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The susceptible-infected-recovered-dead model for long-term identification of key epidemiological parameters of COVID-19 in Indonesia

Muhammad Achirul Nanda[1], Anifatul Faricha[2], Siti Maghfirotul Ulyah[3], Ni'matut Tamimah[4], Enny Indasyah[5], Muhammad Falahudin Malich Salaz[6], Qurrotun Ayun Mawadatur Rohmah[7], Ulfah Abqari[8]

[1]Department of Agricultural and Biosystem Engineering, Faculty of Agro-Industrial Technology, Universitas Padjadjaran, Sumedang, Indonesia
[2]Department of Electrical Engineering, Institut Teknologi Telkom Surabaya, Surabaya, Indonesia
[3]Department of Mathematics, Faculty of Science and Technology, Airlangga University, Surabaya, Indonesia
[4]Department of Marine Engineering, Shipbuilding Institute of Polytechnic Surabaya, Surabaya, Indonesia
[5]Department of Automation Electronic Engineering, Faculty of Vocational, Sepuluh Nopember Institute of Technology, Surabaya, Indonesia
[6]Pharmaceutical Industry, PT. Eisai Indonesia, Bogor, Indonesia
[7]Dr. Soegiri Regional Public Hospital, Lamongan, Indonesia
[8]Department of Public Health, Erasmus MC, University Medical Center, Rotterdam, Netherlands

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ABSTRACT

The coronavirus (COVID-19) epidemic has spread massively to almost all countries including Indonesia, in just a few months. An important step to overcoming the spread of the COVID-19 is understanding its epidemiology through mathematical modeling intervention. Knowledge of epidemic dynamics patterns is an important part of making timely decisions and preparing hospitals for the outbreak peak. In this study, we developed the susceptible-infected-recovered-dead (SIRD) model, which incorporates the key epidemiological parameters to model and estimate the long-term spread of the COVID-19. The proposed model formulation is data-based analysis using public COVID-19 data from March 2, 2020 to May 15, 2021. Based on numerical analysis, the spread of the pandemic will begin to fade out after November 5, 2021. As a consequence of this virus attack, the cumulative number of infected, recovered, and dead people were estimated at ≈ 3,200,000, ≈ 3,437,000 and ≈ 63,000 people, respectively. Besides, the key epidemiological parameter indicates that the average reproduction number value of COVID-19 in Indonesia is 7.32. The long-term prediction of COVID-19 in Indonesia and its epidemiology can be well described using the SIRD model. The model can be applied in specific regions or cities in understanding the epidemic pattern of COVID-19.

Corresponding Author:

Siti Maghfirotul Ulyah
Department of Mathematics, Faculty of Science and Technology, Airlangga University
Surabaya 60115, East Java Province, Indonesia
Email: maghfirotul.ulyah@fst.unair.ac.id

1. INTRODUCTION

A novel coronavirus (COVID-19), originating from Wuhan in Hubei Province, China (on December 31, 2019), has spread to 213 countries and territories worldwide. This virus has brought many new challenges to public health and caused panic for everyone. Up to May 15, 2021, the cumulative number of confirmed cases, the total death and recovered individuals of COVID-19 outbreaks worldwide reached around 163,706 million, 3,392 million and 142,158 million, respectively [1]. Mostly, the people who are at risk of becoming seriously sick to the point of death are over the age of 60 with congenital health problems. The COVID-19 disease, is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [2]. In general, there are 3 symptoms that can indicate someone is infected with COVID-19, i.e., fever (body temperature above 38 °C), dry cough and shortness of breath. To confirm the COVID-19 diagnosis, health workers will conduct examinations based on: i) rapid test to detect antibodies, ii) swab test for detecting viruses in sputum, and iii) a computed tomography scan (CT-scan) to detect infiltrates or fluid in the lungs. According to the World Health Organization (WHO), the incubation period of COVID-19 or the time interval between people who are infected with COVID-19 until it starts showing symptoms, generally is around 1-14 days (most commonly around 5 days).

The COVID-19 epidemic has spread massively to almost all countries, including Indonesia, in just a few months. In Indonesia itself, two confirmed cases of COVID-19 were first reported in Jakarta Province on March 2, 2020 and showed an upward trend. According to study [3], Indonesia is the fourth most populous country in the world consisting of many islands, so it is predicted to suffer greatly for a longer period of time due to an outbreak, compared to other less densely-populated countries. Due to the rapid outbreak spread throughout the world, WHO has established COVID-19 as a pandemic. Therefore, handling COVID-19 requires a strict policy protocol to avoid the spread of more severe outbreaks. This must be supported by various parties, not only the government, but also the public, research institutions, industry, and digital media.

