SCIREA Journal of Computer

http://www.scirea.org/journal/Computer

December 27, 2020

Volume 5, Issue 6, December 2020

A Flattening Curve with Extended SEIR Model–A Case Study with COVID-19

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Abstract

This paper presents the condition of COVID-19 in Australia based on the data of each state and territory. The whole population of Australia can be separated into several groups, which are Susceptible, Exposed, Infected, Recovered, Healthy and Unknown by using the extended SEIR model. According to these groups, policies that are published by Australian governments can be divided and matched with groups based on different purposes. After doing diagnostic, predictive, prescriptive analytics and text analysis to the information of the current situation, the author provided seven recommendations that may help improve the current condition of Australia and flattening the curve of total confirmed cases of COVID-19 in Australia.

Keywords: COVID-19; extended SEIR model; self-quarantine; travel restrictions

1. Introduction

In late December 2019, the first novel coronavirus (COVID-19) patient was diagnosed in Wuhan, China [1]. The infection has been quickly spreading out to other provinces and other countries all over the world. In late January 2020, the first confirmed case of COVID 19 was found in Australia, the federal government then took powerful reactions to lockdown the border to stop the spread of this novel pneumonia. The outbreak of disease however, still came in early March.

Till now, there are two waves of COVID-19 outbreak that happened in Australia, and the total number of confirmed cases has increased significantly during these two periods. The first outbreak brought the total number of confirmed cases to around 8000. The second outbreak is much severe, and the total number of confirmed cases was around 13000 (the data was updated to 22 July).

This paper aims to analyse the impact of the policy measures implemented by the Australian government on the spread of the epidemic, and get a more efficient way to prevent the spreading of the COVID-19, and provide some theoretical basis for the follow-up epidemic prevention process.

2. The Motivation of the Study

Since the first Australian case of COVID-19 was diagnosed in late January 2020, the coronavirus infection has been spreading widely to all states and territories in Australia. Estimation of the future trend by spreading model can be helpful for federal and local governments to make a suitable policy and flattening of the curve in the short term.

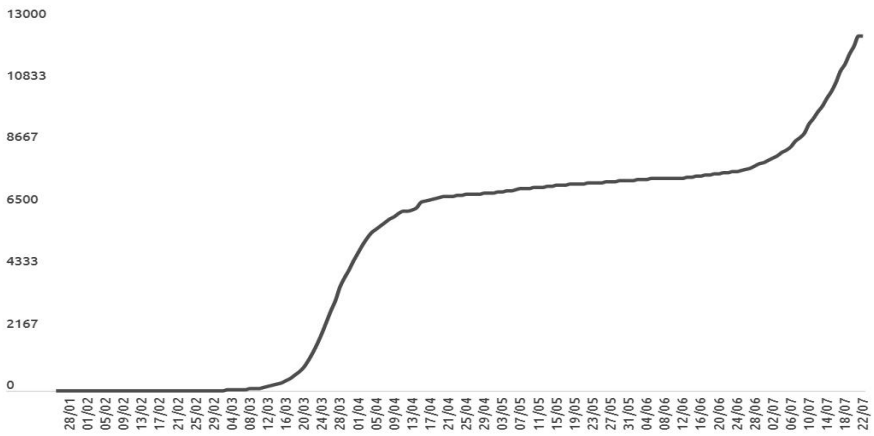

Figure 1. Cumulative view of confirmed cases of COVID-19 in Australia (28 Jan-22 July). Source from Infogram [2].

Figure 1 shows the total number of confirmed cases in Australia from 28 January to 22 July, and we can see from early March to late April, the number exploded and then became flat which lasted around two months. When it comes to late June, the curve increased again because of the outbreak of the second wave in Victoria.

Figure 2 illustrates the bar chart of daily new cases in different states or territories in Australia, and we can see that the first wave of COVID-19 in Australia started in early March. The total period of the first wave was about one and a half months, and the peak of this wave was on 28 March, when 460 cases were confirmed in one day. In late April, the increase of new confirmed cases was getting slow. In the first spreading period, most patients were diagnosed in NSW, but the range of evidence was in whole of Australia.

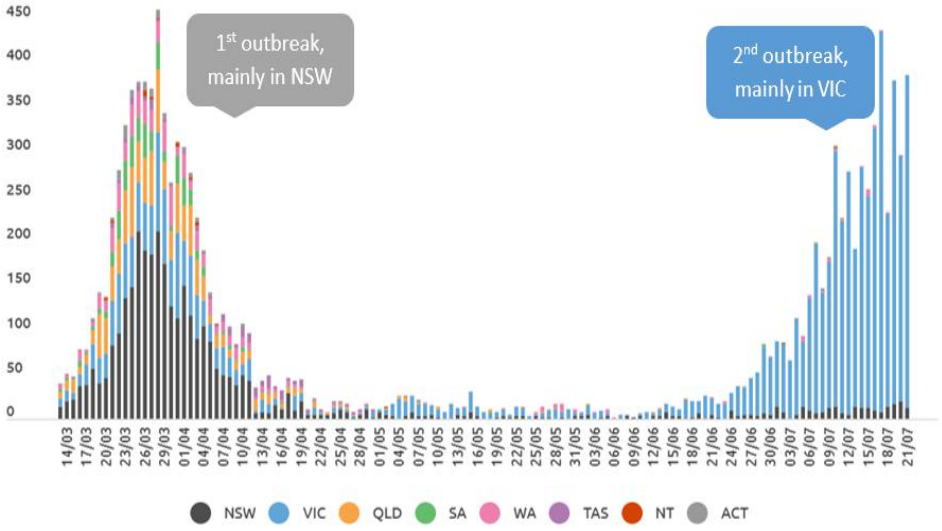

Figure 2. Daily confirmed cases in Australia, separated by states/territories (14 March-22 July). Source from Inforgram [3].

