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Weights optimization using Firefly Algorithm on optimal control of zika disease from dengue symptoms by vaccination

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Abstract. Zika disease is caused by zika virus. Zika virus can be contagious through the *Aedes* biting, such as *Aedes aegypti*. The mosquitoes can also transmit dengue fever. From the problem of zika spread, then in this research can be constructed mathematical model of zika spread from dengue symptoms. In zika spread from dengue symptoms, there are two populations included i.e. human population as host and mosquito population as vector. Because the treatments for zika disease are unavailable, then vaccination is given to susceptible human. Optimal control is used for minimizing the number of infected human and the cost of vaccination. Due to the cost of objective function depends on weights, in this research we will apply Firefly Algorithm (FA) to optimize weights minimizing cost of objective function. FA is based on behavior of flashing characteristics of fireflies. Simulations have been applied and we can obtain comparison the number of human and mosquito with and without control. In addition, we also obtain optimal weight related to the number of infected human and the cost of vaccination.

1. Introduction

Nowadays, many infectious diseases have been discovered and one of them is zika disease which can cause death in its victims. Zika disease is caused by zika virus. Zika virus has been identified in 1947 in monkey rhesus and then it is identified in human in 1952 in Africa. Zika virus can be contagious through the *Aedes* biting, such as *Aedes aegypti*. The mosquitoes can also transmit dengue fever so that dengue fever and zika disease have the relations [14].

From the problem of zika spread, then in this research can be constructed mathematical model of zika spread from dengue symptoms. In zika spread from dengue symptoms, there are two populations included i.e. human population as host and mosquito population as vector [7]. In human population, the victims only show the dengue symptoms and the symptoms of zika disappear. In this phase, the victims have probability for recovery. After latent period, the victims will be infected which have shown the symptoms of zika. Because the treatment and drugs have not discovered yet for zika disease, it is assumed that the victims infected by zika disease will die. Because the treatments for zika disease are unavailable, then vaccination is given to susceptible human.

The purpose of modelling epidemics is to provide policies designed to control the spread of disease [10]. There are many control strategies to bound the spread of zika disease such as vaccination for controlling susceptible human. Optimal control is used for minimizing the number of infected human



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and the cost of vaccination [9]. From previous researches, mathematical model to look for stability the disease [12], stability for predator prey [15] or for controlling the disease has been constructed [8].

In the earlier research from Michalewicz, by heuristic optimization like Genetic Algorithm (GA), we can determine optimal control minimizing objective function based on natural selection of chromosomes [6]. In this research, Firefly Algorithm (FA) will be used. FA was discovered by Xin-She Yang in 2008. It is based on behavior of flashing characteristics of fireflies. These insects communicate, search for prey, and find mates using bioluminescence with varying flaying patterns. One of characteristics of fireflies is the less bright one will move toward to the brighter one. Brighter firefly indicates better objective function as fitness function [5].

In optimal control problem, weight selection is applied by trial and error [2]. Due to the cost of objective function depends on weights [11], in this research we will apply Firefly algorithm to optimize weights minimizing cost of objective function. In previous research, FA has been applied in optimization model [13]. Ant Colony Optimization (ACO) has been applied on SEIR contagious disease [9], Artificial Bee Colony (ABC) has been applied on influenza disease [10].

Simulations have been applied and we can obtain comparison the number of human and mosquito with and without control. In addition, we also obtain optimal weights related to the number of infected human and the cost of vaccination.

2. Optimal Control Zika Disease from Dengue Symptoms Model

Generally, the disease can be modeled as SEIR (Susceptible, Exposed, Infected, Recovered) epidemic model [6]. The model was introduced by Kermack and McKendrick in 1927. At the SEIR epidemic model, there are four compartments of individual : susceptible, exposed, infected, and recovered. Susceptible individual can be infected individual after making contact with infected individual based on disease transmission rate. However, before being infected individual, susceptible individual becomes exposed individual who doesn't show the symptoms of disease during latent time. When the symptoms of disease appear, exposed individual becomes infected individual. Then, infected individual becomes recovered individual when the symptoms of disease have lost [1],[4].

