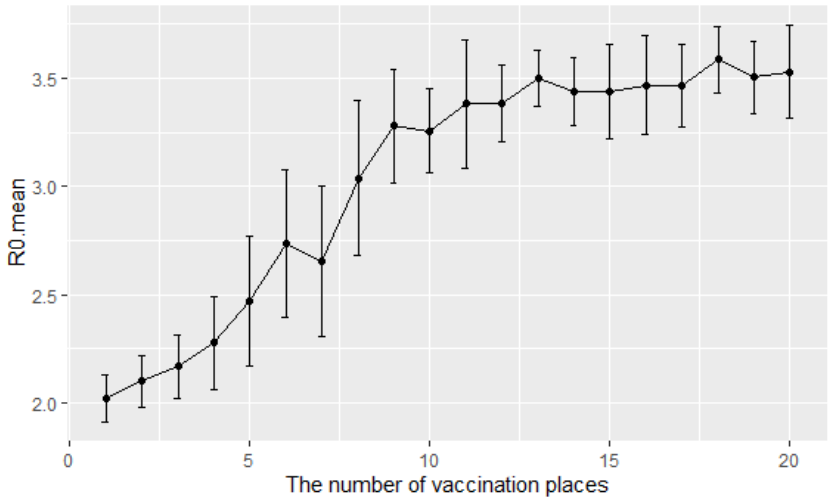

Figure 6. 29% infect chance - R0

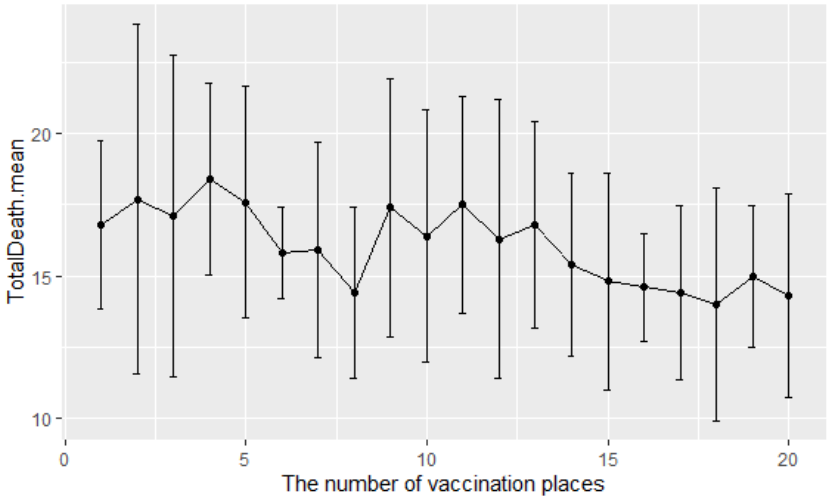

Figure 7. 29% infect chance - Total Death

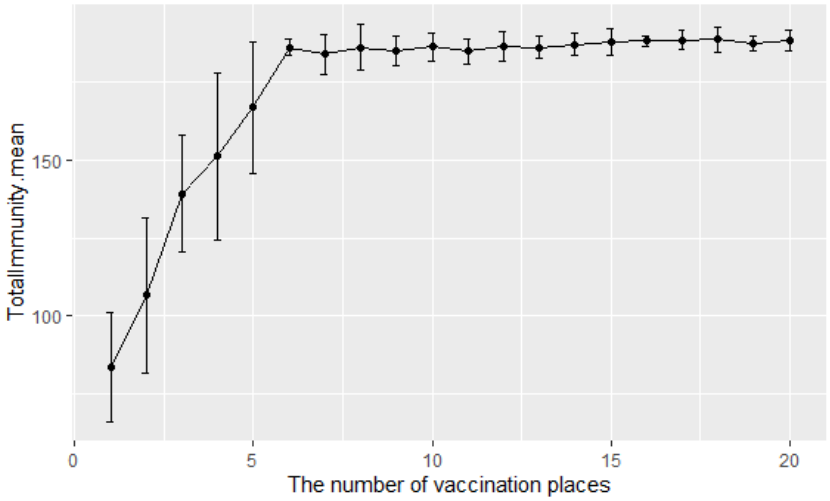

Figure 8. 29% infect chance - Total Immunity

We conducted the same set-up as the second experiment except the infect chance was 15%. This number was reflects a situation where people pay more attention to hygiene, wearing masks, avoiding close contacts, and following the safety guidelines. Although the R0 (Figure 9) still rises along with the number of vaccination places, its means are smaller in comparison to the second experiment. A big improvement can be seen in figure 10, the total death count at with only one vaccination place ($M = 15.7, SD = 4.9$) is significantly better than the control condition ($M = 17.9, SD = 1.79$). Furthermore, the total death count mean is only 8.2(3.39) at 19 vaccination places. That is an indication that we have done a significant job at protecting the vulnerable group. The total immunity count levels off at the same number as in experiment two, six vaccination places. In conclusion, we can see that driving down the infection chance alone can help a lot at protecting the vulnerable and slow down the disease.