According to the report of NSW daily confirmed COVID-19 cases by symptom onset and local health districts [4], the daily new cases confirmed from 10 February to 4 May are mainly in Northern Sydney and South-Eastern Sydney. This is the first outbreak of coronavirus in Australia.

The second outbreak of COVID-19 in Australia started in late June, and different from the first wave, the second one was mainly in Victoria, which constituted 95% of confirmed cases.

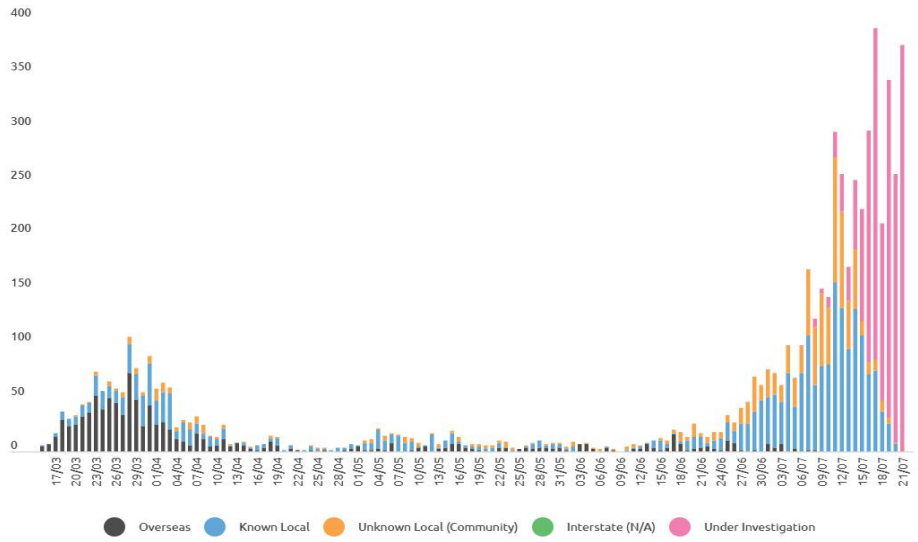

Figure 3. Daily new confirmed cases based on the infected source in VIC (17 March-21 July). Image from Infogram [5].

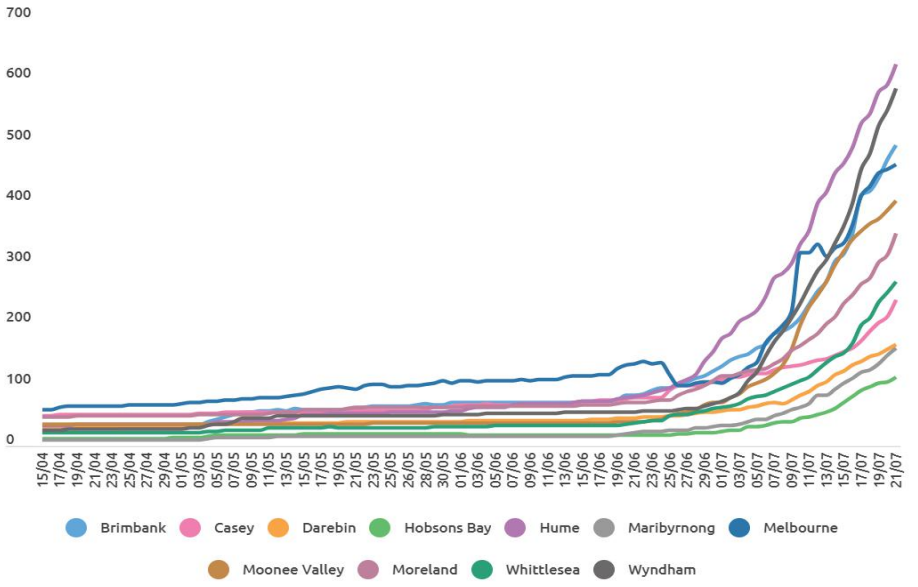

Figure 4. Cumulative view of confirmed cases of COVID-19 in VIC by regions (15 April-21 July). Image from Infogram [6].

Figure 3 and Figure 4 both show the second outbreak of COVID-19 in Victoria. The first chart describes the daily confirmed case based on the source of patients getting infected by using five different colours, which represent the infection source. From this chart, we can see that at the beginning, most of the confirmed cases are from overseas, but most recent patients are infected from the local transmission. However, the second one mainly focuses on total confirmed cases by the area and in this chart, there are 11 different colours which stand for 11 significant regions in Victoria. From this chart, we can get the information that in the first

wave, confirmed cases mainly appeared in Melbourne, but in the second wave, Hume and Wyndham are the most severe regions.