2.1. Mathematical Model of Zika Disease from Dengue Symptoms Model

Zika disease model is the development of standard SEIR epidemic model. In the zika disease model, there are two different populations, such as : mosquito as vector and human as host. Compartment of zika disease model can be seen in figure 1 where in mosquito as vector there are : susceptible mosquito S_m , exposed mosquito E_m and infected mosquito I_m while in human as host there are : susceptible human S_h , exposed human E_h , infected human I_h , and recovered human R_h . N_h is human population total which is constant. N_m is mosquito population total which is constant.

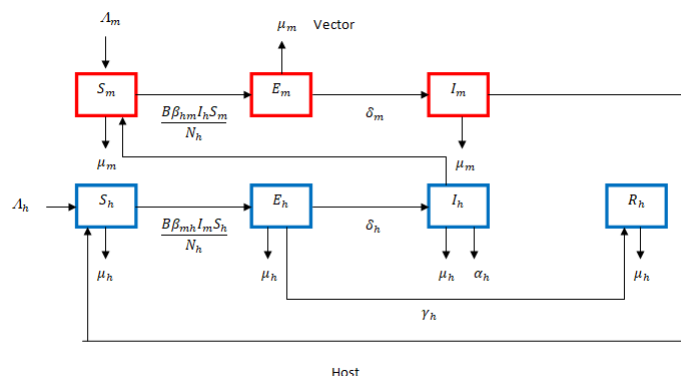


Figure 1. Compartment of Zika Disease from Dengue Symptoms Model.

The mathematical model of zika disease can be constructed in equations (1) - (9).

$$\frac{dS_h}{dt} = \Lambda_h - B\beta_{mh} \frac{I_m}{N_h} S_h - \mu_h S_h - uS_h \quad (1)$$

$$\frac{dE_h}{dt} = B\beta_{mh} \frac{I_m}{N_h} S_h - \delta_h E_h - \mu_h E_h - \gamma_h E_h \quad (2)$$

$$\frac{dI_h}{dt} = \delta_h E_h - \mu_h I_h - \alpha_h I_h \quad (3)$$

$$\frac{dR_h}{dt} = \gamma_h E_h - \mu_h R_h + uS_h \quad (4)$$

$$\frac{dS_m}{dt} = \Lambda_m - B\beta_{hm} \frac{I_h}{N_h} S_m - \mu_m S_m \quad (5)$$

$$\frac{dE_m}{dt} = B\beta_{hm} \frac{I_h}{N_h} S_m - \delta_m E_m - \mu_m E_m \quad (6)$$

$$\frac{dI_m}{dt} = \delta_m E_m - \mu_m I_m \quad (7)$$

$$N_h(t) = S_h(t) + E_h(t) + I_h(t) + R_h(t) \quad (8)$$

$$N_m(t) = S_m(t) + E_m(t) + I_m(t) \quad (9)$$

With positive solutions $S_h(t) \geq 0, E_h(t) \geq 0, I_h(t) \geq 0, R_h(t) \geq 0, S_m(t) \geq 0, E_m(t) \geq 0, I_m(t) \geq 0$

Parameters used in model above are :

- Λ_h : Recruitment rate (birth or immigration) of human population
- Λ_m : Recruitment rate (birth or immigration) of mosquito population
- μ_h : Natural death rate of human
- μ_m : Natural death rate of mosquito
- B : Average daily biting (per day) of the mosquito
- β_{mh} : Transmission rate (per bite) from infected mosquitoes to humans
- β_{hm} : Transmission rate (per bite) from infected human to mosquitoes
- γ_h : The recovery rate of the human population
- δ_h : The mutation rate of human population
- δ_m : The mutation rate of mosquito population
- α_h : The death by disease rate of human

In the human population, the model can be explained as follows :

At the susceptible compartment, recruitment rate (birth or immigration) can increase the number of susceptible. However, disease transmission rate due to contact with infected mosquito through bitings and natural death rate can decrease the number of susceptible. At the exposed compartment, disease transmission rate due to contact with infected mosquito through bitings can increase the number of exposed. However, natural death rate, mutation rate and recovery rate can decrease the number of exposed. At the infected compartment, mutation rate from the exposed can increase the number of infected. However, natural death rate and death by disease rate can decrease the number of infected. At the recovered compartment, recovery rate can increase the number of recovered. However, natural death rate can decrease the number of recovered.

