OPTIMAL CONTROL AND SENSITIVITY ANALYSIS OF COVID-19 TRANSMISSION MODEL WITH THE PRESENCE OF WANING IMMUNITY IN WEST JAVA, INDONESIA

FATUH INAYATUROHMAT†, NURSANTI ANGGRIANI*, ASEP KUSWANDI SUPRIATNA

Department of Mathematics, Universitas Padjadjaran, Jl. Raya Bandung Sumedang Km. 21, Kab. Sumedang 45363
Jawa Barat, Indonesia

Copyright © 2022 the author(s). This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract: In this paper, we developed optimal control and sensitivity analysis on the model of SEIQR COVID-19 transmission in the presence of waning immunity by adding the combination of Partial Rank Correlation Coefficient (PRCC) and Latin Hypercube Sampling (LHS). The most influential parameters to the model are the isolation rate, the infection rate and the recovery rate. We used daily cases of COVID-19 data in West Java, Indonesia to parameterize the infection rate and the recovery rate of the model. Optimal control is applied to the most sensitive parameter i.e. treatments. Treatment is effective to reduce the infected population.

Keywords: COVID-19; LHS; PRCC; waning immunity; isolation; optimal control; sensitivity analysis.

2010 AMS Subject Classification: 92D25, 92D30.

---

*Corresponding author
E-mail address: nursanti.anggriani@unpad.ac.id
†Master of Mathematics Study Program
Received December 30, 2021
1. INTRODUCTION

COVID-19 began in December 2019 in Wuhan city, Hubei province, China. This disease was caused by the virus named SARS-CoV which spread rapidly throughout the world and caused an epidemic [1]. The beginning symptoms of COVID-19 are not nonspecific syndromes, i.e. dry cough, fatigue and fever. These symptoms could involve multiple systems that caused comorbidity, i.e. musculoskeletal (muscleache), gastrointestinal (vomiting, nausea, and diarrhea), neurologic (confusion and headache), and respiratory (sore throat, cough, rhinorrhea, short of breath, chest pain, and hemoptysis) [2]. The origin of COVID-19 is believed to be a zoonotic virus because of sequence identity to the bat-CoV, it is likely that bats are the primary vector for this virus [3,4]. COVID-19 first appeared in Indonesia on March 2, 2020. This was discovered after a citizen was declared infected with the coronavirus after arriving in West Java, Indonesia. As the cases of Covid-19 continue to grow, it is hard to sync between eliminating Covid-19, balancing the economy, and applying the social restriction that will affect many sectors [5]. To minimize the spreading of the disease and stop the pandemic, it is widely assumed that to reach ~67% herd immunity, 175 million Indonesian citizens need to be vaccinated. It means 350 million vaccines are necessary to be supplied nationwide [6]. As the province with the largest population, West Java contributes a large percentage of the total positive cases of COVID-19 in Indonesia.

COVID-19 Researchers are competing to find a solution for COVID-19, whether it is a vaccine or a cure. Mathematician contribute through modelling the dynamics of COVID-19. Mathematical model of COVID-19 transmission with vaccination and treatment [7-9]. Some other models of COVID-19 considering isolation or quarantined compartment [10,11]. Also, a model with waning immunity that caused reinfection of this disease [12]. In our previous research [13], We developed a mathematical model of COVID-19 disease with vaccination and isolation in the presence of waning immunity. We analized the endemic and non-endemic equilibrium with its stability. The Basic Reproduction number ($R_0$) showed the threshold of the model. The non-endemic equilibrium (disease free equilibrium) is locally asymptotically stable when $R_0 < 1$. The endemic equilibrium is locally asymptotically stable with a certain condition when $R_0 > 1$. We concluded that vaccination and isolation are an effective way to reduce the spreading of the disease.
2. MATERIAL AND METHODS

The data used for this research were obtained from pikobar.jabarprov.go.id, the data covers a period of three (2) months, starting from 19th of June, 2021 to the 16th of August, 2021. We continued our research on the Mathematical model of COVID-19 transmission in the presence of waning immunity [13], by adding the combination of Partial Rank Correlation Coefficient (PRCC) and Latin Hypercube Sampling (LHS) to determine the most important parameter of the model. Then, we also added optimal control to the most sensitive parameter i.e. treatments. The population is divided into five compartments, namely Susceptible population ($S$), Exposed population ($E$), Infected population ($I$), Isolated population ($Q$), and Recovered population ($R$). We used daily cases of COVID-19 data in West Java, Indonesia to parameterize the infection rate and the recovery rate of the model. The transition and transmission diagram of the COVID-19 model from (Inayaturohmat, 2021) is given in FIGURE 1. below.