Based on the problems described above, an important step to overcome the spread of new diseases such as COVID-19 is to conceive its epidemiology through mathematical modeling intervention. This modeling is a data-based analysis for comprehensively modeling and forecasting the dynamic pattern of the COVID-19 disease in certain populations. This is useful for those who support the government and health authorities in the resource's allocation. Some important information will be obtained from epidemiological analysis such as the total population of susceptible, infected, recovered, and dead individuals, as well as the infection peak and end of the outbreak. Several analyses and mathematical approaches have been proposed to predict the COVID-19 epidemic's trend in various countries such as: i) in China, i.e., the susceptible-infected-recovered-dead (SIRD) model [4], susceptible-exposed-infectious-removed (SEIR) model [5] and adaptive neuro-fuzzy inference system (ANFIS) model [6]; ii) In Brazil, i.e., the susceptible-infected-asymptomatic-symptomatic-dead (SIASD) model [7]; iii) In Italia, i.e., the SIRD model [4]; and iv) In Utah, i.e., the log-logistic model [8]. However, each country has a different character, culture and level of discipline that will have an impact on the specific epidemic of the coronavirus.

In Indonesia itself, massive research on the prediction of the epidemiology of COVID-19 is widely reported. A number of such studies use a technique based on the support vector regression [9], logistic [10], long short-term memory [11], Morgan-Mercer-Flodin [12], SEIR [13], artificial neural network [14], exponential smoothing [15] and deterministic-stochastic model [16]. However, most of these various techniques are unable to comprehensively explain key epidemiological parameters, including susceptible, infected, recovered, dead people, infection peak and end of the outbreak, and reproduction number. In addition, the performance may not be reliable to apply to current conditions due to the data set used is out of date. Of the various techniques that have been applied, the SIRD model is the most commonly recommended approach and is appropriate to describe the characteristics of epidemic patterns in detail [17]. To date, the potential application of this model has not been reported to understand the COVID-19 outbreak in Indonesia. Researchers explained that the SIRD model was not only able to predict COVID-19, but also other diseases such as the Canine distemper virus [18] and Ebola virus [19]. Clearly, there is a scope to apply the SIRD model in response to the epidemiological pattern of COVID-19, especially in Indonesia.

In general, the conventional SIRD model can only simulate epidemiological patterns in the short-term period without involving optimization techniques and lacking detail in visualizing key parameters. In this study, unlike the SIRD model in general, the proposed SIRD model can explain and track the epidemic pattern in detail based on optimization technique. More specifically, some of the advantages are being able to: i) provide information regarding the key epidemiological parameters, ii) uncover the pattern of these outbreaks starting from the initial stages of spread until they fade out, iii) detect the infection peak of the pandemic, iv) identify the reproduction number, v) describe the rate of infection, recovery and death, vi) adjust the lockdown time, vii) visualize the long-term prediction, and viii) identify the number of susceptible, infected, recovered, and dead people. Besides, the SIRD model implements an optimization technique to produce accurate prediction capabilities. These overall advantages are claimed to be the novelty of the proposed SIRD approach. Therefore, this study aimed to develop the SIRD model, which incorporates the key epidemiological parameters to model and estimate the long-term spread of the COVID-19 epidemic.

2. METHOD

2.1. Data collection

The most recent epidemiological data based on the daily COVID-19 outbreak in Indonesia were retrieved from the COVID-19 National Task Force and KawalCOVID-19. These are a verified online system connected to the Indonesian National Board for Disaster Management and report daily COVID-19 cases from all provinces in Indonesia. We use the recent COVID-19 data from March 2, 2020 to May 15, 2021 to model and forecast the evolution of the COVID-19 pandemic in Indonesia. The COVID-19 pandemic was first confirmed to have spread to Indonesia on March 2, 2020, when a dance instructor and his mother were infected from Japanese citizens. By May 15, 2021, the virus has spread throughout 34 provinces in Indonesia as shown in Figure 1. The provinces of Jakarta, West Java, Central Java, and East Java became the worst-hit of COVID-19, which is indicated by the number of cases ≥ 1,000,000.

