System Dynamics Model of COVID-19 Pandemic Situation: The Case of Phuket Thailand

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ABSTRACT

The outbreak of COVID-19 disease worldwide impacts the world health, social, and economic situations enormously. At present, there is no vaccines for the virus nor medicine which could cure them. Cities locked down and physical distancing seem to be good options to help reduce infection and casualties from the disease. However, these options may not convince members of the public since their daily life and economy are affected. Business cannot be carried on as usual and people suffer. Lockdowns and social distancing are often resisted. This research project uses the System Dynamics Simulations Model to simulate the infection of and recovery from the COVID-19 disease of populations within an administration area. The Susceptible, Infectious, Recovered (SIR) model is employed in the System Dynamic modelling. The case study area is Phuket, Thailand, which is a popular tourist destination. The contact rates among infected people and other people in Phuket are found to be relatively higher than other cities which are not tourist destinations.

CCS Concepts

• **Computing methodologies→ Modeling and simulation→ Simulation types and techniques → Continuous simulation**

Keywords

COVID-19; Contact Rates; System Dynamics; Causal Loop Diagram; SIR Model; Phuket

1. INTRODUCTION

The COVID-19 outbreak took place in December 2019. At first the outbreak was believed to be under controlled and limited within certain areas. January 2020 was the month for the Chinese New Year. People from the Wuhan infected area therefore travelled back to their hometown outside of the city. Due to the movement of people from the first infected city, the COVID-19 disease has been widespread to other parts of PRC. The first infected case outside mainland China was in Thailand on January 13, 2020. The pandemic is now widespread worldwide [1, 2].

Phuket is a popular tourist destination in southern Thailand. Tourists from around the world, mainly from PRC visit Phuket all over the year. On January 28, 2020, a Chinese tourist from PRC was tested positive for the COVID-19 in Phuket [3] [4]. This was the first case that led to further infections. Phuket had the second highest number of COVID-19 infected cases in Thailand after Bangkok. Most of the cases were found from night entertainment places in Patong district [3].

During the same period, the Chinese government has closed the city of Wuhan [5] and asked all people in the city to self-quarantine at home and practice physical distancing. Using these regulations, the Chinese government could then control the situation. It is now well-accepted that physical distancing, together with using masks, face shields, and rubber gloves help reduce infections [6]. Phuket closed the entire Phuket island in early April 2020 and eventually closed the local administration areas. People could not travel across the areas. The number of new infections as of the end of April 2020 was reduced and controlled. Active case finding is also implemented. There needs to be a good balance between health and economy. The purpose of this project is to provide a simulation model which demonstrates the importance of physical distancing and its effects to the number of susceptible, infection, and recovered people in Phuket. Anylogic 8.5 Simulation Software Personal Learning Edition [7] is used to model the pandemic situation in Phuket using the SIR Model[8, 9] which is a well- accepted model for pandemic simulation.

2. PHUKET AND COVID-19 PANDEMIC

Phuket is a world-class tourist destination in the southern part of Thailand on the Andaman Sea coast. The total population as of 2020 is 416,582. It is estimated that around forty million visitors visit Phuket each year. Thus, making over four hundred billion baht a year [10]. Phuket is an asset for the Thai tourist industry. The first COVID-19 infection in Phuket was a 32 years old female Chinese tourist. Then on February 8, 2020 a male Chinese tourist which was associated to the first case was found infected. On March 16, 2020, a family of tourist from Denmark was also found infected. The first case of Thai infectant was found on March 20, 2020, fifty days after the first Chinese case in the city. As of April 6, 2020, Phuket had the second highest infectants in Thailand, only second to Bangkok.

The first patient in Phuket required 52 days to recovered. Later, with experiences, the medical teams reduce average recovery days to 20 which is the same as the average recovery days in the PRC. It is suspected that the higher number of contacts between the infectants and other people, the higher chance to reduce number

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of new infectants. This may sound obvious, but people who suffer from economic downfall from the business and city shutdown argue.

