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Predictive Analysis of Malaysia's Population Dynamics Utilizing Exponential Growth Models and Newton-Raphson Iterative Optimization Techniques

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ABSTRACT

Changes in population and population dynamic modelling are essential for ensuring optimal resource allocation and sustainable development towards guiding strategic planning. Approximately 33.9 million inhabitants can be counted as the current population of Malaysia. The changes in populations are mainly attributed to fertility and mortality change rates, urbanisation, migration, and other socio-economic factors. Most importantly, however, the annual rate of population growth decreased from one point two-five percent in 2019 to one point zero-six percent in 2024 due to the significant effect of COVID-19, which reversed or changed societal norms, increased death rates, and created another kind of economic uncertainty. As a result, the population dynamics within this period present a particularly compelling subject of study. Traditional models, such as exponential and logistic growth equations, often struggle to capture the nonlinear and complex nature of demographic transitions. To overcome this limitation, this study uses the Newton-Raphson method to find the important growth rate (k) in a population model, using historical data from the Macrotrends database covering 2019 to 2024. This iterative method is reputable for its computational efficiency, accuracy, and rapid convergence when deploying in solving nonlinear algebraic equations, despite its sensitivity to initial conditions. The objective here is to provide a more accurate prediction of Malaysia's population in the year 2025. Accurate short-term population forecasting is vital in making informed policy in various sectors such as healthcare, education, infrastructure, and the economy. This study highlights the practical relevance of integrating numerical optimisation techniques into demographic modelling and demonstrates the potential of the Newton-Raphson method as a robust alternative to traditional approaches.

Keywords: Population dynamics, Newton-Raphson method, Demographic forecasting, Nonlinear modeling, COVID-19 impact

1 INTRODUCTION

Population dynamics and growth modelling are two important areas of mathematics that have attracted a profound interest among researchers in public policy, demographic studies, and social science [1], [2]. Accurate estimation of population size is a very vital parameter for organizations, establishments, and governments to facilitate informed decisions regarding effective resource allocation, infrastructure placement, amenities development, and sustainable planning, which can better place the nation, businesses, and establishment on the developmental rail [3], [4]. [5] reported that one of the world's biggest problems is the enormous population expansion, which can affect a country's economic, political, cultural, educational, and environmental circumstances. However, population censuses can be conducted to get the population of a country, but the process is highly expensive, requiring both human and technological resources. Thus, it hinders its frequent conduction. Mathematical models can be used as essential tools to forecast the potential population of a nation using the historical population's past data of the subject under review. The exponential growth model and the logistic growth model, which were proposed by Malthus in 1798 and Verhulst in 1845, respectively, are some of the most common mathematical models that have been deployed in numerous research studies to model population growth [6], [7].

Malaysia, one of the most notably developing and rapidly developing countries, is not exempt from the challenge of population management due to fluctuation in fertility and mortality rates, migration, and urbanization [8], [9]. With the continuous increase in population, individuals are under more strain on the available resources as a result of the ongoing growth in the human population, which is currently around 33.9 million. However, it is now more imperative than ever to identify the major causes of variation in population. Malaysia's population growth has shown a noticeable transition, slowing from a robust 1.25% in 2019 to a more moderate 1.06% in 2024 [10]. This decline raises questions about the factors driving this trend, with the global COVID-19 pandemic emerging as a key influence among others. The pandemic's profound societal disruptions, including increased mortality rates, have directly impacted population growth. Economic uncertainties triggered by the pandemic may have also affected family planning choices, contributing to a decline in fertility rates. Furthermore, restrictions on international migration, such as border closures and travel limitations, likely curtailed the influx of migrants into Malaysia. Pressure on the healthcare system and changes in social behaviour during the pandemic contribute to the complexity of the demographic slowdown. These interconnected components acme the intricate relationship between global crises and demographic dynamics, shaping the evolving trajectory of Malaysia's population growth.