**FIGURE 1.** Transmission and Transition Diagram of COVID-19 Model

From (Inayaturohmat, 2021), The differential equation system with $A = \mu$ as follow :

\[
\begin{align*}
\frac{ds}{dt} &= \mu - \gamma S(t)(E(t) + I(t)) + cE(t) + bl(t) + \alpha R(t) + eQ - \mu S(t) - pqS(t) \\
\frac{dE}{dt} &= \gamma S(t)(E(t) + I(t)) - (c + \varepsilon + \mu)E(t) \\
(1) \quad \frac{dI}{dt} &= \varepsilon E(t) - (\beta + b + \mu + h)I(t) \\
\frac{dQ}{dt} &= hl(t) - (\mu + d + e)Q(t)
\end{align*}
\]
\[
\frac{dR}{dt} = \beta I(t) - (\alpha + \mu) R(t) + pq S(t) + dQ(t)
\]

Table 1 provides the list of the parameters of the model and its values according to previous research and the data from pikobar.jabarprov.go.id.

| Parameter | Description                                           | Value      | Source  |
|-----------|-------------------------------------------------------|------------|---------|
| \(\alpha\) | The Rate at which the recovered become susceptible again | 0.35       | [13]    |
| \(\beta\) | The Rate of recovery                                   | 0.0147     | Estimated |
| \(\gamma\) | The Rate of infection                                  | 0.0001075  | Estimated |
| \(\epsilon\) | The incubation period \(\frac{1}{\epsilon}\)         | 0.15       | [13]    |
| \(\mu\)   | The Rate of natural death                              | 0.015      | [13]    |
| \(b\)     | The Rate at which the infected become susceptible again | 0.025      | [13]    |
| \(c\)     | The Rate at which the exposed become susceptible again  | 0.35       | [13]    |
| \(h\)     | The Rate at which the infected human to be isolated    | 0.35       | Assumed |
| \(p\)     | The Efficacy of vaccination                            | 0.2        | [13]    |
| \(q\)     | The Proportion of vaccination                          | 0.2        | [13]    |
| \(d\)     | The Rate of recovery from isolated                     | 0.5        | [13]    |
| \(e\)     | The Rate at which the isolated become susceptible again | 0.35       | [13]    |

3. Main Results

3.1 Partial Rank Corellation Coefficient (PRCC)

We analyzed the global sensitivity analysis of the model. We used the Latin Hypercube Sampling (LHS) to take samples from each partition evenly and Partial Rank Correlation Coefficient (PRCC) to determine the most significant and sensitive parameters of the model [14-16]. This method shows the correlation between parameters and compartments, it could be a positive or a negative correlation. \((-1,1)\). A positive correlation indicates that each parameter increases, the compartment will also increase, otherwise for a negative correlation The result of sensitivity analysis for all parameters to the infected population is given in FIGURE 2 below.
The most sensitive parameters are rate of isolation \( (h) \), rate of recovery \( (\beta) \), and rate of infection \( (\gamma) \). We can conclude that isolation is an effective intervention to reduce COVID-19 transmission. Recovery rate \( (\beta) \) is also one of the most sensitive parameter, optimal control i.e. treatment can be applied to this parameter to minimize the infected population. Whereas, we used model (1) to analyze the spreading of COVID-19 in West Java by using daily cases of COVID-19 data from pikobar.jabarprov.go.id which is processed into infection rate \( (\gamma) \) with poisson process.

