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Modelos de séries temporais para predição da taxa de mortalidade neonatal

Time series models for neonatal mortality rate forecasting

Modelos de series temporales para la predicción de la tasa de mortalidad neonatal

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Resumo

Objetivo: O objetivo deste trabalho é avaliar modelos de séries temporais paramétricos e não-paramétricos para a predição da taxa de mortalidade neonatal em municípios brasileiros de médio porte. **Método:** Os modelos foram ajustados aos dados históricos de 2010 a 2022 e avaliados com base nas métricas de erro e nos resultados das predições. **Resultados:** De acordo com os resultados, a série histórica da taxa de mortalidade neonatal apresenta perfil estacionário e sazonal. O modelo Auto-Regressivo Integrado de Médias Móveis com Sazonalidade conseguiu captar o perfil da série histórica e realizar projeções mais precisas. Entretanto, foi confirmada autocorrelação residual, o que pode levar a resultados enviesados. **Conclusão:** A partir da análise dos resultados, fica evidenciada a importância da avaliação de modelos paramétricos e não paramétricos para fornecer informações sobre predição de mortalidade neonatal que possam ser utilizados para avaliar e discutir as políticas públicas de saúde no Brasil.

Descritores: Ciência de Dados; Política de Saúde; Atenção Primária à Saúde.

Abstract

Objective: The present work aims to evaluate parametric and non-parametric time series models for forecasting the neonatal mortality rate in medium-sized Brazilian municipalities. **Method:** The models were training using historical data from 2010 to 2022 and evaluated in terms of performance metrics and predictions values. **Results:** According to the results, the time series of the neonatal mortality rate has stationary and seasonal profile. Among the algorithms considered, the Seasonal Autoregressive Integrated Moving Average model was able to capture the pattern of the time series and make predictions with greater precision. However, residual autocorrelation was confirmed, which could lead to biased results. **Conclusion:** From the analysis of the results, the importance of evaluating both parametric and non-parametric models to provide information on information on forecasting neonatal mortality that could be used to evaluate and discuss Brazilian Public Health policies.

Keywords: Data Science; Health Policy; Primary Health Care.

Resumen

Objetivo: El objetivo de este trabajo es evaluar modelos de series temporales paramétricos y no-paramétricos para la predicción de la tasa de mortalidad neonatal en municipios brasileños de tamaño mediano. **Método:** Los modelos fueron ajustados a los datos históricos de 2010 a 2022 y fueron evaluados considerando métricas de error y resultados de las predicciones. **Resultados:** Según los resultados, la serie histórica de la tasa de mortalidad neonatal presenta un perfil estacionario y estacional. El modelo Autorregresivo Integrado de Media Móvil logró captar el perfil de la serie histórica y realizar proyecciones más. Sin embargo, se confirmó la autocorrelación residual, lo que puede llevar a resultados sesgados. **Conclusión:** A partir del análisis de los resultados, se evidencia la importancia de la evaluación de modelos paramétricos y no paramétricos para proporcionar información sobre la predicción de la mortalidad neonatal que pueda ser utilizada para evaluar y discutir las políticas públicas de salud en Brasil.

Descriptores: Ciencia de los Datos; Política de Salud; Atención Primaria de Salud.

Introduction

Neonatal mortality is an important public health outcome, standing out as a significant challenge in achieving the Sustainable Development Goals (SDGs). The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States, targets to eliminate preventable deaths of newborns by 2030. The goal is to reduce neonatal mortality rate to at least as low as 12 deaths per 1,000 live births [1].

In 2020, almost half of child deaths in the world were registered up to 27 days of life, being mainly associated with prenatal, childbirth, and newborn care [2]. In Brazil, despite the advances in reducing the infant mortality rate since the late 2000s, the neonatal mortality rate still remains in high levels [3]. Hence, it is necessary to constantly evaluate Brazilian public policies related to infant and motherhood health and their impact on reducing the neonatal mortality rate.