Average number of contacts per person (contact rate) is relatively high when compared to those of other cities in Thailand due to the tourist city nature which attracts more than fourteen million visitors annually. For other cities, it is approximated to be 25 contacts per person per day. However, Phuket contact rate is different. Some tourist areas have very high contact rate such as Bang La street, Patong district, which is the first infected area in Phuket [11]. The contact rate of such areas was as high as 33 contacts per person per day. The observed number of contacts for each infected patient between January 28, 2020 and April 4, 2020 are shown in Figure 5. The daily contact rates are between 5 to 33 persons per day [3] [4]. We will use these contact rates as a parameter in the proposed System Dynamics simulation model which will determine the number of infected and recovered patients. Less contact rates mean more physical distance and vice versa.

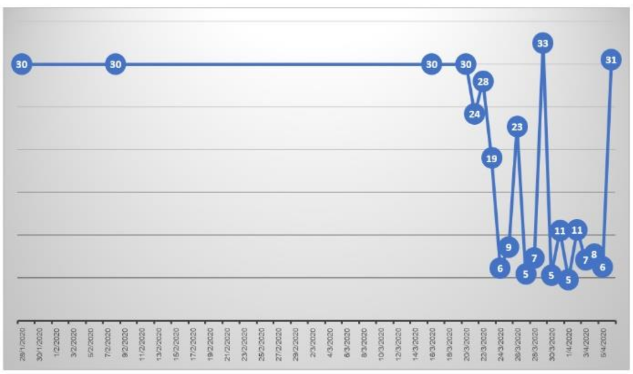

Figure 1. Actual Phuket's contact rates based on the average number of contacts for each infected patient.

3. SIR MODEL

Kermack and McKendrick [12] proposed the Compartment Models back in 1927. This model is a model which is used to reduce the complexity of mathematical models for infectious disease. The population used with the assumption that all men are equaled. This model uses differential equations. However, randomization could also be applied. Compartment Models could be used to forecast characteristics of an infectious outbreaks or time period of the outbreaks. This model can also be used to understand the characteristics of different outbreaks in different situations. SIR (Susceptible-Infectious-Recovered) model is a model which is used to simulate infectious disease outbreaks which is developed from the Compartment Model. This model also employs differential equations. It comprises three parts: S for susceptible, I for infectious, and R for recovered. S, I, and R represent number of people at a time. These values change according to the time when it is assumed that the number of total populations is fixed. In this project, we apply this model to the System Dynamics to find the number of S(t), I(t), R(t) at time (t).

The SIR model is useful particularly for modelling epidemics which short outbreak time. Figure 2 shows the SIR concept diagram.

Figure 2. SIR Concept Diagram [13]

Edelstein-Keshet [14] studied and improved the SIR model based on Kermack and McKendrick [15]. The improved SIR model assumes that all recovered patients have permanent immunity to the disease, all recovered people will not be infected again. According to the SIR concept diagram in Figure 2:

$$\frac{ds}{dt} = -\beta IS$$

$$\frac{dI}{dt} = \beta IS - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

β is the infection rate, γ is the recovery rate, S is Susceptible, I is Infectious, R is Recovered patients N is the summation of (S, I, R). Later there are studies which consider new births and deaths of other causes [13]. Birth rate Death rate of other natural causes are introduced to the equations:

$$\frac{dS}{dT} = \eta - \beta IS - \sigma S$$

$$\frac{dS}{dt} = \beta IS - \gamma I - \sigma I$$

$$\frac{dR}{dt} = \gamma I - \sigma R$$

η is the birth rate

σ is the death rate of other causes

Capasso and Serio [15] , and McCluskey [16] both confirm that the infection rate is the important factor. In our project, since the outbreak period is very short, only within three months, the birth rate and death rate of other causes are not considered.

