2021 IEEE 3rd International Conference on Artificial Intelligence Circuits and Systems (AICAS) | 978-1-6654-1913-0/20/$31.00 ©2021 IEEE | DOI: 10.1109/AICAS51828.2021.9458525

Demography-aware COVID-19 Confinement with Game Theory

Sreenitha Kasarapu*, Rakibul Hassan*, Setareh Rafatirad†, Houman Homayoun†, Sai Manoj Pudukotai Dinakarrao*
*Department of Electrical and Computer Engineering, George Mason University, Fairfax, VA, USA
†Department of Electrical and Computer Engineering, University of California Davis, Davis, CA, USA
*{skasarap, rhassa2, spudukot}@gmu.edu; †{srafatirad, hhomayoun}@ucdavis.edu

Abstract—**In the last decades, emerging and re-emerging epidemics such as AIDS, measles, SARS, H1N1 influenza, and tuberculosis cause death to millions of people each year. In response, a large and intensive research is evolving for the design of better drugs and vaccines. However, studies warn that the new pandemics such as Coronavirus (COVID-19) and even deadly pandemics can emerge in the future. The existing confinement approaches rely on large amount of available data to determine policies. Such dependencies could cause an irreversible effect before proper strategies are developed. Furthermore, the existing approaches follow a one-size fits all approach, which might not be effective. In contrast, we develop a game-theory inspired approach that considers societal and economic impacts and formulates the epidemic control as a non-zero sum dynamic game. Further, the proposed approach considers the demographic information leading to providing a tailored solution to each demography. We explore different strategies including masking, social distancing, contact tracing, quarantining, partial-, and full-lockdowns and their combinations and present demography-aware optimal solutions to confine a pandemic with minimal history information and optimal impact on economy.**

I. Introduction

Human race has adopted and reshaped in the last few decades with the emergence of deadly viruses such as AIDS, measles, SARS, Ebola, H1N1 influenza, and Tuberculosis [1]. These viruses kill millions of people and leave permanent health issues for many others. Such epidemics and pandemics are not new to the mankind and they follow a pattern in spreading [2]. According to the world health organization (WHO), on-going SARS-2 COVID-19 is declared pandemic and has infected over 102 million people and claimed more than 2.3 million lives around the globe as of 31 January 2021 and still increasing. Such pandemic threats, especially, in modern civilization where cities are well connected, comes with an extremely high human and financial cost.

As a measure to confine the COVID-19 pandemics, many public health organizations and government officials including White House are declaring an emergency across the globe [3]. Measures include, but not limited to, mandatory mask usage, lockdown, social distancing and many more. Despite these measures are enforced across the globe, they are followed differently due to the different factors such as demography, population density and distribution (age, race, underlying medical conditions), availability of PPE kits and masks, and varied voluntariness by the people to abide the measures [4].

This research was partially supported by NSF RAPID Program Grant Number CNS-2029291 and CNS-2029414.

The large amounts of data amassed from the previous pandemics such as HIV/AIDS, Cholera, Plague as well as COVID-19 play a key role in devising a confinement strategy. The past epidemics and the adopted measures indicate that the confinement measures followed by a country or a region may not be suitable or effective in another country or region due to the aforementioned factors [2]. Due to variable demographic factors, a one size fits all approach does not have practical benefits. Thus, the challenge of confining the pandemic along with minimal impact on the economy is a non-trivial challenge currently faced. Thus, we plan to build a confinement strategy which considers the demographic information such as population distribution, mobility, urban or suburban location to devise a strategy that best confines the pandemic without severely impacting the economy.

Numerous research works have been proposed on predicting the dynamics of COVID-19 pandemic. Works such as [5], [6] propose compartment model, whereas works in [7] propose agent-based model for forecasting the COVID-19 pandemic. In [6], authors discuss the effectiveness of quarantine and isolation using traditional Susceptible-Exposed-Infected-Recovered (SEIR) model. Authors propose a neural network inspired SIR model that learns how to increase the quarantine control strength which leads to lower the infection rate [8]. Works in [9], [10] report the effectiveness of implementing SEIRD model for long term COVID-19 prediction.

Although the works such as [11] focus on the importance of the demography-based confinement strategy for the COVID-19 epidemic, they do not propose how to confine the spread while utilizing minimum resources. To address this challenge, a game theoretic optimization solution is proposed in this work. Game theory can be modeled to identify the best outcome of a social situation with different strategies involved.