Based on previous study [14], in human population, exposed human is individual who only show the dengue symptoms and the symptoms of zika disappear. In this phase, individual has probability for recovery. After latent period, exposed human will become infected human. Infected human is

individual who have shown the symptoms of zika. Because the treatment and drugs have not discovered yet for zika disease, it is assumed that individual infected by zika disease will die.

In the mosquito population, the model can be explained as follows :

At the susceptible compartment, recruitment rate (birth or immigration) can increase the number of susceptible. However, disease transmission rate due to contact with infected human through bitings and natural death rate can decrease the number of susceptible. At the exposed compartment, disease transmission rate due to contact with infected human through bitings can increase the number of exposed. However, natural death rate and mutation rate can decrease the number of exposed. At the infected compartment, mutation rate from the exposed can increase the number of infected. However, natural death rate can decrease the number of infected.

In addition, there are control function of susceptible human vaccinated u , The effectiveness range of u is $[0,1]$ where value 0 represents control functions are fail or it is not to be applied and value 1 represents control functions are success or it is applied entirely.

The objective function (performance index) which will be minimized is :

$$\min J(u) = \int_0^t [W_1 I_h(t)^2 + W_2 u(t)^2] dt \quad (10)$$

with weights $W_1 > 0, W_2 > 0$. From equation (10), we want to minimize the number of infected human, and the cost of vaccination.

The goal is finding u^* such that minimizing performance index

$$J(u^*) = \min(J(u)) \quad (11)$$

2.2. Pontryagin's Maximum Principle

If u^* are optimal control corresponding state system, there exist adjoint variables :

$$(\lambda_1 \quad \lambda_2 \quad \lambda_3 \quad \lambda_4 \quad \lambda_5 \quad \lambda_6 \quad \lambda_7)$$

which satisfy the following [3] :

$$\frac{d\lambda_1}{dt} = -\frac{\partial H}{\partial S_h} = \lambda_1 B \beta_{mh} \frac{I_m}{N_h} + \lambda_1 \mu_h + \lambda_1 u - \lambda_2 B \beta_{mh} \frac{I_m}{N_h} - \lambda_4 u \quad (12)$$

$$\frac{d\lambda_2}{dt} = -\frac{\partial H}{\partial E_h} = \lambda_2 \delta_h + \lambda_2 \mu_h + \lambda_2 \gamma_h - \lambda_3 \delta_h - \lambda_4 \gamma_h \quad (13)$$

$$\frac{d\lambda_3}{dt} = -\frac{\partial H}{\partial I_h} = -2W_1 I_h + \lambda_3 \mu_h + \lambda_3 \alpha_h + \lambda_5 B \beta_{hm} \frac{S_m}{N_h} - \lambda_6 B \beta_{hm} \frac{S_m}{N_h} \quad (14)$$

$$\frac{d\lambda_4}{dt} = -\frac{\partial H}{\partial R_h} = \lambda_4 \mu_h \quad (15)$$

$$\frac{d\lambda_5}{dt} = -\frac{\partial H}{\partial S_m} = \lambda_5 B \beta_{hm} \frac{I_h}{N_h} + \lambda_5 \mu_m - \lambda_6 B \beta_{hm} \frac{I_h}{N_h} \quad (16)$$

$$\frac{d\lambda_6}{dt} = -\frac{\partial H}{\partial E_m} = \lambda_6 \delta_m + \lambda_6 \mu_m - \lambda_7 \delta_m \quad (17)$$

$$\frac{d\lambda_7}{dt} = -\frac{\partial H}{\partial I_m} = \lambda_1 B \beta_{mh} \frac{S_h}{N_h} - \lambda_2 B \beta_{mh} \frac{S_h}{N_h} - \lambda_7 \mu_m \quad (18)$$

With final conditions : $\lambda_1(T) = \lambda_2(T) = \lambda_3(T) = \lambda_4(T) = \lambda_5(T) = \lambda_6(T) = \lambda_7(T) = 0$