4. SYSTEM DYNAMICS MODEL

System Dynamics is a method created in the mid-1950s by MIT professor Jay Forrester. The principles and modelling language of system dynamics were formed in the 1950s and early 1960s, and remain unchanged today [17] [18].

System Dynamics Model is used to simulate the behavior of the COVID-19 pandemic. The expected simulation result is to convince the public that physical distancing is the key factor to reduce number of infectants which could lead to a controlled pandemic or even the end of it. This is meant to supplement the medical knowledge that physical distancing (or social distancing) reduces the infection of the disease which infects people by droplets from mouth and nose, and short-distance aerosols [19].

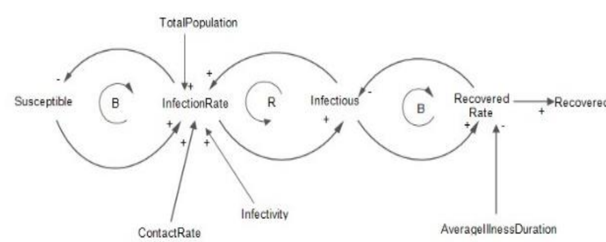

Figure 3. Casual Loop Diagram of COVID-19

A Casual Loop Diagram (CLD) of the COVID-19 infection is shown in Figure 3. It comprises 3 loops. The left most one is the susceptible loop. It is a balancing loop which shows relationship between Susceptible and InfectionRate variables. The direction of the loop from Susceptible to InfectionRate is positive. This means that the changes on the Susceptible, directly leads to the changes of InfectionRate. The direction of the loop from InfectionRate to Susceptible is a negative. This means that the changes on the

InfectionRate inversely leads to the changes of Susceptible. There are also external parameters which influence Infectionrate, namely TotalPopulation, ContactRate, and Infectivity.

The middle loop is the infectious loop. This loop is a reinforcing loop since the changes of InfectionRate directly leads to the change of infectious and vice versa.

The right most loop is a balancing loop. The direction of the loop from Infectious to RecoveredRate is positive. This means that the changes on the Infectious, directly leads to the changes of RecoveredRate. The direction of the loop from RecoveredRate to Infectious is negative. This means that the changes on the RecoveredRate inversely leads to the changes of Infectious. There are also external parameters which influence RecoveredRate, namely AverageIllnessDuration.

After the Casual Loop Diagram is obtained, it is then transformed into a System Dynamics Model diagram. Figure 4 shows the System Dynamics diagram of the COVID-19 pandemic based on the SIR model. It is an improved model of [18].

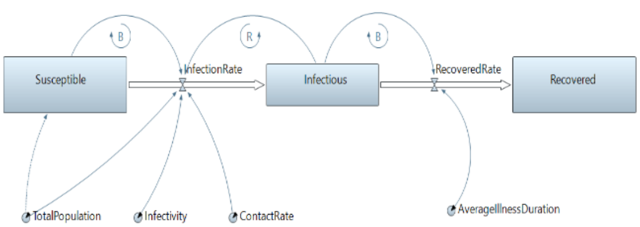

Figure 4. System Dynamics Model diagram of the COVID-19 pandemic based on the SIR model.

The System Dynamics model is the more physical version of the Causal Loop Diagram (CLD). The rectangular boxes represent "stocks", or object types of interest. From Figure 4, there are three stocks namely, Susceptible, Infectious, and Recovered, which correspond with the CLD variables of the same names. InfectionRate and RecoveredRate are "flows" which control the stock levels. Each flow is derived from a CLD variable which has external parameters. The loops from the CLD become corresponding loops in the System Dynamics model. The System Dynamics model is implemented using the Anylogic 8.5 Personal Learning Edition software [7].

The first loop with the symbol B represents a balancing loop between Susceptible and InfectionRate. There are three external parameters, TotalPopulation, Infectivity, and ContactRate which are inputs to the InfectionRate flow. The level of the stock Susceptible is also an input to the InfectionRate flow. The second loop is a reinforcing loop between the InfectionRate flow and the Infectious stock. The third loop is a balancing loop between the Infectious stock and the RecoveredRate flow with AverageIllnessDuration as an input parameter.