Compartmental modellings were used in previous approaches such as [12]. They find the behavioural changes based on the economical factors impacting the cost of different resistant policies. They observed that people tend to follow self-isolation initially and counter it after sometime as the cost for quarantine increases. But this paper does not provide a model which is specific to a particular demographic or takes in any demographic information to produce the results. This effects the predictions because the behaviour of people changes with respect to different demographics conditions, so we establish a model which is demographic-aware.

In this work, we consider compartmental Susceptible-Exposed-Infected-Recovered-Dead (SEIRD) model [9], [10] to predict the COVID-19 epidemic spread [13] and apply a novel non zero-sum game theory to analyze the impact on the epidemic spread as well as the economy under different strategies for different demographics[1].

In the process of finding the optimal strategy to reduce COVID-19, we consider the demographic information such as population, mobility and budget of a given state. This aids in finding the optimal strategy specific to each state, rather than defining a single strategy for all. For different states in the USA, we find the optimal strategy specific to that state to defend the COVID-19, we also present certain cases where virus becomes more powerful, but the predicted confinement strategy can still produce an optimal solution which can subside the severe impacts of the epidemic.

By using game theory strategy, such as Social-Distancing we observed that in New York state we can reduce the number of people infected by upto 40%. But similar strategy did not work for Virginia state and we were able to reduce the number of people infected upto 35% using Masking strategy.

II. Proposed Game Theory-based COVID-19 Confinement

First, we present the modeling of the COVID-19 pandemic followed by the modeling of the cost function and the proposed game theory-based solution.

A. SARS-2 COVID-19 SEIRD Model

We propose a compartmental SEIRD model [9], [10] which can be used to mathematically model infectious diseases. The population is divided into the above mentioned different compartments, the people are progressed between the compartments in the SEIRD order. In other words, at the beginning of the disease, the whole population is Susceptible (S) to the disease, then certain number of people get Exposed (E) to the disease. From the exposed population, certain number of people will be Infected (I) by the disease. Among the people who are infected, certain number of people will be Recovered (R) and certain number of them will be Dead (D). Figure 1 shows our proposed SEIRD model fitted on New York population. As seen, over the time the number of people infected increases and descends after reaching a peak.

$$S'(t) = \frac{dS}{dt} = -\alpha * S * I; E'(t) = \frac{dE}{dt} = \alpha * S * I – \beta * E \quad (1)$$

$$I'(t) = \frac{dI}{dt} = \alpha * S - \beta * I; R'(t) = \frac{dR}{dt} = \beta * I; \quad (2)$$

$$D'(t) = \frac{dD}{dt} = \gamma * I \quad (3)$$

In the above equations α is the transmission rate of the disease, β is the recovery rate of the infected population and γ represent the mortality rate of the infected population.

[1]This work is open-sourced and the code is available at https://github.com/sreenithakasarapu/COVID-19_game

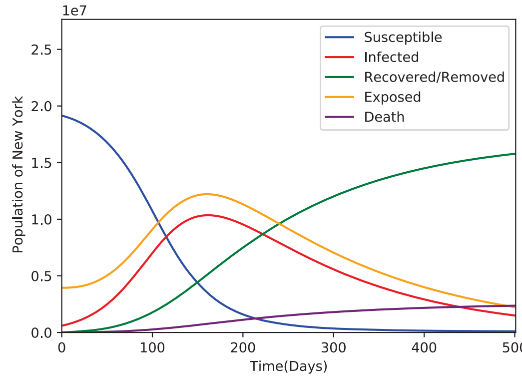


Fig. 1: SEIRD epidemiology for Covid-19 in New York.

We derive this model based on the fact that the COVID-19 has an incubation period i.e., a person who is exposed might not be infected immediately. In addition, COVID-19 may lead to death of an infected person, hence SEIRD is considered in contrast to SEIR or SIR models.

B. COVID-19 Confinement with Game Theory

We use game theory for the epidemic modeling and confinement of COVID-19 here. Game Theory is the process of modeling the strategic changes between two or more players. By measuring the impact of the strategies opted by the players and the associated costs, game theory produces the optimal outcome of the game. We then model different strategies to observe how the outcome of SEIRD changes. For the COVID-19 game, we consider two players, they are, attacker and defender. Attacker tries to increase the number of people infected by the disease and defender tries to decrease the number of people infected by the disease. Figure 2 shows the workflow of our proposed game-theoretic framework for COVID-19 confinement.

