Final Report

Agent-based Simulation of COVID-19 Transmission

CM3203 One Semester Individual Project - 40 Credits

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Abstract

The Agent-Based Model is an approach to model from an individual-based angle. At the beginning of the development of this technology, it was not popular as it required a certain amount of computer power to support. However, it becomes possible to use Agent-Based Modelling to achieve a complex and dynamic system with the development of computer technology over the years. Therefore, more and more researchers have started to use this method to solve problems in their field.[3] In this project, we will use Agent-Based Modelling to build a system that can simulate and visualise the spread of COVID-19 in the crowds. This model will then be used under the limited resource settings to further explore the effectiveness of the three measures and the impact of asymptomatic patients.

Table of content

1. Introduction....4
1.1 Problem description....4
1.2 Aim of the project....5
1.3 The structure of this report....5
2. Background....6
2.1 The context....6
2.1.1 Infectious Disease Modelling: SEIR Model....6
2.1.2 What factors affect the individual being infected....7
• The external factors: The risk of transmission....7
• The internal factors: Immunity....7
2.1.3 The behaviour of the COVID-19 patient....8
• Incubation period and recover duration....8
• Asymptomatic patients....8
2.1.4 Covid-19 measures....8
• Wearing the mask....9
• Social distance....9
• Self-isolation and self-diagnosis....9
2.2 Tool....9
2.2.1 Mesa....9
2.3 The existing solution....11
3. Methodology....13
3.1 System overview description....13
3.2 A overview of a flowchart after the agent is activated....13
3.3 Implementation details....14
3.3.1 The agent-based Model (COVID_19_model.py)....14
• Outside the model : Covid_19_Model class....14
• Inside the model：PatientAgent class....16
3.3.2 Visualization (Vsualization.py)....22
• Agent and environment....22
• Charts....22
• Input controls....23
4. Result....23
4.1 Result description....23
4.2 Result detail....25
5. Future Work....38
6. Conclusion....38
7. Reflection and Learning....39
Reference List....40
The appendix....43

1. Introduction

1.1 Problem description

After the appearance of the first patient, then followed by a country that announced the discovery of a new virus, and now the 'COVID-19' has become the most concerned topic around the world. Based on the data gathered from the community, the researchers have published various types of reports to analyse this pandemic. For example, there are a great number of studies that focus on the process of a person from being infected to recovers, in order to study the characteristics of COVID-19. Also, the various measures released against the transmission of the virus are popular research topics. Although more and more analysis results can support the effectiveness of those measures for now, some of them are controversial when they were raised, which some countries and citizens questioned whether a certain measure is necessary and even refused to follow.

The results obtained through data statistics and analysis are very meaningful, but it has some limitations. On the one hand, it can not provide a global and intuitive perspective to see the occurrence and development of coronavirus. On the other hand, this approach does not allow us to study some issues concerning COVID-19, such as the one we will present next. That is, in the early days of the epidemic, people were unwilling to comply with the measures, and the country had the limited capacity of the testing and hospital. This situation caused many unnecessary deaths and infections. How this situation will change if different numbers of people followed with a certain measure. In the explored measures, which one is most effective against the transmission of COVID-19 and alleviating the burden of the limited resources? And What impact do asymptomatic patients have on the implementation of these measures? Obviously, It is difficult to tell the answer from collecting and analysing data. However, based on these findings from the analysis of realistic data, the approach of modelling may help us to see the spread of the COVID-19 and explore those question.

In epidemiology, mathematical models are often used to study the transmission of infectious diseases. The most famous of which are the SI, SIR, SIRS, and SEIR model. Many scholars have tried to simulate COVID-19 with these models and the outcomes have shown that they are all feasible for simulating the spread of the COVID-19.[13] However, the mathematical models can only give a static and macroscopic result, it cannot be visualised to see the infection from the beginning to the end among the population. Also, the system represented mathematically might be very complex and difficult to understand for the general public.

Alternatively, Agent-Based Modelling could be the solution which is an approach to modelling the complex and dynamic system. Different from mathematical models which are based on a mathematical formula, Agent-Based Models relies on agents

and an environment. The agent is the object that can directly or indirectly affect the patterns of the system and the environment is the container where agents acts. Briefly, Agent-Based Models is made up of a group of autonomous agents defined with behaviour rules. The behaviour makes the agents selectively interact with each other in the environment and then the system-level behaviour will be generated.[3][5] In simple terms, the model is like a world and the agents are the individual in it. They will acts in an environment according to their behaviour. After many iterations, the model presents the system behaviour at a macro level. So, Agent-Based Modelling models the system from the individual point of view and this characteristic makes it possible to visualise the model [19]. It means people can visually observe what happens in this system. Moreover, Agent-Based Modelling is an easier approach for the developer to implement their system, which due to its rules is made up of a list of simple behaviours rather than complex mathematical theory. Therefore, compare to mathematical models, Agent-Based Models meet our requirements better to build a specific and dynamic system.

1.2 Aim of the project

In this project, the aim is to use Agent Base Modelling to simulate and visualise how the COVID-19 spread in the crowds with a simple environment setting. Then, with the basic model, we will further explore the questions that we proposed in the problem description. Firstly, we will explore the case that the model only has the limited capacity of testing and hospital capacity. Based on this situation, we will explore three measures which are keep social distance, wearing a mask or self-isolated and self self-diagnosis under the condition that the number of people who follows measures can be adjusted, to see how they affect the development of the outbreak and the burden of the resource shortage. We expected that the comparison results can answer the question of which measure is the most effective. Finally, we will explore the impact of asymptomatic patients on the epidemic and the effectiveness of the measures.

1.3 The structure of this report

This report will provide more detailed materials to discuss how this system was designed and completed. Firstly, the background will be given to illustrate the knowledge related to this project which will help you understand the rest of the report. Followed by the methodology section. It will start with an overview of the architecture, those explanation will show how this system works at a high level. The report then will look into the detail of my implementation. Afterwards, the result will be given to talk about what I have got from my solution. Also, I will discuss if my result is meaningful and what I need to do in future work. Finally, I will make a conclusion and reflect on my project.

2. Background

In this project, we chose the human as the agent rather than viruses due to it is too microscopic soot so that it is very difficult to directly simulate the behaviour of the virus. Instead, using changes in human states to indirectly represent the spread of the virus which is much easier.

The most important factor in constructing an agent-based model is the behaviour of the agent. So, to make the model closer to reality, we need to understand what state the agent has and what behavior it has in a certain state. Therefore, the first section is mainly about COVID-19 to illustrate the characteristics of this pandemic which are needed in the methodology. However, we have to mention that we only consider the information about Covid-19 from the United Kingdom which due to the performance of the virus in each country is different. After the context, then it will follow with the discussion about the tool to show the way to use Mesa. Finally, it gives a talk to show what I have found in my research stage to introduce the existing solution.

2.1 The context

2.1.1 Infectious Disease Modelling: SEIR Model

COVID-19 is a type of infectious disease, so to some extent mathematical models can help us to understand the state and behavior of virus. Among these models, the behavior described by SEIR model is the most similar to COVID-19.[12] Before discussing this models in detail, it is important to know some concepts which is also the original of the name 'SEIR'.

In the study of infectious diseases, the population was generally divided by the epidemiologist into the following categories: [21]

1) 'S': Susceptible, refers to those who have not gotten the virus but they are susceptible to be infected after contacting an infected person because of bad immunity.
2) 'E': Exposed, refers to people who have been in contact with an infected person but are temporarily unable to infect other people. This period also called an incubation period.
3) 'I': Infected, refers to a person who has been infected and can infect the people who belong to 'S'.
4) 'R': Remove, refers to a person who recovers or dies from the diseases. If the immunization period is limited, members of the R class can revert to the S class.

So, the name of SEIR represents four states of the individual. More specifically, the SEIR model begins with 'Susceptible' who is likely to be infected. After being infected, the 'Exposed' will experience an incubation period before showing symptoms and this patient is not infectious during this period. Then, the 'Infected'

individual will recover or die after a recovery duration (Remove) and he may be infected again.

The process of how COVID-19 infect people is roughly the same as SEIR model describes, while there are two unique features that COVID-19 has. The first one is the patient can infect others during the incubation period but it will be less infectious than in symptomatic patients. The second is the recovered patient will not be infected again once the individual recovers. Although be infected again has occurred, it has only been seen in a few cases worldwide. So we do not consider this situation in this model.

2.1.2 What factors affect the individual being infected

The research shows that the chance of infecting by COVID-19 affects by external and internal factors. The former determines the likelihood that people will be exposed to the virus and the latter determines whether the individual will be infected.[9]

- **The external factors: The risk of transmission**

It is possible that the person will not be infected after being in contact with an infected patient. One of the reasons is that this individual does not reach the virus. The risk that COVID-19 can be transmitted from person to person is affected by many elements. It includes the capability of the virus, the environmental factors, and the contact between the individual and the infected, which the closer the contact is and the more likely it is to be infected. Moreover, it also is affected by whether the patient has symptoms since patients with symptoms such as coughing or sneezing will be more infectious.[9][22]

- **The internal factors: Immunity**

After the individual was exposed to the virus, if he will be infected in the end is determined by the individual itself. So, this is the another reason that the individual may not be infected. Because the better a person's immunity is, the less likely it is to be infected with the virus.[9] Moreover, It is not difficult to find that the condition of our immune system is closely related to our age.[17] There is a pattern that the immunity will gradually decline as age increases. So, it can infer that older people are more likely to be infected because of poor immune system. Meanwhile, the older often suffers from other diseases, so they are more likely to die after infection. In my implementation, it will assign the immunity for agents according to the age group which means we also needs to learn about the age structure of UK. The following is the distribution of the population according to age, which updated on Friday, November 27, 2020.[13]

0-14 years: 17.63%
15-24 years: 11.49%
55-64 years: 12.73%
65 years and over: 18.48%

2.1.3 The behaviour of the COVID-19 patient

- **Incubation period and recover duration**

There is no official report to analyse the incubation period and the recovery duration in the United Kingdom, but the coronavirus advice released by Lloyds Pharmacy gave the timeline of COVID-19 symptoms. It illustrates that patients usually show symptoms within 2 to 14 days and the average incubation period is 5 days. With regards to the recovery duration, it suggests that patients usually recover within 14 days or less, but it can take longer than 14 days in severe cases.[16]

- **Asymptomatic patients**

There is a special type of patient for COVID-19 that needs attention, which is the asymptomatic patients. Usually, it refers the individual who tested positive but does not have any symptoms until they recover, but actually the patients in the incubation period also can be included.

In the beginning, most experts believed that asymptomatic patients have a little infectivity to people. However, more and more studies have shown that asymptomatic patients are more infectious than we expected. A Korean study showed that asymptomatic patients carry the same amount of virus as symptomatic patients in their nasal cavity. So, in theory, it means they have the same possibility to infect others.[1] COVID-19 transmits depending on the droplets which will be released into the air when the patient breathes or talks. Therefore the reason that symptomatic patients relatively are more infectious is that symptoms such as coughing and sneezing will release a larger amount of small droplets.[2]

Although there is still no research to prove how infectious asymptomatic patients are, some studies have found other patterns about asymptomatic patients. Firstly, asymptomatic patient are younger, they usually have good immunity. Secondly, the duration from infection to recovery is longer than 14 days. In other words, an asymptomatic patient will carry the virus for longer. Also, The report suggested that there are 10-30% of patients are asymptomatic patients.[6][8]

2.1.4 Covid-19 measures

In March 2020, there were only a small number of confirmed and dead case in the UK, the government proposed some guidelines such as social distancing and self-isolation measure, but these were not mandatory and they also claimed that wearing masks was not necessary. So people did not realise the seriousness of the epidemic. Afterwards, as the spread of COVID -19, there is an increasing number of people were confirmed and the number of seriously ill people increased. The UK's testing capacity and hospital capacity then began to be inadequate. This is when the UK issued some mandatory measures such as the mandatory wearing a mask indoors issued in September 2020.[11]

- **Wearing the mask**

Wearing a mask is the most controversial measure during the epidemic. Many citizens consider mask-wearing as a useless method for the spread of the virus at first and even the government claimed to agree with this view. With the development of the epidemic, the increase in relevant data provides strong evidence to support that this measure has a positive effect on the control of the epidemic. There is a pathological study found that wearing a mask can reduce the 70% risk to be tested as positive.[2]

- **Social distance**

The closer people are, the more likely they are to be infected. So, the social distance requires the individual to keep a 2m distance or reduce contact with other people to stop the spread of the virus.