Among the strategies to evaluate population health outcomes, prediction models have been commonly applied to predict events and forewarning health. The prediction of health outcomes, including mortality rates, prevalence of chronic diseases, and use of health services, for instance, require reliable data sources as well as health information and appropriate analytical tools. The predictions are important in identifying threats to public health, guiding policies and preventive interventions, and also playing a fundamental role in optimizing public resources, in order to increase impacts [4].

Different models, algorithms, and techniques can be applied to predict health outcomes, using statistical, epidemiological, and computational methods, in order to identify patterns and trends, as observed during the Covid-19 pandemic [5]. However, most studies carried out to predict health outcomes use parametric regression models [6].

Within the different approaches to predict health outcomes, time series forecasting has been widely used [7], especially to evaluate short-term results such as mortality rate [8] and hospital admissions[9]. Time series forecasting models are based on the assumption that historical data may contain intrinsic patterns conveying useful information for predicting future values of the phenomenon under analysis. Nevertheless, the selection of the most appropriate model is quite challenging, especially due the diversity of algorithms available and the different patterns of the data [4,10].

The aim of this work is to evaluate both parametric and non-parametric time series models for forecasting the neonatal mortality rate in medium-sized Brazilian municipalities. The parametric models Auto-Regressive Integrated Moving Average (ARIMA) and Seasonal Auto-Regressive Integrated Moving Average (SARIMA) were evaluated, as well as the non-parametric model Long Short-Term Memory (LSTM).

Related Work

The time series analysis related to public health has proven to be a valuable tool for understanding trends and patterns in health outcomes in epidemiological studies [4,7]. There are several studies that have employed time series models to investigate public health issues in different contexts and regions.

Cao et al. (2017)[11] studied the mortality of children under 5 years in Beijing, China, using the ARIMA model to analyze trends, from 1992 to 2015. Although the children's mortality decreased by 80 % in the period analyzed, an increase of 7.20 % was observed between 2013 and 2015. In addition, the predictions of child mortality by the ARIMA model indicate a slight upward trend for the period from 2016 to 2020, suggesting that maternal and child health care in Beijing still faces challenges. Despite the results and conclusions present, the article does not provide performance metrics of the forecasting model or an appropriate discussion on model development.

The study conducted by Rajia et al. (2019)[12] aims to assess trends in maternal mortality rate, under-five mortality rate, and neonatal mortality rate in Bangladesh. The authors used time series data from 1990 to 2014, and selected the ARIMA model to six-year forecast the outcomes, providing a residual autocorrelation analysis. However, the article lacks in presenting error metrics to appropriately evaluate the precision of the ARIMA model.

Zhang et al. (2022)[13] employed LSTM and ARIMA models to fit monthly, weekly, and daily incidence of hemorrhagic fever in China, from 2013 to 2018, and forecast the incidence in 2019, in order to examine the applicability of each model. Both models were evaluated in continuous and direct forecasting versions. The models using continuous forecasting showed lower values of mean absolute error (MAE), root mean squared error (RMSE), and mean absolute percentage error (MAPE) compared to direct forecasting, for both ARIMA and LSTM models. The results of 2019 forecasting demonstrated that ARIMA was better than LSTM for monthly and weekly predictions, while LSTM was better than ARIMA for daily predictions. In conclusion, both ARIMA and LSTM can be adapted to create forecasting models for the incidence of hemorrhagic fever.

The reviewed studies provide a brief comprehensive overview on the application of time series models in the analysis of public health outcomes. However, it should be highlighted that few studies provided an appropriate model development and precision evaluation, important issues to ensure coherent and unbiased forecasts of health outcomes.

Materials and Methos

In this study, we aimed to provide a comparison of parametric and non-parametric time series models for neonatal mortality rate forecasting. For this purpose, we used the CRISP-DM methodology. However, according to the scope of this work, we focus on the presentation and discussion of the time series models' performance results without providing all the steps for the CRISP-DM.