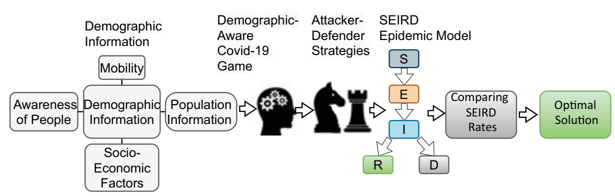


Fig. 2: Workflow of the proposed Demography-aware COVID-19 Confinement.

The attacker's enforced strategies try to speed up the rate of infection, such as reduced incubation, mutation of virus and creating red zones. Reduced incubation strategy decreases the incubation period of the virus, thereby, the exposed person can transmit the virus immediately. Evolving or mutations of the virus makes the traditional defence strategies (including vaccines in some scenarios) less effective and force the defender to employ more costly techniques. Red Zones are certain areas like the malls, gyms, movie theatres, recreational centers, and clubs where there will be more number of people in a closed place, so attacker has the chance to infect more number of people. To enforce these techniques attacker needs to pay certain amount of cost. Thus, the payoff of the attacker is defined as:

$$S_{RI} = (S + R) * C_{RI}; S_E = (S + R) * C_E \quad (4)$$

$$S_{RED} = (S + R) * C_{RZ} \quad (5)$$

In the above equations, α represent the transmission rate, γ represent the mortality rate, C_{RI} represents the cost of reduced incubation, C_E represent the cost of evolution and C_{RZ} represent the cost of red zones, S_{RI}, S_E, S_{RED} represent the cost functions of reduced incubation, evolution and red zone strategies respectively.

The defender's strategies are targeted to decrease the rate of infection, making less number of people infected less. The defender's strategies are masking, social distancing and contact tracing. With masking technique, the people who are susceptible are advised to follow masking and people who are infected will be masked mandatorily, with this the spread of infection can be controlled. In social distancing strategy, the people who are susceptible are advised to follow social distancing and people who are infected will be asked to follow strict social distancing. In contact tracing strategy, the people who are infected are traced and the isolate the people whom they met after infected. The costs associated with each of these strategies are modeled as follows:

$$S_M = C_{MM} * I + C_M * S; S_{CT} = C_{CT} * I \quad (6)$$

$$S_{SD} = C_{SSD} * I + C_{SD} * S \quad (7)$$

In the above equations, C_{MM} represent the cost of mandatory masking, C_M represent the cost of masking, C_{SSD} represent the cost of strict social distancing, C_{SD} represent the cost of social distancing and C_{CT} represent the cost of contact tracing. S_M, S_{SD}, S_{CT} represent the cost functions of masking, social distancing and contact tracing strategies respectively.

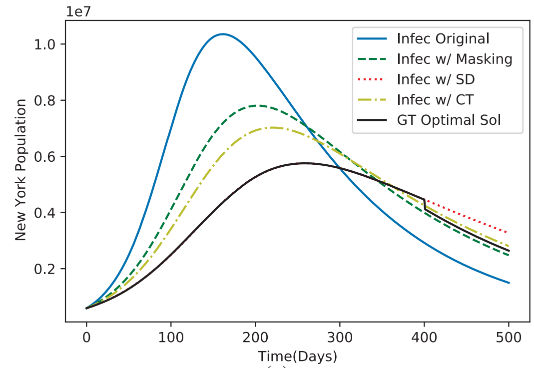
The total defender payoff will be at what rate each of the strategies are enforced and the cost associated to it.

$$P_D = R_M \cdot S_M + R_{SD} \cdot S_{SD} + R_{CT} \cdot S_{CT} \quad (8)$$

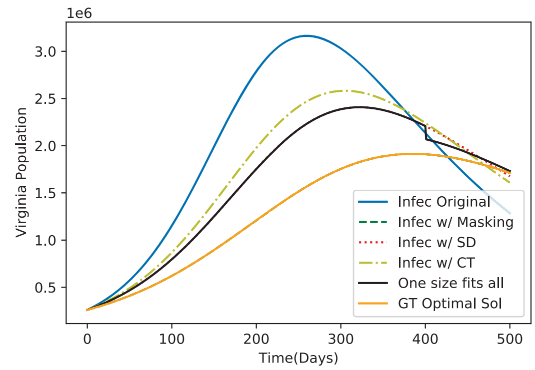
Where, R_M represent the rate of enforcement of masking, S_M represent the masking strategy cost, R_{SD} rate of enforcement of social distancing, S_{SD} represent the social distancing strategy cost, R_{CT} represent rate of enforcement of the contact tracing, and S_{CT} represent the contact tracing strategy cost.