The above-mentioned parameters for our research work are from the actual data collected from the COVID-19 situation in Phuket as mentioned in the earlier sections of this paper. The most significant parameter is the contact rate which is the average number of people which are contacted by an infected people in a day. The contact rates for Phuket during January 28, 2020 and April 6, 2020 are shown in Figure 5.

Year	2020																				
Month	Jan	Feb	March													April					
infection Date	28	8	16	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6
Contact Rate	30	30	30	30	24	28	19	6	9	23	5	7	33	5	11	5	11	7	8	6	31

Figure 5. Phuket's Average Daily Contact Rate January 28, 2020 to April 6, 2020

The daily contact rate is the average number of contacts per infected person per day. The number of contacts in Phuket vary because Phuket is a tourist destination and some parts of Phuket were crowded by tourists, majority of which were Chinese. On the first day of infection, January 28, 2020, there was only one infected person. The person was a tourist from PRC. She had contacted with 30 other people in some tourist places, the contact rate is therefore high. Low contact rates are mostly cases found in more remote residential areas. Other parameters used in the simulation are shown in Figure 6 and Figure 7.

Parameters	Value	Description
TotalPopulation	416,582	Total population of Phuket [10]
Infectivity	0.05	Probability of infection between susceptible and infected person
AverageIllnessDuration	20	Average recovery time of infected patients in Phuket. This value in Phuket is about the same as the value in PRC [20].

Figure 6. Total population, Infectivity and Average illness duration

STOCK	Initial Value	Equation
Susceptible	Totalpopulation-1	$\frac{d(Susceptible)}{dt} = -\text{InfectionRate}$
Infectious	1	$\frac{d(Infectious)}{dt} = \text{InfectionRate - RecoveredRate}$
Recovered	0	$\frac{d(Susceptible)}{dt} = \text{RecoveredRate}$

FLOW	Equation
InfectionRate	Infectious*ContactRate*Susceptible*Infectivity/TotalPopulation
RecoveredRate	Infectious/AverageIllnessDuration

Figure 7. Initial values and equations of stocks and flows in our Systems Dynamic model

5. SYSTEM DYNAMICS MODEL SIMULATION RESULTS

The System Dynamic model of Figure 4 is implemented using the Anylogic 8.5 Personal Learning Edition software. Different contact rates are tested on the model. Number of infectants and recovered patients are observed.

On the first run of the simulation experiment, we set the population of Phuket = 416,582, infectivity = 0.05, average illness duration = 20 days, and contact rate=33, the System Dynamics simulation result after 10 days shows number of susceptible = 20,774.3 people which are not infected, which is only 5% of the population. Number of infected people is 357,976.94 which is 86% of the total population. The rest are 37,830.76 people, which is 9% of the total population either recovered or died. The result is shown in Figure 8. The contact rate 33 is considered high. If continued without any attempt to reduce this number, the number of infectants will reach approximately 357,976 in 10 days. This would lead to a disastrous situation since the medical facilities in the city could not accommodate this number of patients.

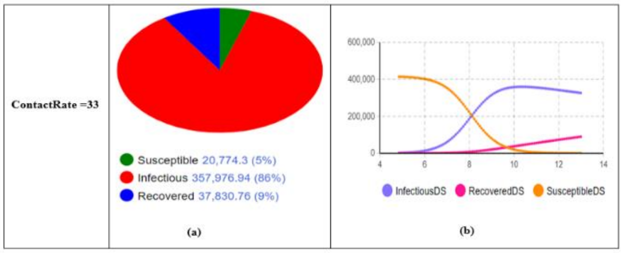

Figure 8. The output result of the System Dynamics simulation when the contact rate = 33.