Above discussion presents the facts that from the beginning of the pandemic, there are two big waves of COVID-19 outbreaking in Australia. More research works can be done to improve the prediction of the spreading trend, and the local governments and communities can make some measurements to prevent the spread of COVID-19.

The motivation of the study is to provide a new model, which can predict the trend of COVID-19 in Australia, so as to help the federal government and researchers find out more methods and interventions to control the condition. To achieve the final goal, firstly, we should investigate the options and gaps of big data analytics with the existing predictive SEIR model. And then combined the actual situation in Australia with the classic SEIR model, we can get an extended SEIR model that can predict the following trend more accurate. As a result, researchers can use this improved model to create more measurements to control the situation and address the problem of COVID-19 in Australia.

3. The SEIR Model

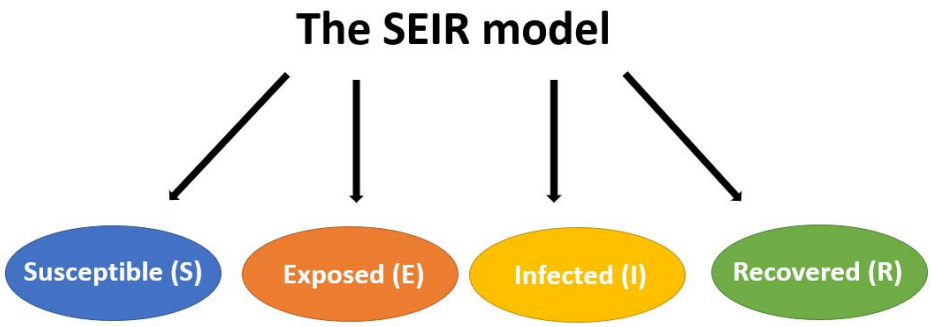

Figure 5. Tree diagram of the SEIR model.

According to Tang et al. [7] and De la Sen [8], in the SEIR model, the whole population can be divided into four groups, which are “S”, “E”, “I” and “R” (shown in Figure 5). The “S” stands for “Susceptible”, which means the number of people who are susceptible to infection. The “E” means people are “exposed” which incubate the disease, but no symptoms of disease appeared. The “I” represents “infectious” or “infective”, which means that there are corresponding external disease symptoms on people, or they are diagnosed. “R” means the recovered population or the “removed-by-immunity” population.

Several variables can influence the result of each Group. The explanations of each variable are:

c: Contact rate, the possibility of healthy people who contact or meet with people infected,
β: Probability of transmission per contact,
q: The percentage of exposed individuals being quarantined,
σ: Transition rate of exposed individuals to the infected Group,
λ: The rate of contacted people who are not infected but quarantined were released into a wider community,
ϱ: Probability of infected individuals having symptoms,
δ_I: Transition rate of symptomatic infected individuals to the quarantined infected class,
δ_q: Transition rate of quarantined exposed individuals to the quarantined infected class,
γ_I: Recovery rate of symptomatic infected individuals,
γ_A: Recovery rate of asymptomatic infected individuals,
γ_H: Recovery rate of quarantined infected individuals,
α: Disease-induced death rate.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

4. The Extended SEIR Model

4.1. Overview of the framework of Extended SEIR model

The framework of the Extended SEIR model is that people in Australia can be divided into several groups based on their experience and physical situations, and they would transfer between different groups according to the change of body conditions. In our Extended SEIR model, there are six groups, which are Susceptible, Exposed, Infected, Recovered, Healthy and Unknown.

4.2. Concepts introduced in the Extended SEIR model

- In the Susceptible Group

The Susceptible Group is defined as people who are under the risks of being infected by COVID-19. That is to say, if some places have confirmed cases, we can determine the whole population in that area as a susceptible group. This Group is set for significant areas, ranging from an entire city to a metropolitan area. The local governments should try to protect people from all age groups, not only for adults but also for children and teenagers [9]. Based on the situation now, everyone can be infected by COVID-19, and people from all age groups have the same probability.

- In the Exposed Group

The Exposed Group is defined as people who are under the risk of being infected by COVID-19 because the suburb or the community they live in has found confirmed cases. Another situation is that people in this Group have been in the same place with confirmed cases, such as the same supermarket or the same restaurant. Compared with the susceptible Group, people in this Group have a higher probability of being infected. Everyone who needs to do self-quarantine or self-isolation should follow the restriction rules. It is suggested that if someone has symptoms during the quarantine period, he or she must have a COVID-19 test as soon as possible.

- In the Infected Group

The Infected Group is defined as people whose test results are positive and who have apparent symptoms of COVID-19. They are contagious and people who treat or contact them should be protected under the exposure suit [10,11]. With the reference to the Queensland's Government website, mild illness should be treated at home and only when people are under higher risk of getting very unwell, they may be treated in hospital [12]. Moreover, if patients are severely unwell, they might be treated in the Intensive Care Unit. However, patients who have symptoms should be taken good care and be treated in hospital instead of isolating at their own home. The ability of medical supplies' production should be increased. In the meantime, medical departments should prepare for purchasing standard-level medical productions from overseas. Support research institutions to find out or create a vaccine for COVID-19.