Defender is supported by the government or public health agencies to control the spread of COVID-19. Thus, the government allocates this budget based on total funds available on different activites to curb the pandemic such as costs for paying front line workers, cost for testing, building hospitals or boosting facilities during pandemic, and providing PPE kits. We assume that the total defender's payoff is less than the allocated budget of the government and the maximum cost defender can pay for enforcing the strategies is equal to maximum amount available in budget.

We build an attacker-defender game, enforce different strategies and observe the changes in the SEIRD epidemic model.



(a)



(b)

Fig. 3: Comparing the effect of strategies on infection rate for (a) New York, (b) Virginia

To be specific to the area we consider demographic information such as population, mobility of the population, number of people incoming and outgoing in a given demography (state) are considered in making a decision of which attacker and defender strategy is best in that demographic location. Based on the transportation rate, the transmission rate (γ) of the disease varies due to more people mobilizing the disease, in which, the transmission rate of the disease is given by

$$\alpha_{new} = \alpha \cdot M_R \quad (9)$$

Where M_R is the mobility of the state, α_{new} represent the new transmission rate varied with respect to mobility.

III. Experimental Results

A. Experimental Setup

The implementation of COVID-19 game on all the 50 states requires a huge amount of memory and time, when performed on CPU, it took 18 hours of time to perform the game theory-based confinement. Thus, to perform the game theory and to make it run fast we used Tesla P100-PCIE-16GB GPU available in Google Colab Pro. We used high-RAM setting of the google colab to provide with higher memory required by the experiment. High-RAM setting provides a maximum GPU RAM of 26GB. It took almost two hours to run the experiment for all the 50 states data [14].

We have considered the population information of all the 50 states and the general mobility of the state. Based on this information, we vary different important factors of the

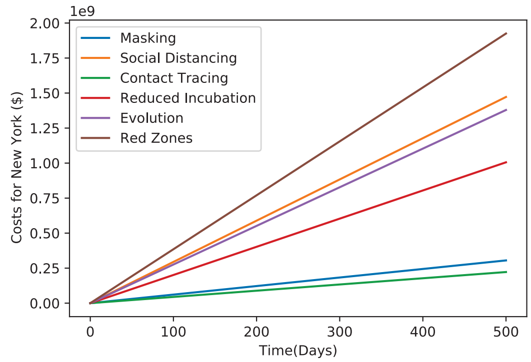


Fig. 4: Comparing the cost for each strategies.

attacker and defender strategies. For instance, if a state has high mobility, it can lead to higher infection rate, and states which are running out of resources to accommodate medical attention for infected patients has low recovery rate and high mortality rate. Based on the urban and sub-urban areas in that state, we consider the effectiveness or rate of the masking or social distancing strategies. We assume that more populated areas make these strategies less effective and increases the effectiveness of the attacker strategies.

B. Impact of Proposed Demographic-aware Game Theory

Figure 3a and 3b shows the impact of each strategy on the infection rate for New York population and the population of Virginia, respectively. As mentioned before, we consider different factors and observed how S, E, I, R, and D are getting affected over a period of time equal to 500 days. For every 100 days, we compare the number of infected cases with each of the strategies and perform a game theory based optimization. And find the optimal solution with lower infection spread and minimal costs. Finally we calculate the overall payoff of attacker and defender to determine the best strategy in the game. We demonstrate the cost for each strategy taken on New York in Fig. 4.

From Fig. 4 we can observe that social distancing cost is higher than other defender strategies Contact Tracing costs are the lowest as it is only performed on people who are infected recently where other strategies are applied on whole population. Masking strategies costs are much lower than social distancing strategy but close to contact tracing.