- **Self-isolation and self-diagnosis**

Self-isolation refers that the individuals are advised to isolate themselves at home until recovered once they find symptoms such as cough and fever. The patients are not allowed to walk outside during this quarantine time.[18] For self-diagnosis, it refers that not all people can be cured by their own immunity, and people in self-isolation with poor immunity may be life-threatening. Therefore, the government has put forward a concept of self-diagnosis, only patients with very serious conditions can go to the hospital.[20]

2.2 Tool

2.2.1 Mesa

The implementation of this project will under Mesa which is a python framework for Agent Base Modelling. It includes three types of modules, which are modelling, analyzing and visualizing. In fact, we can complete an agent-based model with just the modelling module, but It would be cumbersome because we have to collect the data at each step and process it by our own. So the analyzing module provides the component to help us collect and analyse the data which can simplify the implementation process. For the visualizing module, It is used to visualise the data collected to allow the developer to see how the agent is acting when the model is run.

- **Modelling module**

When we implement the model, two main classes are needed which are agent and model and required to inherit the Agent and Model class in Mesa. The agent class is used to define the attributes and various behaviours of the agent. And the model class includes global parameters and methods to manages all agents globally. In the generic Model class, there are many build-in components are provided to help us to build the model. And two of the important components need to be known which is the scheduler and grid because it will be mentioned in my implementation.

1) The grid is the component that provides some function related to the environment in the model. For example, we can get the position of the agent in the environment through it. In other words, it can be regarded as an interface to the environment.
2) The scheduler is the component to determine the way how the agent is activated. It means we can set the order to let the agent act through this scheduler. In this project, the agent will be activated at the same time at each iteration.

- **Analysing Module**

The data generated by the model is the key to understand the system. Mesa provides a data collector to help the developer to collect and summarise the data. In general, the data can be extracted from the agent level or model level. At the agent level, it can record the value of the attributes or the place the agent is at each step. Also, it can compute the pattern at the model level to generate different types of analysis chart, but we have to provide the way to compute.

- **Visualizing Module**

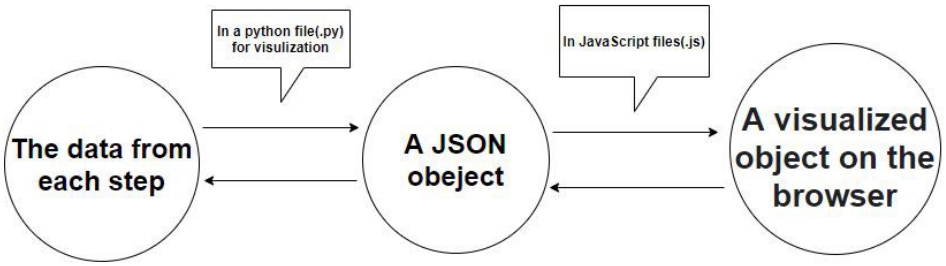


Fig. 2.1. *How the collected data is processed can then be visualized on the web page.*

Th Fig.2.1 shows how the data can be visualized in Mesa. To be specifically, After the model is started by the local server, the data collector will collect the data from the model. At each step, these data will be converted into a JSON object in a python file and pass it to the corresponding JavaScript files. Finally, it then will be drawn on the browser. So, the process of visualizing needs to consider two sides which one python file for models and some js files for the website. In fact, Mesa has already provided some modules to help the developer convert and render the data on the website using the included JavaScript library. So, the user only has to consider how they want to represent the object. For example, the CanvasGrid module collects how to draw the agent from the developer via an agent portrayal class. Also, the size of the grid needs to be provided. And this module will then tell the JavaScript side to draw the agent and grid as required. Except for the agent and grid, some chart can also draw on the website by the corresponding modules as the data being provided.
[19]

2.3 The existing solution

I found three similar cases to my project that includes the content about using ABM for the simulation and visualisation of Covid-19. The following figures are the result of these three solutions. In these three solutions, they all chose human as the agent, but the number of agent states they considered was different. Namely, they have chosen different corresponding mathematical models. To be specific, the agent-based model created by Erik Cuevas for his research only considered two states of the agent which are susceptible (Blue) and Infected (Red).[4] In Fig 2.2., it showed his result which there was only one red dot in the environment at first (k=1). As the number of iterations increased, the number of red circles then gradually increased and eventually almost all agents were infected (k=300). In his approach, the susceptible agent may be infected if he is within n meters with the infected agent. Whether to be infected or not depends on a possibility assigned to this agent. This possibility represents all the factors that can affect the infection. A random number will be generated and compared with this probability. Then, if it is greater than this possibility, the agent will be infected. Otherwise, it will not.

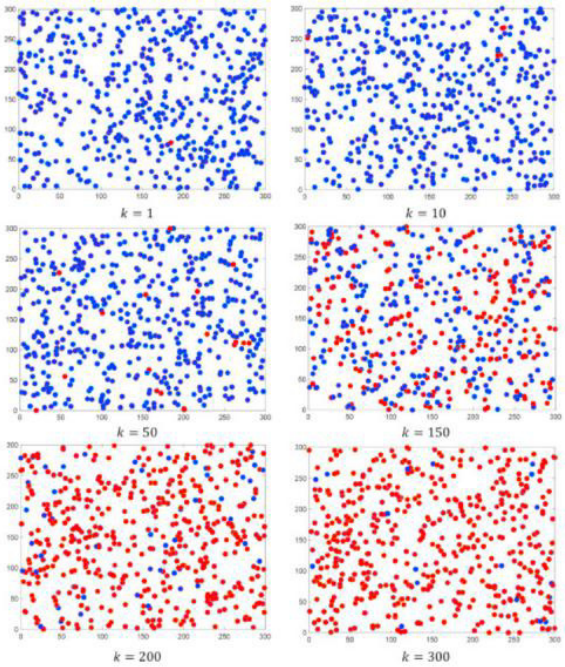


Fig 2.2. *The first existing solution from Erik Cuevas for his project 'An agent-based model to evaluate the COVID-19 transmission risks in facilities' .(k is the number of iterations)*

The other two developers considerd the agent has three states which also known as the SIR model in the mathematical model. In addition to the visualisation of the model, they also provided a chart to record the number of agents in each state for every steps to study the trend of the outbreak at a macro level. Fig 2.3. shows a screenshot for the video form Csala Dénes, in this video he only introduced what is agent-base modelling and showed his result but he did not provide his approach in detail which it is not very informative [7].

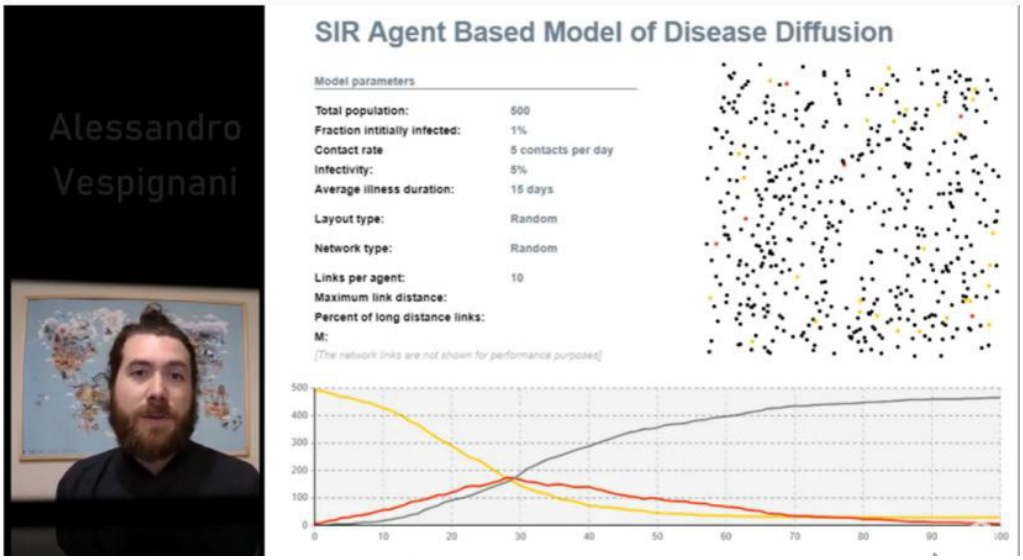


Fig 2.3. *The second existing solution from Csala Dénes which is a video introducing what is ABM and his result of his project.*

For the third project showed in Fig 2.4. which developed by Jekyll is the most similar one to my project because we are both implementing our models under Mesa[14]. In his implementation, the way he decided whether a virus will be infected was determined by a random number (0 -1) which represents how close contact the agent with the infected agent. And the agent will be infected if its close contact is smaller than the value his model set when this agent is in the same grid with the infected.

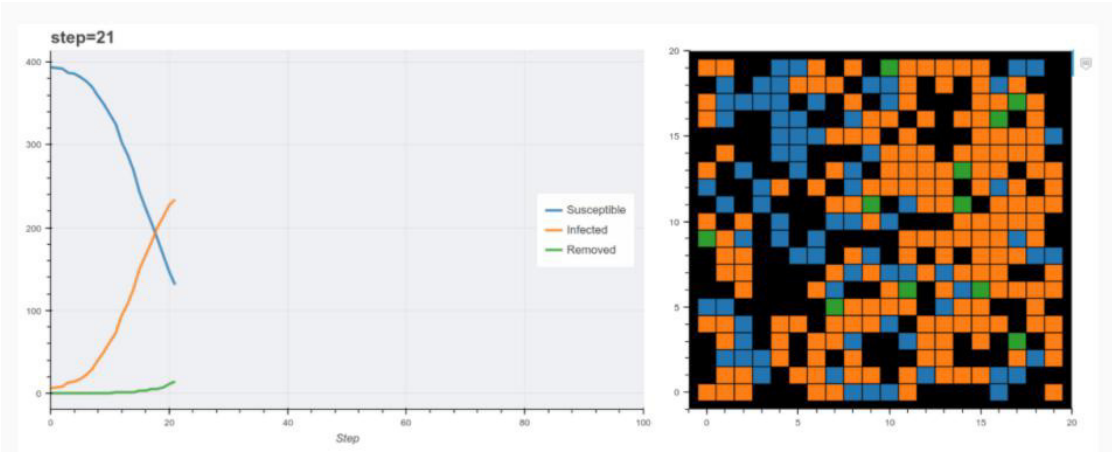


Fig 2.4. *The third existing solution from Jekyll for his project 'A simple agent based infection model with Mesa and Bokeh'.*

In fact, the way from Jekyll to decide if infecting only considered the external factor but ignored the difference between individual. And Erik' approach considered the internal and external factor together. However, I will consider these two factors individually in my solution due to whether the agent is infected or not is affected by these two factors successively. So, I think it would be more close to reality in this way. Compare to the state of the agent, I would consider the SEIR model since the patient of COVID-19

has an incubation period. Moreover, there is a problem from Jekyll' s visualization that caught my attention, which it only has one colour in a cell. So I thought it would be difficult to observe if there are more than one states of the agent in the same grid. So, it will improve this in my solution.

