University of Michigan

Math 462 Final Project

The Cost of Quarantine: Analysis of Social Network Models Based on Haslemere Data

Zhengxu Tang, Jess Yang, Yufei Chen

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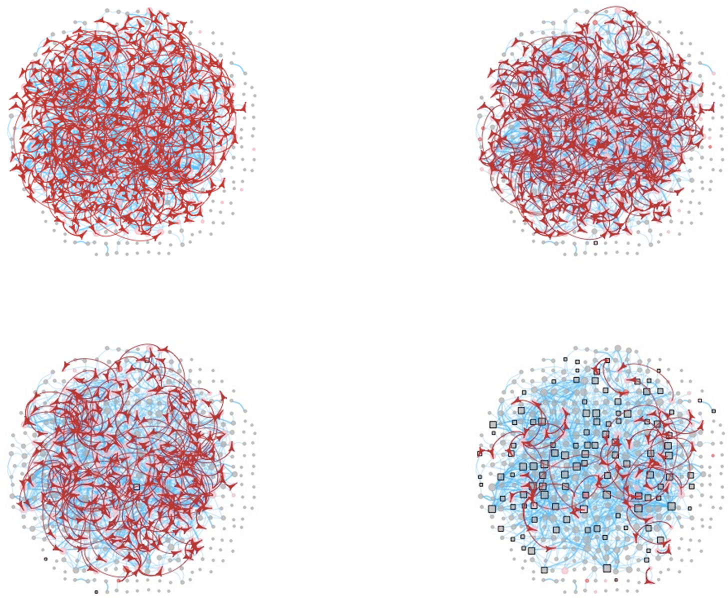

Figure 1: COVID-19 transmission paths under different quarantine strategies

COVID-19 is a highly contagious respiratory illness caused by the novel coronavirus SARS-CoV-2. One of the main ways to control the spread of the virus is through measures like quarantine. Quarantine is a public health measure that involves the separation and restriction of movement of people who have been exposed to a contagious disease to prevent its spread. During quarantine, people are advised to stay at home or in a designated location for a specific period of time, typically 14 days, to monitor for symptoms and reduce the risk of spreading the virus to others. The COVID-19 pandemic has highlighted the critical role of quarantine in preventing the spread of the virus. However, quarantine can be a controversial measure, as it can cause economic disruption. In this paper, we are going to analyze the cost-effectiveness of quarantine during the spread of alpha by using a model that simulates the social network of individuals in Halsemere, a small town in England. Then, based on the results of the simulations, we can calculate the actual medical cost and labor loss of each given case. The goal of this paper is, by comparing the cost of each case, to find the most cost-effective level of quarantine, which may become a useful reference for future research or pandemic.

The social network model we used to simulate the spread of alpha is modified from a model published in 2020 (Firth et al. 2020). It's mentioned in the paper that by using a real-world network to study the spread of SARS-CoV-2 and evaluating control strategies, it is possible to simulate contagion dynamics and contact tracing more accurately and realistically. Additionally, it's important to notice that since the detailed data on individuals in the town of Haslemere was collected by an app-based contact tracing, the structure of these data provides strong support to the contact simulations of our model. Therefore, simulating the contacts of individuals in Haslemere is significant in terms of modeling the spread of diseases in the UK and is potentially valuable for understanding and controlling the spread of actual infectious diseases in the future. After getting the results from our simulation for weekly alpha infection cases, a cost model allows us to roughly calculate a specific cost for each level of the quarantine method. This cost model is developed from a model used in a paper that analyzes the isolation costs in two Australian states (Melia et al. 2021). The original cost model of the Australian paper is useful to this paper because the structure of the calculations for quarantine cost is similar to the situation in the UK. One major difference between the quarantine policy of Australia and the UK is that, for local residences in the UK, there is no requirement for hotel isolation, so we made adjustments in our cost model accordingly. Another meaningful change to the original cost model we adopted is that our cost model includes an additional part: the labor-loss model which was not analyzed in the Australian paper.