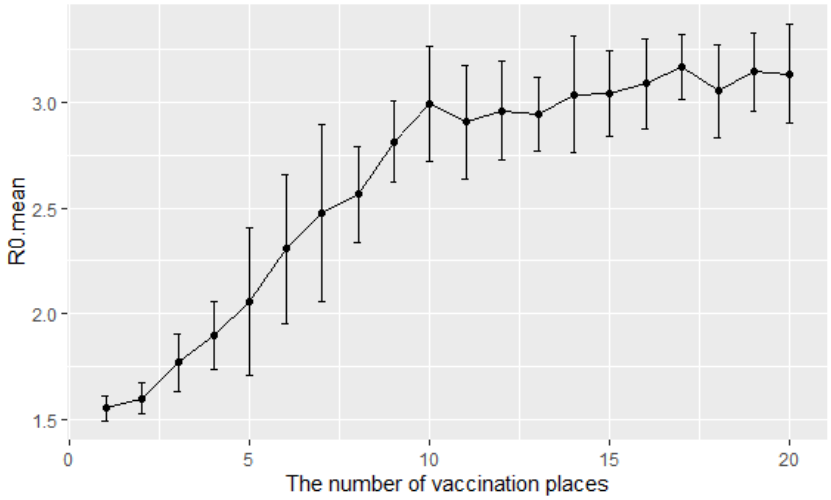

Figure 9. 15% infect chance - R0

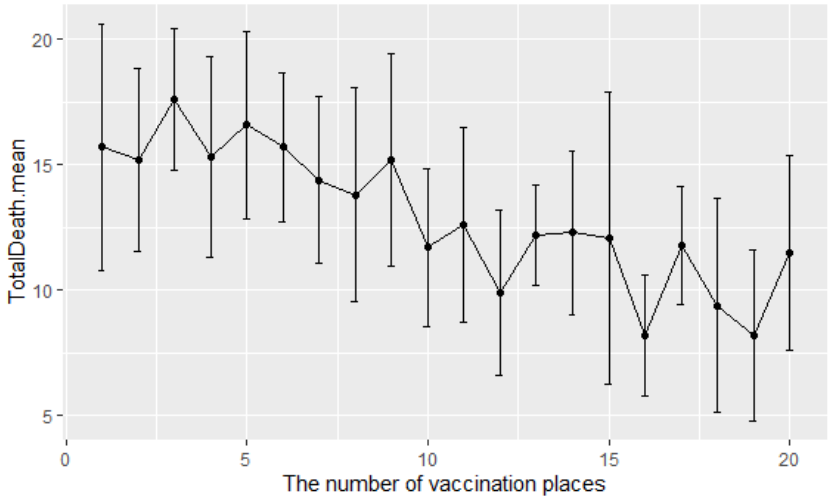

Figure 10. 15% infect chance - Total Death

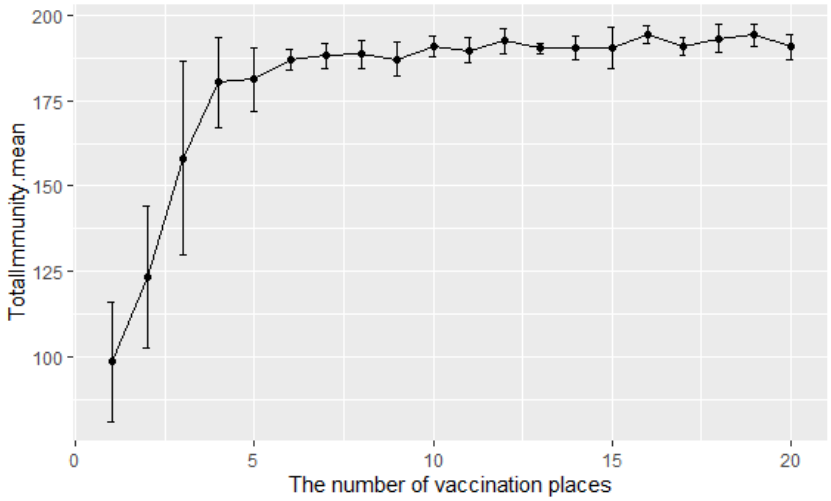

Figure 11. 15% infect chance - Total Immunity

Conclusions

In conclusion, a vaccine is an essential element to create group immunity and enable people to return to a normal life. However, the results from the model suggest that we still need to conduct social-distancing measures and other quarantine policies while the vaccine is being distributed to the whole population. Vaccines might require several doses and can't provide immunity in a short time. In other words, people can be infected by the virus before the vaccine gives them immunity, this reduces efficiency of the vaccine. Even if we eventually reach group immunity with vaccines, vaccinations alone will not be able to drive down the mortality rate. Better policies and strategies need to be deployed so that the vulnerable group can get the vaccines first. In addition,

social-distancing measures will still take place to protect them while waiting for the vaccine to take effect. The model also gives us an interesting insight into how vaccination places might become hubs that help to spread the virus. This phenomenon might explain the transmission rate in places such as supermarket, cinemas, hospitals, etc. and why health workers are so vulnerable to the disease. There are many promising future developments for our model. First of all, the R0 formula we presented in the report might not be ideal. We may test the model with a Bayesian approach in the future (Equation 2) to estimate the effective reproduction rate R_t (systrom, n.d.). This approach has the advantage of taking into account the rate in which new cases arrive every day. Secondly, people in the real world do not move randomly, they go to places if it has a purpose. So we may implement some sort of buildings for them like supermarkets, schools, companies, etc. to go there regularly. Thirdly, we may implement immigration, so agents can move to different regions. Those implementations will help answer questions on how and when to resume travel and business activities while the vaccine is being distributed. We also may implement specific behaviour for the vulnerable group to understand more about them. Last but not least, if the data that we have, is more reliable, we may attempt to construct a model that can predict new cases, R_t, or vaccine distribution rates more accurately.