Where the Hamiltonian is :

$$\begin{aligned}
 H = & W_1 I_h(t)^2 + W_2 u(t)^2 + \tag{19} \\
 & \lambda_1 \left(\Lambda_h - B\beta_{mh} \frac{I_m}{N_h} S_h - \mu_h S_h - u S_h \right) + \lambda_2 \left(B\beta_{mh} \frac{I_m}{N_h} S_h - \delta_h E_h - \mu_h E_h - \gamma_h E_h \right) + \\
 & \lambda_3 \left(\delta_h E_h - \mu_h I_h - \alpha_h I_h \right) + \lambda_4 \left(\gamma_h E_h - \mu_h R_h + u S_h \right) + \\
 & \lambda_5 \left(\Lambda_m - B\beta_{hm} \frac{I_h}{N_h} S_m - \mu_m S_m \right) + \lambda_6 \left(B\beta_{hm} \frac{I_h}{N_h} S_m - \delta_m E_m - \mu_m E_m \right) + \\
 & \lambda_7 \left(\delta_m E_m - \mu_m I_m \right)
 \end{aligned}$$

Furthermore, we can find optimal control u^* :

$$\begin{aligned}
 \frac{\partial H}{\partial u} &= 0 \\
 2W_2 u - \lambda_1 S_h + \lambda_4 S_h &= 0 \\
 u = \min \left(1, \max \left(0, \frac{(\lambda_1 - \lambda_4) S_h}{2W_2} \right) \right) & \tag{20}
 \end{aligned}$$

2.3. Forward-Backward Sweep Method

Forward backward sweep method applied on optimal control dengue fever model can be designed as follows [3]:

Suppose state variables and adjoint variables are :

$$\begin{aligned}
 f_1 = \frac{dS_h}{dt}, f_2 = \frac{dE_h}{dt}, f_3 = \frac{dI_h}{dt}, f_4 = \frac{dR_h}{dt}, f_5 = \frac{dS_m}{dt}, f_6 = \frac{dE_m}{dt}, f_7 = \frac{dI_m}{dt} \\
 g_1 = \frac{d\lambda_1}{dt}, g_2 = \frac{d\lambda_2}{dt}, g_3 = \frac{d\lambda_3}{dt}, g_4 = \frac{d\lambda_4}{dt}, g_5 = \frac{d\lambda_5}{dt}, g_6 = \frac{d\lambda_6}{dt}, g_7 = \frac{d\lambda_7}{dt}
 \end{aligned}$$

The algorithm to compute objective function as fitness function with parameter weights $W_1 > 0, W_2 > 0$ is :

control_zika(W_1, W_2)

while(process has not converged yet)

$u_{old} = u$

1. Compute solution of state variables forward with initial condition $x(0) = (S_h(0), E_h(0), I_h(0), R_h(0), S_m(0), E_m(0), I_m(0))$ are given using Runge Kutta fourth order.

$$\begin{aligned}
 k_{1i} &= f_i(t, x_i(t), u(t)), i = 1, 2, \dots, 7 \\
 k_{2i} &= f_i \left(t + \frac{h}{2}, x_i(t) + \frac{h}{2} k_{1i}, \frac{u(t) + u(t+h)}{2} \right), i = 1, 2, \dots, 7 \\
 k_{3i} &= f_i \left(t + \frac{h}{2}, x_i(t) + \frac{h}{2} k_{2i}, \frac{u(t) + u(t+h)}{2} \right), i = 1, 2, \dots, 7 \\
 k_{4i} &= f(t+h, x_i(t) + hk_{3i}, u(t+h)), i = 1, 2, \dots, 7 \\
 x_i(t+h) &= x_i(t) + \frac{h}{6} (k_{1i} + 2k_{2i} + 2k_{3i} + k_{4i}), i = 1, 2, \dots, 7
 \end{aligned}$$

2. Compute solution of adjoint variables backward with final condition $\lambda(T) = (\lambda_1(T), \lambda_2(T), \lambda_3(T), \lambda_4(T), \lambda_5(T), \lambda_6(T), \lambda_7(T))$ are given using Runge Kutta fourth order.

$$k_{li} = g_i(t, x_i(t), \lambda_i(t), u(t)), i = 1, 2, \dots, 7$$

$$\begin{aligned}
k_{2i} &= g_i \left(t - \frac{h}{2}, \frac{x_i(t) + x_i(t-h)}{2}, \lambda_i(t) - \frac{h}{2} k_{1i}, \frac{u(t) + u(t-h)}{2} \right), i = 1, 2, \dots, 7 \\
k_{3i} &= g_i \left(t - \frac{h}{2}, \frac{x_i(t) + x_i(t-h)}{2}, \lambda_i(t) - \frac{h}{2} k_{2i}, \frac{u(t) + u(t-h)}{2} \right), i = 1, 2, \dots, 7 \\
k_{4i} &= g_i(t-h, x_i(t-h), \lambda_i(t) - h k_{3i}, u(t-h)), i = 1, 2, \dots, 7 \\
\lambda_i(t-h) &= \lambda_i(t) - \frac{h}{6} (k_{1i} + 2k_{2i} + 2k_{3i} + k_{4i}), i = 1, 2, \dots, 7
\end{aligned}$$