3. Methodology

3.1 System overview description

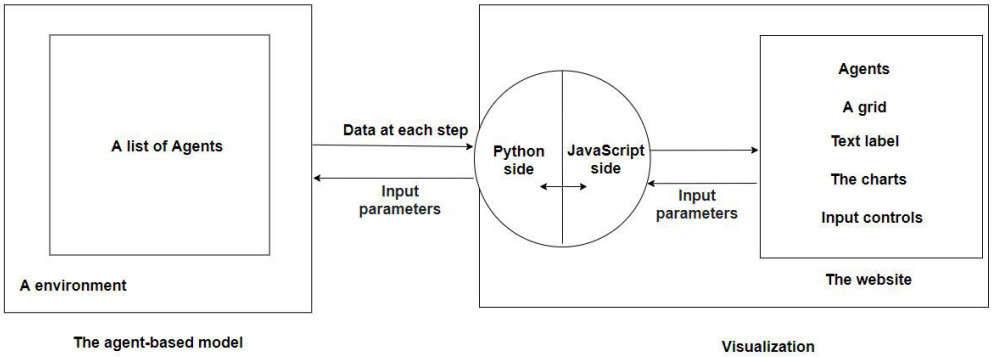
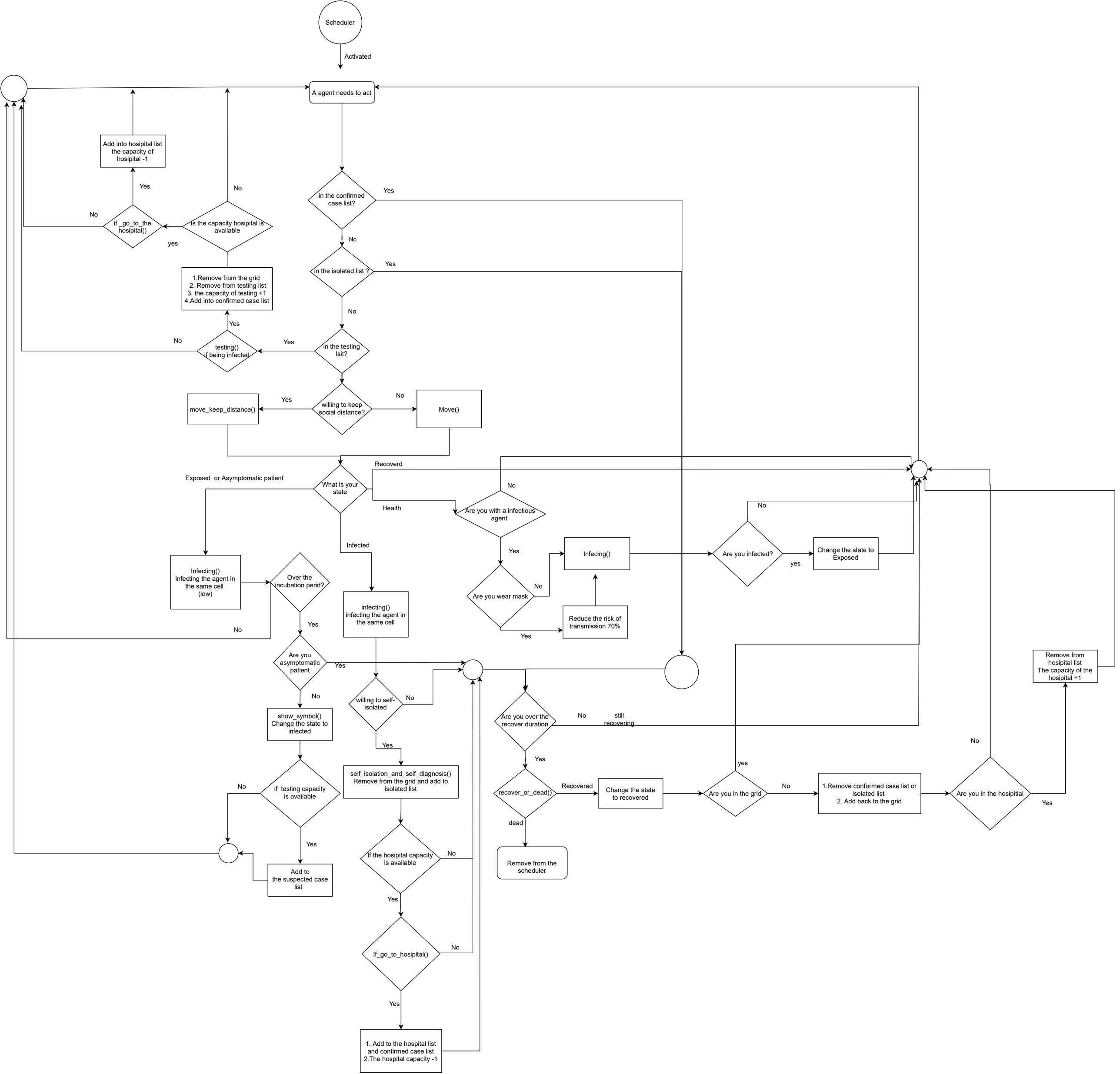


Fig 3.1 *A overview of the composition of the system and how they are connected .*

In Fig 3.1, it shows the structure of this system from a high level. In General, this system consists of two core part which is the agent-based model itself and its visualization. In the iteration of the agent-based model, the agents with the different state will constantly perform certain behaviours in an environment. Each iteration can be regarded as a step. At each step, data related to visualization will be collected by the python side of the visualization. And how to visualize the object are also defined in this python file. All this information will then tell the JavaScript side of visualization how to draw those objects on a local browser which including the agents, grid, text label, charts and input controls. In the contrast, the parameters input from the input controllers can be passed from the website to the model so that it can add the factors into the model or adjust the proportion of people who observe a certain measure to allow the system to explore the question we want.

3.2 A overview of a flowchart after the agent is activated

In my solution, the behavior of a agent is not constant because its state changes. Also, different behaviors are not independent, they will affect each other. Therefore, the flowchart can better illustrate and summarize what kind of judgment the agent will need to make in each iteration in my implementation. There are some some used words I have not covered yet but I will discuss in the following implementation details.


Scheduler
Activated
A agent needs to act
in the confirmed case list?
Yes
No
in the isolated list ?
Yes
No
in the testing lsit?
Yes
willing to keep social distance?
Yes
move_keep_distance()
No
Move()
testing() if being infected
Yes
No
1.Remove from the grid
2. Remove from testing list
3. the capacity of testing +1
4.Add into confirmed case list
is the capacity hosipital is available
No
yes
if _go_to_the hosipital()
Yes
No
Add into hosipital list the capacity of hosipital -1
What is your state
Recoverd
Health
Infected
Exposed or Asymptomatic patient
Are you with a infectious agent
No
Yes
Are you wear mask
No
Yes
Reduce the risk of transmission 70%
Infecing()
Are you infected?
No
yes
Change the state to Exposed
Infecting() infecting the agent in the same cell (low)
Over the incubation perid?
Yes
No
infecting() infecting the agent in the same cell
Are you asymptomatic patient
Yes
No
show_symbol() Change the state to infected
if testing capacity is available
No
Yes
Add to the suspected case list
willing to self-isolated
No
Yes
self_isolation_and_self_diagnosis() Remove from the grid and add to isolated list
If the hosipital capacity is available
No
Yes
If_go_to_hosipital()
No
Yes
1. Add to the hospital list and confirmed case list
2.The hospital capacity -1
Are you over the recover duration
No
still recovering
Yes
recover_or_dead()
Recovered
dead
Remove from the scheduler
Change the state to recovered
Are you in the grid
yes
No
1.Remove conformed case list or isolated list
2. Add back to the grid
Are you in the hosipitial
No
Yes
Remove from hosipital list The capacity of the hosipital +1

3.3 Implementation details

3.3.1 The agent-based Model (COVID_19_model.py)

The implementation of this agent-based model can be regarded as outside the model and inside the model. Outside the model, it needs to be global to manage the operation of the model. And inside the model, it is only focus on the state and behavior of the agent.

- **Outside the model : Covid_19_Model class**

Initialisation

After the start of the model, the model will first initialize a n*n grid and a required number of agents {a1.....an}, which all the agent belong to the health state at this stage. The initialization of each agent also will be assigned the age, immunity, external factor, and incubation period which showed in Fig 3.2. To better explain what these attributes are used for and how they are assigned, they will be described in detail in the following Agent section. Except for these attributes, there are two attributes, infecting_duration and recovering, which will be initialized to 0. It is used to record if this agent is over incubation_period or recover_duration respectively so that the agent can change the state. Moreover, five boolean values are used to distinguish whether the agent complies with a measure and if he is asymptomatic patients. And all these values will be initialized to False.

```
class PatientAgent(Agent):
    def __init__(self, unique_id, status, age, immunity, incubation_period, external_factor, model):
        super().__init__(unique_id, model)

        self.status = status
        self.immunity = immunity
        self.age = age
        self.external_factor = external_factor
        self.recover_duration = 14
        self.incubation_period = incubation_period

        # after the agent being infected, it will have a incubation_period which is no symbol
        self.infecting_duration = 0
        # after the agent being infected, it need to take x ticks to recover
        self.recovering = 0
        # if the agent follow a certain measure
        self.keep_distance = False
        self.have_mask = False
        self.isolated = False
        # if the agent is asymptomatic patients
        self.is_asy_patient = False
```

Fig3.2. *The attributes in the agent class*

Then, the model will place the agent randomly into a cell in the grid through the grid component and added into the scheduler so that it can be activated to act. However, the infection will only occur when the model randomly selected an agent ‘ai’ to be the first Infected agent at step 1. Then, as the agent walk around, the interaction between

agent will start to allow the virus spread in the crowd.

In addition, if the factor to be explored is added to the model via an input, then after the agent has been initialised, the model will also need to select the required proportion of agents to follow the factor. That is, in a loop, agents are randomly selected from the scheduler, and their corresponding boolean value is then set to Ture. If the number of agent reaches the required number, it will jump out of the loop to complete the selection.

Data collection and compute

A data collector is set outside the model. So, it can directly collect the required attribute of each agent at each step. But for the data from the model level, it needs to provide the way of how to compute it from the atomic data for the data collector so that it can collect automatically. For this project, there are only the immunity needs to be collected from the agent. From the model, there are several methods I created to be used to compute the percentage of the agent in each state. For every method, I first used a loop to count the number of agents in a state at each step and then calculated the percentage of agents in this state out of the total number of agents. Also, there are another two methods to record the capacity of the testing and hospital from the parameters of the model. Then, all these data are collected and stored in this data collector and will be used in the python side of the visualization.

Choose agents to test

After the limited capacity of testing and hospital has been added into the model, the capacity will be available until the step reaches 10 which due to the virus cannot spread if it is applied too early. Also, this will be able to show a lack of resources because of too much demand. if the capacity is on, the agent who shows the symbol will be added to a suspected cases list, but this agent still can move around. In a loop, the model will first select the agent from this suspected cases list and add it to the test list. If there is still sufficient capacity, the model will then randomly select agents on the grid. So there will also be a list to record which agent is on the grid. The loop will be stopped when the testing capacity is 0. Furthermore, the model will no longer choose the agent to test until there is no infected agent in the environment, and the test will start again as soon as a new infected person appears.

Remove the dead agent from the Scheduler

After the agent died, it can directly remove from the grid but cannot remove from the scheduler during the iteration. This is because one iteration is the process of the scheduler to activate each agent to act. Although it seems that the agents are activated at the same time in each iteration. But the scheduler is actually a list, and all the agents are activated in this loop one by one. So removing an agent in the loop will cause the total number of agents to be reduced, which will cause the error. So, the dead agent will be added to a list and then be removed outside the iteration.

- **Inside the model：PatientAgent class**

In the agent class part, I will discuss how I realized the state and behavior of the agent gained from reality which introduced in the background. And it will be divided into two parts to discuss. The first part illustrates my implementation when there is not any factors added into the model. The second part talks about what changes and additions will be made to the state and behavior after the factors are added.

Part 1: Before adding the parameter from the input

The agent will be in one of five states in my solution which are Heath, Exposed, Infected, Dead and Recover. In each state, the agent has different behaviour that is summarized with the corresponding method in my implementation in Table 3.1.

Status:	Behaviour	Method
Health (2)	1) Walk around randomly 2) Change the state	move() Infecting()
Exposed (1)	1) Walk around randomly 2) Change the state 3) Infect others (lower infectivity)	move() show_symbol() Infecting()
Infected (0)	1) Walk around randomly 2) Change the state 3) Infect others	move() recovering_or_dead() Infecting()
Recover (3)	1) Walk around randomly	move()
Dead (-1)	none	Remove from the scheduler

Table 3.1. *The agent has five possible states in this stage and the number behind is how they are represented in the code. Each state will have different behaviour and the table was given the behavior will be achieved in which method.*

Move()

The agent can choose the surrounding cells to walk around or stay put. The surrounding cells can be got from get_neighborhood which is a build-in method in grid component, then randomly choose one from all possible position and set the new position.