2 Methods

2.1 Haslemere Social Network Model

2.1.1 Elements of Model

We used the Haslemere social network model[?] to simulate the number of COVID -19 cases within 10 weeks under different quarantine conditions. The model was derived from the data of 468 people living in Haslemere (>13 yrs.).collected by a mobile application for the research purpose of 2017-2018 BBC Epidemic Project. The application recorded individuals' mobile information such as locations, distance to other people using the app and time spent in one area within a 3-day period. This allowed us to obtain the essential features for constructing the social network model, which include:

(a) Nodes: Nodes: The network consists of 468 nodes, representing the same number of individuals for whom social contact data was successfully collected.

(b) Edges: Each edge represents the number of social contacts a person has had within a 3-day period. Here we defined a social contact as "events when the average pairwise distances between individuals within a 5-min time interval were 4m or less" . If one or more social contacts are observed, there will be an edge between the corresponding nodes in the model. The number of edges for one specific node is consistent with the social tracking data obtained from the person that node represents.

(c) Weights: The weights were calculated based on the number of days in which social contacts were observed. Between any 2 nodes, if no contact was observed in any days, it means "no link"; if contacts were observed in 1 day out of 3 days, it means a "weak link"; similarly, we defined a "moderate link" as 2 persons have contacts in 2 days and a "strong link" as 2 persons have contacts in all 3 days. Therefore, we assigned weights based on the type of link between 2 nodes.

(d) Directions: Since the contact information is mutual, the edges in the model do not have directions.

2.1.2 Assumptions

The model was built based on following assumptions:

(a) Weak to moderate level of social distancing: In the Haslemere social network model, we assume a weak to moderate level of social distancing during the COVID-19 period, and therefore weak links were removed from the network. Less social contacts possibly indicate longer social distance between two persons.

(b) Susceptible, infected and recovered: assume there are three types of people: "susceptible", "infected" and "recovered" in the model. Deaths are classified as "recovered" since both recovered individuals and deceased individuals will no longer have any further impact on the model. We do not take reinfection into consideration, since the simulation time is short (10 weeks).

For infected individuals, it is assumed that they will recover 7 days after the onset of symptoms.

(c) Incubation Period: after infection, the infected person will go through an "incubation period". During this period, the infectiousness of the infected person is randomly determined at the point of infection using a Bernoulli Distribution.

The length of the incubation period is randomly assigned for each infected person using a Weibull Distribution.

2.1.3 Case 1: No Quarantine

In 2, at the first timestep, a certain number of people are randomly selected as "infected". (The default initial value is 1) After Person A get infected, he has a chance to infect others in the following timesteps at a probability P. Here P is defined as :

$$P(t, s_i, p_i) = 1 - e^{-\lambda(t, s_i, p_i)} \tag{1}$$

In 1, t is the infector's exposure time, s_i is the infector's asymptomatic status (Whether A will develop symptoms at the onset point) and p_i is the presymptomatic status (Whether A is infectious in the incubation period). Two statuses are assigned once a person gets infected. $\lambda(t, s_i, p_i)$ is the transmission rate defined as:

$$\lambda(t, s_i, p_i) = A_{si} I_{ei} \int_{t-1}^{t} f(u; \mu_i, \alpha_p, \omega_p) du \tag{2}$$

In 2, A_{si} is the scaling factor, I_{ei} is the weight of an edge, $f(u; \mu_i, \alpha_p, \omega_p)$ is the probability density function of a skewed normal distribution with the slant parameter $alpha_{pi}$ and the scale parameter ω_{pi}; $\mu_i$is the location parameter that depends on the infector's onset time. [?]

Assume B is a contact of A who gets infected by A. At the point of infection, B will be assigned 2 statuses – s_i (if asympotomatic) and p_i (if presymptomatic). If B is presymptomatic, B can infect others in the incubation period. In case 1, no matter B is asymptomatic or not, B's contacts are at the risk of being infected after the onset time. 2

2.1.4 Case 2: Quarantine

In this case, only symptomatic individuals can be found and put in quarantine. Therefore, the only difference between case 1 and case 2 is at the onset time, if B shows symptoms, it will be in quarantine. However, B still has a chance to infect others before quarantine since B is possibly infectious in the incubation period (presymptomatic) or B can affect others in the delay between the onset time and quarantine (1 - 2 d). Quarantine lasts for 14 days which ensures everyone gets recovered after this.