$$P(R_t|k|t) = \frac{P(R_t) * L(k_t|R_t)}{P(k_t)} \tag{2}$$

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Appendix

Netlogo code

```
turtles-own [category my-immune-time was-in-infected-area alive-time
↪  immune-level time-till-next-vacination
↪  i-am-already-infected-for-so-many-hours i-am-already-ill-for-so-many-hours
↪  vacination-target]
patches-own [infectious]
globals [
  new_day
  total_days
  ;; These are for the culmulative graph
  total_infected
  total_recovered
  total_dead
  total_immune
  ;; these are for r0
  nb-infected ;; total infected people at end of a tick
  nb-recovered ;; total recovered people at end of a tick
  nb-infected-previous ;; previous tick total infected
  initial-people
  initial-healty
  beta-n
  r0
  gamma
]


to setup ;; Make all the turtles based on the sliders
  clear-all
  ask patches [set pcolor background]
```

```
  create-turtles starting-healty [ setxy random-xcor random-ycor set category
↪  "healty" set color green set was-in-infected-area 0 set shape "person"] ;;
↪  spawn healty turtles
  create-turtles starting-infectious [ setxy random-xcor random-ycor
↪  become-infected set shape "person"] ;; spawn infected turtles
  ;; create-turtles starting-ambulance [ set size 2 setxy random-xcor
↪  random-ycor set category "ambulance" set color white set shape "truck"] ;;
↪  spawn infected turtles
  ;; create-turtles 1 [ set size 2 setxy 0 0 set category "hospital" set color
↪  white set shape "house" set color red + 3] ;; spawn infected turtles
  create-turtles how-many-vacinaiton-places [set size 3 setxy random-xcor
↪  random-ycor set category "vaccine_place" set color yellow set shape
↪  "target"]
  ;; These are all to calculate r0
  set total_recovered 0
  set total_immune 0
  set initial-people starting-infectious + starting-healty
  set initial-healty starting-healty
  set nb-infected-previous starting-infectious
  reset-ticks
end



to calculate_days
  ;; Run day calculations
  let hours-in-day 24
  set total_days floor (ticks / hours-in-day)
  ifelse ticks mod hours-in-day = 0 [set new_day true] [set new_day false] ;;
↪  is ticks mod ticks-in-day 0 then it is a new day
end
```

```
to go  ;; Main function.
  if count turtles with [category = "infected"] + count turtles with [category
↪  = "ill"] = 0 [stop] ;; stop if there are no danderous people anymore
  calculate_days
  ifelse show-infect-area [
    ask patches with [infectious = true] [set pcolor background set infectious
↪  false ] ;; This is the else
  ] [ask patches [set pcolor background set infectious false]]



  ask turtles with [category = "ill"] [ ill ]
  ask turtles with [category = "never-recover"] [ never-recover ]
  ask turtles with [category = "infected"] [ move infected]
  ask turtles with [category = "healty"] [ move healty]
  ask turtles with [category = "immune"] [ move immune]
  ask turtles with [category = "vaccine_place"] [inject-vacine-into-people]
  select-vacinate-targets

    if new_day [ ;; calculate r0 every day
    calculate-r0
    set nb-infected-previous nb-infected
    set nb-infected 0
    set nb-recovered 0]
  tick
end



to move
  set alive-time alive-time + 1
```

```
  ;; Function to move turtles
  ifelse vacination-target = true [
    let vacine_places turtles with [category = "vaccine_place"]
    if count vacine_places > 0 [
      set heading towards min-one-of vacine_places [distance myself]]
    forward 1
  ]
  [;; Normal random move
    right random 30
    left random 30
    forward 1]
end



to healty
  ;; This function is run by all healty turtles
  set color green
  test-if-should-become-infected
end



to infected
  ;; This function is run by all infected turtles
  create-infection-area
  set i-am-already-infected-for-so-many-hours
↪   i-am-already-infected-for-so-many-hours + 1
  if i-am-already-infected-for-so-many-hours >
↪   after-how-many-days-can-you-become-ill * 24 and random 100 <
↪   getting-ill-chance [
      set category "ill"
      set color red - 3
```

```