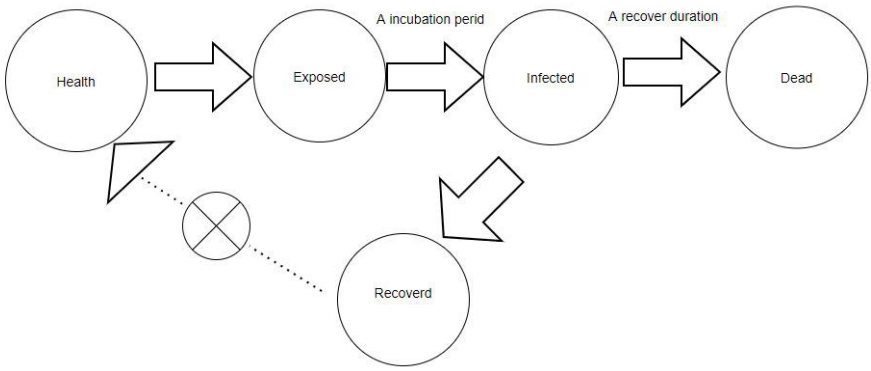


Fig 3.3. *How the agent's state might changes in my solution.*

Once the first infected agent starts to infect others, the agents then will start to change their state. According to the characteristics of COVID-19 patients we introduced in the background. the state changes are in stages which shows in Fig 3.3.

Infecting()

A health agent has the probability to be infected if he moves in the same cell with an infectious agent (Exposed and Infected). Whether the agent will be infected, determined by both the external factor (The risk of transmission) and the internal (immunity) as we discussed in the background.

The external factor is a value between 0-1 and assigned to the agent by a uniform distribution. This value represents the possibility of the agent exposure to the virus if he is in the same cell as an Infected agent. But for an Exposed agent, it is less infectious than an Infected agent, so this probability will be smaller. So far, I have not found any research results on how much the infectivity of asymptomatic patients is that of symptomatic one. But we will refer to a study that uses a mathematical model to study ' SARS-CoV-2 Transmission From People Without COVID-19 Symptoms ' and Its baseline is that the infectivity of asymptomatic patients is 75% of that of symptomatic patients.[15] So, if the agent is with an asymptomatic agent, this possibility will be P *75%. Afterwards, we use a random selection of 0 or 1 from this probability to decide if this agent reach the virus. 1 represents that the agent has been exposed to the virus, and 0 means not. If the result is 1, then the final outcome of the infection is determined by his immunity.

Immunity is a number between 0-100, which the closer to 100 and the better the immunity is. In the background, we already discussed that immunity is related to age. Therefore, the assignment of an agent' s immunity is based on the age group.

The age group	The mean value
0 - 14	70
15 - 24	60
25-55	50
55+	50

Table 3.2. *Four types of agent group. The immunity of most agents in each age group is around their mean value.*

According to the proportion of each age group and the pattern that immunity decreases with age, we used four normal distributions with decreasing mean value to represent the distribution of immunity for each age group. In Table 3.2. , it shows the specific value. We then assume that agents with immunity above 70 will not be infected after being exposed to the virus. Otherwise, they will be infected. This is supported by the existing founding that the positive results under 18 years old account for only 1.8% of the total. It means people around this age are not easy to be infected.[23] However, because of the feature of the normal distribution, it can allow the immunity of most agents to be around the mean, but there are also extreme values. Therefore, there will still be infected persons in the age group 0 -14, and the agent from other age groups will not be infected if his immunity is higher than 70. After the decision of these two factors, it will then changes his state to be 'Expose' if the agent is infected.

show_symbol()

The Exposed agent will experience an incubation period to show the symbol. It means the state needs to be changed to'Infected' if the infecting_duration is over the value assigned. The incubation period is assigned to the agent from a random array with values in the range 2 -14 and a mean of 5. To be specific, this random array is implemented by n/2 small arrays, in which n is the number of the agent. The small array contains only two numbers. This two number is generated from a loop. In this loop, the first number is randomly selected from 2-14, then the second number is calculated by subtracting the first value from twice the average. If the result of the second number is not within the range of values , the loop restarts, otherwise the loop ends and save it to the small array. So, we can get a random array that meets the requirements by generating n/2 sets of small arrays like this. However, this method has a disadvantage. That is, although the average number of the array is 5 , there will be no 9-14 value in this random array which due to there is no value in 2-14 to match it.

recovering_or_dead()

Once the agent is in an Infected state, the attribute 'recovering' will start to count the step. Considering that the agent's recovery time will be adjusted in the subsequent section, the recovery duration of all agents is initialized to a fixed value, which is 14. Once the agent' s recovering time is over 14, the agent with the immunity greater than 40 will recover. But if the immunity is less than 40, the agent might die. Because 40 is

the mean value of the normal distribution for the age group 55+.And the analysis report from the British government gave a table that records the number of deaths by age group. It showed that most of the deaths caused by COVID-19 are older than 50 and very few young people(0-49) died. [11]

Part 2: After adding the parameter from the input

After those factors were added into the model, the behavior and state of agent will be changed in a certain situation which summarized in Table 3.3. We then will discuss every factor in detail.

Status:	Behaviour	Method
Exposed In the test list	~~1)Walk around randomly~~ 2) Change the state ~~3)Infect others (lower infectivity)~~ **4) being tested**	~~move()~~ show_symbol ~~Infecting()~~ **testing()**
Infected In the test list	~~1)Walk around randomly~~ 2) Change the state ~~3)Infect others~~ **4)Go to the hospital (conditional)** **5)being tested**	~~move()~~ recovering_or_dead ~~Infecting()~~ **if_go_to_the_hospital()** **testing()**
Infected who follows the measure self isolation and self_diagnosis	~~1)Walk around randomly~~ 2) Change the state ~~3)Infect others~~ **4)Go to the hospital (conditional)** **5)Isolated after showing symbol**	~~move()~~ recovering_or_dead() ~~Infecting()~~ **if_go_to_the_hospital()** **self_isolation_and_self_diagnosis()**
Any state who follows the measure keep distance	**1) Walk around to the cell which has the fewest agent**	**move_keep_distance()**

Table 3.3. *After the factors added into the model, the behaviour of the agent will be affected. Therefore, those with the ~~line removed~~ represent agent no longer having this behaviour and those bold fonts represent the behaviour they have added.*

The testing and hospital

In Table 3.3., it shows that the infectious agents need to be tested if they are selected into the test list which realized in the testing() method and the method if_go_to_the_hospital() will determine if the confirmed agent can go to the hospital.

testing()
Once an agent was tested and confirmed (Exposed and Infected), It will be added to the confirmed list. The agent in this list will be removed from the grid to prevent him from infecting other agents and will not have the behaviour of moving. After being tested, this agent then will be removed from the suspected cases list so that it will not be selected to test again. Also, The testing list will remove this agent to release resources. This agent will be added back to the grid once he recovered.

if_go_to_the_hospital()
The agent can choose to go to the hospital only if he has a very bad condition which immunity is smaller than 40. For the agent who went to the hospital, the recovery time will increase 7 to 11 days because patients in very poor condition usually need more than 14 days to recover. Also, The immunity of this agent will add a random value from 1-20. The reason for increasing the immunity value between 1 to 20 is that not all agents will recover directly after being admitted to the hospital, and some still may die. In the immunity distribution, the minimum immunity of an agent is usually around 20. So, after increasing the immunity, the agent's immunity may be greater than 40, then he will recover. If it is still less than 40, then he will still have the possibility of dying.This agent will be added back to the grid once he recovered from the hospital and the state will be changed as cured which is a new state, but this state still belongs to the recovered state which shows in Figure 3.4.

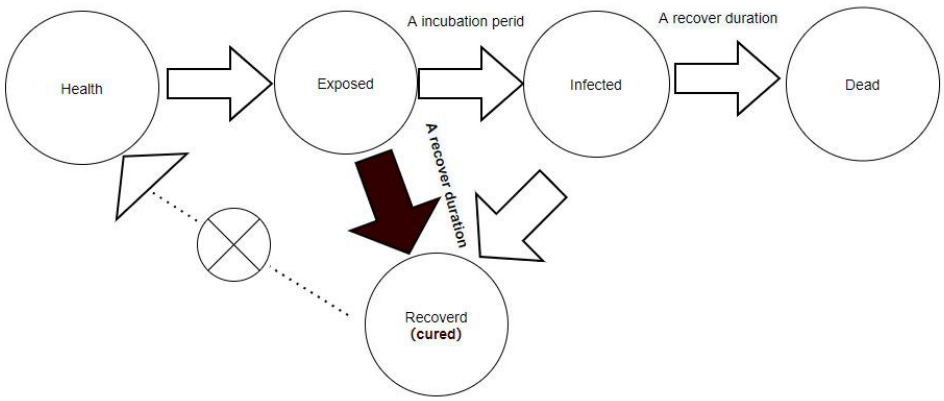


Fig 3.4. *After the measures added into the model, the state of the agent will be affected. Mainly the inclusion of asymptomatic patients and hospitals will lead to new state changes which are bold fonts.*

Asymptomatic patients
In Fig 3.4., the black arrow shows that there will be a new state change from 'Exposed' to 'Recover' which actually caused by asymptomatic patients added to the model. This is because asymptomatic patients still belong to the exposed agent. The difference is that asymptomatic patients will not show symptoms after the incubation period, but directly enter the recovery period. So, a new state changing will have.

However, we also can not ignore the characteristic of asymptomatic patients as we discussed in the background, which the recovery time of an asymptomatic patient will be longer than 14 days and asymptomatic patients are those with better immunity so they will not die. So, except for setting the boolean value to Ture when the model chooses agents to be asymptomatic patients, the model also needs to conditionally select the agent which the immunity of the agent must be greater than 50. Also, the recovery time for the selected agent needs to be increased by 5-10 to meet the requirements.

Wearing mask:

Infecting()

In the background we know from existing studies that wearing a mask can reduce the likelihood of a positive test by 70%. And the purpose of wearing a mask is to reduce our exposure to the little droplets in the air which carrying the virus[2]. So, it means that wearing a mask affects external factors and what this measure reducing is the risk of transmission. So, in our implementation, we achieved the measure of wearing a mask by reducing the possibility of the external factor. In other words, the external factor of the agent who wears a mask will reduce 70% before starting the mechanism of whether to be infected.

Social distance

move_keep_distance()

The implementation of social distancing should be 2m between the agent, but there is no way to be accurate to 2m in my solution which due to the environment I use is the grid. Then, I realized that people did not enforce very strict distances in the crowds, and they usually consciously observe social distances by simply moving to less crowded areas. So, in my implementation the agents are willing to keep their distance from others , they will not walk around randomly. Instead, they move in a direction. That is, towards the place with the least people. So, before moving, the number of the agent in the surrounding cell will be counted and then move into the cell which has the fewest agent.

Self isolation and self-diagnosis

self_isolation_and_self_diagnosis()

The Infected agent who is willing to self-isolation and self-diagnosis cannot move around and infect others. So, he will be added to an isolated list and removed from the grid. The agent in this list will not have the behaviour of moving. Once the agent recovered, it will back to the grid. Moreover, the agent can choose to go to the hospital if his immunity is smaller than 40 which is achieved by the method if_go_to_the_hospital().

3.3.2 Visualization (Vsualization.py)

As the model runs, the data stored in the data collector will then pass to this python file to visualize the following object. All the JavaScript file I used is provided by Mesa and his JavaScript library, so I will not discuss in this report.

- **Agent and environment**

For the agent, it will be represented by a circle but a different state of agent will be filled into a different colour. In order to improve the visualization of my solution which mentioned in the existing solution. The implementation of visualization is able to show all states if there are more than one agent in a cell. This requires agents in different states not only to have differences in colour but also to have differences in size so that they can be displayed in one cell. Moreover, in order to prevent the agent from being covered, the layer should be set according to the radius. Therefore, Table. 3.4. summarizes how agents in different states should be visualized.

States	Colour	Layer	radius
Infected	Red	1	1
Exposed	Yellow	2	0.9
Asymptomatic	Orange	3	0.8
Health	Blue	4	0.7
Recover	Green	5	0.6
Cured	Purple	6	0.5

Table. 3.4. *The agent in each state will be draw in different colour, layer and radius.*

This description details will be defined in an agent portrayal class. Then a CanvasGrid class will be instantiated to receive the defined agent portrayal class and the size of the grid and tell the way to the corresponding JavaScript file to draw on the website.

- **Charts**

Although the above simulation and visualization allow us to see how the virus has spread, it cannot provide us with data to analyze the problems we posed. Therefore, in the visualization, we also need some charts to help us show data generated by the model at each step. So we can analyze it.