2.1.5 Case 3: Primary Contact Tracing

The difference between primary contact tracing and quarantine happens at the point of quarantine: when B is quarantined, all of B's primary contacts will also be in quarantine.

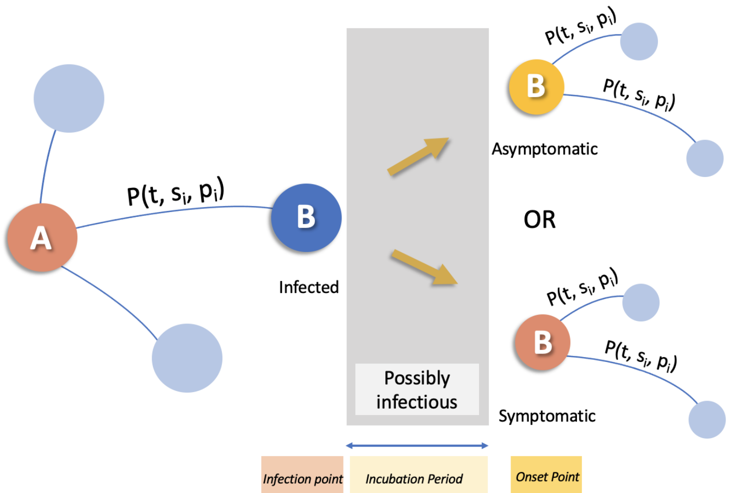

Figure 2: No Quarantine

The picture shows the process of spreading COVID starting at the first time step (Day 1). Red shows "infected", blue shows "susceptible" and yellow shows the asymptomatic status.

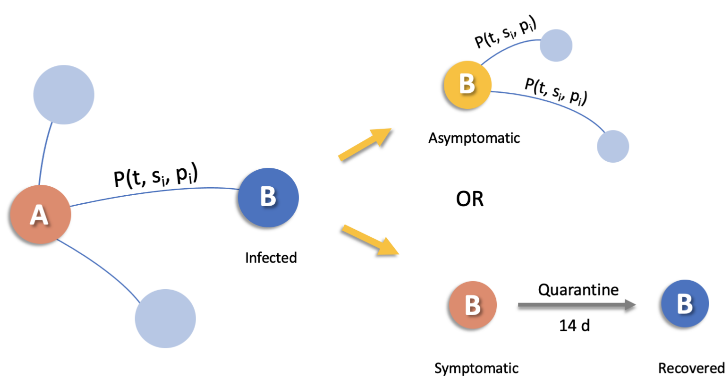

Figure 3: Quarantine

In this case, symptomatic individuals are going to be quarantined for 14 days. Asymptomatic individuals are not detected and continuing spreading COVID.

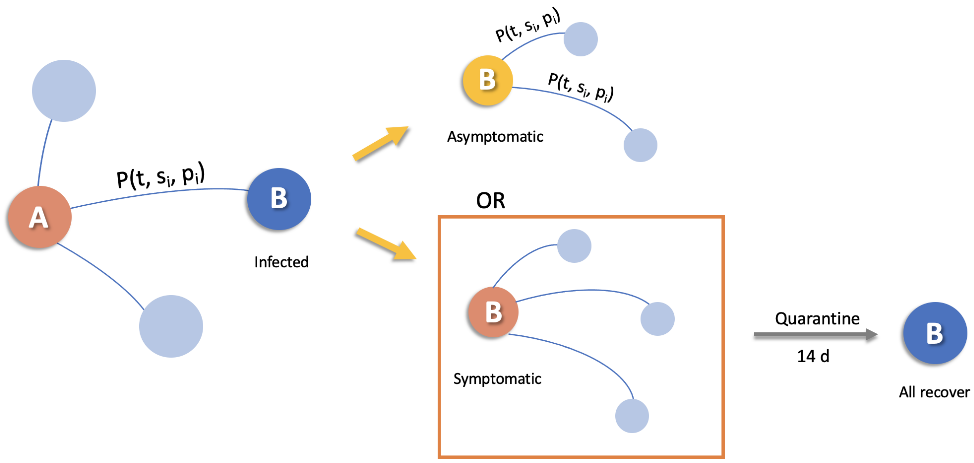

Figure 4: Primary Contact Tracing

In this case, symptomatic individuals and their direct contacts are going to be quarantined for 14 days. Asymptomatic individuals are not detected and continuing spreading COVID.