### 3.2 Daily Cases of COVID-19 in West Java

Daily Positive confirmation data for COVID-19 in West Java from 19\(^{th}\) of June 2021 to 16\(^{th}\) of August 2021 can be seen in FIGURE 3 below.
The Indonesian government imposed social restrictions to minimize the daily cases of COVID-19 in Indonesia in several stages, two of the latest are “PPKM Darurat” and “PPKM 4 level”. The effect of social restriction to daily cases of COVID-19 can be seen in the Table 2 below:

**Table 2. Effect of social restriction to daily cases of COVID-19**

| Enforcement of Social Restriction | West Java |
|----------------------------------|-----------|
|                                  | 2 Weeks Before | 2 Weeks After |
|                                  | Time of Enforcement | Enforcement |
| PPKM Darurat (3rd – 25th July 2021) | Increasing Cases | Decreasing Cases |
| PPKM 4 Level (26th July – 2nd August 2021) | Increasing then Decreasing Cases | Decreasing Cases |

From Table 2. We know that the enforcement of social restriction by The Indonesian Government is effective to reduce daily cases of COVID-19 in West Java. When the cases increase, the policy is PPKM Darurat which is the highest level. Then, the cases started to decrease, the regulations can be relaxed to a lower level so it changed to PPKM 4 level. PRCC shows that the isolation rate ($h$) is a very influential parameter to the model. We can conclude that the enforcement of social
restriction is on point considering the data and PRCC of the model.

The number of COVID-19 cases based on data of Daily cases of COVID-19 in West Java from 19th June 2021 to 16th August 2021. Therefore, It can be analyzed by using poisson process with rate \( \lambda \) which is time dependant [17-19]. Assume \( t = (0,59) \), We can estimated the infection rate \( \beta \) and the recovery rate \( \gamma \). Daily cases of COVID-19 can be seen as the Poisson process with the rate \( \lambda_1 = 5,367 \) people per day [18]. By dividing \( \lambda_1 \) with the total population of West Java, we have the infection rate \( \gamma = 0.0001075 \). Daily recovery cases of COVID-19 can be seen as the Poisson process with the rate \( \lambda_2 = 4,652 \) people per day [20]. By dividing \( \lambda_2 \) with the total population of the infected (assume including the exposed and the isolated population) in West Java, we have the recovery rate \( \beta = 0.0147 \).

3.3 Optimal Control of COVID-19 Model with Waning Immunity

The optimal control of the covid-19 transmission model is to obtain a policy which is a treatment to the infected population and isolated population. The constant treatment parameter value \( u \) and \( v \) are assumed to be the control \( u(t) \) and \( v(t) \) that will be determined optimally. The purpose is to minimize the infected population \( I(t) \) and isolated population \( Q(t) \) by adding control variable \( u(t) \) and \( v(t) \). Performance index function as follow:

\[
J(u, v) = \int_0^{t_f} (TI + Uv^2 + BQ + Au^2)dt
\]

with \( 0 \leq t \leq t_f, 0 \leq u \leq 1 \) and \( 0 \leq v \leq 1 \).

s.t

\[
\frac{dS}{dt} = \mu - \gamma S(t)(E(t) + I(t)) + cE(t) + bI(t) + aR(t) + eQ - \mu S(t) - pqS(t)
\]

\[
\frac{dE}{dt} = \gamma S(t)(E(t) + I(t)) - (c + \epsilon + \mu)E(t)
\]

\[
\frac{dI}{dt} = \epsilon E(t) - (v(t)\beta + b + \mu + h)I(t)
\]

\[
\frac{dQ}{dt} = hI(t) - (\mu + u(t)d + e)Q(t)
\]

\[
\frac{dR}{dt} = v(t)\beta I(t) - (\alpha + \mu)R(t) + pqS(t) + u(t)dQ(t)
\]

where \( S(t) \geq 0, E(t) \geq 0, I(t) \geq 0, Q(t) \geq 0, R(t) \geq 0, \) \( 0 \leq t \leq t_f, 0 \leq u \leq 1 \) and \( 0 \leq v \leq 1 \).
\( T \) and \( B \) are the weight of the infected and the isolated population, respectively. \( U \) and \( A \) are the cost of treatments on the performance index function.

The Hamiltonian function for optimal control model as follow:

\[
(8) \quad H = TL + Uv^2 + BQ + Au^2 \\
+ \lambda_1 (\mu - \gamma S(t)(E(t) + I(t)) + cE(t) + bI(t) + \alpha R(t) + eQ - \mu S(t) - pqS(t)) \\
+ \lambda_2 (\gamma S(t)(E(t) + I(t)) - (c + \varepsilon + \mu)E(t)) \\
+ \lambda_3 (E(t) - (v(t)\beta + b + \mu + h)I(t)) \\
+ \lambda_4 (hI(t) - (\mu + u(t)d + e)Q(t)) \\
+ \lambda_5 (v(t)\beta I(t) - (\alpha + \mu)R(t) + pqS(t) + u(t)dQ(t))
\]

where \( \lambda_i \) for \( i = 1,2,\ldots,5 \) is adjoint variable for \( S, Q, E, I, R \).