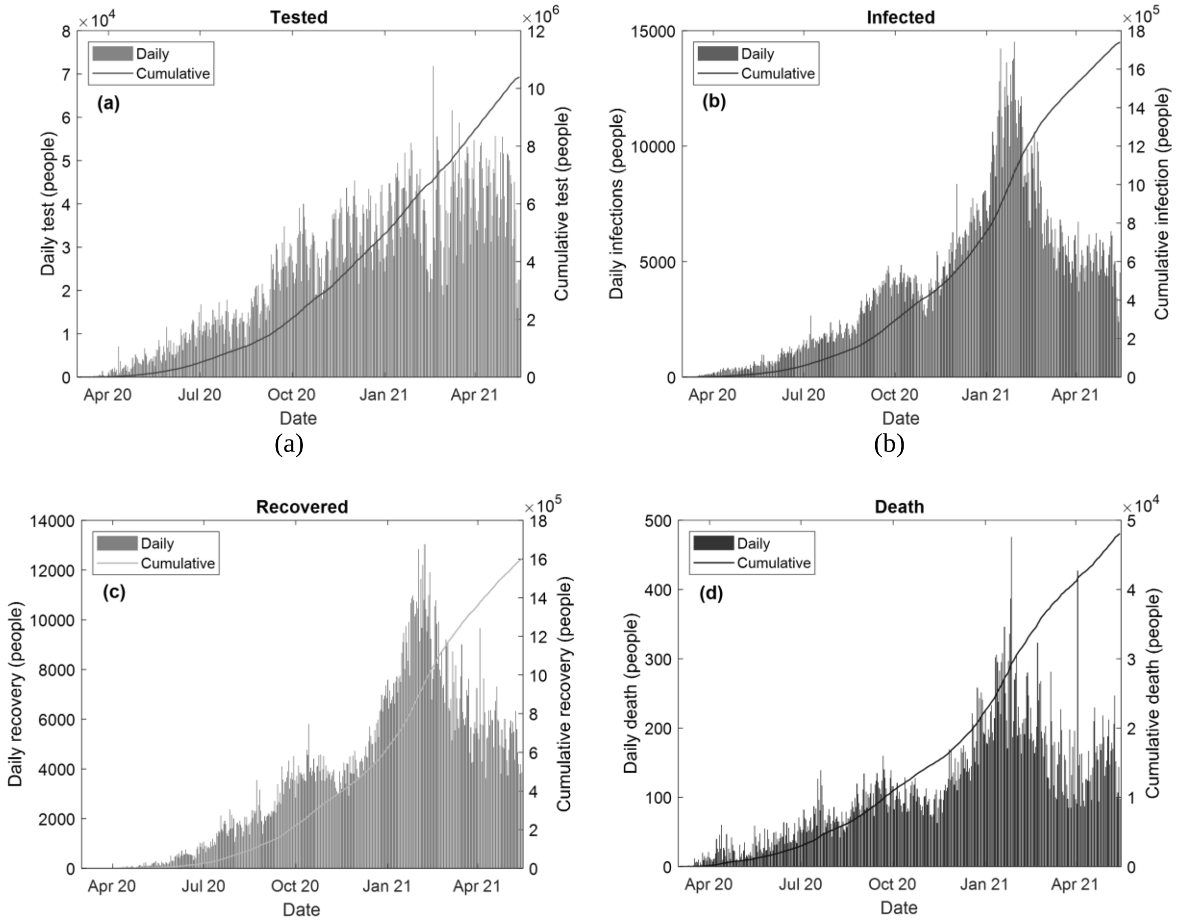
Figure 1. Map of the confirmed cases of the COVID-19 pandemic in Indonesia [20]

2.2. Preliminary insight from the reported COVID-19 data

The number of people tested for COVID-19, infected, recovered and who have died in Indonesia is detailed in Figure 2. This whole graph shows the cumulative cases on the right side and daily cases on the left side. As of May 15, 2021, the number of COVID-19 testing conducted by the Indonesian government was ≈10,400,000. This value is still lower compared to its neighbors (i.e., Singapore, Malaysia, Thailand, and Vietnam). This relates to the fact that the implementation of COVID-19 testing in Indonesia is based on contact tracing from infected people previously instead of widespread testing. The number of daily COVID-19 tests reached the highest peak (around 72,000) on February 18, 2021 and has a decreasing trend over time as shown in Figure 2(a). In the case of infected people, the cumulative number of daily reported cases increased exponentially during this early phase from March 2, 2020 to May 15, 2021, where a total of ≈1,700,000 people is reported to have been infected with COVID-19. Figure 2(b) shows that the highest peak of COVID-19 transmission in Indonesia occurred on January 27, 2021. In addition, the initial visualization of COVID-19 in Indonesia confirmed that the number of recovered people was greater than those who died from the virus as shown Figure 2(c)-(d). The daily death rate also shows an upward trend from end September 2020 to end January 2021 and then a downward trend in the next period. The response of the Indonesian government to overcome the COVID-19 outbreak was to ensure the implementation of social and physical distancing such as banning public events, school closures and restricting commerce.

2.3. SIRD model

Mathematical modeling is a recognized powerful tool to investigate transmission and epidemic dynamics. COVID-19 outbreaks can be described using an ordinary differential equations (ODEs) approach, i.e., SIRD model. This model depicts the spread of an infectious disease in a population split into three non-intersecting classes: susceptible, infected, recovered, and dead. Susceptible (S) represents individuals who are healthy but can contract the disease, infected (I) represents individuals who suffer from the disease and can transmit it to the susceptible, recovered (R) represents individuals who recovered from the disease, and death (D) is a dead individual. The schematic diagram of the SIRD model is illustrated in Figure 3.