Scope

The present work is an ecological study to evaluate parametric and non-parametric time series models for predicting neonatal mortality rates. The data is related to the neonatal mortality from January 2010 to December 2022 of the medium-sized municipalities in Brazil, according to the classification criteria defined by the Brazilian Institute of Geography and Statistics (IBGE). This stratification aims to mitigate disparities observed in health outcomes across Brazilian municipalities, seeking to establish a homogeneous group for analysis [14].

Data extraction

Data on the number of inhabitants, live births, and neonatal deaths were utilized. The data on live births and neonatal mortality were obtained from the Live Birth Information System (SINASC) and Mortality Information System (SIM) of the Brazilian Ministry of Health. Resident population data per municipality were acquired from the Brazilian Institute of Geography and Statistics (IBGE) and used for classifying the municipalities' according to the population criteria defined by them. The neonatal mortality rate was calculated by dividing the number of neonatal deaths recorded by the number of live births in the same municipality and period, multiplied by 1,000.

Development of forecasting time series models

Initially, the neonatal mortality rate time series was checked for stationarity by using the Augmented Dickey-Fuller (ADF) test. This statistical test assumes as the null hypothesis that a unit root is present in a time series sample, indicating non-stationary data. The alternative hypothesis of the ADF test considers the absence of a unit root, leading to the conclusion that the series is stationary [15]. A significance level (p-value) of 5% was set for the hypothesis test. In addition, seasonal decomposition of time series by Loess (STL) was used to decompose the data into trend component, seasonality part, and residues.

The parametric models ARIMA and SARIMA were fitted to the neonatal mortality rate data using the auto-arima function, considering the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) penalization criteria. For this purpose, the data was split into a training dataset (from January 2010 to December 2021) and a test dataset (from January 2022 to December 2022). The estimated errors of the ARIMA and SARIMA models were analyzed by the Durbin-Watson residual autocorrelation test. In this statistical test, the null hypothesis indicates no correlation among the residuals, a requirement to extrapolate the model to future times [10].

For the LSTM model training a hyperparameter fine-tuning was conducted considering the number of training epochs, dropout, and number of neurons per layer (Table 1). A batch size of 32 and the Adam optimizer were used in all experiments. Mean squared error (MSE) was set as loss function. We used the hold-out method for training, splitting the data into training dataset (from January 2010 to December 2021), validation dataset (from January 2021 to December 2021), and test dataset (from January 2022 to December 2022).

The performance of the ARIMA, SARIMA, and LSTM models were compared considering the following metrics calculated on the test dataset: mean squared error (MSE), root mean squared error (RMSE), and mean absolute percentage error

(MAPE), in which lower values indicate better precision. Furthermore, the forecast of the neonatal mortality rate for 2023 was evaluated and compared with non-official data released by Ministry of Heath on May 2024 for previously consulting.

Table 1 – Hyperparameters and values evaluated in the fine-tuning of the LSTM model for neonatal mortality rate forecast.

Hyperparameter	Values
Epochs	50, 100, 150
Dropout	0.2, 0.1, 0.05, 0.025, 0.0125, 0.00625, 0.003125
Number of neurons layer 1	128, 256, 512
Number of neurons layer 2	32, 64
Number of neurons layer 3	16, 32
Number of neurons layer 4	8, 16, 32