Classical methods of population estimation rely massively on direct extrapolation of historical data or the deployment of predefined growth models such as exponential or logistic growth models. While these methods are effective in many cases, these approaches may fail to capture the nuances of non-linear factors influencing population growth, such as changes in policy, urbanization, economic fluctuations, and environmental pressures, among others [11]. Current methods for estimating population size in Malaysia rely heavily on conventional mathematical models that may not be easily understood or adequately address the complexities of real-world data [12]. These models often involve solving complex mathematical formulations using sophisticated approaches that are difficult to comprehend. Traditional analytical methods are reported to be either impractical or computationally expensive due to the intricacies of the equations involved. Additionally, the presence of uncertainties in population data introduces further challenges in achieving reliable estimates. Recent advances in computational methods for population prediction have deployed machine learning, simulation, and statistical modeling to address complex demographic problem. Machine learning models, such as neural networks and ensemble methods, have demonstrated superior accuracy and efficiency in inferring demographic parameters from large genomic datasets, often outperforming traditional and statistical approaches which requires assumptions about data distribution or stationarity, though they still require substantial, data and preprocessing to function optimally [13].

This research deploys iterative numerical techniques, specifically the Newton method, also known as the Newton-Raphson method, named after Joseph Raphson and Isaac Newton. It is a straightforward and promising technique for solving nonlinear algebraic equations [14]. This technique is very popular for its efficiency and robustness in root-finding problems, providing increasingly accurate approximations to the roots (or zeroes) of real-valued functions. It is often preferred over other variants, such as the bisection and secant methods, among others. It exhibits quadratic convergence, whereas its variants exhibit superlinear convergence [15], [16]. It also uses exact derivatives in computation, which facilitate effective and accurate updating of estimation, while its close variant, particularly secant, approximates the derivative using two previous points [17]. However, Newton's method requires the derivative to be known and may diverge if the starting point is too far from the root, while the secant method avoids the need for explicit derivatives, making it more convenient in some cases [18], [19]. However, [20] asserted that the Newton-Raphson method can be deployed to solve a set of non-linear algebraic equations. This has further increased its usability in solving various problems, such as finite element analysis and power-flow calculations. Efficiency and convergence of the Newton-Raphson method could be jeopardised if the initial guess is far from the actual solution, the derivative is hard to get or discontinuous, and the function has multiple roots in the interval under consideration [21]. Moreover, a study conducted by [22] asserted that the choice of technique for solving non- linear algebraic equations depends on the problem we are solving. Thus, in order to ensure convergence, the initial guess value needs to be selected close enough to a true solution; the Kantorovich theorem provides extremely conservative constraints and is essentially the sole known sufficiency condition for the NR method's convergence [23]. The logistic model solved using the NR methods offers mathematical transparency, simplicity, and greater interpretability with clear parameters like carrying capacity, growth rate, and initial population over the black box phenomenon in the machine learning algorithm.

Machine learning and ARIMA models are known for their better flexibility, but our logistic-based approach bridges a crucial gap by providing precise, explainable, and efficient forecasting, especially relevant in demographic studies focused on meaningful parameters like growth rate. Our finding demonstrates the usefulness of the Newton-Raphson method in calculating the growth rate and predicting the population size of Malaysia in 2025 as a near-future benchmark to evaluate short-term policy planning and assess whether current growth trends align with national development projections. The research also showcases that numerical approaches remain indispensable options when the analytical method of solving non-linear algebraic equations seems impossible or difficult to deal with while offering a better approximation option.

2 MATHEMATICAL FRAMEWORK

Numerical methods are essential tools for solving nonlinear algebraic equations, particularly when analytical solutions are infeasible or difficult to interpret. Commonly used methods in root-finding include the bisection method, secant method, false Position method, and Newton-Raphson method. Among these, the Newton-Raphson method stands out for its efficiency and simplicity. Its iterative, solution-refining approach makes it indispensable in fields such as engineering, physics, and social sciences, especially in economics. The Newton-Raphson formula is easily derivable from the famous Taylor series expansion of a function $f(x)$ around an initial guess value x_0 such that:

$$f(x) \approx f(x_0) + f^{'}(x_0)(x - x_0) \tag{1}$$

where $f^{'}(x_0)$ is the first derivatives of $f(x_0)$ at x_0 . Suppose $f(x_0)=0$ in the root finding problem instance we have:

$$0 = f(x_0) + f^{'}(x_0)(x_1 - x_0) \tag{2}$$

Rearranging and solve for x we have:

$$x_1 = x_0 - \frac{f^{'}(x_0)}{f(x_0)} \tag{3}$$

Newton-Raphson method in one variable can be implemented provided that the function $f(x)$ is differentiable and we have initial guess x_0. Equation (3) can be extended for successive approximations of the root such that;

$$x_{n+1} = x_n - \frac{f^{'}(x)}{f(x)} \tag{4}$$

where x_{n+1} is the new solution, x_n is the previous solution, while $f(x)$ and $f^{'}(x)$ are the non-linear algebraic equation and its derivative, respectively. In using the Newton-Raphson formula one begins with a preliminary conjecture or initial guess x_0 that is logically close to the actual root. Next, the goal is approximated by its digression line, which is calculated using calculus tools. Finally, the x-intercept of this digression line is calculated, which is easily accomplished with basic algebra. The technique can be iterated, and the x-intercept will usually provide a better estimate of the function's root than the initial guess. The scheme is stopped using any known stopping criteria at the user description or accuracy needed. The number of iterations and the difference between successive approximations are common stopping criteria to assess convergence. The criterion evaluates the differences between two successive iterations, as expressed in equation (5).

$$\left| x_{n+1} - x_n \right| < tolerance\ value \tag{5}$$

The tolerance value is typically set to be a very small real number, ensuring that the difference between two successive values of x_i is negligible and practically insignificant. At that point, the value of x_{n+1} can be assumed to be an approximate root to the non-linear algebraic equation.

3 METHODOLOGY FOR POPULATION GROWTH USING EXPONENTIAL MODEL

To apply the exponential growth model using the Newton-Raphson method for Malaysia's population prediction, we assume that the population follows the exponential growth equation such that:

$$p(t) = p_0 e^{kt} \tag{6}$$

where

$p(t)$: the size of population at time t p_o : the initial size of the population in Malaysia

k : the growth rate of population size t : the time in year

We then rewrite equation (6) to solve for k using known population data at time t as shown in equation (7).

$$k = \frac{1}{t}\ln\left(\frac{p(t)}{p_0}\right) \tag{7}$$

We utilize population growth data and set up a nonlinear equation as shown in equation (8). We need to find the value of k such that $f(k) = 0$:

$$f(k) = p(t) - p_0.e^{kt} \tag{8}$$

Using Newton-Raphson method, solve for the value of k iteratively such that:

$$k_{n+1} = k_n - \frac{f(k_n)}{f^{'}(k_n)} \tag{9}$$

The derivative of the function in equation (8) is as shown in equation (10):

$$f'(k) = -t.p_0.e^{kt} \tag{10}$$

With an initial guess, say k_0, we find the successive value of k using the Newton-Raphson method until the difference $|k_{n+1} - k_n| < 10^{-6}$. Lastly, once this condition is met, the algorithm will cease, and the value of k_{n+1} is recorded as the approximated solution of $f(k)$, the refined value of k can then be utilized in the exponential model to predict the population for Malaysia at any desired time.

4 DATA INFORMATION AND NUMERICAL ILLUSTRATION

The population size and growth rate data for Malaysia were sourced from the Macrotrends website [24]. The data extracted for the years 2019 to 2024 were presented in Table 1. The time frame of 2019 to 2024, though relatively short, is intentional and focuses on examining population dynamics in Malaysia during the COVID-19 period. This era encapsulates the commencement of the pandemic, its peak impact, and the immediate aftermath, which significantly influenced demographic indicators such as birth rates, mortality rates, migration, and other economic activity.