C. Observations

Here, we present our observation on how does a demographic-aware game theory lowers the infection rate over the "One size fits all" approach.

As New York has higher transmission rate of virus due to the high mobility rate, we gave this increased transmission rate as input to the game and as observed in Fig. 3a that by using Social Distancing strategy the number of people infected is much lower than all the other strategies. From our game-theoretic solution, we can observe that it picks the Social Distancing strategy as the optimal solution till 400 days of infection and picks the masking strategy after that as the masking strategy has lower infection rate. Our proposed game-theoretic optimal solution has approximately 40% lower number of infected people than the original number at peak infection stage.

When it comes to the Virginia population, we can observe that Masking achieves a lower infection rate than the Social Distancing strategy as shown in Fig. 3b. If we were to adopt the "One size fits all" approach, then we would be picking the Social distancing approach like New York but that will lead to higher infection rate for the people of Virginia. So, based on the demographic information of Virginia, our game theory picks Masking as the optimal strategy. By which, the number of infected people is approximately 35% lower than the actual infected population when the curve reaches the peak.

We vary the demographic information specific to each state and vary the transmission rate of virus accordingly, to obtain the optimal strategy of attacker and defender in each state.

IV. Conclusion

In this work, we propose a demography-aware COVID-19 confinement strategy where a game-theoretic optimization is adopted in order to achieve an optimal confinement solution for different confinement strategies. We consider the demographic impact on given confinement strategy and solve for optimal strategy while to lower infection rate. We present that one strategy that being the optimal for one demographic region might not be the optimal solution for different demographics.

References

[1] A. Barac *et al.*, "Innovative approaches in diagnosis of emerging/re-emerging infectious diseases," *Frontiers in Microbiology*, vol. 11, 2020.

[2] A. L. Bertozzi *et al.*, "The challenges of modeling and forecasting the spread of covid-19," *Proceedings of the National Academy of Sciences*, vol. 117, no. 29, pp. 16 732–16 738, 2020.

[3] "Covid-19 disaster declarations." in *https://www.fema.gov/disasters/coronavirus/disaster-declarations*.

[4] Why do some people refuse to wear a face mask in public? [Online]. Available: https://www.health.com/condition/infectious-diseases/coronavirus/face-mask-refuse-to-wear-one-but-why

[5] Y. Fang *et al.*, "Transmission dynamics of the covid-19 outbreak and effectiveness of government interventions: A data-driven analysis," *Journal of medical virology*, vol. 92, no. 6, pp. 645–659, 2020.

[6] B. Tang *et al.*, "The effectiveness of quarantine and isolation determine the trend of the covid-19 epidemics in the final phase of the current outbreak in china," *International Journal of Infectious Diseases*, vol. 95, pp. 288–293, 2020.

[7] N. M. Ferguson *et al.*, "Impact of non-pharmaceutical interventions (npis) to reduce covid-19 mortality and healthcare demand. imperial college covid-19 response team," *Imperial College COVID-19 Response Team*, p. 20, 2020.

[8] R. Dandekar and G. Barbastathis, "Neural network aided quarantine control model estimation of covid spread in wuhan, china," *arXiv preprint arXiv:2003.09403*, 2020.

[9] E. L. Piccolomiini and F. Zama, "Monitoring italian covid-19 spread by an adaptive seird model," *MedRxiv*, 2020.

[10] I. Korolev, "Identification and estimation of the seird epidemic model for covid-19," *Journal of econometrics*, vol. 220, no. 1, pp. 63–85, 2021.

[11] J. B. Dowd *et al.*, "Demographic science aids in understanding the spread and fatality rates of covid-19," *Proceedings of the National Academy of Sciences*, vol. 117, no. 18, pp. 9696–9698, 2020.

[12] Evolutionary game theory modelling to represent the behavioural dynamics of economic shutdowns and shield immunity in the covid-19 pandemic. [Online]. Available: https://royalsocietypublishing.org/doi/10.1098/rsos.201095

[13] J. S. Weitz and J. Dushoff, "Modeling post-death transmission of ebola: challenges for inference and opportunities for control," *Scientific reports*, vol. 5, no. 1, pp. 1–7, 2015.

[14] Coronavirus (covid-19) data in the united states. [Online]. Available: https://raw. githubusercontent.com/nytimes/covid-19-data/ master/us-counties.csv