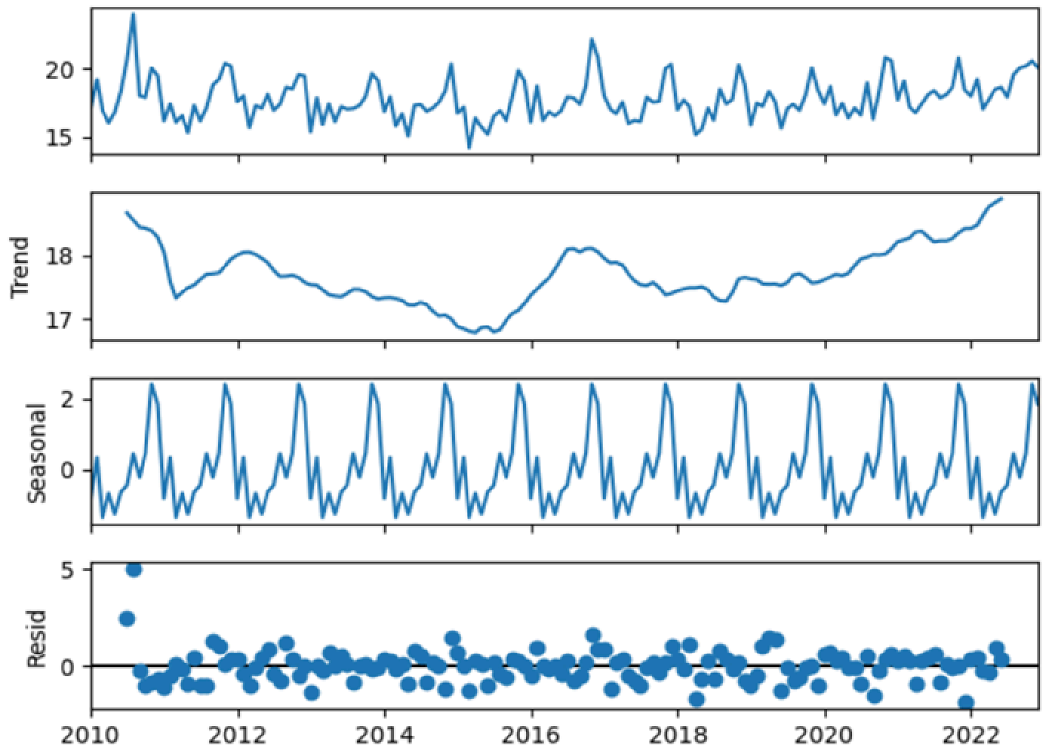
Results and Discussions

The neonatal mortality rate in Brazilian medium-sized municipalities varied between 14 and 24 deaths per 1,000 live births over the period analyzed (2010-2022), being above the goal established by the United Nations. Furthermore, according to the Augmented Dickey-Fuller (ADF) statistical test, the time series of neonatal mortality rate is stationary (p-value = 0.0191).

Data in a stationary time series fluctuate randomly around a constant mean value, representing some stable equilibrium, i.e., its statistical properties are constant over time. This result indicates that for Brazilian medium-sized municipalities, there was no significant progress in reducing neonatal mortality from 2010 to 2022. In addition, it is possible to identify a seasonal behavior in the time series (Figure 1) in which highest neonatal mortality rates were observed at the end of each year in the analyzed period.

ARIMA, SARIMA, and LSTM models are frequently used for time series forecasting in different contexts. On one hand, the ARIMA and SARIMA models are relatively easier to interpret, implement, and execute, even though there are some limitations in predicting non-linear time series. On the other hand, neural networks, such as the LSTM, are more complex and robust for predicting dynamic systems, requiring greater computational resources compared to the parametric prediction models [10].