Table 1: The Malaysia population and corresponding growth rate

Year	Population	Growth rates
2019	32,804,020	1.25%
2020	33,199,993	1.21%
2021	33,573,874	1.13%
2022	33,938,221	1.09%
2023	34,308,525	1.09%
2024	34,671,895	1.06%

Our interest in this study is restricted to the Malaysian population from 2019 to 2024. From Table 1, we can calculate the population in 2024 using the growth rate in 2024, but we opted to calculate the population growth using the exponential growth model solved using the Newton-Raphson method to compute the growth rate inherent in the Malaysia population for 2024 and used the computed growth rate for 2024 to predict the population for 2025. Subsequently, the Malaysia population for 2025 calculated using the refined population growth will be compared with the actual population size for 2025 using the provided growth rate in Table 1. Below is a numerical illustration of the approach. Setting the initial population in 2019 as $p_0 = 32,804,020$, we model the Malaysia population using the relation in equation (8), and data for 2024. With $p(2024) = 34,671,895$, equation (8) is transformed into equation (11):

$$f(k) = 34,671,895 - 32,804,020 \times e^{5k} \tag{11}$$

We need to apply the Newton-Raphson method to find the appropriate value of k such that $f(k) \approx 0$. From the information on the population growth in Table 1, we guess the initial value as $k = 0.01$ and compute $f(k)$ and $f^{'}(k)$ as shown below:

$$f(k) = 34,671,895 - 32,804,020 \times e^{5(0.01)}$$

$$f^{'}(k_0) = -5 \times 32,804,020 \times e^{0.05}$$

Taking the value of $e^{5\times0.01} = e^{0.05} = 1.05127$

$$f(k_0) = 34,671,895 - 32,807,020 \times (1.05127) = 182,859$$

$$f'(k_0) = -5 \times 32,807,020 \times (1.05127) = -172,445,180$$

Update k such that:

$$k_1 = 0.01 + \frac{182,859}{172445180} = 0.01 + 0.001060 = 0.01106$$

Taking $k_1 = 0.01106$ and computing sequences of k_2, k_3 and so on until when $|k_{n+1} - k_n| < 10^{-6}$ which occurs after just 4 iterations and the value of k_4 is found to be 0.011474.

We then predict the population in 2025 taking $e^{0.06884} \approx 1.07123$:

$$p(2025) = p_0 \times e^{6k} = 32,804,020 \times 1.07123 = 35,140,650$$

The population for the year 2025 is predicted to be 35,140,650.

5 THE FLOWCHART

The flowchart in Figure 1 illustrates the process of predicting population growth using the exponential growth model solved using Newton-Raphson method.