On the second run of the simulation experiment, we change the contact rate to 23, the System Dynamics simulation result after 14 days shows number of susceptible = 35,551.04 people which are not infected, which is only 9% of the population. Number of infected people is 336,469.23 which is 81% of the total population. The rest are 44,561.73 people which is 11% of the total population either recovered or died. The result is shown in Figure 9. This contact rate 23 is still considered high. If continued without any attempt to reduce this number, the number of infectants will reach approximately 336,469 in 14 days. This would also lead to a disastrous situation since the medical facilities in the city could not accommodate this number of patients.

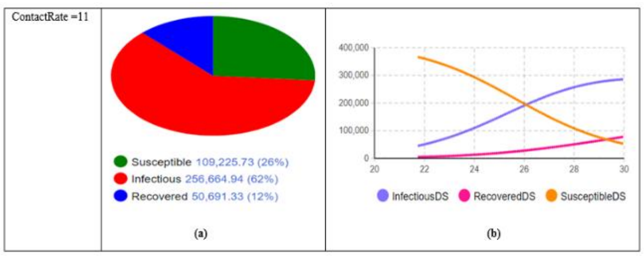

Figure 9. The output result of the System Dynamics simulation when the contact rate = 23.

On the third run of the simulation experiment, we change the contact rate to 11, the System Dynamics simulation result after 14 days shows number of susceptible = 109,225.73 people which are not infected, which is only 26% of the population. Number of infected people is 256,664.94 which is 62% of the total population. The rest are 50,691.33 people, 12% of the total population which are either recovered or died. The result is shown in Figure 10. The contact rate is still considered high. If continued without any attempt to reduce this number, the number of infectants will reach approximately 256,665 in 28 days. This would also lead to a disastrous situation since the medical facilities in the city still could not accommodate this number of patients.

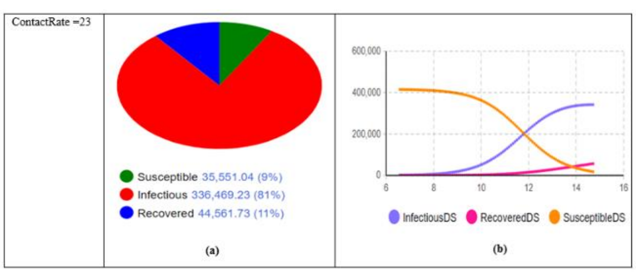

Figure 10. The output result of the System Dynamics simulation when the contact rate = 11.

On the fourth run of the simulation experiment, we change the contact rate to 5, the System Dynamics simulation result after 30 days shows number of susceptible = 416,979.49 people which are not infected. This is almost 100% of the population. Number of infected people is only 402.14 which is almost 0% of the total population. The rest are 100.36 people which is almost 0% of the total population either recovered or died. The result is shown in Figure 11. The contact rate is considered very low. The infected number 402 people in 30 days can be handled by the health care facilities in Phuket.

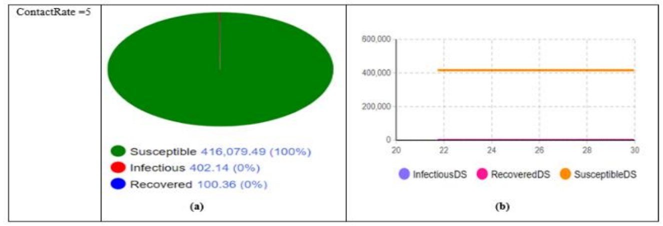

Figure 11. The output result of the System Dynamics simulation when the contact rate = 5.

From the above simulation experiments, the results show that the smaller contact rates lead to smaller number of infections. A slightly higher contact rate could lead to much higher infections, so high that medical facilities could be overwhelmed. The highest contact rate 33 could bring the infection number to 350,000 within less than 10 days. The smaller contact rate 11 could prolong the same number of infections to 30 days. Physical distancing is therefore a crucial factor in the prevention of the COVID-19 outbreak in the city of Phuket.