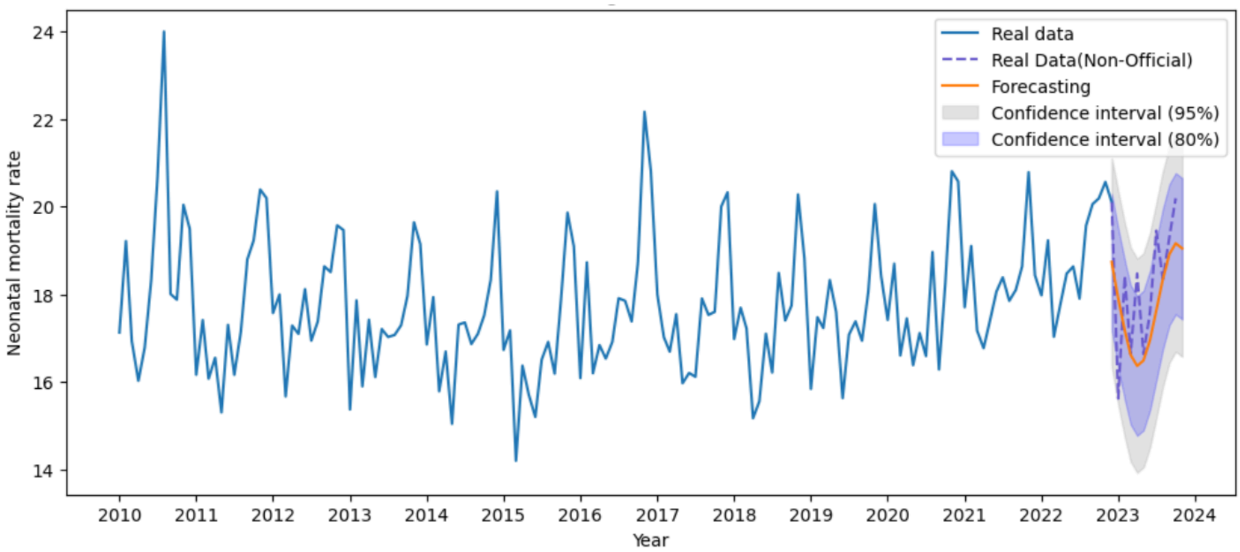
Figure 1 – Seasonal decomposition of neonatal mortality rate in Brazilian medium-sized municipalities time series.



According to the results, the ARIMA(2,0,3) model was selected, based on the AIC and BIC penalization criteria. This model has two autoregressive (AR) terms and three moving average (MA) terms, allowing the model to capture both short-term dependence and the relationship between previous forecast errors and the current value of the series. Additionally, since the time series is stationary, there are no differencing terms.

The prediction of future values of neonatal mortality rate using the ARIMA model is presented in Figure 2. A decrease in the neonatal mortality rate is observed in the first quarter of 2023, followed by an increase in the values at the end of the year. This pattern is consistent with the seasonal behavior of the time series, although the noise observed due to the random variability of the data has been smoothed out. In addition, the Durbin-Watson test at 5% significance level (D = 1.913) indicates that autocorrelation is not present. In addition, compared to the non-officially data released by the Ministry of Health, it could be noticed that the neonatal mortality rate values are in the 95 % confidence interval, indicating an accurate prediction.

Figure 2 – Neonatal mortality rate forecasting for medium-sized Brazilian municipalities for the year 2023 using the ARIMA(2,0,3) model.



Similarly, SARIMA(0,0,1)(0,1,1) model was selected for forecasting the neonatal mortality rate (Figure 3), based on the AIC and BIC penalization criteria. In this model, there is a moving average (MA) component for both the non-seasonal and seasonal components, with differencing only for the seasonal component. The forecasting for 2023 by SARIMA model followed the seasonal pattern of the time series, with an increase in neonatal mortality rate values at the end of the year. Comparing with the non-official data from the Ministry of Health, values of neonatal mortality rate are in the 95 % of confidence level, following the forecasting pattern. Additionally, SARIMA model was able to capture both seasonality and noise in the time series data. However, it was confirmed a negative residual autocorrelation, according to the Durbin-Watson test at 5% significance level (D = 0.1850). Therefore, the independence of residuals assumption is violated, and it can lead to biased predictions.

The LSTM model was optimized, as describe in Table 1 in Section 3, through a hyperparameter fine-tuning study, resulting in a neural network with 256 neurons in the first layer, 32 neurons in both the second and third layers, and 16 neurons in the fourth layer, 150 epochs, and a dropout rate of 0.0125. The predictions made by the optimized LSTM model are presented in Figure 4. Unlike the ARIMA and SARIMA models, the prediction of the LSTM model indicates an increase in the neonatal mortality rate in the first quarter of 2023, followed by a decrease at the end of the year. This pattern differs from both the seasonal behavior observed in the time series and the non-official data.