1) A bar chart to show the distribution of immunity of the agent
2) A line chart to show the number of the agent in different states at each step
3) A line chart to show the capacity of the testing and hospital at each step
4) 4 Text label to show the parameter in the model including the number of the agent, hospital capacity, test capacity and the number of the dead agent.

As for implementation, it need to instance the corresponding module provided by Mesa and input the data stored in the data collector to this module, then it will help to render the object on the website.

- **Input controls**

The exploration of the problem requires adding factors to the original model or changing the proportion of agents that comply with the measures. So the system needs some input controls to help us interact with the system to change the parameters in the model.

1) One check box to add the limited capacity of testing and hospital into the model
2) A slider to control the proportion of people who observe social distance in the model
3) A slider to control the proportion of people who observe wearing mask in the model
4) A slider to control the proportion of people who observe self-isolation and self-diagnosis in the model

These input controller can be realized by the component 'UserSettableParameter' provided by Mesa and set in the model parameter. So it can pass the input value into the model

4. Result

4.1 Result description

Each case requires multiple experiments and the final result is from the average of the results of the 10 experiments. There are several reason we have to get the result in this way.

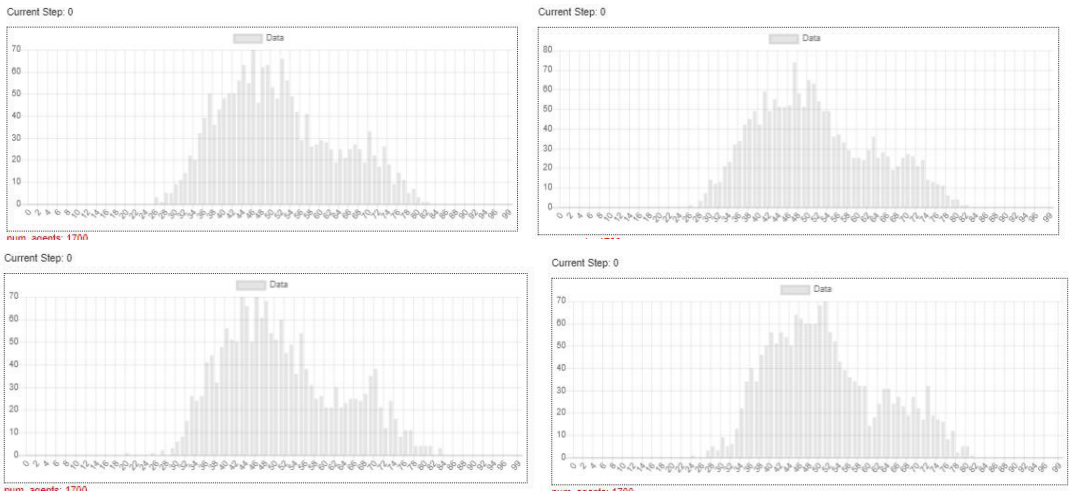


Fig 4.1. *Each time the model is restarted, the immunity of the agent will be reassigned. These four diagrams are intended to show the distribution of the agent's immunity is rough, although it has a certain pattern.*

The first reason is that all the attribute and parameter will be reinitialized in every run of the model. Although the assigned parameters have a certain pattern as a whole, there are still differences. For example, the distribution of immunity of the agent has a general pattern, but it can be seen in Fig 4.1. that the pattern is somewhat rough.

Therefore, it is one of the reasons that can cause different results. Also, there is still a lot of randomness in the model, which will also affect the results. For example, randomly select the first infected agent and the agents distributed in the grid around this first infected agent are also random. Moreover, the agents who are selected to follow a certain measure is random in each run. Because of these randomnesses the results may be skewed. Therefore, we need to experiment multiple times, and then average the outcomes to get the general direction of the results.

All experimental results will be placed in the appendix. In the results section, we only analyze the final results. Some raw data was discussed which are marked in red in the appendix, it can be found through the corresponding headings.

The result analyse will base on:

A. **What was the proportion of infected agent when it reach the peak**
   This value represents the maximum number of infected people present during the spread of the virus. The larger the value, the more serious the outbreak. In the comparison, if the value decreases, the measure is effective in curbing the spread of the virus.

B. **When did the proportion of infected agent reach the peak**
   This value can be seen as the speed of spread of the virus, if the virus spreads quickly, the value will peak in a short time. It can be used to judge whether the measures are effective in slowing down the spread of the virus. If the measures are effective, then the time (step) to reach the peak will be delayed and also the peak value, A, will be reduced.

C. **When will the proportion of infected agent drop to 0**
   It means there is no more infected agent in the scheduler.

D. **How many agent dead**

E. **How many agent did not be infected**

F. **How long did it last to the shortage of test capacity**
   This value represents the insufficient testing capacity. The larger the value, the smaller the resistance of the testing capacity to the epidemic. In the comparison, if this value is reduced, it indicates that the measures are effective in reducing the burden of testing capacity.

G. **How long did it last to the shortage of hospital capacity**
   This value represents the insufficient hospital capacity. The larger the value is, the smaller the resistance of the hospital capacity to the epidemic. In the comparison, if this value is reduced, it indicates that the measures are effective in reducing the burden of hospital capacity.

4.2 Result detail

Case I : The basic model

Description:
The basic model is to simulate and visualise how the virus spreads in the crowds without any intervention. In other words, the model did not add the hospital and testing capacity and other factors to be explored to interfere with the spread of the virus.

Parameters Setting: None

Aim: This case aims to analyze how the epidemic will develop when there is no any intervention.

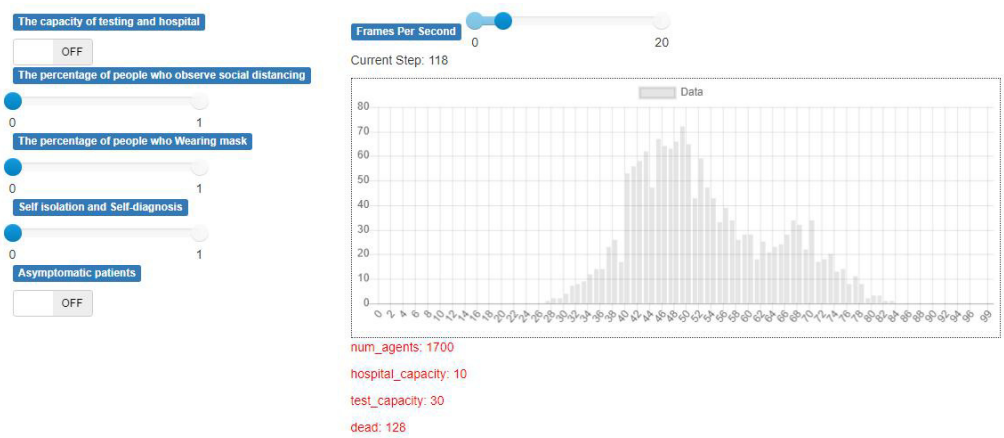


Fig 4.2. *The controller on the left is where we use it to add the parameters into the model. The bar chart on the right is used to show the immunity distribution of the agent in each experiment. The text label is used to show the number of the agent, the capacity of the hospital and testing and the number of dead.*

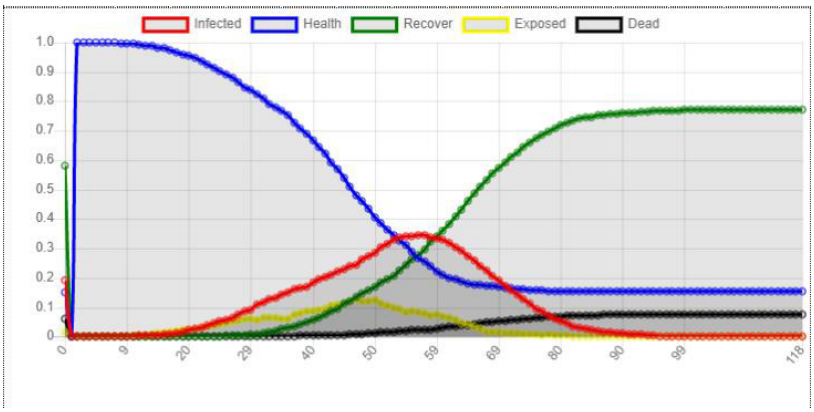


Fig 4.3. *The line chart records the percentage of agents in each state at each step from a macro perspective.*

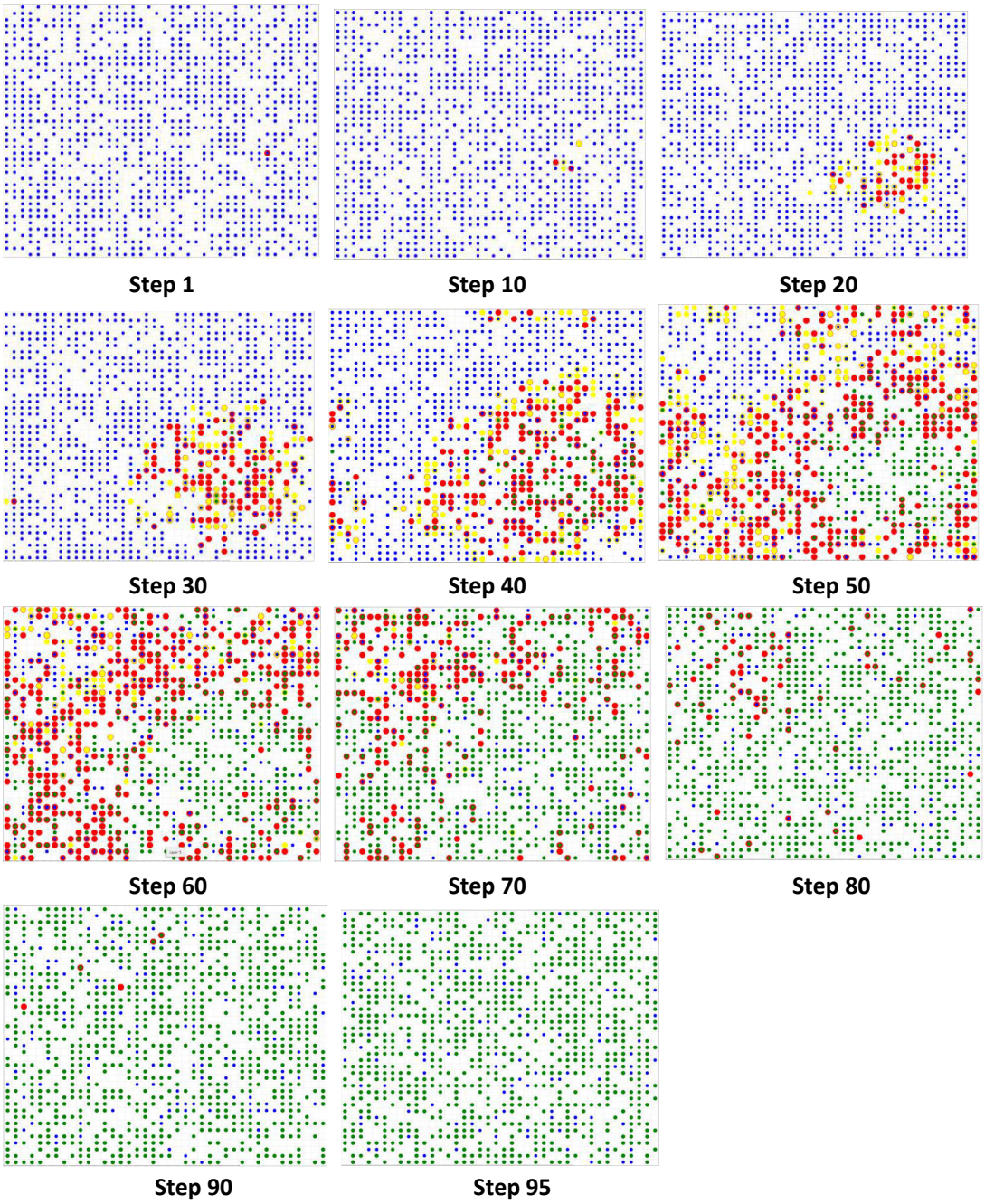


Fig 4.4. *These diagrams show how the virus spread in the crowds. After the simulation starts, the screenshot is recorded starting at step 1, followed by every 10 steps until there is no infectious agent in the grid.*

	A	B	C	D	E	F	G
	0.349	57.9	106.6	130.2	0.1511	None	None

Table 4.1. *The result of Case I which records the final results obtained from the line chart in 10 experiments.*

Result analysis:

In Fig 4.4., we can observe that a red circle appeared and along with a blue circle in the grid at step 1. This red circle is the first infected agent chosen by the model and it also means the agent with a different state can be shown in a single cell. As the step increased, this infected agent moved around on the grid. Then, other infected agents started to appear near this agent. At step 10, there were only a few infected agents, but we can see that the virus began to spread in all directions, centred on the first infected person at step 20. Also, in that infected area, the inside area was mostly red in colour, while the outer part of the area is mostly yellow. This is because the agents in the middle have been infected earlier and have passed the incubation period, while the later infected agents were still incubating. From step 30 to step 60, the virus accelerated its outward expansion and the entire environment was contaminated with the virus by step 60. However, we also can see that at step 30, the recovered agent started to appear where the virus first was. It then increased like the spread of the virus until there were no more infected people in the environment at step 95.

