

Data-Driven Susceptible–Infected–Recovered–Dead (SIRD) Modeling Framework for Long-Term Estimation of Critical Epidemiological Parameters of COVID-19 Dynamics in Indonesia

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KEYWORDS

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ABSTRACT

The COVID-19 pandemic has demonstrated complex nonlinear transmission dynamics that require robust mathematical and data-driven modeling frameworks for long-term epidemiological forecasting. This study proposes a data-driven Susceptible–Infected–Recovered–Dead (SIRD) modeling framework to estimate key epidemiological parameters governing COVID-19 spread in Indonesia. The model integrates classical compartmental epidemiology with data-informed parameter calibration techniques to improve long-term predictive stability under variable intervention scenarios. Building upon established epidemic modeling literature (Annas et al., 2020; Caccavo, 2020), the proposed framework incorporates dynamic transmission rate estimation, mortality-adjusted recovery processes, and time-varying reproduction number analysis. Comparative evaluation with SEIR-based and statistical forecasting approaches demonstrates that the SIRD structure provides a computationally efficient yet sufficiently expressive representation of disease progression trends in resource-constrained environments.

The study further incorporates insights from optimization-based forecasting methods and neural network prediction frameworks to enhance parameter robustness under uncertain reporting conditions (Al-qaness et al., 2020; Nyoni et al., 2020). Validation against Indonesian epidemiological datasets and global benchmarks shows that the proposed framework achieves improved stability in long-term forecasting of infection and mortality trends. The findings highlight the importance of integrating deterministic epidemiological models with adaptive data-driven calibration mechanisms for improved pandemic decision support systems.

1. Introduction

Background

The COVID-19 pandemic has created unprecedented challenges for public health systems globally, particularly in developing countries such as Indonesia, where healthcare infrastructure constraints amplify uncertainties in disease tracking and response strategies. Classical epidemiological models such as SIR, SEIR, and their extensions have been widely adopted to understand disease transmission dynamics (Annas et al., 2020; Harapan et al., 2020). Among these, the SIRD model introduces mortality as a separate compartment, making it more suitable for diseases with significant fatality

outcomes.

The evolution of COVID-19 modeling has transitioned from purely deterministic frameworks to hybrid data-driven systems integrating optimization, machine learning, and statistical forecasting techniques (Al-qaness et al., 2020; Bastos & Cajueiro, 2020). However, many models still struggle to maintain stability over long-term horizons due to parameter uncertainty and reporting inconsistencies.

Problem Statement

Despite extensive research, existing models often fail to simultaneously achieve computational efficiency,

interpretability, and long-term predictive accuracy. In Indonesia, variability in reporting systems and intervention policies further complicates parameter estimation. Therefore, there is a need for a robust SIRD-based framework that can integrate real-world data variability with stable epidemiological parameter estimation.

Objectives

The primary objectives of this study are:

1. To develop a data-driven SIRD modeling framework for COVID-19 dynamics in Indonesia.
2. To estimate critical epidemiological parameters including transmission, recovery, and mortality rates.
3. To evaluate long-term forecasting stability under variable conditions.
4. To compare the proposed framework with existing epidemiological and AI-based models.

3.4 Scope and Significance

This study focuses on long-term epidemiological behavior rather than short-term prediction. It bridges classical mathematical epidemiology and modern data-driven modeling approaches, contributing to improved pandemic preparedness strategies. The inclusion of mortality dynamics enhances realism in modeling COVID-19 progression in Indonesia.

Literature Review

Classical epidemic modeling has evolved significantly from simple compartmental frameworks to advanced hybrid computational systems. The SIRD model has been widely adopted for COVID-19 due to its ability to capture mortality explicitly (Caccavo, 2020). Annas et al. (2020) demonstrated SEIR-based stability analysis in Indonesia, highlighting the importance of parameter sensitivity in forecasting accuracy.

Data-driven forecasting approaches such as neural networks and smoothing techniques have been applied to COVID-19 prediction with varying success. Nyoni et al. (2020) used artificial neural networks for daily case prediction, while Harini (2020) employed exponential smoothing methods for case identification. Although

effective in short-term forecasting, these approaches often lack epidemiological interpretability.

Optimization-based approaches have also gained traction. Al-qaness et al. (2020) proposed hybrid optimization methods for forecasting confirmed cases in China, improving accuracy under nonlinear conditions. Similarly, Faricha et al. (2020) compared predictive models for outbreak estimation, emphasizing the importance of hybridized analytical structures.

The theoretical foundation of reproduction numbers and epidemic thresholds is well established in infectious disease modeling (van den Driessche, 2017; Liu et al., 2020). These works provide mathematical grounding for understanding disease propagation limits.

Indonesia-specific studies, such as Nuraini et al. (2020) and Ndi et al. (2020), highlight the variability of transmission patterns and the importance of localized calibration. Governmental data sources (Kemenkes) provide essential empirical grounding for model validation.

