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A SIR-UC EPIDEMIC MODEL: THE ANALYSIS OF SUSCEPTIBLE-INFECTED-REMOVED (SIR) EPIDEMIC MODEL WITH THE COVERAGE OF HEALTH INSURANCE (UNCOVERED AND COVERED INDIVIDUALS)

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ABSTRACT

The Susceptible-Infected-Removed (SIR) model is a widely used epidemic model that simulates the spread of infectious diseases within a population. It classifies individuals into susceptible, infected, and removed states, with the number of individuals in each state being time-dependent variables denoted by S(t), I(t), and R(t), respectively. The model considers direct contact transmission between infected and susceptible individuals. In developed countries, some people cannot afford medical treatment. On the contrary, the recovery rate of infected individuals in the population is directly proportional to the number of people receiving medical treatment. Affordable health insurance increases the number of people receiving medical treatment; thus, insurance should be considered an aspect of the epidemic model. The main purpose of this research is to analyze the effect of insurance on the SIR epidemic model. This research classifies individuals in both S(t) and I(t) based on their insurance coverage status. This model assumes permanent immunity for R(t). Thus, it is unnecessary to classify individuals in this state based on their insurance coverage status because they do not spread the disease nor have potential to be re-infected. Numerical simulation is organized to find the effect of insurance in SIR model by analyzing the equilibrium point. The result based on the equilibrium point suggests that the insurance in the SIR epidemic model: (1) decreases the I(t) because it accelerates the recovery rate; (2) decreases the (t) because there is fewer infected people for recovery; (3) increase the S(t) because there is less infected people to transmit the disease, compared to the SIR model without the insurance.

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1. INTRODUCTION

The Susceptible-infected-removed (SIR) model is an epidemic model simulating the spread of an infectious disease in a population. In the model, the number of individuals in the population N classified into three time-dependent states: susceptible state $S(t)$, infected state $I(t)$ and removed state $R(t)$ [1], where the independent variable t>0, is a certain duration of the period after the initial observation and $N = S(t) + I(t) + R(t)$. The susceptible are individuals with the potential to be infected by the disease [2]. Infected individuals may spread the disease to the susceptible by direct contact such as coughing, sneezing, physical touching, and others [3][4]. The Individuals removed from the disease gained permanent immunity.

In 1927, [5] developed the SIR model in the early twentieth century. This model is a system of differential equations and does not possess an explicit solution of the formula. Numerical methods are necessary to calculate the solution of the model. Later, there are many modifications of SIR model. Acronyms for epidemic models are often based on the flow patterns between the compartments such as SIR, SIRS, SEI, SEIS, SEIR, SEIRS, MSEIR, MSEIRS, SI, and SIS [6]. The research to formulate the SIR epidemic model based on the case still continues today. The latest research about the epidemic model was released when the coronavirus infection spread at the beginning of 2020.

If there is a delay between the acquisition of infection and the infectious state, then the exposed state is added to the model. If the removed do not have permanent immunity, then the model does not end at the removed state but rather creates a loop by going back to the susceptible state instead. If there is a vaccination that prevents infection for a certain period, then the vaccinated state is added to the model [7][8]. Most of these epidemic models assumed that the recovery rate is constant.

Recovery rate is a quantity describing the elasticity of the number of people recovering from the disease per unit of time. It indicates the process of recovery, transferring people in the state $I(t)$ to $R(t)$. If every person has the same probability to recover through certain medical treatments, then the recovery rate is dependent on the number of people received the medical treatments.

Without medical insurance some of the infected people do not receive medical treatments because of financial issue, mostly in developing countries. [9] stated that 70% of health expenditure in India is OOP (Out-of-Pocket) spending, and only 16% of the population were covered with health insurance. In China, only 9.5% of the population were covered, many people could not afford basic health care and were suffering from expensive medical expenses before the reformation of health policy in 1999. The policy was trying to use social insurance systems and payroll taxes to provide their citizens. Later, this policy was re-established and expanded in 2003. The result of this health insurance policy led to an increase in the use of preventative health care, a decrease in the likelihood of being sick and faster recovery because insurance covered people who could not afford basic health care. In Indonesia, the data of RSKIA SADEWA Hospital shows that BPJS - the health insurance managed by the government - increases the number of inpatients from 2011 to 2019 [10].