From the intuitive observation of the spread of the virus, we can find that the spread of the virus is like igniting a fire in the grass. The fire will spread from the point of fire to the surroundings, and the fire will also start to extinguish from the place where it caught fire. At step 95, we also can observe that not all agents will be infected because there are still some small blue circles in the environment.

In Table 4.1, it shows that the infection rate reached its highest peak at step 59.3 (B) throughout the spread of the virus, which 34.9% (A) agent were in an Infected state. After this inflexion point, the number of infected agents began to decline. At step 106.6 (C), there were no infected people in the grid which also mean the percentage of infected agent dropped to 0. Moreover, it told that only 256.87 (1.511% E) agents were not infected in the end among 1700 agents. In those infected agents, there were about 130.2 deaths (D), which accounted for about 0.0902 of the infected population. It is almost nearly 0.1. According to the current record of the United Kingdom, 4,431,043 people have been confirmed with COVID-19 in the UK and the death toll was 127,598 by 8th May.[24] The calculated death rate was approximately 0.02880. However, this death rate was the result of various epidemic prevention measures taken by the British government. So, compare these two result, If this model is accurate, the measures implemented by the British government have prevented many people from being infected and dying.

In summary, the spread of the virus is rapid, and the consequences of the epidemic are also very terrifying if there is no any intervention.

Case II (1) : The basic model **with a limit number of testing and hospital capacity without asymptomatic patients.**

Description:
In this case, we simulates and visualises in the situation which the basic model with a limited number of testing and hospital capacity without asymptomatic patients.
The capacity of hospitals and testing was originally intended to be set based on the population to their capacity ratio according to the data released by the United Kingdom. But I found that the calculated capacity of the hospital would be less than 0, so I finally set two values that I think are reasonable.That is, the testing capacity is 30 and the hospital capacity is 10. Also, these capacity will only be available when the number of deaths reaches 10 which explained the reason in implementation part.

Parameters Setting:
1) added 30 testing capacity and 10 hospital capacity into the model

Aim: This case aims to analyze how the the epidemic will develop if there is only limited resources and how effective are these limited capacities in preventing the epidemic through comparison with Case I.

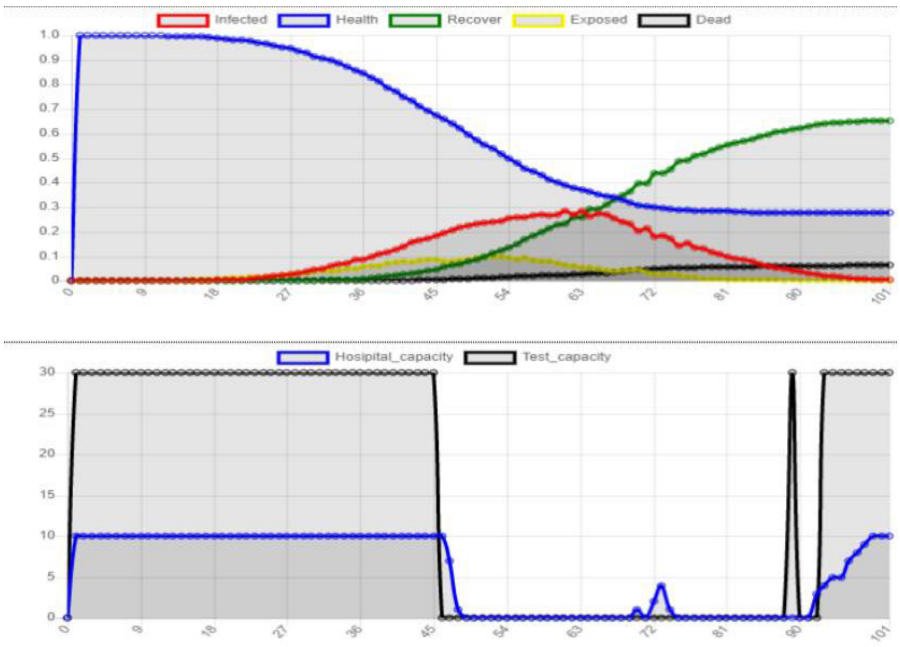


Fig 4.5. *Except the chart shown in Case I, there is also a line chart to record the capacity of the hospital and the test in the following experiments.*

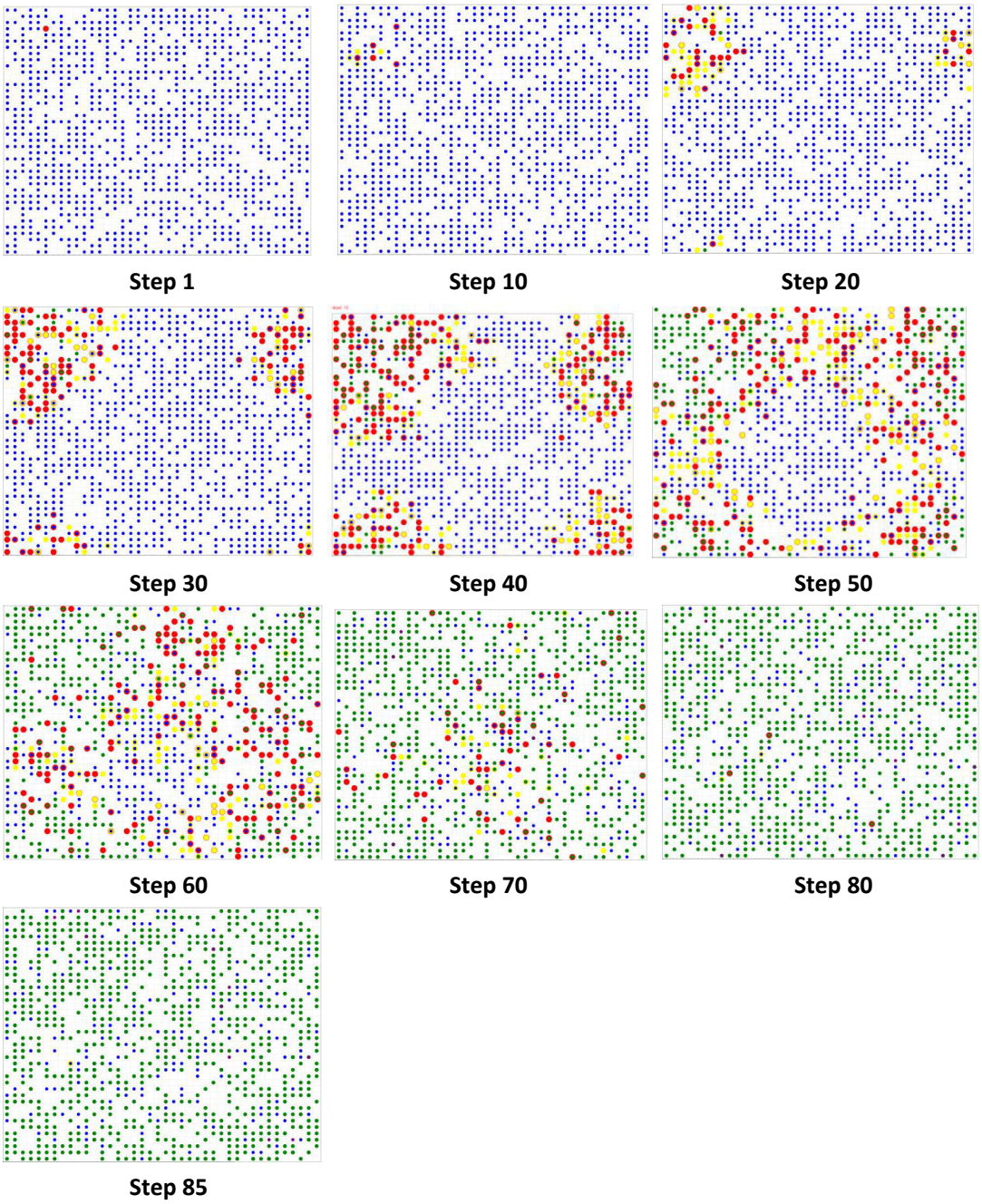


Fig4.6. *These diagrams show how the virus spread in the crowds after the limited hospital and testing capacity added to the model. After the simulation starts, the screenshot is recorded starting at step 1, followed by every 10 steps until there is no infectious agent in the grid.*

	A	B	C	D	E	F	G
	0. 3259	57. 2	101	114. 3	0. 2203	45. 4	39. 4

Table 4.2. *The result of Case II(1) which records the final results obtained from the line charts in 10 experiments.*

Result analysis:
In Fig 4.6. we can observe that the spread of the virus was the same as in Case I before the capacity of the hospital and testing became available. The testing started at step 40 when the death toll reached 10. After testing began, the Infected agent in the environment began to decrease. Compared to Case I at step 50, the number of red circles was significantly reduced. Although the virus still spread throughout the grid eventually, there were no infected agents left on the grid at step 80, which was 10 steps earlier than in Case I. However, at this step the percentage of the infected agent in the line chart had not yet dropped to zero, as those agents who had been removed from the grid were still recovering.

	A	B	C	D	E	F	G
Case I	0.349	57.9	106.6	130.2	0.1511	None	None
Case II (1)	0.3259	57.2	101	114.3	0.2203	45.4	39.4
	−0.024	−0.7	−5.6	15.9	+0.0692		

Table 4.3. *Compare the result of Case I and Case II(1)*

With the limited number of testing and hospital capacity, the step for the infection rate reaching its highest peak in both cases were around 57(B), which there was only a 0.7 difference between them. I consider that the step should be roughly the same because the number of experiments was only 10. The peak value was reduced but it is only by 0.024(A). Also, agents that were not infected only increased by 0.0692(E). But it has to mention that the time for the percentage of infections to drop to 0 was about 6 steps shorter than Case I(C). I think it is due to the testing measure will remove the infected agent from the grid so that the virus cannot be transmitted. In other words, there is no more infectious agent on the grid after step 85 as shown in the example above, so the time for the number of infected agents to drop to 0 will be earlier. As for the number of dead, there were only about 15.9 people less than Case I(D).

In summary, compared to the data from Case I, such limited hospital capacity and testing capacity have a certain effect on the prevention and control of the epidemic, but the effects are very small.

Case II(1.1) : The basic model with a limit number of testing and hospital capacity without asymptomatic patients **but added the measure keep social distance.**

Description:
This case simulates and visualises based on Case II (1) but we added the measure the social distance measure into the model. 40% and 70% is the percentage of the agent who follow the measure. This parameter is added to the model through sliders.

Parameters Setting:

1) Added 30 testing capacity and 10 hospital capacity into the model
2) Added the measure of **keeping social distance** with different percentage of agent who follows the measure.

Aim: This case aims to analyze the effectiveness of social distancing through comparison with Case II (1).