(a) (b)

(c) (d)

Figure 2. The COVID-19 trend in Indonesia: (a) people tested for COVID-19, (b) infected people, (c) the number of recovered people, and (d) the number of dead people

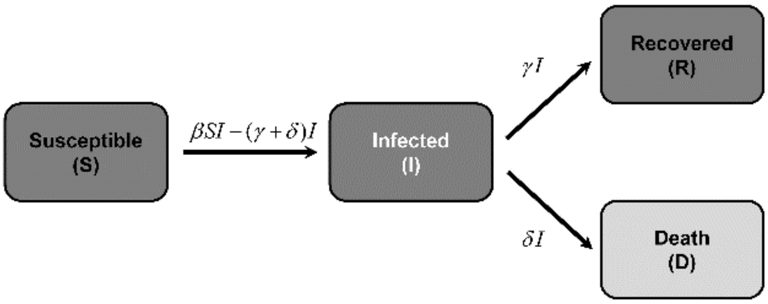


Figure 3. Compartments of the SIRD model

Some assumptions in applying the SIRD model are explained as follows. Firstly, every individual in the same compartment has spatial homogeneity. Secondly, the reference population is constant, meaning that there were no births, deaths, and migrations in the simulation period of the model. Thirdly, disease transmission is through contact between susceptible and infected individuals. Lastly, it is also assumed that recovered people cannot be re-infected. The SIRD model is described by the following system of four differential equations.

$$\frac{dS}{dt}=-\beta SI \tag{1}$$

$$\frac{dI}{dt} = \beta SI - (\gamma + \delta)I \qquad (2)$$

$$\frac{dR}{dt} = \gamma I \qquad (3)$$

$$\frac{dD}{dt} = \delta I \qquad (4)$$

$$N(t) = S(t) + I(t) + R(t) + D(t) \qquad (5)$$

Let us define $S(t), I(t), R(t)$ and $D(t)$ as the number of susceptible, infected, recovered, and dead people at time t, respectively. Due to the dynamic evolution of the COVID-19 outbreak, the size of each class can change over time and N is the total population size (Census-based data for Indonesia $N = 268 \times 10^6$ people). Also, based on reported data of COVID-19, the initial condition of I_0, R_0, and D_0 can be defined with values 2, 0, and 0, respectively. In this study, the package of the SIRD model for COVID-19 outbreaks is applied to model and forecast on the COVID-19 in Indonesia. This model was performed in a MATLAB 2016b environment.

The SIRD model has several parameters that must be optimized to provide reliable forecasting. These parameters are among others: i) β is the infection rate, i.e., the probability per unit time that susceptible individuals are exposed to the disease when entering contact with an infected person; ii) γ is the recovery rate; and iii) δ is the death rate. In this study, the optimization process was performed with an easy built-in function 'ode45' solver in MATLAB 2016b based on an explicit Runge-Kutta formula. We calibrated the parameters β, γ and δ of the SIRD model to fit the COVID-19 data. The upper and lower bounds in each parameter are β (0-0.7), γ (0-1) and δ (0-0.5). The global objective function was to minimize the residual values between prediction results and reported COVID-19 data by finding the most optimal combination of the parameters.

2.4. Reproduction number

Human-to-human transmission of COVID-19 has been reported, and evaluation of transmissibility plays an essential role in predicting the pandemic's probable size. In this case, the SIRD model introduces the reproduction number parameter, $\Re_0$. This parameter is defined as the expected number of secondary cases produced by a single (typical) infection in a completely susceptible population, where an infected individual has contracted the disease and susceptible individuals are healthy, but can acquire the disease [21]. Basically, reproduction number is a key parameter that can be used to guide control strategies in dealing with outbreaks. If $\Re_0 < 1$, then the outbreak will fade out; vice versa, if $\Re_0 > 1$ then the epidemic will persist to infect individuals in the population. According to study [4], the larger the value of $\Re_0$, the harder it is to control the epidemic. It is straightforward to exhibit that the reproduction number is computed by (6).

$$\Re_0 = \frac{\beta}{\gamma + \delta} \qquad (6)$$

2.5. Model evaluation

The epidemic trend of COVID-19 is projected from the beginning of the outbreak March 2, 2020 to July 31, 2022. The results of the SIRD model analysis are evaluated by comparing the prediction results and actual values [22]. In this case, we predict the cumulative number every day in each compartment (i.e., infected, recovered, dead). The evaluation metric coefficient determination (R^2) are applied to measure the performance of the proposed model. The R^2 is defined as the proportion of the variance in the dependent variable that is predictable from the independent variables [17]. A good model should have a high R^2.