- In the Recovered Group

The Recovered Group is defined as people who recover from COVID-19, and the test results are negative. Converting people from the infected Group to this Group is the purpose of hospital and health departments. The higher transferring rate, the better effect of treatment. People who recovered from COVID-19 can keep healthy and avoid getting infected again. Scientists can use plasma donated by people who have recovered from the coronavirus disease to develop new effective treatment.

- In the Healthy Group

The Healthy Group is defined as people who have experienced 14-days self-quarantine, and the test results are negative of COVID-19. The number of people in this Group can show the

spreading area and ability of COVID-19 and can deliver the effect of taking quarantine policy after confirmed cases found in a new area. In this part, what we want to see is the increasing rate of healthy people in all populations and keep them in a healthy status, not only physical health, but also mental health in the future [13]. Although treating infected people is the primary job for health departments, they should prevent most of the population who are healthy from COVID-19 at the same time.

- In the Unknown Group

- The unknown Group is defined as people who are out of any preparation. Based on the framework of Knowns and Unknowns [14], there will always be a part that is beyond individuals' imagination. In COVID-19 environment, we can consider people who attended events such as the protesting for George Floyd as an unknown group. The departments try to solve the event as soon as possible if it happened.

4.3. The Proposed Extended SEIR model

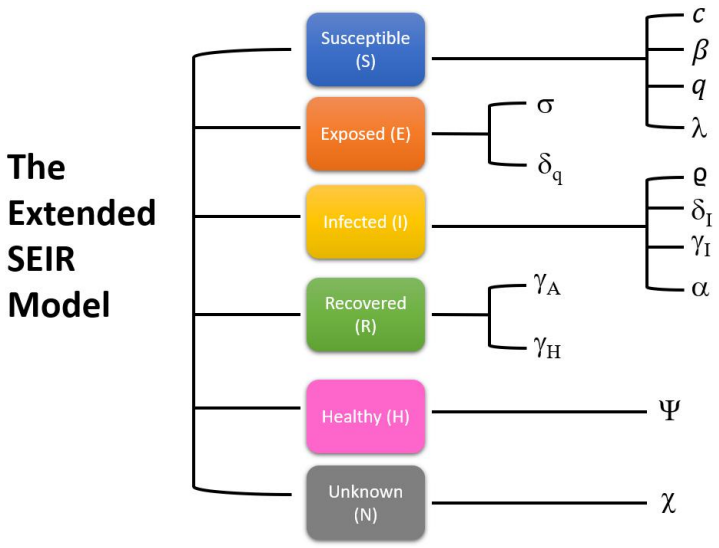

Figure 6. Tree diagram of the Extended SEIR model.

Considering the actual situation of COVID-19 in Australia, the SEIR model can be extended by introducing two more groups. Two additional groups are "Healthy (H)" and "Unknown (N)". The explanation of the Extended SEIR model can be found in Figure 6.

"Healthy" means that people who have contact with confirmed patients or people who are potentially being infected are healthy, and after the quarantine period their COVID-19 test results are negative. "Unknown" means that the rest of people in the whole population and they are under the uncertain situation, which means none of the above types suits them.

In these two groups, the variables can be explained as follows:

Ψ: The rate of quarantined healthy individuals. This rate can analyse the conversion rates of individuals from susceptible Group to healthy Group but not to infected Group, which can be explained as the percentage of people who are required to do self-quarantine but finally not being infected. Adding this Group into the model helps detect the spreading ability of the COVID-19, as this part can reflect the number of healthy individuals directly. According to the result, we can distinguish people by their age groups, gender, living environment, lifestyle and so on. Finally, we can provide suggestions to people to prevent the COVID-19 effectively.

χ: The part of an unknown situation. According to the Knowns and Unknowns framework, the knowledge can be separated into two parts that are knowns and unknowns, and in each of them, it can also be divided into two parts: knowns and unknowns. For most individuals, it is easy to recognise that there is something that we know, and there is something that we do not know. And in some particular scenarios, there are some "unknown knowns", which can be explained as people understand the knowledge even, when they never realise this 'knowns'. In this part, the variable "χ" means the rest of situation, which is "unknown unknowns". Based on this framework and combined with what is required in the COVID-19 period, this variable can be regarded as the contingency situation, such as what we need to do if the medicine is out of stock, what we should do if an emergency incident occurred (e.g. Killing of George Floyd), and how can these events influence the situation in the future.

To sum up, the transmission dynamics is governed by the following system of equations:

$$S'^{1} = -(\beta c + cq(1-\beta))\,S(I + \theta E) + \lambda S + N, \quad (1)$$

$$E' = \delta_q(1-q)\,S(I + \theta E) - \sigma E + N, \quad (2)$$

$$I' = \varrho E - (\delta_I + \alpha + \gamma_I)\,I + N, \quad (3)$$

$$R' = \gamma_I I + \gamma_A E + \gamma_H H + N, \quad (4)$$

$$H' = \Psi E + H + N, \quad (5)$$

[1] where ′ is the derivative with respect to time.