3. Compute optimal control u^* using equations (20).

4. Update optimal control

$$u \leftarrow \frac{u + u_{old}}{2} \quad (21)$$

End

5. Compute objective function as fitness function

$$J(u) = \sum_{k=0}^{T-1} (W_1 I_h(k)^2 + W_2 u(k)^2) \quad (22)$$

3. Firefly Algorithm

Firefly Algorithm (FA) was discovered by Xin-She Yang in 2008. It is based on behavior of flashing characteristics of fireflies. These insects communicate, search for prey, and find mates using bioluminescence with varying flashing patterns. The FA is based on the rules [5]:

1. All fireflies are unisex so they attract one another.
2. Attractiveness is proportional to firefly brightness. For any couple of flashing fireflies, the less bright one will move toward to the brighter one. Attractiveness is proportional to the brightness and they both decrease as their distance increases. If there is no brighter one than a particular firefly, it will move randomly.

The brightness of a firefly is affected or determined by the landscape of the objective function. In the FA, attractiveness of a firefly is assumed to be determined by its brightness which is related with the objective function. The brightness of a firefly at particular location x can be chosen as $f(x)$, where $f(x)$ is the objective function. However, if the attractiveness β is relative, it should be judged by the other fireflies. Thus, it will vary with the distance r_{ij} between firefly i and firefly j .

In this algorithm, the weights used are W_1, W_2 related to the number of infected human and the cost of vaccination.

The overall algorithm for optimizing the weights W_1, W_2 using FA is as follows :

1. Generate initial population position of fireflies $x^i = (W_1^i, W_2^i), i = 1, 2, \dots, \max pop$ and compute the fitness value

$$f(x^i) = control_zika(W_1^i, W_2^i), i = 1, 2, \dots, \max pop$$

2. Determine the best firefly in the population with the its position

$$i^{\min} \leftarrow \arg \min_i (f(x^i), i = 1, 2, \dots, \max pop) \quad (23)$$

$$x^{i^{\min}} \leftarrow \arg \min_{x^i} (f(x^i), i = 1, 2, \dots, \max pop) \quad (24)$$

3. Do the iteration as follows :

for $i = 1 : \max \text{ pop}$

for $j = 1 : \max \text{ pop}$

if ($f(x^j) < f(x^i)$)

a. Compute the distance between firefly i and firefly j

$$r_{ij} = \|x^i - x^j\| = \sqrt{\sum_{t=1}^T (x_t^i - x_t^j)^2} \tag{25}$$

b. Compute the attractiveness function of firefly

$$\beta \leftarrow \beta_0 e^{-\gamma r_{ij}} \tag{26}$$

c. Generate $u_i = \alpha(\text{rand} - \frac{1}{2})$, with $\text{rand} \sim U(0,1)$

d. Update the movement of firefly i

$$x^i \leftarrow (1 - \beta)x^i + \beta x^j + u_i \tag{27}$$

End

End

end

Generate $u_{\min} = \alpha(\text{rand} - \frac{1}{2})$, with $\text{rand} \sim U(0,1)$

Update the movement of best firefly

$$x^{i\min} \leftarrow x^{i\min} + u_{i\min} \tag{28}$$

4. Repeat step 3 until stopping criteria is achieved.

4. Results

Parameters used on FA simulations are $\beta_0 = 1, \gamma = 5, \alpha = 0.1$ with the number of fireflies are 10 and maximum iterations are 50.

Parameters and initial values used on zika disease model can be seen at table 1 and table 2 respectively [7] :

Table 1. Parameters of zika disease model.