Inpatients are quarantined in the hospital and are away from the normal social environment. SIR model states that disease transmission rate (β) represents how fast the infection occurs in the population of $S(t)$ from the $I(t)$. BPJS (and other affordable health insurance) encourages people to receive medical treatment in hospital because they are financially covered. It reduces the number of infectious individuals in a normal social environment and increases the overall recovery rate of the population. Thus, insurance may decrease the value of β because it secluded individuals of $S(t)$ from the infected individuals $I(t)$, whom now are quarantined inpatients. This research modifies the SIR model such that the individuals in both $S(t)$ and $I(t)$ are divided based on the insurance coverage status. The main purpose of this research is to analyze the effect of insurance on the SIR epidemic model based on the model modification and its application.

2. RESEARCH METHODS

This research modifies SIR model by adding insurance in it with four cases of scenarios. This paper name the modified model, SIR-UC epidemic model. The SIR-UC model for four cases- represented in Table 1 is described in the section two. A numerical simulation is presented to show the effect of insurance by comparing the result of SIR and SIR-UC epidemic model.

Table 1. The Modification of SIR by Adding Insurance

Health Requirement / Type of Insurance	Only Susceptible Can Make Insurance Contract	Susceptible and Infected Can Make Insurance Contract
Whole Life	Case 1	Case 3
Term Life	Case 2	Case 4

The basic SIR epidemic model classifies individuals in population into susceptible ($S(t)$), infected ($I(t)$), and removed ($R(t)$). Meanwhile, SIR-UC epidemic model classifies people into uncovered susceptible ($S_U(t)$), insurance covered susceptible ($S_C(t)$), uncovered infected ($I_U(t)$), covered infected ($I_C(t)$) and removed ($R(t)$). Both SIR and SIR-UC epidemic model are used to compute the number of people in state $S(t)$, $I(t)$ and $R(t)$ in the variable t (time). In SIR-UC model,

$$S(t) = S_U(t) + S_C(t) \text{ and}$$
$$I(t) = I_U(t) + I_C(t).$$

This paper considers some assumptions. First, the fixed probability of a being person diseased and removed are independent of age, sex, social status and race. But, the number of people infected or removed is dependent to the number of people receiving medical treatments. Second, the removed gains immunity that prevents the disease from recurring. Third, the birth rate ($\boldsymbol{\alpha > 0}$), the mortality rate because of the observed disease ($\boldsymbol{\varepsilon > 0}$), and the mortality rate because of the other causes ($\boldsymbol{\delta > 0}$) are constants. Fourth, all new-born belongs in state $\boldsymbol{S(t)}$ for SIR and $\boldsymbol{S_U(t)}$ for SIR-UC model, meaning the disease is not heritable and so does the immunity. Lastly, the population is homogenously mixed.

2.1 SIR Epidemic Model

The SIR model (without insurance) is presented by Figure 1. The disease transmission rate ($\beta > 0$) and recovery rate ($\gamma > 0$) are constant in SIR model [11][12]. The population is homogenously mixed, thus a susceptible has the same probability to make a contact with infected [13][14]. The SIR model is the following system of ordinary differential equation (ODE) presented in **System (1)**.

$$\begin{aligned}\frac{dS(t)}{dt} &= \alpha\, N(t) - \delta\, S(t) - \beta \frac{S(t)\, I(t)}{N},\\ \frac{dI(t)}{dt} &= \beta \frac{S(t)\, I(t)}{N} - (\delta + \varepsilon + \gamma)\, I(t) \text{ and}\\ \frac{dR(t)}{dt} &= \gamma I(t) - \delta\, R(t).\end{aligned} \tag{1}$$

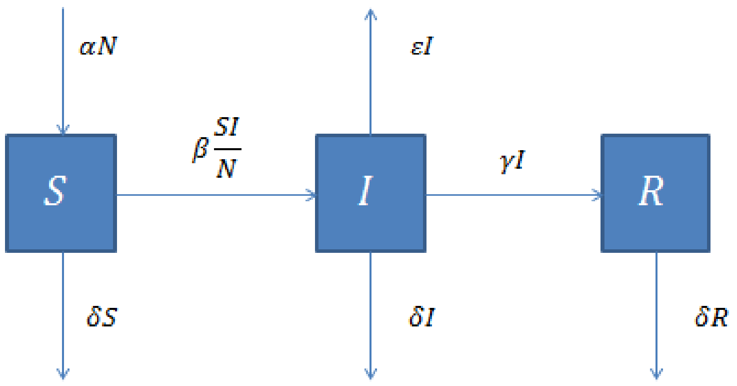

Figure 1. Schematic of SIR Epidemic Model

2.2 SIR-UC Epidemic Model

This research modifies the SIR epidemic model into SIR-UC model by adding the health insurance in the model. The schematic of the SIR-UC model is represented in Figure 2.