In the extended SEIR model, we stratify the populations into six groups: susceptible(S), exposed(E), infected with obvious symptoms(I), recovered(R), healthy(H), and unknown(N). And in the equations, we add ′ to show the variation of each group's population. The 'c' means contact rate and the 'β' illustrates the percentage of transmission per contact. The 'q' is the proportion of exposed people being quarantined, while '1-q' means people who are exposed to virus but do not be

quarantined, and people in this part and be calculated into exposed(E) or infected(I) when they have symptoms. 'Ψ' illustrate the percentage of quarantined heathy individuals, and this is the transmission from exposed(E) group to healthy(H). The figure 'N' is counted in every equation, because the unforeseen situation could happen in each stage of the whole system. For example, individuals who are counted in the recovered(R) may diagnosed by mistake whose test results are still positive, but they do not have obvious symptoms, as a result they would be recounted into group exposed.

5. Application of Extended SEIR for Diagnostic Analysis for COVID-19

To improve the results caused by variables, the government, states(territories) and local communities published rules and the goals can be achieved are as follows:

5.1. Variables considered in "S" group:

To control the contact rate (c), people should keep a 1.5-meter social distance when they meet anyone else except their close families. The second measure adapted by states and territories is closing borders, and only people who have the exemption can cross borders between different states [15-19]. During the second wave of COVID-19 outbreak, the government of Victoria published more strict policies compared with other states. We choose two restrictions that are related to the contact rate. The first one is that all people in Victoria must wear masks when going out, and the second one is that people can only stay at home with their families, which means individuals cannot visit each other [20].

For the probability of transition (β) and quarantined rate (q), the government suggests that firstly, people should maintain good handwashing behaviour and cough/sneeze hygiene, and it is better to wear masks when going out. Secondly, people who have travelled from overseas are required to do centralised isolation for 14 days [15].

For the rate of contacted people who are not infected but quarantined were released into wider community (λ), everyone in this situation is required to have a 14-days self-quarantine when they move into a new state/territory.

5.2. Variables considered in "E" group:

For the transition rate of exposed individuals to the infected Group (σ), it is encouraged that people in Australia could download the COVIDSafe App so that the way of spreading virus can be found quickly [21]. After that, wearing masks and washing hands frequently are useful methods to reduce the possibility to get infected. Furthermore, individuals should maintain 1.5-meter social distance when going out and, if possible, stay at home with close families and cancel all public activities, such as party and visiting.

To improve the situation of the transition rate of quarantined exposed individuals to the quarantined infected class (δ_q), state governments enhance the supervision of self-quarantine, increase the frequency of checking by officers. This measure can be an effective way to reduce the number of people who break the quarantine rules. And to reduce the chance of people getting infected before self-quarantine, wearing masks and washing hands frequently, maintaining a 1.5-meter social distance when going out, and staying at home are the "three golden rules" that should be implemented.

5.3. Variables considered in "I" group:

In this Group, we mainly focus on people working in the hospital and test centres and those confirmed COVID-19 patients who are receiving treatment in hospital. The measurement that published in order to accurate the probability of infected individuals having symptoms(ϱ) is that people should be tested to check whether they are infected or not.

For the transition rate of symptomatic infected individuals to the quarantined infected class(δ_I), it is suggested that when people have similar symptoms with COVID-19, they should do a test as soon as possible. In hospitals or test centres, healthcare volunteers or senior medical students who help doctors or nurses should pay more attention to people in this Group to make sure they follow the quarantine rules strictly.

To determine the disease-induced death rate (α), we should test the reason of death carefully. This is to make sure the death is resulted from coronavirus (or syndrome caused by coronavirus), and not because of other diseases.

5.4. Variables considered in "R" group:

Firstly, in the part of the recovery rate of symptomatic infected individuals (γI), healthcare workers should take good care of patients and calculate carefully about the number of people recovered. Secondly, what we need to do for a recovery rate of asymptomatic infected individuals (γA) is that medical research institutes could use the clinical data to figure out the percentage of death, recovery and other conditions; as a result, they can analyse the feature of the coronavirus. Thirdly, the recovery rate of quarantined infected individuals (γH) can show the effect of quarantine rules. People who are in this Group should do in-depth research on their serum because they recovered by their immunity only with the help of medicine.

5.5. Variables considered in "H" group:

For the rate of quarantined healthy individuals (Ψ), people in this Group are encouraged to do exercises in private or secure places, such as balcony or garden of their homes. At the same time, individuals should keep windows open to enjoy the fresh air and pay attention to their mental health. People should remember to follow protection suggestions, such as washing hands and wearing masks. They could also monitor their physical condition, such as measuring body temperature every day.

5.6. Variables considered in "N" group:

The unknown part (χ) can be regarded as the intercept term in the linear regressions. This variable will always be in the formula, but the quantity or the influence of this variable is unknown. However, this variable should be included in the situation that is under consideration. The preparation of preventing hidden parts may come from all aspects, including anything that you can, and you cannot imagine. As a result, it is better to set up a particular office to solve this problem.

As a result, these variables are the key reasons that would affect the output of the extended SEIR model. And they are the central part for us to discuss in the following sections.