Parameters	Value
Recruitment rate (birth or immigration) of human population Λ_h	5
Recruitment rate (birth or immigration) of mosquito population Λ_m	500
Natural death rate of human μ_h	1
Natural death rate of mosquito μ_m	$\frac{1}{70 \times 365}$
Average daily biting (per day) of the mosquito B	$\frac{1}{21}$
Transmission rate (per bite) from infected mosquitoes to humans β_{mh}	0.5
Transmission rate (per bite) from infected human to mosquitoes β_{hm}	0.33
The recovery rate of the human population γ_h	0.33
The mutation rate of human population δ_h	$\frac{1}{8.5}$
The mutation rate of mosquito population δ_m	$\frac{1}{7.5}$
The death by disease rate of human α_h	$\frac{1}{3.5}$
	0.3

Table 2. Initial value of zika disease model.

Initial Value	Value
Susceptible human $S_h(0)$	39830
Exposed human $E_h(0)$	20
Infected human $I_h(0)$	50
Recovered human $R_h(0)$	100
Susceptible mosquito $S_m(0)$	1500
Exposed mosquito $E_m(0)$	200
Infected mosquito $I_m(0)$	100

The simulations of optimal control zika disease model can be seen at figure 3 – figure 5 while figure 2 is FA simulation.

Figure 2 shows optimization process of FA. At the first iteration, the position of fireflies are random. In the optimization process, we update the brightness of fireflies so that the fireflies move toward to the brighter firefly with minimum fitness function. Optimal weights obtained are $W_1 = 0.101, W_2 = 6.131$ with minimum fitness is 619955.388

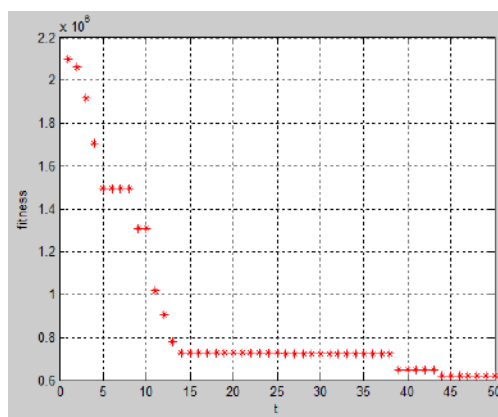


Figure 2. FA Optimization Process.

Figure 3(a)-(c) shows numerical solution of susceptible mosquito, exposed mosquito, and infected mosquito with and without control respectively. From the graph, the effect of vaccination can reduce the number of exposed mosquitoes and infected mosquitoes.

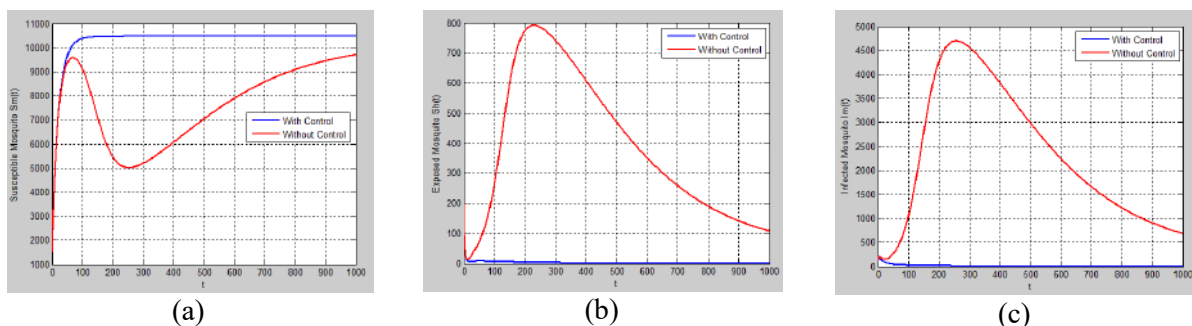


Figure 3. Numerical Solutions of Mosquitoes as Vector. (a) Susceptible Mosquito (b) Exposed Mosquito. (c) Infected Mosquito.

Figure 4(a) shows numerical solution of susceptible human with and without control. The number of susceptible human with control is lower than without control because vaccination effect which decrease the number of susceptible human. Figure 4(b) shows numerical solution of exposed human with and without control. Figure 4(c) shows numerical solution of infected human with and without

control. The number of exposed human and infected human with control is lower than without control. Figure 4(d) shows numerical solution of recovered human with and without control. The number of recovered human with control is higher than without control because vaccination effect which increase the number of recovered human.