3. RESULTS

3.1. The SIRD model optimization and evaluation

The compartments of SIRD model are fitted on the actual data to obtain an in-depth description of the COVID-19 epidemic pattern. The SIRD model works to build the line curve as a best-fit, which is the best approximation of the given set of data. This best-fit is the optimal solution provided by minimizing the smallest possible error prediction [23]. The optimal parameter values have been found based on the predetermined upper and lower bounds. Based on the numerical analysis, the optimal pair values of the parameters $\beta, \gamma,$ and δ are 0.0953, 0.0027 and 0.0034, respectively as shown Table 1. Numerous techniques, including genetic algorithm [24] and fuzzy logic [25], can be used to further improve these hyperparameters. Overall, those parameters are useful for modeling and forecasting on the COVID-19 pandemic based on the SIRD model. Based on the analysis, the parameter γ is the lowest value, it means that the recovered people exposed by COVID-19 is complicated and takes longer. This phenomenon has the same characteristics in the COVID-19 outbreak in Italy, where the recovered rate is lower than the infection and death rate of COVID-19 outbreak [4], the difference in this phenomenon can be caused by variations in public health interventions in each country [26].

Table 1. The results of the evaluation of predictions on each compartment model

Compartment model	Parameter	Optimal rate value (1/day)	Evaluation metric of R^2
Infected	β_0	0.0954	0.9834
Recovered	γ_0	0.0027	0.9211
Dead	δ_0	0.0034	0.9696
		Mean	0.9580

Furthermore, the prediction results in each compartment generated by the SIRD model are validated with actual reported data from COVID-19 in Indonesia (time period from March 2, 2020 to May 15, 2021). Based on the analysis, the infected model has the highest R^2 (0.9834) versus the dead (0.9696) and recovered model (0.9211). This result can be explained through Figure 4, where the infected model more coincides with the data than recovered and dead model, visually. So, this impacts the high R^2 value in the infected compartment model compared to others. R^2 has a range between 0–1 and refers to the correlation between the prediction obtained by the SIRD model and the COVID-19 data. Overall, the average R^2 of the compartments is 0.9580. For comparison, Al-qaness [6] reported that the flower pollination algorithm using the Salp swarm algorithm (FPASSA) method for predicting confirmed cases of COVID-19 in China achieved an R^2 of 0.9645.

3.2. Long-term COVID-19 forecasting

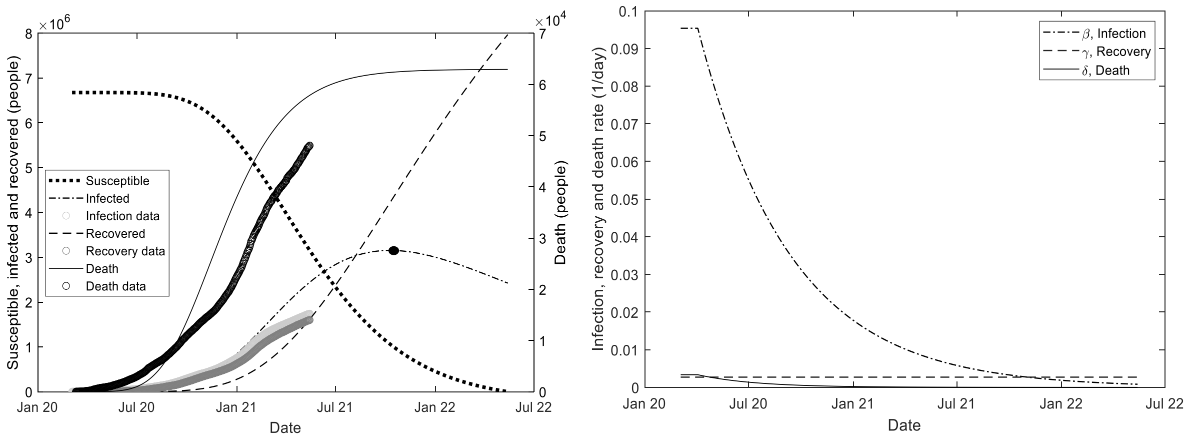
The long-term forecasting results of COVID-19 in Indonesia are depicted in Figure 4. Visually, based on the SIRD model, the infected and death compartments follow the sigmoid or logistic curve trend, while the recovered compartment shows the characteristic of the exponential curve trend. The solid and dashed lines denote the long-term trend of coronavirus in each compartment based on the fits of SIRD model, and hollow circles show reported COVID-19 data. The solid black circle (●) on the black dashed line is the infection peak of a pandemic of the COVID-19 in Indonesia, i.e., November 5, 2021. (b) Infection, recovery, and death rate of the COVID-19 outbreak. The epidemiology can be well described using the best-fit lines of the SIRD model. As can be seen in Figure 4, the model is able to provide long-term projections until the mid of 2022 by minimizing the smallest possible errors. However, it can be remarked from Figure 4(a) that the model is less able to follow the trend in the data regarding recovered. In more detail, the model diminishes the number of recovered people over a period of time. It should be noted that we have modified the upper and lower bounds of each parameter to find the most optimal combination with the smallest possible error. However, specifically for the recovered compartment, the model is still less able to follow the death trend data. So, Figure 4 is the optimal solution given by the SIRD model. In the future, the implementation of various machine learning, such as long short-term memory [27], Jordan recurrent neural network [28], deep learning [29] and support vector regression [30], may present an attractive research challenge.