6. Application of Extended SEIR for Predictive Analytics for COVID-19

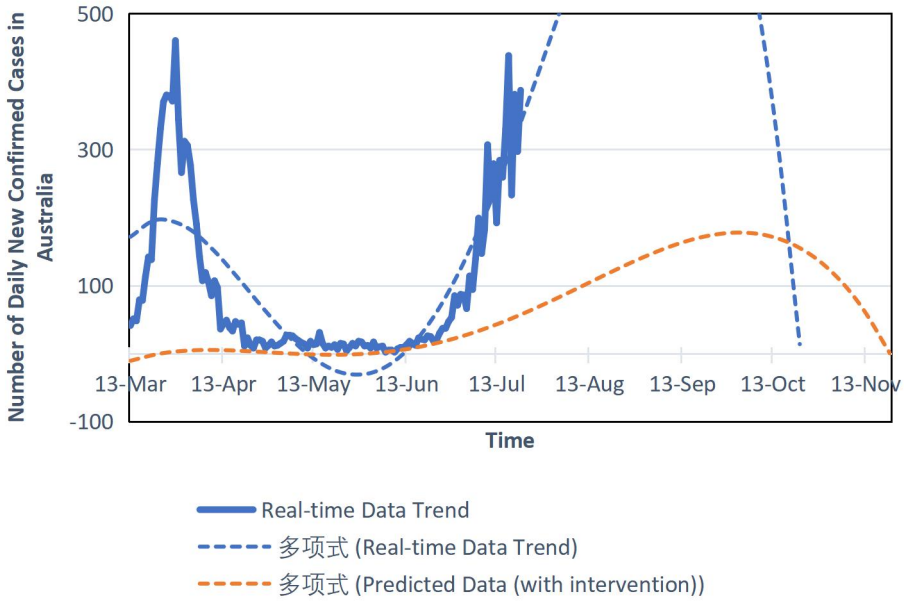

Figure 7. The prediction of daily confirmed cases with the "flattening curve".

According to Figure 7, the full blue line in this chart illustrates the actual condition of daily COVID-19 confirmed cases in Australia from 13 March to 22 July. The dotted blue line shows the trendline by polynomial regression with the predicted trend. Based on the result of prediction, there will be a peak of daily new confirmed cases in early September and then the number of regular new confirmed instances will have a decreasing trend.

The dotted orange line in the chart is the trend of infected cases of COVID-19 in Australia if we take effective interventions, which are based on the result of analysing variables in extended SEIR model to slow down the spreading of coronavirus. In this situation, the daily confirmed cases would increase slowly, and the peak of number would also be smaller than the real data. As a result, the problem of shortage of medical personnel and supplies would be solved, and the number of total cases and the whole health condition would be controlled under a perfect level.

The experimental results show that with the government's intervention, the spreading of COVID-19 can be extremely reduced, and the number of confirmed cases would be controlled under a reasonable situation. These results can be proved by comparing with the real-time data trend of daily new confirmed cases of Australia, China, the United States, and India (See Figure A1-A3). According to these figures, we can see that because of the government's intervention, the trend of new confirmed cases in China has been flattened and almost reduced

to 0. However, the trend of the US and India were increasing rapidly and even losing control afterwards.

7. Application of Extended SEIR Model and Text Analysis for COVID-19

Using the open-source software, Wordclouds.com [22] and Wordarts.com [23], several word clouds of the recent news were made. They can be used as resources reflecting the current situation of Australian measures to defend the COVID-19. We can conclude the theme of a news report into four components: medical, quarantine, police, and mask [24-26]. These keywords are related to different groups of the extended SEIR model.

Results demonstrated that the first component included words such as medical, supply, response, health and short. These words can reflect that the medical departments and organisations were suffering a shortage of medical supplies and healthcare workers [27,28]. That is to say, with this lack of medical supplies, many hospitals are suffering from a shortage of medicine or personal protective equipment (PPE) such as masks, protection suits and hand sanitizer. In shortage of workforce, a large number of healthcare workers was tested positive of COVID-19 [29], and most of the personnel lack of clinical training, which means many senior medical students who have no or limited clinical experience are working as assistants with doctors in the hospital. This first word cloud can be corresponded with infected group and recovered group, because the shortage of medical equipment would have impact on testing and treatment of confirmed cases. As a result, the rate of transmission between these groups may decrease.

The keyword of the second component is quarantine, and other outstanding words are travel, case, test, hotel, and air. In this part, quarantine is the main topic. From news on this topic, we can find that people travel from overseas to Australia or travel between states should get a test of COVID-19 and should do 14-days self-quarantine because of the government's restriction. This set of keywords are related to the susceptible group and exposed group, as people who travel to another place and go to public places such as hotel and restaurant have higher risk to be susceptible and exposed in a coronavirus environment.

The third component included words such as police, isolate, missing, false and found. These keywords are related to Group H and Group N. Local government did some measurements to make sure people who should be quarantined are actually quarantined, but from the information we collected, the current policies may be ineffective. This news shows that there

are limited police officers available to do routine checks of people who should be isolated or quarantined in their home. This would lead to inadequate supervision and cannot make sure all of the people are following the quarantine rules. Moreover, some people provided false personal information, such as wrong name and address. This situation may be caused by no certain rules or policies to follow [30,31].

