A SYSTEM DYNAMICS APPROACH TO UNDERSTANDING THE COVID-19
(NOVEL CORONAVIRUS) PANDEMIC

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Abstract

The novel coronavirus disease (COVID-19) pandemic has caused an overwhelming impact on lives around the world. Countries around the world have scrambled to implement various control measures such as social distancing, community lockdowns, quarantines in varying degrees of stringency and success. This paper proposed the application of the system dynamics (SD) modeling framework to capture the complex relationships, feedbacks, and delays present in a disease transmission system so that policies may be developed to effectively target the issue. In this study, three common policies, namely social distancing, quarantine, and vaccination, were integrated into the basic flu model to assess which would be the most effective in mitigating the infection and identify the portion of the system it would be best to leverage actions on. Results revealed that policies that remove the possibility of transmission through quarantine and vaccination performed best in reducing the spread and consequences of the pandemic. This model may help policymakers evaluate potential policy alternatives, especially when responding to high-risk issues such as a pandemic.

Keywords: COVID-19, System Dynamics, Flu Pandemic, Response Strategies, Policy Development

Introduction

Coronavirus disease 19 (COVID-19) shocked the globe with its first outbreak in China. The virus spread exponentially due to the mobility of people traveling from one country to another. This led the World Health Organization to declare COVID-19 as a global pandemic (WHO, 2020). The number of infected people worldwide has reached approximately 10 million and is still increasing (Hart and Halden, 2020). The healthcare sector has been exhausted due to the increasing number of infected individuals and the lack of supply and manpower to battle COVID-19.

Furthermore, the lockdown initiative of the government has taken a toll on businesses and the economy. The COVID-19 has different symptoms that affect the respiratory system, leading to fever and fatigue. There are different diseases in the past which target the respiratory system, such as the severe acute respiratory syndrome (SARS) and the Middle East respiratory syndrome (MERS) (Yang et al., 2020). Currently, a vaccine for COVID-19 is under research and development, and some are in clinical trials, which may take some time. To buy time and not overwhelm the medical sector, different strategies and actions should be implemented by the government. Hence, the planning and implementation of the policymakers with the knowledge of the virus can be a good investment (Ejima and Nishiura, 2018). Analytical approaches can be helpful, which offers efficient and impactful solutions for policy development. However, these methods are trial and error basis and cannot be an option during a pandemic because of its inefficiency and inaccuracy, which might cause worse problems.

System dynamics (SD) is a tool to aid in policy development, used in different applications such as technology diffusion and supply chain (Alamerew & Brissaud, 2020). The advantage of SD in modeling pandemic studies is that it can represent human behavior as "soft" variables (Doyle & Ford, 1998). It organizes the factors involved in causal loops. Also, it capitalizes on delays in correlation with the factors involved, the area, and timing (Deng et al., 2020). It can simulate the model (pandemic) that is more robust than forecasting models (Thiel et al., 2014). This was then applied by creating policies that can guide the government in assessing lockdowns and strategies imposed in a certain area (Ibarra-Vega, 2020). The complexities of a disease outbreak system such as that of the COVID-19 pandemic necessitates a systematic
approach, particularly the System Dynamics modeling framework, to understand. Because the COVID-19 pandemic is still an ongoing global issue, data on it and its behavior is not yet complete and is constantly changing. SD allows the behavior of COVID-19 to be analyzed without the need for particularly accurate data, as it is a behavior-driven modeling approach. The different variables and relationships, feedbacks, and delays that exist within the system are cohesively considered in this study to establish guidelines that would aid stakeholders in reducing the spread and mortality of the virus within a community.

Model Development

System dynamics is used to assess the effectiveness of various policies to minimize the impact of the novel coronavirus COVID-19 on communities in terms of the number of infected individuals and deaths. This is done in two stages, starting with the basic flu model, which captures the transmission of common flu disease. When the basic model is validated and verified, the policies are incorporated into the model to demonstrate the impact of the basic system strategies. The SD methodology also allows interventions to be implemented at various times along the planning period to determine the importance of timing in achieving the best results on the system’s objectives.

2.1. Basic Flu Model

The framework proposed in this study adapts the existing Susceptible-Infectious-Recovered (SIR) model of Grassly and Fraser (2008). Four main states were considered in this study: the vulnerable or susceptible population, the infected or exposed, the sick or symptomatic, and the total deaths shown in Figure 1. Following the natural infection process, the vulnerable population is decreased as they become infected and flow into the infected population. New infections occur due to the exposure of a susceptible individual to an infected individual. After a certain incubation period, infected individuals develop symptoms, from which a certain percentage becomes recoveries, while some add to the number of total deaths.

![Figure 1. Basic Flu Model](image)

2.2. Solution Modelling

The basic flu model is extended to capture three common public health interventions, namely (1) social distancing, (2) quarantine, and (3) vaccination, as presented in Figure 2. Social distancing will decrease the rate of exposure between susceptible and infected populations. Placing infected individuals under quarantine will reduce the number of infected persons the vulnerable population can come into contact with while inoculating the vulnerable population with a vaccine will decrease the susceptible population.
Simulation Results

The SD model formulated in this study was implemented in the STELLA software developed by isee systems. Mathematical equations were formulated for each variable presented in the stock-and-flow diagrams shown in Figures 1 and 2. These equations were used to express the relationships between the variables, and parameter constants are used to convey the magnitude of these relationships.