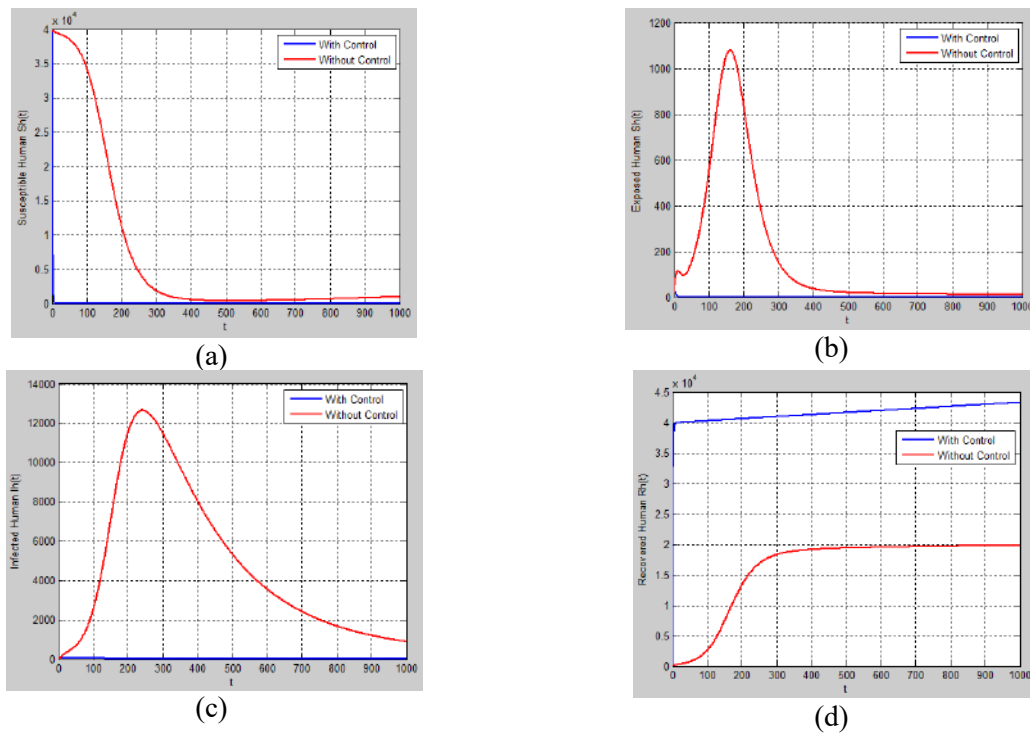


Figure 4. Numerical Solutions of Human as Host. (a) Susceptible Human (b) Exposed Human (c) Infected Human (d) Recovered Human

Figure 5 shows control function of vaccination. The control function has the range of effectiveness between 0 to 1 where value 0 represents control functions are fail or it is not to be applied and value 1 represents control functions are success or it is applied entirely.

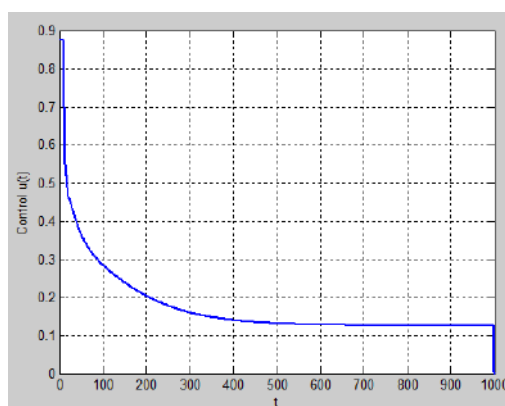


Figure 5. Vaccination as Optimal Control

5. Conclusion

FA can optimize the weights of optimal control zika disease model. From the simulations, the position of fireflies are random. In the optimization process, we update the brightness of fireflies so that the fireflies move toward to the brighter firefly with minimum fitness function. When FA has obtained optimal weights related to the number of infected human and the cost of vaccination, optimal weights

are applied on zika disease simulation. Based on parameters of zika disease model, we can compare numerical solution of susceptible mosquito, exposed mosquito, infected mosquito in mosquito population and susceptible human, exposed human, infected human, and recovered human in human population when vaccinationns are applied.

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