Multi-agent systems and AI-based epidemic simulations further extend modeling capabilities but often require high computational cost (Vykylyuk et al., 2021; Nadini et al., 2020). Compared to these, SIRD-based frameworks remain computationally efficient and interpretable.

Importantly, control and optimization methodologies from engineering domains, such as proportional-integral and fuzzy logic systems, demonstrate the relevance of adaptive control strategies in dynamic systems (Ahlem et al., 2020). Although originally applied to power systems, such methodologies inspire adaptive parameter tuning in epidemiological models.

METHODOLOGY

SIRD Model Structure

The SIRD model divides the population into four compartments:

- Susceptible (S)
- Infected (I)
- Recovered (R)
- Dead (D)

The governing equations are:

- $dS/dt = -\beta SI/N$
- $dI/dt = \beta SI/N - (\gamma + \mu)I$
- $dR/dt = \gamma I$
- $dD/dt = \mu I$

where β represents transmission rate, γ recovery rate, and μ mortality rate.

This structure is widely used for COVID-19 modeling due to its simplicity and interpretability (Caccavo, 2020; Berge et al., 2017).

Data-Driven Parameter Estimation

The framework employs a hybrid calibration strategy combining statistical optimization and numerical simulation. Parameter estimation is performed using least-squares minimization against reported infection and mortality data.

Inspired by optimization techniques in forecasting models (Al-qaness et al., 2020), the objective function minimizes error between predicted and observed values:

$$E = \sum (I_{obs} - I_{pred})^2 + (D_{obs} - D_{pred})^2$$

Reproduction Number Estimation

The basic reproduction number R_0 is defined as:

$$R_0 = \beta / (\gamma + \mu)$$

This metric is critical for evaluating epidemic intensity (van den Driessche, 2017; Liu et al., 2020).

Data Sources and Preprocessing

Data is obtained from Indonesian health reports and global COVID-19 datasets (Worldometer, Kemenkes). Preprocessing includes normalization, smoothing, and outlier removal to handle reporting inconsistencies.

Model Calibration Strategy

A time-window-based calibration approach is used to adjust parameters dynamically. This ensures adaptability to policy interventions and behavioral changes in population dynamics (Pan et al., 2020).

Results / Findings

The proposed SIRD framework demonstrates strong alignment with observed COVID-19 trends in Indonesia. Transmission rates exhibit temporal variation consistent with intervention phases. The model successfully captures peak infection periods and subsequent decline phases.

Mortality estimation remains stable across long-term simulations, indicating robustness of the μ parameter under noisy data conditions. Recovery dynamics align with observed clinical progression trends reported in epidemiological studies (Harapan et al., 2020).

Comparative analysis shows that SIRD outperforms simple statistical models in stability, while maintaining competitive accuracy against neural network-based approaches (Nyoni et al., 2020). However, AI-based models show higher short-term precision but lower interpretability.

A key finding is that dynamic recalibration significantly improves forecasting reliability. Without recalibration, error accumulation increases over time. With adaptive updates, prediction error remains bounded.

The inclusion of engineering-inspired control perspectives (Ahlem et al., 2020) demonstrates that stability-enhancing mechanisms can improve epidemiological parameter convergence, particularly under fluctuating data conditions.

Overall, the model achieves consistent long-term trend prediction, making it suitable for policy-level decision support.

Discussion

The results highlight the trade-off between model simplicity and predictive richness. While advanced AI models provide higher short-term accuracy, they lack transparency and epidemiological interpretability. In contrast, the SIRD framework offers clear causal structure and parameter interpretability.

The integration of data-driven calibration enhances classical compartmental models, bridging the gap between deterministic and stochastic approaches. This hybridization aligns with trends in epidemic modeling literature (Anastassopoulou et al., 2020; Bastos &

Cajueiro, 2020).

However, limitations exist. The model assumes homogeneous mixing, which may not reflect Indonesia's heterogeneous population structure. Spatial variations and mobility patterns are not explicitly modeled. Additionally, underreporting of cases introduces uncertainty in parameter estimation.

The inclusion of mortality as a separate compartment improves realism but may still oversimplify healthcare system constraints. Future extensions should incorporate hospital capacity constraints and vaccination dynamics.

Importantly, the repeated application of adaptive control-inspired methodologies (Ahlem et al., 2020) suggests that interdisciplinary approaches can significantly enhance epidemiological modeling stability. This cross-domain insight opens new research directions in adaptive epidemic control systems.

Conclusion

This study developed a data-driven SIRD modeling framework for long-term estimation of COVID-19 epidemiological parameters in Indonesia. The model effectively integrates classical compartmental dynamics with adaptive parameter estimation techniques, providing stable long-term forecasts of infection and mortality trends.

The results demonstrate that the SIRD framework offers a balanced trade-off between interpretability and predictive capability. While not as flexible as machine learning models, it provides superior transparency and robustness for policy-oriented applications.

Future research should focus on integrating spatial heterogeneity, vaccination effects, and real-time adaptive learning mechanisms. Hybrid models combining epidemiological theory with advanced optimization techniques are recommended for improved pandemic forecasting systems.

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