Figure 3 – Neonatal mortality rate forecasting for medium-sized Brazilian municipalities for the year 2023 using the SARIMA(0,0,1)(0,1,1) model.

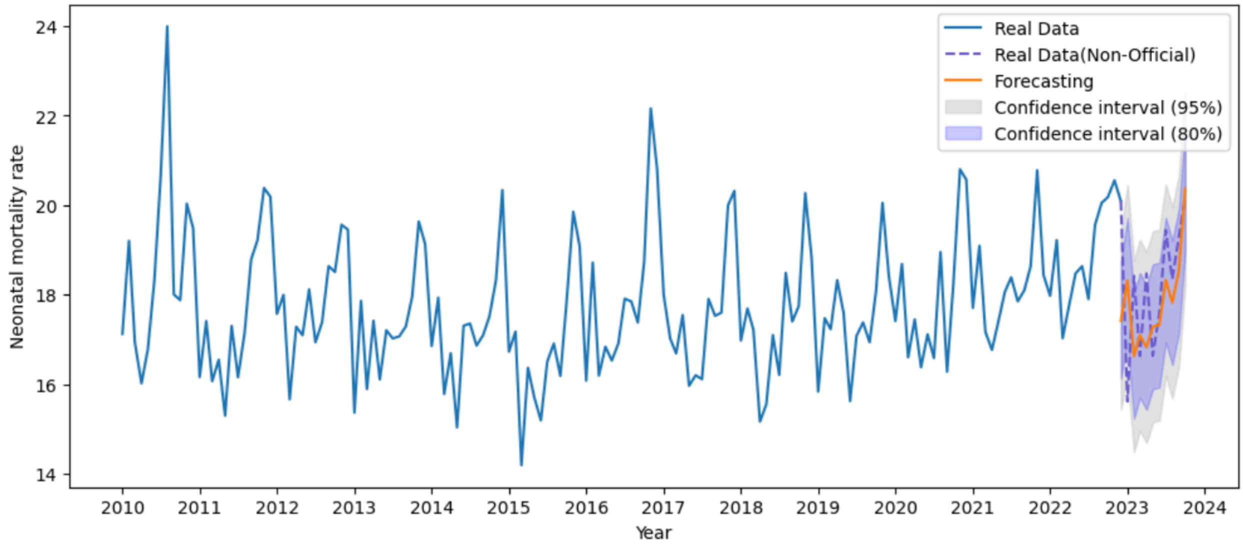
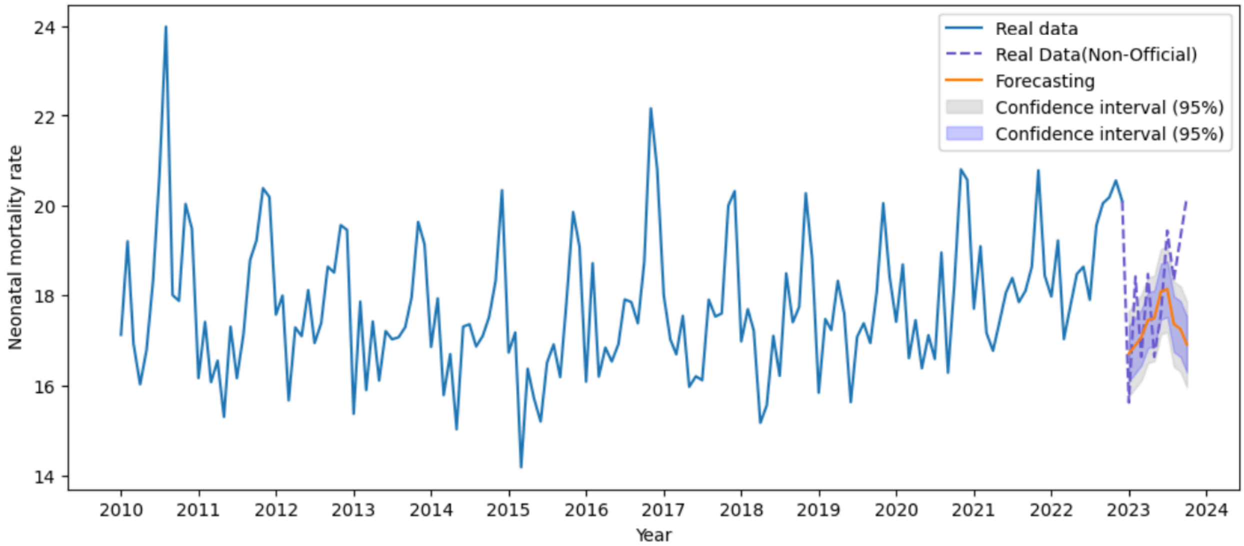