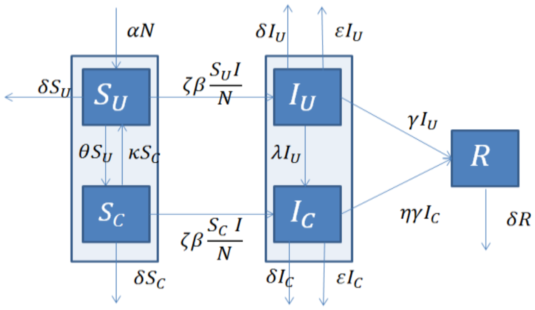

Figure 2. Schematic SIR-UC model

Let the function $f(x)$ indicates the recovery rate and variable x indicates the percentage of people in state I receiving the medical treatment, where $0\% \leq x \leq 100\%$. The normal recovery rate in SIR model (without insurance coverage) is $f(x) = f(x_U) = \gamma$, where $0\% \leq x_U < 100\%$ is the number of treated people uncovered by insurance. If health insurance covers all the cost of the medical treatment, then all the infected people will get health treatment or $x_C = 100\%$, $x_C > x_U$. By the assumption, the probability of a person being removed is constant, thus

$$f(x_C) = \frac{x_C}{x_U}\gamma = \eta\,\gamma, \text{where } \eta > 1.$$

Parameter η represent the effect of insurance toward the recovery rate. Recovery rate is directly proportional to the number of people receiving medical treatment, while affordable health insurance increases the number of people receiving health treatment. Thus, individuals with health insurance coverage have faster overall recovery rate than individuals without insurance coverage.

The recovery rates

$$f(x_C) = \eta\,\gamma > \gamma = f(x_U),$$

Thus, the insurance in SIR model increases the recovery rate. This increment only affects $I_C(t)$ because all of population in state $I_C(t)$ can receive medical treatments, but does not affects $I_U(t)$ because they do not covered by health insurance [15][16].

In contrast, insurance would affect both $I_C(t)$ and $I_U(t)$ on the disease transmission rate because this parameter is dependent to $I(t)$. Insurance affects $I(t)$ by reducing $I_C(t)$. Let the function $g(y)$ indicates the disease transmission rate and variable y indicates the percentage of people in state I not recovering from their disease, where $0\% \leq y \leq 100\%$. The normal disease transmission rate in SIR model is

$$g(y) = \beta, \text{ where } y = I(t) - \gamma I(t).$$

Health insurance increases the recovery rate, thus the percentage of people in state I not recovering from the disease should be decreased to

$$y_C = I(t) - \gamma I_U(t) - \eta\gamma I_C(t).$$

By the assumption, the probability of a person being removed is constant, thus

$$\begin{aligned} g(y_C) = g(y_U) &= \frac{I(t) - \gamma I_U(t) - \eta\gamma I_C(t)}{I(t) - \gamma I(t)}\beta \\ &= \frac{I(t) - \gamma(I_U(t) + \eta I_C(t))}{I(t) - \gamma I(t)}\beta \\ &= \zeta\,\beta\,, \text{where } \zeta < 1. \end{aligned}$$

The disease transmission rate

$$g(y_C) = g(y_U) = \zeta\,\beta < \beta = g(y),$$

Thus, the insurance in SIR model decreases the disease transmission rate.

There are four cases of scenario about the health insurance policy in the model. Case 1, only people in state S can make insurance contract. If the contract is granted, then health insurance will cover the insured for his whole life. This research focus only on a disease and ignore the other caused of physical harm, thus people in state R is considered healthy but do not need to make a contract of health insurance because they acquired the immune preventing them to be infected again. Case 2, only people in state S can make insurance contract, but the health insurance only cover the insurance temporarily. If the contract is expired, then they have to make a new contract to be insured by the insurer. Case 3, the health insurance covers the insurers for his whole life and people in state S and I can make the contract. This policy is made if a population is in crisis of both financial and disease. Case 4, people in state S and I can make the contract, but the health insurance only cover the insured temporarily.