The results of the SD model will demonstrate the behavior of key variables across time as influenced by feedbacks, relationships, and delays present in the system. Nonetheless, it is important to establish that SD cannot predict the values of these variables. Instead, the results of the model may only be used to gain an understanding of how the variables behave over time.

3.1. Basic Flu Model Run

The basic flu model was validated before solution alternatives were integrated with the model. The simulation results of the base runner are shown in Figure 3. The graphs reveal that the virus will eventually run its course when the susceptible population has been depleted, which occurs when the population has all become infected. The end of the virus is evidenced by the "flattening of the curve" for the vulnerable, infected, and sick populations, and a plateau in the curve for total deaths.
3.2. Solution Runs

Three different policies were tested on the basic flu model to determine which would be most effective in lowering the peak of the infection and minimizing the overall number of infected individuals and deaths caused by the pandemic. Figures 4 to 6 present how the behavior of the pandemic changes when each of the policies is implemented at the beginning of the pandemic, particularly at time 0. Each of the graphs depicts two curves, wherein the blue curve is the status quo, and the red curve represents the new behavior when the strategy is implemented.

![Figure 4. Behaviors of the Infected Population when (a) Social Distancing, (b) Quarantine, and (c) Vaccination is Implemented at Time 0.](image)

![Figure 5. Behaviors of the Sick Population when (a) Social Distancing, (b) Quarantine, and (c) Vaccination is Implemented at Time 0.](image)

![Figure 6. Behaviors of the Sick Population when (a) Social Distancing, (b) Quarantine, and (c) Vaccination is Implemented at Time 0.](image)

Social distancing does little to minimize the pandemic. Based on Figures 4a, 5a, and 6a, the virus's peak is only reduced and delayed slightly, which only prolongs the duration that the pandemic affects the community. Because the infections' peak is still high, this solution still carries the risk of overloading the health and hospital capacity. Effective quarantine operations show great potential in addressing the pandemic outbreak because it is able to greatly reduce the peaks of the infected, sick, and deaths caused by the virus. However, it carries with it the assumption that the infected population is quickly and efficiently quarantined even before they become asymptomatic and before they come into contact with anyone from the susceptible population, which means that the government should implement proper measures for testing and contact tracing.

On the other hand, vaccination presents itself as the "miracle cure" to the pandemic. If vaccination of the susceptible population is done at the beginning of the disease outbreak, the susceptible population is quickly removed from the equation, immediately reducing most of the probability of infections, sickness, and deaths to occur as evidenced by the flat red curves in Figures 4c, 5c, and 6c. Thus, among the three, vaccination is the most effective approach. However, in the context of the COVID-19 pandemic, this is not yet possible because of the novelty of the virus strain. Doctors and researchers are pushing the development
of the vaccine, before the expected incidence of the virus’ "second wave."

Aside from deciding which strategy to implement, the timing of implementing these interventions is also an important consideration. Figures 7 to 9 illustrate how the policies’ effectiveness will change when implemented at different times on an equal interval. Each graph in Figures 7 to 9 is composed of four curves. The blue curve represents the earliest implementation of the strategy, followed by red, pink, and green curves. The graphs reveal that the timing plays a huge role in the solution’s impact, wherein the effectiveness decreases significantly for each solution as their implementation is delayed. In fact, it may be observed that past a certain amount of time implementing social distancing and quarantine will have around the same performance in controlling the number of people who are infected and get sick, and the total number of deaths.

Nonetheless, it may still be observed that quarantine curves are still narrower than those of social distancing, implying that quarantine will be able to snuff out the spread of the pandemic quicker. Vaccination remains to be the best approach to address the outbreak. However, the decrease in its effectiveness is significant even with equal delays presented with social distancing and quarantine.

![Figure 7. Behaviors of the Infected Population when (a) Social Distancing, (b) Quarantine, and (c) Vaccination is Implemented at varying time delays.](image)

![Figure 8. Behaviors of the Sick Population when (a) Social Distancing, (b) Quarantine, and (c) Vaccination is Implemented at varying time delays.](image)

![Figure 9. Behaviors of the Sick Population when (a) Social Distancing, (b) Quarantine, and (c) Vaccination is Implemented at varying time delays.](image)
Conclusions

The COVID-19 pandemic is a complicated issue with deep-rooted impacts in several sectors, including public health, the economy, and the environment. As the outbreak is still an ongoing problem plaguing several countries, details about it are still evolving. Thus, systematic and comprehensive analysis frameworks such as System Dynamics would be a valuable tool to support the understanding and decision-making of governing and policy-making bodies. This would ensure that mitigation and control planning to address the pandemic would holistically capture the relationships between and within affected sectors. Based on the simulation results, interventions aimed towards minimizing the possibility of transmission are the most effective. These include removing the susceptible population through vaccination or the infected population through quarantine. This study demonstrated the potential of System Dynamics in the application of policy development for pandemic outbreaks. Several extensions may be explored, such as delving deeper into the dynamics of social distancing, quarantine, and vaccination, as the current study only considers these on a high-level perspective. Other interventions may be integrated into the model, such as hospital and resource capacities and community lockdowns.

References