      set pcolor gray] ;; every 24 hours you have a chance to become ill
end



to ill
  set vacination-target false
  set i-am-already-ill-for-so-many-hours i-am-already-ill-for-so-many-hours +
↪  1
  if i-am-already-ill-for-so-many-hours > 96 [
    ifelse i-am-already-ill-for-so-many-hours > 240 and random 100 < 20 and
↪  new_day = true [set category "immune" set total_immune total_immune + 1
↪  set nb-recovered nb-recovered + 1] ;; After 14 days if you recover, you
↪  are immune
      [ifelse random 100 < chance-to-recover and new_day = true [set category
↪  "healty" set total_recovered total_recovered + 1 set nb-recovered
↪  nb-recovered + 1] ;; After 4 days you have a chance-to-recover% chance to
↪  recover
        [if random 100 < chance-to-die and new_day = true [set category
↪  "never-recover" set total_dead total_dead + 1] ;; After 4 days you have a
↪  chance-to-die% chance to never recover
  ]]]
end



to select-vacinate-targets
  while [count turtles with [vacination-target = true] <
↪  max-vacination-at-the-time and count turtles with [category = "healty" and
↪  vacination-target != true] > 0 ] [

    ask one-of turtles with [(category = "healty" or category = "infected")
↪  and vacination-target != true] [
```

```
        set vacination-target true
      ]
    ]

end


to inject-vacine-into-people
  ask turtles in-radius 4 with [vacination-target = true] [
    ifelse category = "healty" [
      set vacination-target false
      set immune-level immune-level + 1
      if immune-level = vacinations-needed-to-become-immune [ ;;become
↪  vacinated
        set category "immune"
        set total_immune total_immune + 1
        set color blue]]
    [set vacination-target false] ;; not healty.
  ]
end


to never-recover ;; function that runs when by never recover
  set color gray
end


to immune
  set color blue
  ;; This function is run by all immune turtles
end
```

```
to create-infection-area
  ask patches in-radius infect-range [
    set infectious true
    if show-infect-area [set pcolor red - 2]
  ]
end



to become-infected
  set category "infected"
  set color red
  set nb-infected nb-infected + 1
  set total_infected total_infected + 1
end

to test-if-should-become-infected
  ;; If turtle is on patch that has infect-time-left than there is a change
↪  that a turtle gets infected
  ifelse infectious = true [
    set was-in-infected-area was-in-infected-area + 1
    if was-in-infected-area > 20 [
      become-infected
    ]
  ] [
    if was-in-infected-area > 0 [
      if random 100 < infect-chance [
        become-infected
      ]
      set was-in-infected-area 0
```

```
    ]

  ]
end



to calculate-r0 ;; Taken from travel and controll

  let new-infected sum [ nb-infected ] of turtles
  let new-recovered sum [ nb-recovered ] of turtles
  let susceptible-t count turtles with [ category = "healty" ]  ;; Number of
↪  susceptibles now
  let s0 initial-healty ;; Initial number of susceptibles

  ifelse nb-infected-previous < 10
  [ set beta-n 0 ]
  [
    set beta-n (new-infected / nb-infected-previous)       ;; This is the
↪  average number of new secondary infections per infected this tick
  ]

  ifelse nb-infected-previous < 5
  [ set gamma 0 ]
  [
    set gamma (new-recovered / nb-infected-previous)     ;; This is the
↪  average number of new recoveries per infected this tick
  ]

  if ((initial-people - susceptible-t) != 0 and (susceptible-t != 0))   ;;
↪  Prevent from dividing by 0
```

```
  [
    ;; This is derived from integrating dI / dS = (beta*SI - gamma*I) /
↪   (-beta*SI)
    ;; Assuming one infected individual introduced in the beginning, and hence
↪   counting I(0) as negligible,
    ;; we get the relation
    ;; N - gamma*ln(S(0)) / beta = S(t) - gamma*ln(S(t)) / beta, where N is
↪   the initial 'susceptible' population.
    ;; Since N >> 1
    ;; Using this, we have R_0 = beta*N / gamma = N*ln(S(0)/S(t)) / (K-S(t))
    set r0 (ln (s0 / susceptible-t) / (initial-people - susceptible-t))
    set r0 r0 * s0 ]
end
```