In **Figure 2**, the distinctive of case 1 to 4 is expressed as follows.

Case 1: $\kappa = \lambda = 0$ and $\theta > 0$.

Case 2: $\lambda = 0$, $\theta > 0$ and $\kappa > 0$.

Case 3: $\kappa = 0$, $\theta > 0$, and $\lambda > 0$.

Case 4: $\theta > 0$, $\lambda > 0$, and $\kappa > 0$.

The formula of the SIR-UC epidemic model is a system of ODE presented in **System (2)**. This formula focuses on Case 4 because the formulas of SIR-UC epidemic model for Case 1 to Case 3 are easily modified from **System (2)** by the previous expression.

$$\frac{dS}{dt} = \frac{dS_U}{dt} + \frac{dS_C}{dt},$$

where

$$\frac{dS_U}{dt} = \alpha N - (\delta + \theta)S_U - \zeta\beta\frac{S_U\, I}{N} + \kappa\, S_C,$$

and

$$\frac{dS_C}{dt} = \theta S_U - (\delta + \kappa)S_C - \zeta\beta\frac{S_C\, I}{N}.$$

$$\frac{dI}{dt} = \frac{dI_U}{dt} + \frac{dI_C}{dt}, \tag{2}$$

where

$$\frac{dI_U}{dt} = \zeta\beta\frac{S_U\, I}{N} - (\delta + \varepsilon + \gamma + \lambda)I_U,$$

and

$$\frac{dI_C}{dt} = \zeta\beta\frac{S_C\, I}{N} - (\delta + \varepsilon + \eta\,\gamma - \lambda)I_C.$$

$$\frac{dR}{dt} = \gamma\, I_U + \eta\,\gamma\, I_C - \delta\, R.$$

3. RESULTS AND DISCUSSION

This simulation numerically demonstrates the proposed model. Let a city has the initial population $N = 3.380.875$ from the beginning of observation, with the number of people in state $S_U(0) = 216.972, S_C(0) = 522.851$, $I_U(0) = 462.149$ and $R(0) = 0$.This population grows with birth rate $\alpha = 0.2108\ \times 10^{-1}$ per year. A disease is spreading in the population. The probability of the susceptible being infected by the disease is $\beta = 0.9467$ and the probability of the infected being removed is $\gamma = 0{,}2846$. The death rate caused by the disease is $\delta = 6{,}6300 \times 10^{-3}$ and the death rate by other causes is $\varepsilon = 1{,}5000 \times 10^{-3}$. This simulation assumes that $\alpha, \beta, \gamma, \delta$ and ε are constant parameters.

If there is no health insurance in this simulation, then there is no reduction in the epidemic spreading rate ($\zeta = 1$) there is no boost for recovery rate ($\eta = 1$). The addition of health insurance in the simulation implies the results in **Figure 3**. The parameters used in the SIR model and the SIR-UC model with four different cases of scenario listed in the **Table 2**.

Table 2. The Parameter in the Simulation of SIR-UC Model

Case	Type of insurance	ζ	η	θ	κ	λ
0	No insurance (normal SIR model)	1.00	1.00	0,00	0.00	0.00
1	Whole life coverage, only covers healthy people	0.80	1.20	2.12×10^{-1}	0.00	0.00
2	Temporary coverage, only covers healthy people	0.80	1.20	2.12×10^{-1}	0.20	0.00
3	Whole life coverage, covers anybody	0.80	1.20	2.12×10^{-1}	0.00	0.50
4	Temporary coverage, covers anybody	0.80	1.20	2.12×10^{-1}	0.20	0.50