The fourth component included words such as mask, wear, advise, use and public. Wearing a mask or not is a hot topic since the beginning of the COVID-19. At first, the health department did not encourage people to wear masks [32,33], but these days, the government of Victoria requires people who go out must wear a mask [20]. This measure can change the situation into a good one effectively. Keywords in this cloud are related to infected, healthy, and unknown group. In this part, making good protection measurements are really helpful for flattening the curve of confirmed cases and protect more individuals who are not being infected or stay in the virus-spreading environment.

By analysing the word clouds of recent news, we can use those keywords to match the variables in the extended SEIR model. It can reflect the advantages and disadvantages of current measurements from the content of the news. And then, we can provide further suggestions from different aspects to solve the problem we meet and improve the policies.

8. Results Discussion

Based on the analytics we did in Section 5, 6 and 7, the results of the flattening curve with Extended SEIR model in different parts can be concluded as the following measurements.

To improve the situation of the “S” group, the recommendation is that schools located in the place where active cases have been found should be closed, and all courses turn to online teaching. A school is a place that children get together, and most children come from different families in nearby communities. It is a public place where children are exposed to high risk of being infected if one of the children was infected in somewhere else. And it can result in the local transmission.

To decrease the rate of people in group “E”, the suggestion is that people living in high-risk regions should stay at home all the time until no more active cases. According to the restrictions accepted by Italy, people should stay at home all the time and do not go out unless

some essential activities such as shopping for food. At the same time, to cut the transmission of coronavirus, all public events are forbidden, and all public places are locked [34].

People who are self-isolating should be gathered in some unique places. People who are self-quarantining in their own home at potential risks of being infected, so that his/her close family members have a high risk to be affected. However, there are no restrictions for them, which means they can go out like ordinary people. In this situation, the risk of spreading the virus is increased. Local government can select some places such as hotels chosen, sports arenas or the government can build a "Mobile Cabin Hospital" to bring them together and quarantine. As a result, the risk of local transmission can be decreased to the lowest level. This suggestion is suitable for both group "E" and group "I".

To solve the problem in the hospital and decrease the number of people in Group "I", the recommendation is that low-risk regions could offer medical support to the high-risk areas. A shortage of medical personnel and medical supplies is faced by high-risk areas such as Victoria and Greater Sydney. Doctors and nurses in other states such as ACT and WA could be drafted to support Victoria and Great Sydney in a short time.

According to the research result of King's College London, people who recovered from the COVID-19 may lose immunity in months [35]. In this situation, this kind of people should register in the local hospitals' documents about their personal information so that they could do health examination regularly to prevent a recrudescence of COVID-19.

For people in "H" group, they need to do COVID-19 test follow the requirements and keep self-quarantine during the waiting-result time. After 14-days self-quarantine, if the test results of people are healthy and they follow the quarantine rules strictly during this period, they should be free to go back to their normal life. However, they still need to do protection in case they are infected afterwards.

Finally, trying to figure out group "N" is an essential part for us to do. According to the Knowns and Unknowns framework, there is always a part that people do not know. We need to do some preparation to do with this situation when it happens. For example, set up some backup plans, and they can start from any aspects, no matter how wild they are.

9. Contribution

The contribution of this study is the extended SEIR model that can be useful for Australian government and local communities to make some measurements to control the spreading of this novel pneumonia in Australia. Especially two new “Healthy” and “Unknown” groups, which focus on more detailed information and the part that the classic model ignored, can provide comprehensive information for medical institutions to analyse COVID-19.

Moreover, the idea in this paper can be used in other fields besides the measurements of COVID-19. It is a good endeavour to modify existing models according to the actual situation and then make life much better for all individuals.

10. Conclusion

In conclusion, the findings of this paper highlight the preventive and practical methods for the whole population. For people who have not been infected, they should pay attention to their health such as keep 1.5-meter social distance, washing hands before eating and do some exercise in private places for their mental health as well. For people who have been infected, they had better follow the doctor’s advice and do self-isolation strictly. For people who have recovered from the coronavirus, they could pay attention to their physical condition and keep in touch with the local hospital in case they feel unwell again.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, Pengdi Zhao; writing—review and editing, Elizabeth Chang and Pengdi Zhao; visualization, Pengdi Zhao; supervision, Elizabeth Chang; project administration, Pengdi Zhao.