They will go through a 14-day quarantine. Assume everyone will be recovered after 14 days if infected.

Similarly, for asymptomatic people, they will never been found out in our model.

2.1.6 Case 4: Secondary Contact Tracing

In the last case, at the onset time, B, B's contacts and all contacts of B's contacts will be put in quarantine for 14 days, which is the strictest way of disease control among all cases.

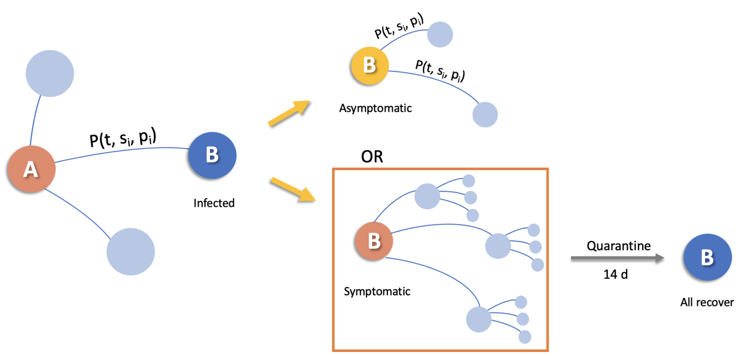

Figure 5: Secondary Contact Tracing

In this case, symptomatic individuals, their direct contacts and the direct contacts of their contacts are going to be quarantined for 14 days. Asymptomatic individuals are not detected and continuing spreading COVID.

2.2 Cost Model

The cost model of this paper consists of two aspects: medical cost and labor loss. Firstly, the medical cost model has three stages: 1. individuals; 2. patients / susceptible; 3. home isolation/ward-based care / ICU or high dependency care. To be more specific, the medical cost model starts with a certain number of individuals at stage one. After that, each individual can either become a patient or be categorized as susceptible with certain probabilities at stage two. According to the data collected from Coronavirus (COVID-19) latest insights published by the Office for National Statistics, 8.1 percent of all individuals were infected during the spread of alpha. Therefore, this model randomly assigns 8.1 percent of all individuals as infected, meaning they are assigned to the patient group, and the rest are categorized as susceptible.

As we have experienced in the real world, individuals show different symptoms and different levels of severity after infections. Thus, at stage three, patients are randomly assigned to either one of the three categories based on their levels of severity with the following percentages: approximately 0.6236 out of 100,000 patients need ICU or high dependency care; about 10.0982 out of 100,000 patients need ward-based care; the rest only needs home isolation. Based on the data collected from a paper published in the European Journal of Public Health, the ward cost and ICU cost in the UK are £586.59 per night and £4847 per night. The median length of stays for ward care and ICU care is 8 days and 12 days. Assuming there's no cost for individuals who only need home isolation, this model can calculate the exact medical cost of each quarantine case with the data mentioned above. The decision tree of the medical cost model is provided below:

In addition to the medical cost, labor loss also has a significant impact when calculating the economic disruption of isolation and quarantine. Due to the fact that individuals' wages vary with many factors, this model only considers the loss of working days. It is assumed that patients under the age of 14 and above the age of 65 have no job. Therefore, these

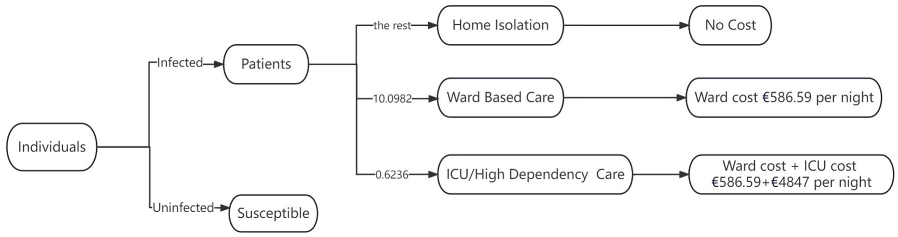

Figure 6: Dune shape at t=500

patients have no wage loss in this model. According to the data published on the official UK government website for data and insights on coronavirus (COVID-19), about 74.30 percent of all patients are from the age of 15 to 64, who are considered to have wage loss in this model. To calculate the total labor loss, the exact loss of working days for each individual depends on his level of severity, meaning the length of stay for home isolation, ward-based care, or ICU care. The decision tree of the labor loss model is provided below:

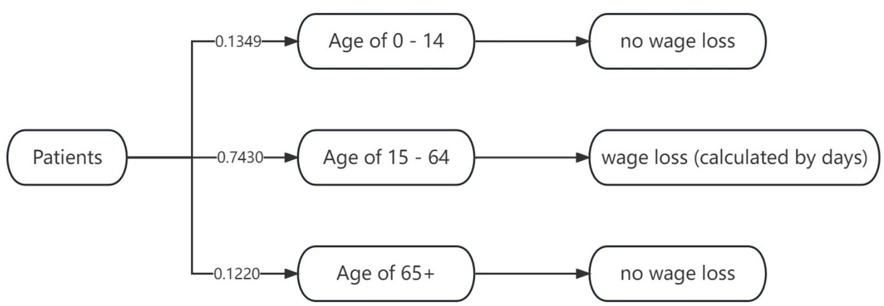

Figure 7: Dune shape at t=500

3 Results

In this project, we look at both qualitative and quantitative results to assess and evaluate the model in question. First, we look into the qualitative effects that how the different quarantine methods will influence the final Covid case.

3.1 Qualitative Results and Analysis

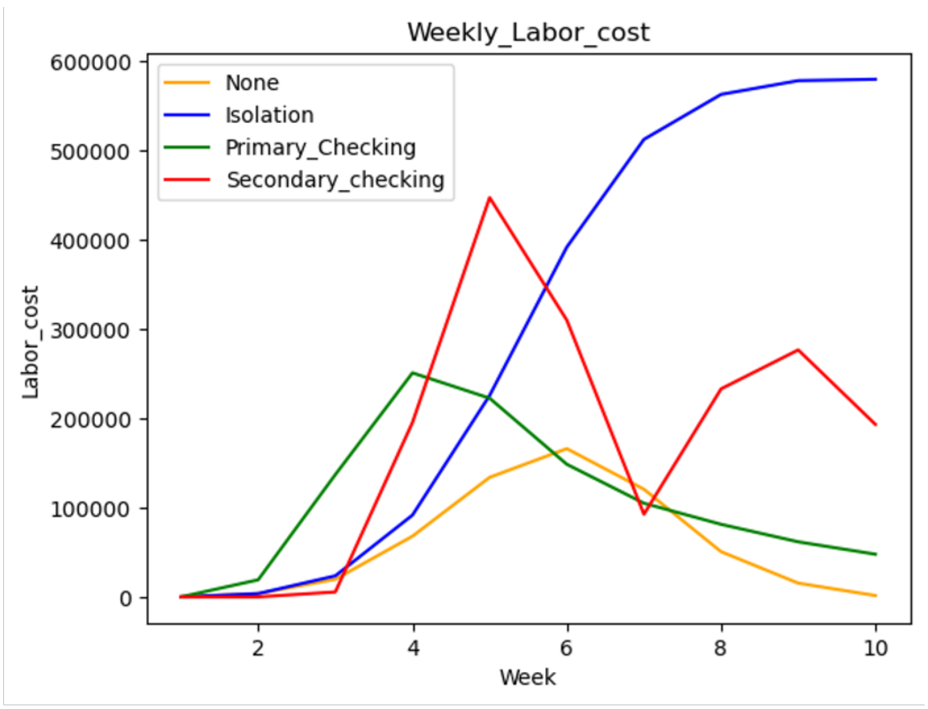

Figure 8: Weekly Labor cost

Figure 1 shows the result of our network model after running 10 weeks(70 days) by choosing different quarantine methods. Figure 1 displays four distinct network diagrams, illustrating the progression of COVID-19 cases and quarantine measures. Within each diagram, gray dots symbolize individuals, while blue lines denote social connections. Quarantined persons are enclosed within boxes. A notable observation is a decline in red lines, which represent COVID-19 cases, as the diagrams progress from left to right and top to