Result:

	A	B	C	D	E	F	G
40%	0.2132	65.2	111.4	78.7	0.4653	40.6	29.2
70%	0.1359	66.5	106.9	42.4	0.6814	33	18.1

Table 4.4. *The result of Case II(1.1) obtain from the line charts in 10 experiments.*

Result analysis:

	A	B	C	D	E	F	G
Case II (1)	0.3259	57.2	101	114.3	0.2203	45.4	39.4
40% Case II (1.1)	0.2132	65.2	111.4	78.7	0.4653	40.6	29.2
	−0.1127	+8	+10.4	−35.6	+0.245	−5.4	−10.2

Table 4.5. *Compare the result of Case II(1) and Case II(1.1) when there 40% agent following the measure.*

In Table 4.5., it shows that the peak values were decreased by 11.27% (A). Also, the number of deaths has been reduced by 35.6 (D) and the uninfected agents have also increased from 374.51 to 791.01(E). These comparative data came from when only 40% of people comply with this measure. In Table 4.4., we can learn that the result was even better if the number of people who comply is increased to 70%. However, different from Case II (1), the time to the peak and the time for the infection to drop to zero were both extended by 8 and 10.4 steps (B, C). This may be because 40% of agents observing social distancing can only delay the spread of the epidemic but cannot stop. In this project, observing social distancing means that the agent always goes to places with the fewest agent. And 60% of people still do not follow the measure, so the infection will definitely occur when the crowd is dense. While when the number of people who observe social distancing increases to 70%, it can find in Table 4.4.(C) that although the time to reach the peak was still longer, the time for the number of infected agents to drop to 0 was shorter(106.9) than when it was only 40 %. This may be because the virus will not spread so easily as the number of people complying with the measure increases.

For the duration of testing and hospital capacity shortages, we can see that in the Case II(1), their shortage of time for testing and hospital was 45.5 and 39.4(F, G). But with 40% of people complying with social interactions, the time shortage was reduced by 5.4 and 10.2 respectively. And when the number of agents increased to 70%

complied, this number decreased even more(Table 4.4., G,F)

In summary, the social distancing measure can effectively prevent and control the spread of the epidemic, and it can also reduce the burden on the situation of insufficient resources. Furthermore, if a small number of people comply with the measures, it controls the epidemic by delaying the spread of the virus. However, as the number of compliance increases, the end time of the epidemic will be brought forward.

Case II(1.2): The basic model with a limit number of testing and hospital capacity without asymptomatic patients **but added the measure wearing a mask.**

Description:
This case simulates and visualises based on Case II (1) but we added the measure wearing a mask. 40% and 70% is the percentage of the agent who follow the measure. This parameter is added to the model through sliders.

Parameters Setting:
1) Added 30 testing capacity and 10 hospital capacity into the model
2) Added the measure of **wearing a mask** with different percentage of agent who follows the measure.

Aim: This case aims to compare and analyse the result from social distance (Case II(1.1)) and wearing a mask(Case II(1.2)) to figure out which is one more effective.

Result:

	A	B	C	D	E	F	G
40%	0.1359	72.2	120.2	46.7	0.6547	36.2	18
70%	0.0433	99.1	136.5	18.6	0.838	23.6	8.1

Table 4.6. *The result of Case II(1.2) obtain from the line charts in 10 experiments.*

Result analysis:

	A	B	C	D	E	F	G
40% Case II (1.1)	0.2132	65.2	111.4	78.7	0.4653	40.6	29.2
40% Case II (1.2)	0.1359	72.2	120.2	46.7	0.6547	36.2	18
	−0.0773	+7	+8.8	32	−0.1894	−4.4	−11.2

Table 4.7. *Compare the result of Case II (1.1) and Case II (1.2).*

When the added measure is wearing a mask, we can found in Table 4.7. that the peak value was even smaller (A) which was 0.2132 vs 0.1359. Also, the time for the peak value (C) and the number of the infected agent became 0 (B) also longer than Case II(1.1). The difference in these values was not yet significant. Compare to the number of dead and uninfected people (D, E), only 46.7 people died on average and more than 65% of the agent were not be infected in Case II (1.2) which indicate that the measure to wear masks can reduce more deaths and infections than social distance.

In addition, the measure of wearing a mask resulted in fewer hospital and testing capacity shortages (F, G), the duration reduced about 4.4 and 11.2 respectively. From the raw data, it can find that the duration of the hospital shortage was 0 on three occasions.

However, it must be pointed out that it seems there is an undesirable result in Table 4.6., in which the time for the proportion of infected people to be 0 should be shortened, but the results show it was longer when 70% of people wearing masks (C). So, I checked the original data and found that three values deviate far from most results. I think the reason for this extreme value is because the testing starts when the number of deaths reaches 10. And wearing a mask will reduce the risk of transmission, so the infection will not occur in a large area like the example given before but it appears sporadically if there are 70% of agent wear a mask. It means that if most people infected in the early stage are those with better immunity, then the death toll will rise very slowly. Also, the time to the peak is also much longer. Therefore, I think it is reasonable to have the situation in which it took longer for the proportion of infected people to drop to zero. And it can be seen in Table 4.6. that other data are not affected and presents a better picture as the number of people complying with measure increased to 70%. Especially, we can see that the death toll was only 18 when 70% agents have complied with wearing a mask.

In summary, we can conclude that the measures to wear masks are effective in preventing and controlling the epidemic and alleviating the shortage of resources from a comparison of all the figures. And this effect is better than the effect of complying with social distance which analyzed in Case II (1.1). This is mainly reflected in the number of deaths, the number of people who have not been infected, and the duration of the shortage is greatly reduced.

Case II(1.3) : The basic model with a limit number of testing and hospital capacity without asymptomatic patients **but added the measure self-isolation and self-diagnosis.**

Description:
This case simulates and visualises based on Case II (1) but we added the measure self-isolation and self-diagnosis.

Parameters Setting:

3) Added 30 testing capacity and 10 hospital capacity into the model
4) Added the measure of **self-isolation and self-diagnosis** with different percentage of agent who follows the measure.

Aim: This case aims to analyze what is the most effective measure among the three measures through comparison between Case II (1), Case II (1.1), Case II (1.2), Case II (1.3).

Result:

	A	B	C	D	E	F	G
40%	0.2617	58.5	114.3	92	0.3102	49.9	35.9
70%	0.2003	63.2	107.2	68.8	0.4767	42.7	32.6

Table 4.8. *The result of Case II(1.3) obtain from the line charts in 10 experiments.*

Result analysis:

	A	B	C	D	E	F	G
Case II (1)	0.3259	57.2	101	114.3	0.2203	45.4	39.4
40% Case II (1.1)	0.2132	65.2	111.4	78.7	0.4653	40.6	29.2
40% Case II (1.2)	0.1359	72.2	120.2	46.7	0.6547	36.2	18
40% Case II (1.3)	0.2617	58.5	114.3	92	0.3102	49.9	35.9

Table 4.9. The result form Case II(1), Case II(1.1), Case II (1.2) and Case II (1.3) to compare the Effectiveness of three measures.

Firstly, we compare Case II (1.3) with Case II (1.1) first in *Table 4.9*. It is clear in *Table 4.9.* that the peak value (A) and deaths(D) toll was higher than Case II (1.1). Also, it can be calculated that 15.51% more agents were infected in Case II (1.3) than in Case II (1.1) (0.4653 vs. 0.3102) (E). Moreover, by comparing the time when the peak appeared and the time when the proportion of infected people dropped to zero, it told that the measure of self-isolation and self-diagnosis(Case II (1.3)) was not as good as social distance (Case II (1.1)) to slow down the spread of the virus because these two values were smaller. So, we can conclude that the effect of social distancing will be better than the effect of self-isolation and self-diagnosis from these comparisons. Therefore, without comparison with Case II (1.2), we can infer that wearing a mask is the best measure for epidemic prevention and control in these three measures.

We then compare to the Case II(1) to analyse if self-isolation and self-diagnosis is effective. We can learn from the Table 4.9. that the result presented by this measure is still better than the situation with only limited resources by comparing A, B, C, D, E. However, regarding the effect of this measure in reducing the resource shortages, the result of Case II (1.3) shows that it did not have a positive effect on insufficient testing

capacity (F) because the duration of insufficient capacity was greater than that of Case II (1) (49.9 vs 45.4). After check the raw data, there was an extreme value in both situations in which 40% and 70% of people follow the measure. After many re-experiments, I found that it was because there was an infected agent that could not be sent to be tested in time and stayed on the grid in the later stage of the process selecting an agent to test. Therefore, the testing continued until that agent was found. The time of insufficient capacity then would be extended. However, I think this phenomenon is unreasonable in my solution. Because it should be that the agent with symptoms will be sent for testing first, and will not wait until the test to search it among the agents. So, it means there still is a bug in my implementation. And this error only appeared in self-isolation and self-diagnosis measures. So, there should be a conflict between the isolated list and the confirmed case list and I will look for the source of this problem in future work. However, the results showed that this measure is still effective for the shortage of hospitals(G), although the effect is not so obvious compared to the other two.

In summary, apart from the questionable data, other data showed that self-isolation and self-diagnosis is effective measure in preventing and controlling the epidemic, and it has little effect on reducing the burden on the hospital. But comparing the other two measures, the effect is the worst. So, we can conclude that the three measures ranked as effective in preventing and controlling outbreaks and reducing the burden of resource shortages were wearing a mask, social distance and finally self-isolation and self-diagnosis.

Case II (2) : The basic model with a limit number of testing and hospital capacity **with asymptomatic patients**

Description:
These cases simulate and visualise in the situation which the basic model with a limited number of testing and hospital capacity but with asymptomatic patients. Then, we added three measures respectively which are social distance, wearing a mask and self-isolation and self-testing to explore the impact of asymptomatic patients on the implementation of these measures.

Parameters Setting:
1) Added 30 testing capacity and 10 hospital capacity into the model.
2) Added a certain measure with different percentage of agent who follows the measure.
3) Added asymptomatic patients.

Aim: This case aims to analyze the impact of asymptomatic patients to the implementation of these measures.

Result:

Case II(2.1) : Add agents who are willing to **keep social distance**

	A	B	C	D	E	F	G
40% Case II(2.1)	0.162	60.3	160.4	86.2	0.374	66.2	37.1

Table 4.10. *The result of Case II(2.1) obtain from the line charts in 10 experiments.*

Case II(2.2) : Add agents who are willing to **wearing a mask**

	A	B	C	D	E	F	G
40% Case II(2.2)	0.095	70.36	158.55	52.27	0.60	53.82	31.36

Table 4.11. *The result of Case II(2.2) obtain from the line charts in 10 experiments.*

Case II(2.3) : Add agents who are willing to **self isolation and self-diagnosis**

	A	B	C	D	E	F	G
40% Case II(2.3)	0.2208	57.8	132.6	108.7	0.2295	58.2	41.3

Table 4.12. *The result of Case II(2.3) obtain from the line charts in 10 experiments.*

Result Analysis：

Before starting to analyse, we need to compute the changes of the data in each measures after the asymptomatic patients added to the model.

	A	B	C	D	E	F	G
40% Case II(1.1)	0.2132	65.2	111.4	78.7	0.4653	40.6	29.2
40% Case II(2.1)	0.162	60.3	160.4	86.2	0.374	66.2	37.1
	−0.0512	−4.9	+49	+7.5	−0.0913	+25.6	+7.9

Table 4.13. *Compare the result Case II(1.1) and Case II(2.1) and compute the changes in the data to see the impact of asymptomatic patients on the measure social distance.*

	A	B	C	D	E	F	G
40% Case II (1.2)	0.1359	72.2	120.2	46.7	0.6547	36.2	18
40% Case II(2.2)	0.095	70.36	158.55	52.27	0.60	53.82	31.36
	−0.0409	−1.84	+38.35	+5.57	−0.0547	+17.62	+13.36

Table 4.14. *Compare the result Case II(1.2) and Case II(2.2) in Table 4.6 and compute the changes in the data to see the impact of asymptomatic patients on the measure wearing a mask.*

	A	B	C	D	E	F	G
40% Case II(1.3)	0.2617	58.5	114.3	92	0.3102	49.9	35.9
40% Case II(2.3)	0.2208	57.8	132.6	108.7	0.2295	58.2	41.3
	−0.0409	−0.7	+18.3	+16.7	−0.0807	+8.3	+5.4

Table 4.15. *Compare the result Case II(1.3) and Case II(2.3) and compute the changes in the data to see the impact of asymptomatic patients on the measure self isolation and self -diagnosis.*

	A	B	C	D	E	F	G
Table 4.13.	−0.0512	−4.9	+49	+7.5	−0.0913	+25.6	+7.9
Table 4.14.	−0.0409	−1.84	+38.35	+5.57	−0.0547	+17.62	+13.36
Table 4.15.	−0.0409	−0.7	+18.3	+16.7	−0.0807	+8.3	+5.4

Table 4.16. *this table summarized the data changes in the results of the implementation of three measures in Table 4.13., Table.4.14. and Table.4.15. in the case of asymptomatic patients and no asymptomatic patients.*

In Table 4.16., it shows that the peak value (A) of all measures dropped by about 0.05 after adding asymptomatic patients into the model. I think this result is reasonable which due to 25% of patients will be selected to be asymptomatic patients in my solution, and their infectivity is less than that of the infected agent. So, there then will not be as many agents infected at the same time as before. However, this does not mean that asymptomatic patients have no effect on the implementation of the measures. In fact, other data in the table showed that asymptomatic patients have a negative impact on the effectiveness of their measures to prevent the spread of the virus. The first one that can support this conclusion is the time for the peak value(B). The data showed that it had been advanced in three measures which means the spread of the virus was a little faster than before. Secondly, the time for the proportion of infected people to reach zero was much longer than before (C) which showed that the virus has been spreading in the environment longer. Finally, the conclusion was also reflected in the total number of deaths (D) and agents who are infected (E) which both values were increased in three measures. In addition, asymptomatic patients also aggravated the lack of the capacity of testing and hospital capacity. F and G showed the increase in the duration of the shortage of resources appeared in three measures. In particular, it had the most obvious impact on the testing capacity. This is because a large amount of testing capacity is needed to screen the population to find asymptomatic patients.