Based on the SIRD model, each compartment can be discussed as follows. Of the total population of Indonesia (268 million people), there are ≈ 6,700,000 people who are susceptible to the COVID-19 epidemic (susceptible compartment). The SIRD model places the infection peak of COVID-19 outbreak in Indonesia on November 5, 2021 and predicts a maximum of total cumulative of infected people up to ≈ 3,200,000. After passing the peak phase, the downward trend in the outbreak will occur slowly, and this assumes that there are no new confirmed coronavirus cases anymore. So, the government can focus on handling infected patients. Also, the SIRD model confirms that at the end of the epidemic, COVID-19 in Indonesia will cause up to ≈ 63,000 deaths and result in up to ≈ 3,437,000 recoveries.

The kinetic of COVID-19 spreading in Indonesia in each compartment can be observed in detail in Figure 4(b) (see Table 1 for each initial rate value). At the beginning of the spread of outbreaks in Indonesia in early March, infection had the highest rate compared to recovered and death. That is, more people were infected with COVID-19 than those who died or recovered. The recovered compartment shows a constant rate over time which means there is a great chance of recovery from infected people. The analysis also estimates that the death rate will drop to zero around July 2021 and that most infected people will undergo a recuperation process.

3.3. Reproduction number of the COVID-19 in Indonesia

As can be seen in Figure 5, the solid black circle (●) shows the initial sign that the pandemic will start to fade out ($\Re_0 < 1$), i.e., November 5, 2021. The black dashed line acts as a keen threshold between the disease dying out or leading to an epidemic. Using the epidemic model generated by SIRD approach, we report an estimation of the reproduction number of COVID-19 during the early stage until it fades out. The $\Re_0$ value at the early spreading of COVID-19 in Indonesia was 15.71. This value is still lower than that of China at the beginning of the outbreak (i.e., 22.5) [4]. In this study, the highest peak of $\Re_0$ can be found on April 3, 2020. The $\Re_0$ value is very closely related to the rate of infection, recovery, and death of the outbreak, that the higher the infection rate and the lower the recovery and death rate, then the higher the $\Re_0$ value (6). Based on the analysis, the average reproduction number value COVID-19 in Indonesia is 7.32, meaning that every single sick person COVID-19 can infect 7.32 people (the grey filled area in Figure 5). The spread of the pandemic will begin to fade out after November 5, 2021 (right after reaching the peak phase) where outbreak handling can be easily controlled. However, it should be noted that in that period, the government will still be dealing with a number of infected people who need to be cured.



(a) (b)

Figure 4. Long-term prediction of COVID-19 outbreak (a) the fits of SIRD model in each compartment and (b) infection, recovery and death rate of the COVID-19 outbreak

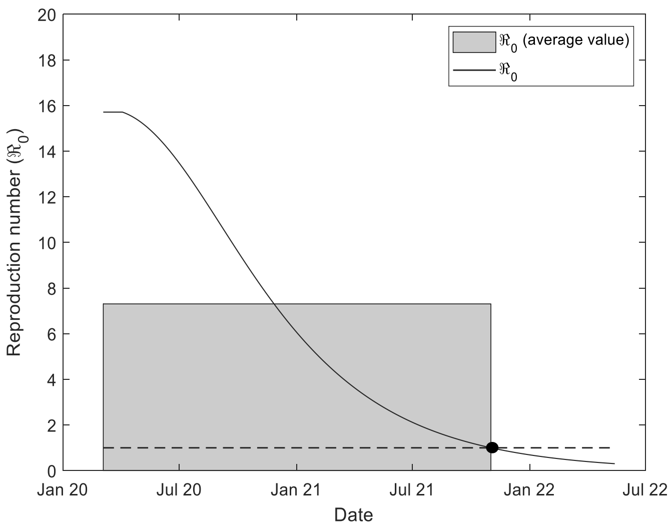


Figure 5. The reproduction number of COVID-19 in Indonesia at the early stage until it fades out

The $\Re_0$ knowledge is crucial information because it is related to virus handling. The value of $\Re_0 > 1$ reflects the ability of an infection spreading under no control, and vice versa. Based on the literature studies, researchers have reported $\Re_0$ of COVID-19 values in several countries, i.e., 8.3 in China [4], 3.9 in Italia [4], 3.86 in Malaysia 3.86 [31], 2.48 in Thailand [31] and 0.9 in Singapore [32]. The effective steps for flattening the $\Re_0$ curve of COVID-19 are lockdown, large-scale social restrictions, as well as social and physical distancing.