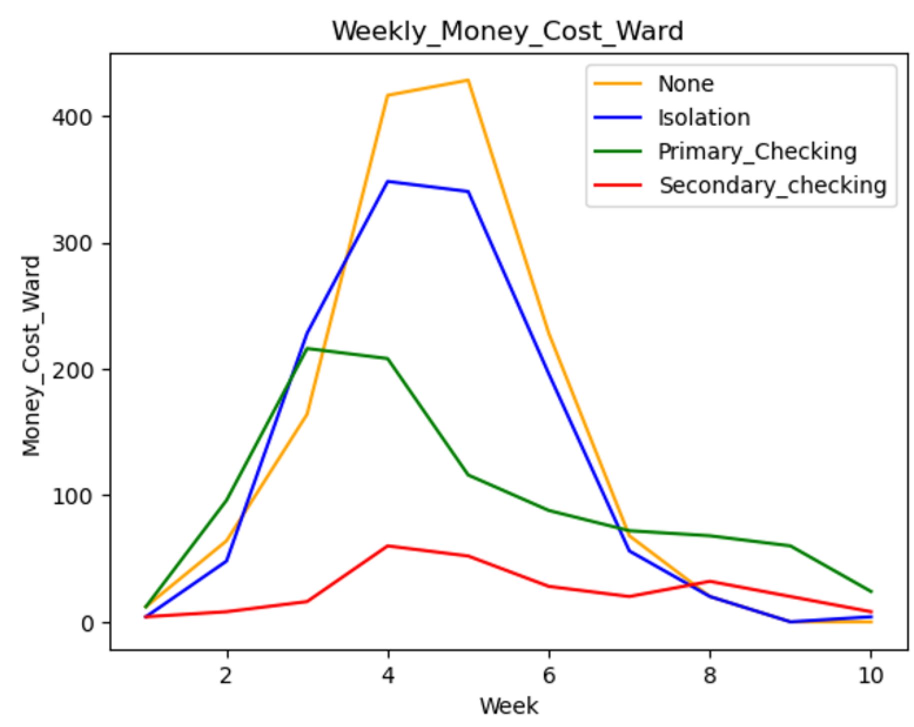

Figure 9: Weekly Money Cost Ward

bottom. Conversely, the prevalence of boxes, signifying isolated individuals, exhibits an inverse trend. Specifically, the top-left image represents a scenario without quarantine measures in place. The rapid transmission rate is evident, as within 10 weeks of simulation, all individuals within the tree network contract COVID-19. The top-right image, however, demonstrates the impact of quarantining COVID-19 patients. After 10 weeks, the number of infections is reduced compared to the scenario with no preventive measures, but the effect remains limited, as the red lines resemble a situation without isolation. Moving to the bottom-left image, we observe a significant reduction in red lines, while the small boxes indicate an isolation increase. This scenario depicts the implementation of close-contact quarantining, which isolates not only the infected individuals but also those who have been in close contact with them. This strategy effectively disrupts COVID-19 transmission pathways and reduces transmission efficiency, known as primary tracing. Finally, the bottom-right image portrays the most stringent quarantine measures, where secondary tracing is employed. This method isolates not only close contacts of COVID-19 patients but also close contacts of those close contacts. Compared to the previous three scenarios, this approach results in a substantial reduction in COVID-19 infections. However, this progress comes at the expense of a larger number of individuals experiencing isolation. In summary, we observe that given a constant total number of individuals and social connections within the network, stricter quarantine policies prove more effective in preventing the spread of COVID-19. However, this could also result in a higher number of people being isolated at home, leading to a significant loss of labor force and increased hospitalization costs for COVID-19 patients. To analyze these aspects accurately, we use the data from network modeling combined with a cost model design to create Figures 8 and 9. Figure 8 represents the weekly labor cost, illustrating the labor force losses associated with different policies. Figure 9, on the other hand, showcases the weekly financial costs of medical treatment for COVID-19 patients under varying probabilities. As expected, Figure 9 aligns with general knowledge of COVID-19, revealing a decrease in the number of cases and subsequent reduction in medical costs as control measures are strengthened. However, Figure 8 presents unexpected findings. Initially, we hypothesized that stricter control measures would lead to more people in isolation, resulting in higher labor costs. In reality, isolating only infected individuals incurs the largest labor cost, as such controls fail to disrupt or even weaken the transmission chain of COVID-19. This, in turn, leads to more infections and consequently higher costs. Surprisingly, the most stringent isolation method, secondary tracing, demonstrates lower labor costs. This is because secondary tracing effectively suppresses the spread of the virus, causing the number of transmissions to rapidly decrease after peaking in the fourth week, and subsequently reducing labor costs.