The Co State equation of the control optimal model as follow:

\[
(9) \quad \frac{d\lambda_1}{dt} = -\lambda_1(t)(-\gamma(E(t) + I(t)) - \mu - pq) - \lambda_2(t)\left(\gamma(E(t) + I(t))\right) - \lambda_5(t)pq \\
(10) \quad \frac{d\lambda_2}{dt} = -\lambda_1(t)(-\gamma S(t) - c) - \lambda_2(t)(\gamma S(t) - (c + \varepsilon + \mu)) - \lambda_3(t)\varepsilon \\
(11) \quad \frac{d\lambda_3}{dt} = -T - \lambda_1(t)(-\gamma S(t) + b) - \lambda_2(t)\gamma S(t) - \lambda_3(-v(t)\beta + b + \mu + h)) \\
- \lambda_4(t)h - \lambda_5(t)v(t)\beta \\
(12) \quad \frac{d\lambda_4}{dt} = -B - \lambda_1(t)e - \lambda_4(t)(-\mu + u(t)d + e) - \lambda_5(t)u(t)d \\
(13) \quad \frac{d\lambda_5}{dt} = -\lambda_1(t)\alpha - \lambda_5(t)(-\alpha + \mu))
\]

by solving the optimal control model with \( 0 \leq (u,v) \leq 1 \), we get \( u^* \) and \( v^* \) as shown below:

\[
u^* = \min \left\{1, \max \left\{0, \frac{\lambda_4 dQ - \lambda_5 dQ}{2A}\right\}\right\}
\]

\[
\nu^* = \min \left\{1, \max \left\{0, \frac{\lambda_3 \beta I - \lambda_5 d\beta I}{2U}\right\}\right\}
\]

### 3.3 Numerical Simulation

The purpose of this numerical simulation is to display the dynamics of the population which is divided into two cases. Case [i] is the dynamics of the population without control by setting \( u^* = \)
0 and \( v^* = 0 \). Case [ii] is the dynamics of the population with control where \( 0 < (u^*, v^*) \leq 1 \) based on the value of the given parameters in Table 1 and initial values \( S(0) = 0.6, E(0) = 0.1, I(0) = 0.05, Q(0) = 0.05 \) and \( R(0) = 0.2 \). The result can be seen in Figure 5 below. Figure 6 show the treatment (\( u^* \) and \( v^* \)) that needs to be applied to the population will decrease over time.

**FIGURE 5.** Population Dynamics without control [i] and with control [ii]

**FIGURE 6.** Optimal Control \( u^* \) and \( v^* \)
From Figure 7 and Figure 8, we can see that the isolated and the infected population is decreasing faster with optimal control $u^*$ and $v^*$. It means, for these populations, treatment (control) is the recommended solution compared to waiting for human immunity to cure itself (without control) [21]. Even there is no certain cure for COVID-19, treatments for patient is a must especially patient with comorbidity i.e. Tuberculosis, Pneumonia, etc.
4. CONCLUSION

In this paper, we presented an SEIQR model of COVID-19 in the presence of waning immunity. Sensitivity analysis was done using Partial Rank Correlation Coefficient (PRCC) and optimal control in the form of treatment to the isolated and the infected populations is added accordingly. We used daily cases of COVID-19 data from pikobar.jabarprov.go.id to do the numerical simulation. From the data, we showed that the Indonesian government policy of social restriction is on point, this is supported by the result of the PRCC. The PRCC shows that the isolation rate \( (h) \), the infection rate \( (\gamma) \), and the recovery rate \( (\beta) \) are the most influential parameters (most sensitive) to the model. It can be concluded that optimal control in the form of treatment is effective and faster to decrease the spreading of COVID-19 than without any control.

ACKNOWLEDGMENTS

This research is supported and funded by Universitas Padjadjaran through Beasiswa Unggulan Pascasarjana Padjadjaran (BUPP) with contract number 1595/UN6.3.1/PT.00/2021. Also, the authors thank the reviewers for the valuable review of this paper.