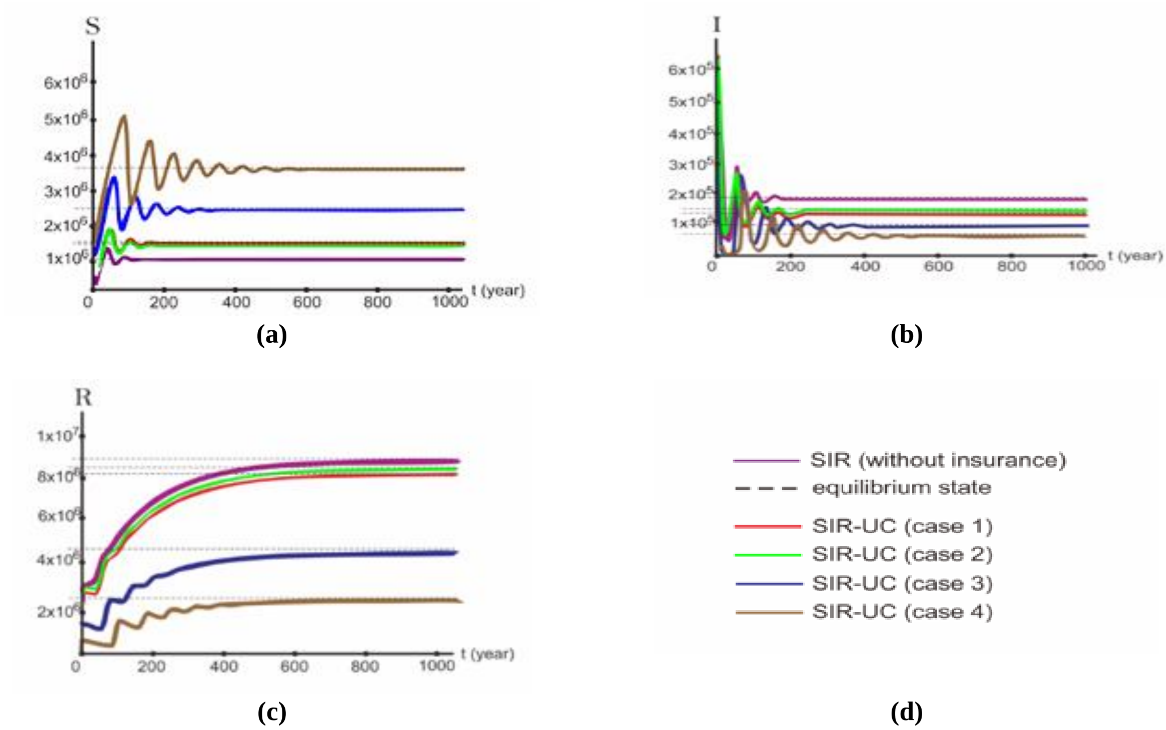

Figure 3. The result comparation of the SIR and the four cases of SIR-UC model (a) whole life coverage, only covers healthy people, (b) temporary coverage, only covers healthy people, (c) whole life coverage, covers anybody and temporary coverage, covers anybody

This section analyzes the obtained result in Figure 3. The analysis consists of two subsections: (1) equilibrium solution and (2) stability of the model. The equilibrium solution of the result in Figure 3 is shown in Table 3 with 2 digits of decimal places and maximum of 1000 iterations with the Runge-Kutta method in solving the initial value problems of the models.

Table 3. Comparison of Equilibrium Solution Between the SIR and SIR-UC model

Variable	Measures	Unit	SIR	SIR-UC (case 1)	SIR-UC (case 2)	SIR-UC (case 3)	SIR-UC (case 4)
S	t_S^*	days	218	198	328	521	744
	$S(t_S^*)$	people	1.05×10^6	1.51×10^6	1.44×10^6	2.47×10^6	3.66×10^6
	$\frac{S(t)}{N}$	percent	9.81%	14.11%	13.46%	32.50%	57.19%
I	t_I^*	days	220	395	319	478	856
	$I(t_I^*)$	people	2.20×10^5	1.81×10^5	1.91×10^5	0.99×10^5	0.57×10^5
	$\frac{I(t)}{N}$	percent	2.06%	1.69%	1.79%	1.30%	0.89%
R	t_R^*	days	894	938	924	878	850
	$R(t_R^*)$	people	9.42×10^6	9.01×10^6	9.06×10^6	4.98×10^6	2.69×10^6
	$\frac{R(t)}{N}$	percent	88.04%	84.21%	84.67%	65.53%	42.03%

The equilibrium solution of variable S is $S(t)$ where $\frac{dS}{dt} = 0$ at $t \geq t_S^*$, thus

$$\lim_{t\to\infty} S(t) = S(t_S^*). \quad (3)$$

Equation (3) defines equilibrium value of $S(t)$ and t_S^* is the minimum amount of time (in year) required to reach the value after the initial time. This definition also applies to variable I and R with the minimum time of t_I^* and t_R^* respectively.