Appendix A

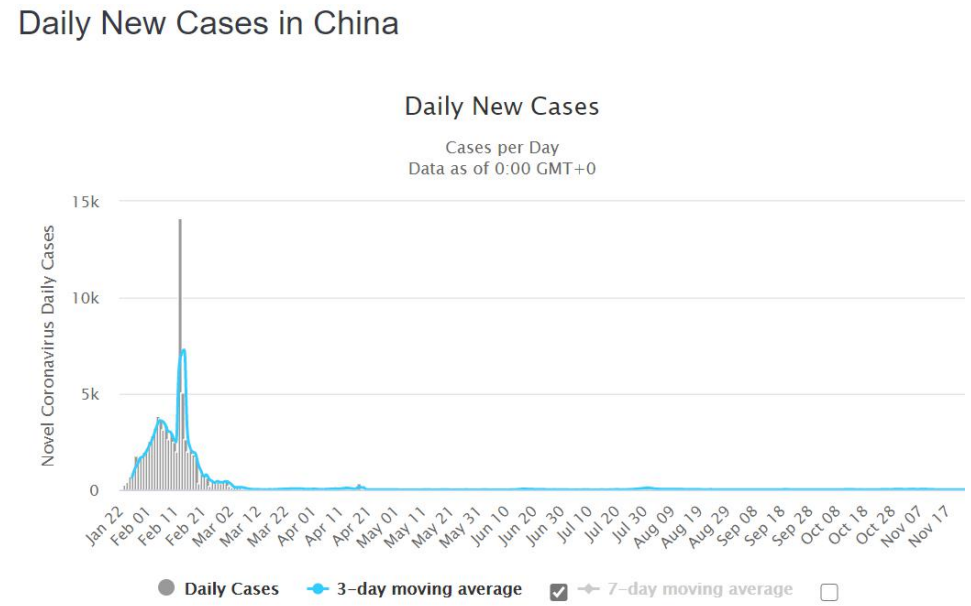

Figure A1. Daily New Coronavirus Cases in China [37].

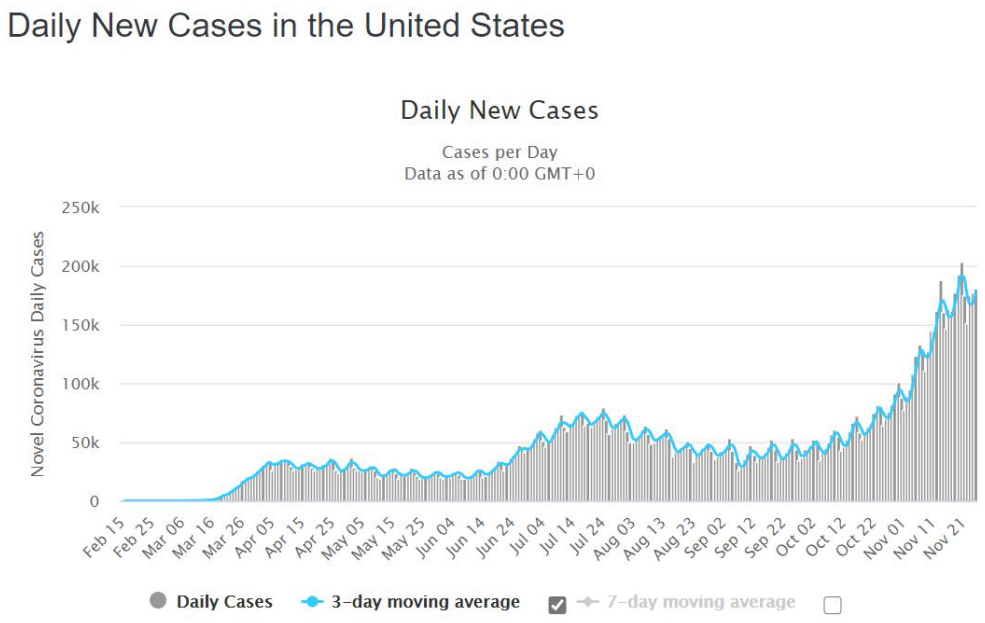

Figure A2. Daily New Coronavirus Cases in the United States [36].

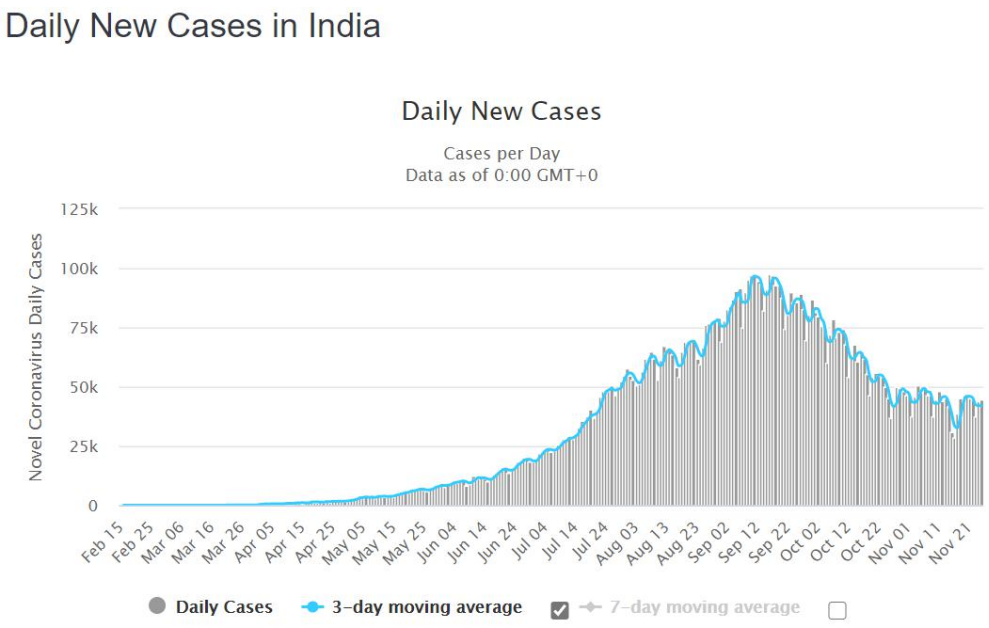

Figure A3. Daily New Coronavirus Cases in India [38].

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