CONFLICT OF INTERESTS

The author(s) declare that there is no conflict of interests.

REFERENCES

[1] C. Huang, W. Ye, L. Xingwang, et al. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China, The Lancet 395 (10223) (2020), 497–506.

[2] Y.C. Wu, C.S. Chen, Y.J. Chan, The outbreak of COVID-19: An overview, J. Chinese Med. Assoc. 83 (3) (2020), 217–220.

[3] S. Perlman, Another decade, another coronavirus, N. Engl. J. Med. 382 (2020), 760–762.

[4] N. Zhu, D. Zhang, W. Wang, et al. A novel coronavirus from patients with pneumonia in China, 2019, N. Engl. J. Med. 328 (8) (2020), 727–733.
INAYATUROHMA, ANGGRIANI, SUPRIATNA

[5] M. Muhyiddin, H. Nugroho, A year of Covid-19: A long road to recovery and acceleration of Indonesia’s development, J. Perencanaan Pembangunan (Indones. J. Develop. Plan.) 5 (2021), 1–19.

[6] Y. Ophinni, A.S. Hasibuan, A. Widhani, et al. COVID-19 vaccines: Current status and implication for use in Indonesia, Acta Med. Indones. (Indones. J. Intern. Med.) 52 (2020), 388–412.

[7] M.L. Diagne, H. Rwezaura, S.Y. Tchoumi, J.M. Tchuenche, A mathematical model of COVID-19 with vaccination and treatment, Comput. Math. Methods Med. 2021 (2021), 1250129.

[8] M. Yavuz, E.O. Coslar, F. Gunay, et al., A new mathematical modeling of the COVID-19 pandemic including the vaccination campaign, Open J. Model. Simul. 9 (2021), 299–321.

[9] G. Webb, A COVID-19 epidemic model predicting the effectiveness of vaccination in the US, Infect. Dis. Rep. 13 (2021), 654–667.

[10] A. Zeb, E. Alzahrani, V.S. Erturk, G. Zaman, Mathematical model for coronavirus disease 2019 (COVID-19) containing isolation class, BioMed Res. Int. 2020 (2020), 3452402.

[11] M.A. Rois, Trisilowati, U. Habibah, Local sensitivity analysis of COVID-19 epidemic with quarantine and isolation using normalized index, Telematika 14 (2021), 13–24.

[12] N. Anggriani, M.Z. Ndii, R. Amelia, W. Suryaningrat, M.A.A. Pratama, A mathematical COVID-19 model considering asymptomatic and symptomatic classes with waning immunity, Alexandria Eng. J. 61 (2022), 113–124.

[13] F. Inayaturohmat, R. N. Zikkah, A. K. Supriatna, et al., Mathematical model of COVID-19 transmission in the presence of waning immunity, J. Phys.: Conf. Ser. 1722 (2021), 012038.

[14] S. Marino, I.B. Hogue, C.J. Ray, D.E. Kirschner, A methodology for performing global uncertainty and sensitivity analysis in systems biology, J. Theor. Biol. 254 (2008), 178–196.

[15] E. Gu, A nonparametric method for estimating partial correlation coefficient, J. Biometrics Biostat. 03 (2012), 8.

[16] P. Schober, C. Boer, L.A. Schwarte, Correlation coefficients: appropriate use and interpretation, Anesthesia Analgesia. 126 (2018), 1763–1768.

[17] S. Osaki, Applied stochastic system modeling, Springer-Verlag, Berlin, (1992).

[18] H.M. Taylor, S. Karlin, An introduction to stochastic modeling, Academic Press, New York, (1998).

[19] S.M. Ross, Stochastic processes, Second Edition, John Willey & Son Inc, New York, (1996).
OPTIMAL CONTROL AND SENSITIVITY ANALYSIS OF COVID-19 MODEL IN WEST JAVA

[20] M. Alawiyah, D.A. Johar, B.N. Ruchjana, Homogeneous Poisson process in daily case of covid-19, J. Phys.: Conf. Ser. 1722 (2021), 012078.

[21] H.Z. Mukhlida, G. Khairunnisa, Rindu, Review of trial therapies and treatment for COVID-19: Lessons for Indonesia, J. Kesehatan Masyarakat Nasional (Nat. Public Health J.), Spec. Iss. 1 (2020), 99–104.