Figure 3 and Table 3 show that the equilibrium value of $I(t)$ is proportionally to $R(t)$. In system of ODE in **System (1)** and **System (2)**, the increment of people in state R relies on the number of people in state I (or I_U and I_C in SIR-UC model) thus this proportionally in the result is founded by the model. The interpretation of this condition is "only infected people recover," thus the higher amount of people in state R does not associated with better model.

The assumption of the constant parameter $\delta > 0$ indicates that $I(t)$ is propotional to $\delta I(t)$. It means that the high number of people in the state I leads to more death caused by the disease. Since $I(t)$ is also proportional to $R(t)$, thus $R(t)$ is propotional to the death caused by the disease in the population by syllogism. In conclusion, model with lower $I(t)$ and $R(t)$ has lower number of deaths caused by the disease.

The disease spreads by the contact between people in state I and S, thus $S(t)$ is reversely proportional to $I(t)$because less people in state I indicates less disease spreading and prevents people in state S from infection. This idea matches results shown in Figure 3 and Table 3. The model with the lowest equilibrium solution for $I(t)$ has the highest of $S(t)$.

The addition of insurance in SIR model affects the equilibrium solution of the model as follows. The Figure 4 explains these effects of insurance in SIR model with flow diagram.

1. It reduces the population in state I and the death caused by the infection.
2. The reduction of population in state I cause reduction of population in state R.
3. The population in state S increased, because insurance prevents the disease from spreading by faster recovery process and reduces the disease spreading rate.

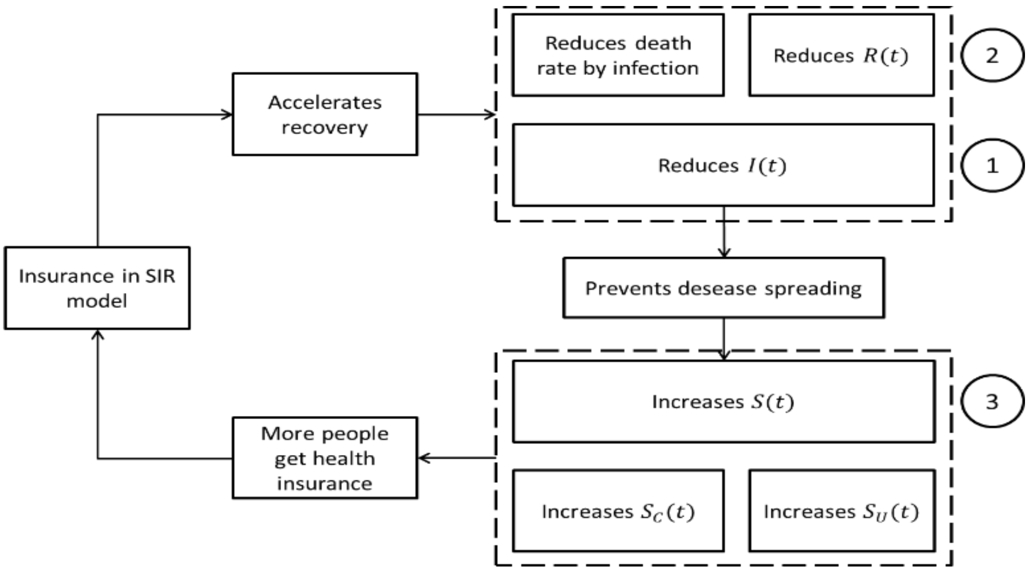

Figure 4. **The effects of insurance in SIR model**

4. CONCLUSIONS

Based on the results and discussion, it is concluded that the addition of insurance in SIR model affects the equilibrium solution of the model. Insurance assists infected people to get medical treatment in hospital financially. If the number of people receiving the treatment is increased, then it will accelerate the overall recovery rate in the population. Without affordable health insurance, some people cannot afford the medical treatment. Faster recovery rate reduces $I(t)$ overtime. The reduction of individuals in state $I(t)$ causes reduction of population in state $R(t)$, because $R(t)$ represents the individuals who had experienced the disease and now the infected individuals are now lower in number. The reduction of population in state $I(t)$ also increase the number of individuals in $S(t)$, because it reduce the number of infection and the population is still multiplying at the constant birth rate with less death rate.

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