4. DISCUSSION

We have developed the SIRD model that incorporates the key epidemiological parameters to model and estimate the spread of the COVID-19 epidemic in Indonesia. Our model formulation is data-based analysis by considering publicly available COVID-19 data from March 2, 2020 to May 15, 2021. The key parameters β, γ, and δ has been optimized by minimizing the minimum error prediction to provide a long-term projection of COVID-19. The proposed model is able to uncover the pattern of these outbreaks starting from the initial stages of spread until they fade out. This understanding plays an important role for the implementation of public limitation policies designed by the government in reducing the epidemic severity.

Based on the numerical analysis, the optimal pair values of the parameters β, γ, and δ are 0.0953, 0.0027 and 0.0034, respectively. In principle, these three parameters can vary from country to country depending on population density, culture, demography, travel patterns and other factors. Parameter β as the infection rate of the spread of COVID-19 in Indonesia is relatively high. We strongly suspect that this is related to the cultural factors of the Indonesian people, one of which is the shake hands culture embedded from the past until now in various layers of social class; unfortunately, this is an effective way to transfer coronavirus.

Important findings in this epidemic modeling reveal that the spread of the pandemic will begin to fade out after November 5, 2021. However, the end of this outbreak can come sooner if a vaccine has been found and the whole society avoids various factors having an impact on increasing the infection rate. The cumulative number of infected people recovered people and dead people is estimated to reach ≈ 3,200,000 people, ≈ 3,437,000 people and ≈ 63,000 people, respectively. Based on the performance evaluation, the proposed SIRD model shows the cumulative number prediction capability in each compartment, which is quite satisfactory with an average value of R^2 is 0.9580. In addition, this study shows that the average reproduction number value of COVID-19 in Indonesia is 7.32. This value is higher than the average reproduction number of SARS in 2003, i.e., 2.5 [33]. Because COVID-19 is a new epidemic, special treatment is needed to overcome its spread.

In Indonesia, the real action of the government in combating the COVID-19 outbreak is with large-scale social restrictions (PSBB) policy instead of lockdown policy. PSBB is a limitation of certain activities in an area suspected of being infected with COVID-19. This policy has been going on since April 7, 2020, which can be extended and stopped at any time. Considering the reproduction number curve in this study, and to avoid the second COVID-19 wave, at least the PSBB is applied until the end of August 2020. After August 2020, all economic activity can be reopened with regard to health protocols (known as 'new normal') and until the COVID-19 vaccine is truly found.

At this point, we need to declare that the proposed SIRD model does not consider many factors that play an important role in the pattern of disease spread such as heterogeneous population characteristics (i.e., age level and people who have health problems), impact of asymptomatic infectious cases, government policy interventions, incubation period of COVID-19 and medical facilities. However, an interesting point in this study is that the model has fulfilled one of the assumptions required in the SIRD approach, i.e., no migration. That is, at present, susceptible people are living in alienation similar to those required by imposing restrictions on mobility and social life. Thus, the model successfully mimics this situation and the predicted results will be more accurate. We remark that the proposed approach is quite general and as such can be applied in certain regions or cities in understanding epidemic patterns. Also, to describe the complex dynamics of a crowd that involves several interacting people, the SIRD approach can be combined with multi-agent modeling [34], [35]. This model assumes that each individual person represents an agent that moves within a limited area and interacts with other agents according to specific rules. This combination will be an attractive future research direction.

A crucial aspect of COVID-19 outbreak, rather than the percentage of infections and even the death rate, is the capacity of the health care system. The high number of infected people and the low number of intensive care units (ICUs), as well as respiratory aid such as ventilator are some of the factors that can exacerbate the current situation. To respond to this, the Indonesian government has built a new hospital with a capacity of 1,000 beds on Galang Island in anticipation of a health system failure. Based on this phenomenon, it can be concluded that no country is truly prepared for a large number of critical patients.

Therefore, we hope that the results of our analysis have a significant contribution to the explanation of key aspects of the COVID-19 outbreaks' epidemiology so that this virus fades out as soon as possible regionally, in Indonesia, and internationally.

5. CONCLUSION

Knowledge of epidemic dynamics patterns is an important part of making timely decisions and preparing hospitals for the peak of the COVID-19 outbreak. In this work, we proposed the SIRD model, which incorporates the key epidemiological parameters capable of forecasting the spread of COVID-19 in Indonesia. Based on the numerical analysis, the spread of the pandemic will begin to fade out after November 5, 2021. Thus, the government needs to prepare strategic steps to adapt in overcoming coronavirus. As a result of this COVID-19 attack, the cumulative number of infected people, recovered people and dead people sequentially is estimated to reach ≈ 3,200,000 people, ≈ 3,437,000 people and ≈ 63,000 people, respectively. Moreover, the key epidemiological parameter indicated that the average reproduction number value of COVID-19 in Indonesia is 7.32. Based on performance evaluation, the proposed SIRD model is able to predict the cumulative number in each compartment with the average value of R^2 being 0.9580. The results of this prediction are quite satisfying and thus, have the potential to be applied in certain regions or cities in understanding the epidemic pattern of COVID-19.