Figure 4 – Neonatal mortality rate forecasting for medium-sized Brazilian municipalities for the year 2023 using the LSTM model.



In order to evaluate the accuracy of the forecasting models, the MSE, RMSE, and MAPE metrics were calculated on the test dataset (Table 2). According to the results, it is possible to observe that the SARIMA model has the lowest error metrics values, indicating better precision. This result is consistent with the pattern of the analyzed data, since the SARIMA model is indicated for time series that exhibit seasonal autocorrelation, even though the Durbin-Watson test shows that it can lead to biased predictions. Furthermore, the application of SARIMA is especially appropriate when the data present seasonal variations that are not adequately addressed by first differencing [10].

Table 2 – Performance metrics of time series models for forecasting the neonatal mortality rate of medium-sized Brazilian municipalities.

Model	MSE	RMSE	MAPE
ARIMA	2.0820	1.4429	0.0696
SARIMA	1.3413	1.1581	0.0512
LSTM	1.6947	1.3018	0.0583

The LSTM model has higher precision compared to the ARIMA model. However, it exhibited higher values of MSE, RMSE, and MAPE than the SARIMA model. Despite the LSTM model being more robust compared to parametric models, the decrease in its performance may be due to the extent of the data used in training. In the comparative studies conducted by Joosery and Deepa (2019)[16] and Taslim and Murwantara (2022)[17], the accuracy of the LSTM model decreased with the increase in the training dataset. On the other hand, the accuracy of ARIMA models was not affected by the amount of data used. The results of these studies also suggest that the ARIMA model has superior precision compared to the LSTM model when more than one-year time series data is used in training.

Despite the differences observed in the predictions using the selected algorithms, it is possible to obtain a reliable model for neonatal mortality rate based on historical data. Further studies could be carried out to evaluate the predictions for future years in order to provide knowledge for governments and public policies makers. However, it is important to highlight the risks related to the inadequate use of forecasting models, especially in the context of public health. Since time series models are built in using historical data, it is necessary to ensure that the data are consistent and representative of future scenarios. Otherwise, misuse of prediction models can lead to inadequate decisions regarding the use of public resources and policies.

Conclusions

This study aimed to compare parametric and non-parametric time series models to forecast the neonatal mortality rate of medium-sized Brazilian municipalities, based on historical data from 2010 to 2022. The results obtained indicate that the SARIMA model had better accuracy in the predictions compared to the LSTM and ARIMA models, despite a residual autocorrelation being observed. However, all selected models were able to predict the seasonal behavior of the neonatal mortality rate. The results of this work show the importance of the use of forecasting models in public health in providing evidence based on time series data that could be used to improve health assistance, public policies, and the use of national expenditures. Different studies show that the LSTM model, typically used for forecasting, has its accuracy reduced when more than one-year time series data is used. Therefore, future works should incorporate the extent of time series data used in LSTM model training as a variable, evaluating its effect on precision.

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