In summary, after asymptomatic patients added to the environment, although the spread of the virus is not so that swift and violent, it extends the time to transmit in the environment. Furthermore, for the three measures, we can see from the results that the effects of all measures have been weakened to varying degrees.

5. Future Work

Whether the result is meaningful is connected with whether the model can reflect reality. If all the parameters and settings of the model are taken from real data, then the model is successful. For my results, although it seems reasonable, I think the model is not completely in line with reality. The first reason is that some of the parameters in my model are taken from real data, but there are still some parameters that are not supported by the truth. For example, the infectivity of asymptomatic patients. And there are some parameters that I have not taken into consideration which are the cure rate and death rate of critically ill patients in the hospital. The second reason is that there are still some errors and a lot of randomness in my model and we can see that randomness will produce a large deviation in the results from the above analysis of the results.

Therefore, I still need to improve my model from the following points:

1) Fix the bug found during the analysis. And from the preliminary analysis, I think it is maybe due to the conflicts between self-isolation and self-diagnosis measures and testing, resulting in occasionally a single infect agent that cannot be selected to test in time.

2) There is a study have found that the proportion of deaths in hospitals due to the COVID-19 in the UK accounted for 30% of the total proportion. So, the death or cure of an agent in the hospital is no longer based on a random increase in immunity, but proportions that have been studied.

3) Try to find a solution in Mesa in which the parameters will not change but use those parameters for all experiments when restarting the model.

6. Conclusion

Countries in the world are still fighting against COVID-19. Although the UK was short of resources in the early days, it had a large amount of testing capacity and hospital capacity at this time. However, not all countries can invest as much capital and manpower as the United Kingdom. There are still many countries in the world that are short of resources, and the number of confirmed and death continues to increase. Our results show that limited testing and hospital capacity alone is not enough to resist the invasion of the virus. But with limited resources, people who follow the measures can effectively delay the spread of the virus and reduce the number of deaths. If there are no more resources, this is their way to eliminate the virus in their country as soon as possible. Moreover, every country needs to pay attention to the screening of asymptomatic patients, because compared with symptomatic patients, they are the hidden danger in the epidemic due to it may negatively affect the measures taken by the government to a certain extent.

7. Reflection and Learning

When I chose this project I did so because I had seen similar simulations on social media about the spread of viruses. I thought it would be very interesting if I could use what I had learned in my undergraduate studies to make this project. But when I delved into the subject, I found that everything was new to me. So I started to learn what is Agent-Based Modelling, how to use the framework following the tutorial of Mesa. I quite enjoyed this learning process, and I felt very excited when I can realize the diffusion of the little red dot in the environment. However, because the implementation plan considered in the preliminary preparation stage are not comprehensive enough so that some methods that have been implemented are not enough to meet the new requirements, I often changed my plan in the process of implementing this project which wasted a lot of time. This situation also appeared at the stage of writing the report. I always rediscovered the shortcomings of my implementation method, but at this stage, there was no much time left for me to improve it. Except for the code part, I also ignored there are the formal regulations to write a formal report before I started to write the report, so the initial report I had was very substandard. The reason for these mistakes I summarized is that I always do not consider them deeply before starting something, so this leads me to spend more time to improve it later.

Overall, I think it will be a valuable experience for me to complete this project during these months. Not only did I learn a lot of new knowledge and techniques, but I also realized that the only way to get rid of anxiety is to resolve the source and persistence. Moreover, time management and comprehensive planning are important, they are important factors in doing things efficiently. I believe that what I have acquired in this period will benefit me in my later stages of learning in the future.

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The appendix

Note: The numbers marked in red are the data discussed in the analysis.

Case I: The basic model

	A	B	C	D	E	F	G
1	0.33	50	94	127	0.15	None	None
2	0.39	56	102	141	0.14	None	None
3	0.35	60	106	137	0.156	None	None
4	0.34	53	102	120	0.154	None	None
5	0.369	59	97	120	0.15	None	None
6	0.345	55	119	124	0.165	None	None
7	0.36	56	113	122	0.146	None	None
8	0.348	68	118	141	0.149	None	None
9	0.33	57	104	130	0.155	None	None
10	0.328	65	111	140	0.146	None	None
	0.349	57.9	106.6	130.2	0.1511		

Case II(1) :The basic model with a limit number of testing and hospital capacity without asymptomatic patients

	A	B	C	D	E	F	G
1	0.29	56	102	112	0.255	47	42
2	0.335	56	107	110	0.19	46	41
3	0.311	59	94	112	0.235	48	40
4	0.324	57	95	114	0.258	43	39
5	0.345	53	101	107	0.20	43	41
6	0.338	63	102	122	0.21	48	39
7	0.298	59	112	122	0.22	41	41
8	0.356	59	96	120	0.188	44	42
9	0.332	56	100	97	0.227	51	33
10	0.33	54	101	127	0.22	43	36
	0.3259	57.2	101	114.3	0.2203	45.4	39.4

Case II(1.1) : Add 40% agents who are willing to keep social distance

	A	B	C	D	E	F	G
1	0.27	65	120	95	0.348	42	35
2	0.20	61	117	67	0.489	37	32
3	0.177	70	105	55	0.574	38	33

4	0.24	78	123	95	0.378	36	28
5	0.251	65	107	96	0.367	38	36
6	0.214	60	116	88	0.457	53	34
7	0.214	62	102	72	0.45	37	35
8	0.18	54	105	73	0.53	44	21
9	0.23	73	116	83	0.448	45	19
10	0.156	64	103	63	0.612	36	19
	0.2132	65.2	111.4	78.7	0.4653	40.6	29.2

Add 70% agents who are willing to keep social distance

	A	B	C	D	E	F	G
1	0.1	59	96	26	0.77	40	16
2	0.14	55	108	41	0.67	25	19
3	0.113	67	112	35	0.754	43	19
4	0.17	65	110	55	0.60	35	19
5	0.12	69	108	40	0.69	38	18
6	0.19	81	118	53	0.58	30	18
7	0.132	75	106	44	0.70	33	18
8	0.144	54	98	45	0.67	25	17
9	0.14	59	98	49	0.65	29	20
10	0.11	81	115	36	0.73	32	17
	0.1359	66.5	106.9	42.4	0.6814	33	18.1

Case II(1.2) : Add 40% agents who are willing to wear mask

	A	B	C	D	E	F	G
1	0.145	80	120	46	0.635	31	18
2	0.118	70	104	37	0.7	31	18
3	0.15	66	112	45	0.614	27	17
4	0.126	63	125	46	0.66	38	18
5	0.186	67	112	66	0.565	40	18
6	0.148	77	121	52	0.616	34	20
7	0.11	72	111	36	0.7	34	16
8	0.14	104	156	42	0.678	49	18
9	0.113	72	121	46	0.679	42	17
10	0.123	51	120	51	0.70	36	20
	0.1359	72.2	120.2	46.7	0.6547	36.2	18

Add 70% agents who are willing to wear mask

	A	B	C	D	E	F	G
1	0.05	148	193	28	0.8	27	16
2	0.052	113	149	21	0.78	29	11
3	0.037	82	132	17	0.84	20	0
4	0.039	95	124	18	0.87	23	12

5	0.048	95	122	21	0.83	22	0
6	0.041	108	173	16	0.80	24	0
7	0.04	94	119	19	0.87	16	14
8	0.041	66	100	17	0.856	29	10
9	0.040	87	125	15	0.884	30	10
10	0.045	103	128	14	0.85	16	8
	0.0433	99.1	136.5	18.6	0.838	23.6	8.1

Case II(1.3) : Add 40% agents who are willing to self isolation and self diagnosis

	A	B	C	D	E	F	G
1	0.328	58	98	117	0.255	47	29
2	0.29	50	121	94	0.298	40	29
3	0.19	58	118	65	0.40	60	36
4	0.314	52	93	96	0.274	41	38
5	0.27	55	112	93	0.255	35	39
6	0.25	67	121	90	0.333	39	31
7	0.245	62	126	98	0.318	80	34
8	0.28	62	122	109	0.255	62	47
9	0.24	68	129	87	0.314	55	37
10	0.21	53	103	71	0.40	40	39
	0.2617	58.5	114.3	92	0.3102	49.9	35.9

Add 70% agents who are willing to self isolation and self diagnosis

	A	B	C	D	E	F	G
1	0.15	63	122	48	0.597	40	40
2	0.194	67	113	74	0.43	34	32
3	0.27	75	120	80	0.33	48	30
4	0.15	50	89	64	0.575	43	27
5	0.17	46	95	70	0.548	26	33
6	0.194	67	129	67	0.434	81	37
7	0.219	77	54	77	0.41	39	35
8	0.186	54	124	64	0.5	42	31
9	0.19	61	116	56	0.523	39	25
10	0.28	72	110	88	0.42	35	36
	0.2003	63.2	107.2	68.8	0.4767	42.7	32.6

Case II(2) :The basic model with a limit number of testing and hospital capacity with asymptomatic patients

Case II(2.1) : Add 40% agents who are willing to keep social distance

	A	B	C	D	E	F	G
1	0.15	64	152	79	0.387	68	40

2	0.174	60	157	78	0.37	65	38
3	0.154	51	150	92	0.46	73	37
4	0.23	62	128	78	0.277	42	28
5	0.1735	60	147	88	0.367	53	35
6	0.155	54	144	88	0.363	45	29
7	0.13	57	205	81	0.4	112	41
8	0.12	59	175	90	0.39	73	45
9	0.17	76	186	102	0.355	65	41
	0.162	60.3	160.4	86.2	0.374	66.2	37.1

Case II(2.2) :

	A	B	C	D	E	F	G
1	0.0909	56	137	50	0.628	64	27
	0.108	77	147	60	0.54	48	25
2	0.12	64	148	62	0.577	54	36
3	0.098	72	152	51	0.608	50	31
4	0.0876	80	178	52	0.594	56	32
5	0.08	74	168	53	0.628	62	36
6	0.094	70	186	44	0.599	37	59
7	0.09	79	159	43	0.637	57	25
8	0.11	69	162	53	0.59	39	18
9	0.076	64	147	46	0.641	59	25
10	0.092	69	160	61	0.568	66	31
	0.095	70.36	158.55	52.27	0.60	53.82	31.36

Case II(2.3) :

	A	B	C	D	E	F	G
1	0.20	53	132	103	0.24	76	53
2	0.22	56	151	120	0.214	58	44
3	0.239	57	114	113	0.22	59	40
4	0.228	59	126	110	0.223	47	42
5	0.19	57	136	105	0.262	69	32
6	0.243	59	116	121	0.219	54	42
7	0.24	60	135	104	0.221	59	41
8	0.203	59	150	107	0.229	55	54
9	0.218	61	132	100	0.234	48	28
10	0.227	57	134	104	0.233	57	37
	0.2208	57.8	132.6	108.7	0.2295	58.2	41.3