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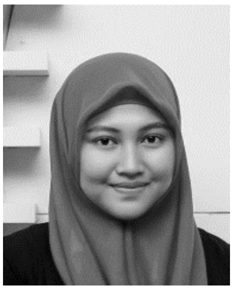
BIOGRAPHIES OF AUTHORS

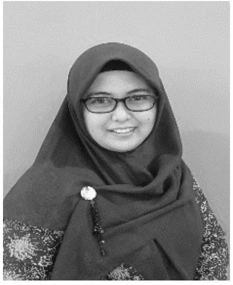
Muhammad Achirul Nanda is a lecturer in the Department of Agricultural and Biosystem Engineering, Faculty of Agro-industrial Technology, Universitas Padjadjaran. He completed Ph.D. degree at 25 years old in the field Agricultural Engineering at the IPB University, Indonesia. In terms of collaboration, he performed a research Internship at Research Institute for Sustainable Humanosphere, Kyoto University in 2020. His research interests include smart and precision agriculture, artificial intelligence system and non-destructive measurement. In addition, he is a member of the Indonesian Society of Agricultural Engineering (PERTETA). He can be contacted at email: m.achirul@unpad.ac.id.



Anifatul Faricha started her undergraduate program in 2010 with a Bidik Misi Scholarship at Electrical Engineering, ITS, Surabaya Indonesia. In 2014, she received a scholarship from Taiwan to continue her Master's Program at the Graduate Institute of Automation and Control (GIAC), National Taiwan University of Science and Technology (NTUST). Then, in 2020, she received a MEXT Scholarship from the Japanese Government to continue her doctoral studies at Tokyo Institute of Technology, Department of Information and Communication Engineering. She has joined ITTelkom Surabaya since 2018. Her research interests include Machine Learning, Electronic Nose, Sensor System, Artificial Intelligence, Diffraction Based Overlay, Chip Metrology, and Amperometric Sensor. She can be contacted at email: faricha@ittelkom-sby.ac.id.

Siti Maghfirotul Ulyah is a junior lecturer at the Department of Mathematics Universitas Airlangga. She finished her bachelor study in Statistics, Institut Teknologi Sepuluh Nopember in 2014. Then, she continued her master’s degree in finance, National Taiwan University of Science and Technology. She was awarded a scholarship from the Ministry of Religious Affairs Indonesia during her undergraduate study and scholarship from NTUST for her master study. Her research interest is in Financial Statistics, Stochastic Modelling and Time Series Analysis. She can be contacted at email: maghfirotul.ulyah@fst.unair.ac.id.

Ni'matut Tamimah is a junior lecturer in the Marine Engineering Department, Shipbuilding Institute of Polytechnic Surabaya since 2018. Her Education background started from 2009 in Physics major, Universitas Airlangga. In 2014, she received a scholarship from the Taiwan Government to continue Master Program at the Graduate Institute of Applied Science (GIAS), National Taiwan University of Science and Technology (NTUST). She can be contacted at email: nimatuttamimah@ppns.ac.id.



Enny Indasyah is a lecturer in Department of Electrical Automation Engineering, Faculty of Vocational, Institut Teknologi Sepuluh Nopember (ITS) Surabaya. She started the bachelor program in 2009 in Telecommunication Engineering Department, Electronic Engineering Polytechnic Institute of Surabaya (EEPIS). In 2013, she received fresh graduate Scholarship from Indonesia Government to continue the master program in Electrical Engineering Department, Institut Teknologi Sepuluh Nopember (ITS) Surabaya. Then, in 2014, she received scholarship from Taiwan for Double degree master program in Computer Science Department, National Taiwan University of Science and Technology (NTUST). Her research focus includes image processing, artificial intelligence, data science, machine vision and machine learning. She can be contacted at email: enny_indasyah@its.ac.id.

Muhammad Falahudin Malich Salaz works in Pharmaceutical Industry, PT Eisai Indonesia, Bogor 16810, West Java Province, Indonesia. He completed the bachelor degree in Department of Pharmacy, Universitas Indonesia. He can be contacted at email: malich.salaz@gmail.com.

Qurrotun 'Ayun Mawadatur Rohmah is a General practitioner in Dr. Soegiri Regional Public Hospital, Lamongan, Indonesia. She completed the bachelor degree in the Faculty of Medicine, Universitas Diponegoro. She can be contacted at email: 12qurrotun.ayun@gmail.com.

Ulfah Abqari is Ph.D. student of Infectious Diseases and Public Health in the Department of Public Health, Faculty of Medicine and Health Science, Erasmus MC, University Medical Center, The Netherlands. She took a bachelor degree of Public Health in Faculty of Public Health, Universitas Airlangga Surabaya. Her Ph.D. study focuses on promoting early case detection of leprosy in Indonesia incorporated in the multi-country study of PEP++ in Brazil and India. He can be contacted at email: ulfah@nlrindonesia.or.id.