3.2 Quantitative Results and Analysis

For the quantitative analysis, Figures 10 to 12 display tables related to the costs incurred due to COVID-19. Although our model only accounts for 468 people, and the data sources are typically scaled to 100,000 people, the information provided is still valuable. Figure 12, in particular, reveals that the Weekly Labor Cost for isolation alone is approximately 1.6 times higher than that for secondary tracing. Figure 10 demonstrates that implementing primary tracing results in the lowest Weekly Ward Cost, while Figure 11 shows that applying secondary tracing leads to the lowest Weekly ICU Cost. Figures 13 and 14 illustrate the impact of various quarantine methods on the final outcomes of COVID-19 cases and the number of quarantined individuals after 70 days of simulation. Figure 13, which presents the Total COVID Cases, indicates that there is no significant difference between using the isolation method alone and applying no method. However, when primary tracing and secondary tracing are employed, the total case count drops considerably. Surprisingly, Figure 14 reveals that isolation generates the highest number of quarantined individuals, while primary tracing results in the lowest number when some method is applied. Figure 15 depicts the COVID-19 outbreak trend, highlighting a spike in cases during the third and fourth weeks of the simulation. This period represents the primary phase of the outbreak, after which the number of cases returns to a lower level.

Week	None	Isolation	Primary_Tracing	Secondary_Tracting
1	0.00	0.00	0.00	0.00
2	3702.51	3704.91	19162.91	2.40
3	19746.75	23616.33	137083.01	5566.57
4	68033.72	91681.36	251043.81	195506.07
5	133984.78	225786.03	222669.75	447474.16
6	166150.39	391957.28	148640.28	310193.39
7	120640.30	512722.35	104982.81	92641.09
8	50678.18	563123.78	81333.92	233137.06
9	15427.14	578528.08	61718.59	276773.05
10	1542.71	580061.79	47825.16	193303.17
cum	579906.52	2971181.95	1074460.28	1754596.99

Figure 10: Weekly Ward Cost

Week	None	Isolation	Primary_Tracing	Secondary_Tracting
1	0.991115	0.330372	0.991115	0.330372
2	5.285944	3.964458	7.928916	0.660743
3	13.545232	18.831177	17.840062	1.321486
4	34.358638	28.742322	17.179319	4.955573
5	35.349753	28.081579	9.580774	4.294830
6	18.831177	16.188204	7.268173	2.312601
7	5.616316	4.625201	5.946687	1.651858
8	1.651858	1.651858	5.616316	2.642972
9	0.000000	0.000000	4.955573	1.651858
10	0.000000	0.330372	1.982229	0.660743
cum	115.630032	102.745543	79.289165	20.483034

Figure 11: Weekly ICU Cost

Week	None	Isolation	Primary_Tracing	Secondary_Tracting
1	0.000000	0.000000e+00	0.000000e+00	0.000000e+00
2	3702.515728	3.704916e+03	1.916292e+04	2.400000e+00
3	19746.750547	2.361634e+04	1.370830e+05	5.566574e+03
4	68033.726495	9.168136e+04	2.510438e+05	1.955061e+05
5	133984.787893	2.257860e+05	2.226698e+05	4.474742e+05
6	166150.393276	3.919573e+05	1.486403e+05	3.101934e+05
7	120640.304124	5.127224e+05	1.049828e+05	9.264109e+04
8	50678.184022	5.631238e+05	8.133392e+04	2.331371e+05
9	15427.148865	5.785281e+05	6.171860e+04	2.767731e+05
10	1542.714887	5.800618e+05	4.782516e+04	1.933032e+05
cum	579906.525836	2.971182e+06	1.074460e+06	1.754597e+06