We run the simulation experiments 9 times, varying the contact rates. The result relationships between contact rate and number of infectious after 14 days of the COVID-19 outbreak in Phuket is shown in Figure 12. The x axis is the sequence number of the experiment, the y axis is the contact rates. The number of infectious drops sharply after the contact rate is less than 10. Relationships between contact rate and susceptible after 14 days of the COVID-19 outbreak in Phuket is shown in Figure 13. The lower contact rates result in higher number of susceptible but not infectious people.

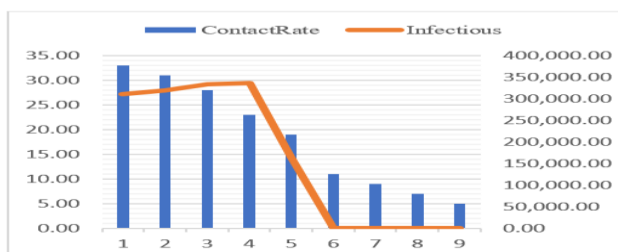

Figure 12. Relationships between Contact Rate and Infectious

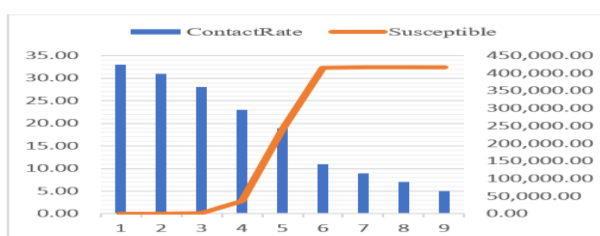

Figure 13. Relationships between Contact Rate and Susceptible

We also observed more recent actual infections that took place in Phuket during April 7, 2020 and April 19, 2020. This is shown in Figure 14. During the period, the city of Phuket and the Thai Government have imposed strict regulations to reduce physical distancing thus reducing the contact rates. Phuket is locked down. No transportation of people to and from Phuket are allowed. Local administration areas borders are also closed. People are encouraged to stay and work from home. From April 11, 2020 onward, the contact rates are less than 5. The number of new infectants reduced to small numbers and down to zero on April 16, 2020.

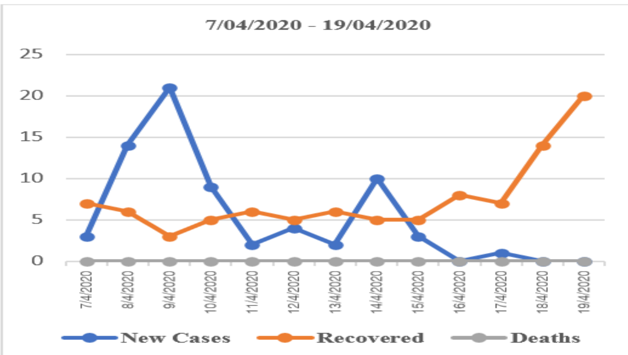

Figure 14. Number of new COVID-19 infected cases in Phuket during April 7, 2020 and April 19, 2020.

6 Conclusions

This simulation project employs the System Dynamics Model as the simulation method to model the infections caused by the COVID-19 outbreak in the city of Phuket, Thailand. The Susceptible, Infectious, Recovered (SIR) model is used to model the infections. The software tool used in this project is Anylogic 8.5 Personal Learning Edition. Contact rates are used as an important factor. The contact rate is an indicator of physical distancing. At first, the contact rate in Phuket was high due to the tourist destination nature. With high contact rate, the simulation results show possible sharp infection rates which are so high that healthcare facilities in Phuket could not handle. Slightly lower contact rates would only delay the high number of infections a little bit further. Only contact rate less than 10 contacts per person per day shows number of infectants small enough to be handled by the healthcare facilities in the Phuket cities. Actual infected cases also reconfirm the simulation results.

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