Figure 12: Weekly Labor Cost

Week	None	Isolation	Primary_Tracing	Secondary_Tracting
1	3	1	3	1
2	19	13	27	2
3	60	70	81	7
4	164	157	133	22
5	271	242	162	35
6	328	291	184	42
7	345	305	202	47
8	350	310	219	55
9	350	310	234	60
10	350	311	240	62

Figure 13: Total Covid Case

Week	None	Isolation	Primary_Tracing	Secondary_Tracting
1	0	0.0	0.00	0.0
2	0	2.4	12.42	0.0
3	0	15.3	88.85	3.6
4	0	59.4	162.70	126.7
5	0	146.3	144.28	290.0
6	0	254.0	96.28	201.0
7	0	332.3	68.00	60.0
8	0	365.0	52.70	151.1
9	0	375.0	40.00	179.4
10	0	376.0	31.00	125.3

Figure 14: Total Quarantine people

Week	None	Isolation	Primary_Tracing	Secondary_Tracting
1	3	1	3	1
2	16	12	24	2
3	41	57	54	4
4	104	87	52	15
5	107	85	29	13
6	57	49	22	7
7	17	14	18	5
8	5	5	17	8
9	0	0	15	5
10	0	1	6	2

Figure 15: Weekly Covid Case

4 Discussion

This study is an extension of the Haslemere social network model. We modified the social network model based on the model proposed in the paper [?] and created cost models for medical and labor costs of COVID-19 interventions in order to determine the most cost-effective approach to quarantine. The social network model we took advantage of is derived from social tracking data, making the portrayed features such as links and nodes more realistic compared to purely theoretical models. In addition, more than just taking medical costs into consideration, we included labor costs in the cost model, which provides a more accurate reflection of the true cost of quarantine.

However, there are some limitations of our model. First, we did not consider reinfection due to the limited timesteps of our simulation, while reinfection can occur in reality, especially when new variants of COVID-19 show up. Also, young kids were excluded in the Haslemere data who are important components of the population.

In the future, there are many directions to explore based on the model we are working on. First, we can modify the number of nodes to simulate the spread of COVID-19 in a larger population. Second, we can research how other interventions including wearing mask and vaccination influence the cost of quarantine by adjusting the transmission rate in the model. People are also encouraged to apply our cost models to other simulation of COVID-19 to analyze the cost-effectiveness of quarantine strategies.

5 Variable

Parameter	Assumed value(s)	Details and references
Sampled		
Incubation period (mean and s.d.)	5.8 days (2.6)	[9,29]
Serial interval	Location = incubation period For post-symptomatic transmission, slant = ∞, scale = 2 For presymptomatic transmission, slant = -∞, scale = incubation period.	Based on data in [9]
Delay from onset/tracing to isolation, and from isolation to testing (median and 5th-95th percentiles)	**0.9 days (0.3-3.9) days ('short')** 3.5 days (0.7-8.2) days ('medium')	Assumed (short) and [30] (medium)
Fixed		
Initial cases	**1**, 5	Assumed
Scaling parameter (and corresponding empirical estimate of the reproduction number R_0)	0.5 (2) ,**0.8 (2.8)**, 2 (3.5)	[31]
Percentage asymptomatic individuals	20**%**, **40**%	[12]
Infectiousness of asymptomatic individuals	50% (relative, to symptomatic)	Assumed
Percentage individuals infectious pre-onset	**20**%, 40**%**	[9,32]
Outside infection rate	0.0001**, 0.001,** 0.005, 0.01	Assumed
Percentage of contacts traced	30%, 60%, **90%**	Assumed
Maximum number of tests	0, 5, 25, 50	Tested
Test false positive rate	0.02	[28]
Test false negative rate	0.1	Based data from early infection stages in [20]

Figure 16: Social Network Variable

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