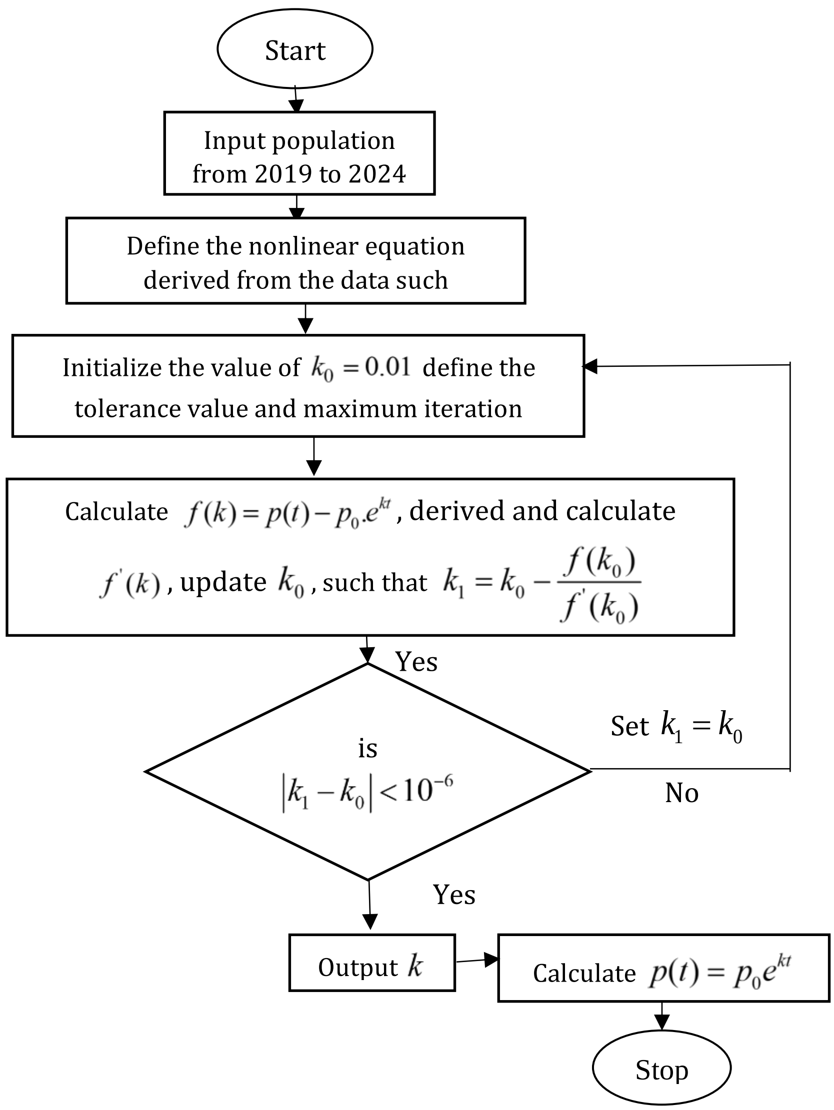

Figure 1: The flowchart illustrating the step in the build-up

Pseudo code for the algorithm

```
# Input population data from 2019 to 2024
# Define the population model equation (f(k)) and its derivative (f'(k))
f(k) = P(t) + P0 exp(kt)
# Initialize parameters
k_initial = some_initial_guess  # Initial guess for growth rate in  2024 population
tolerance = 1e-6 # Convergence criterion
max_iterations = 100 # Maximum number of iterations
# Newton-Raphson iteration
iteration = 0
while iteration < max_iterations:
   f_P = calculate_f(k_initial) # Evaluate f(k) at k_initial
   f_prime_P = calculate_f_prime(k_initial) # Evaluate f'(k) at k_initial
   # Update the estimate
   k_new = k_initial - f_k / f_prime_P
   # Check convergence
   if abs(k_new - k_initial) < tolerance:
      print (f"Estimated population growth for 2025: {k_new}")
   # Update for next iteration
   Calculate   P_new = P_initial ×exp (k-new * t)
   print      P_new
# end
```

6 PRESENTATION AND DISCUSSION OF RESULTS

The implementation of the Newton-Raphson method and all related computations in this study were performed using MATLAB R2024b, a high-level numerical computing environment well-suited for iterative numerical methods. The code was executed on a computer with the following specifications: Intel(R) Core (TM) i3-4130T CPU @ 2.90GHz (4 logical cores), 8 GB of RAM (8192 MB), and Windows 10 Pro for Workstations 64-bit (Build 17134) as the operating system. The Newton-Raphson method was implemented using a user-defined function that incorporated symbolic or numerical derivatives, depending on the nature of the population model. Based on the numerical illustration described in section 4, the approximated value of k that yielded $f(k) \approx 0$ for the Malaysia population data in 2024 is computed to be 0.011474 as opposed to the 1.06% in the real data from Macrotrends [24]. The estimated Malaysia population in 2025 using the growth rate computed using the Newton-Raphson method is calculated to be 35,140,650. Table 2 shows the real Malaysia population alongside with the predicted Malaysia population from the year 2019 to 2025.

Table 2: Comparison of actual and predicted Malaysia population based on growth rate computed using the Newton-Raphson method

Year	Population	Predicted population
2019	32,804,020	32,804,202
2020	33,199,993	33,182,581
2021	33,573,874	33,565,511
2022	33,938,221	33,952,859
2023	34,308,525	34,344,678
2024	34,671,895	34,741,018
2025	35,058,048	35,141,932

To better visualize the relationship between the actual and predicted population size, we plot the graph of the information in Table 2 up to 2024.

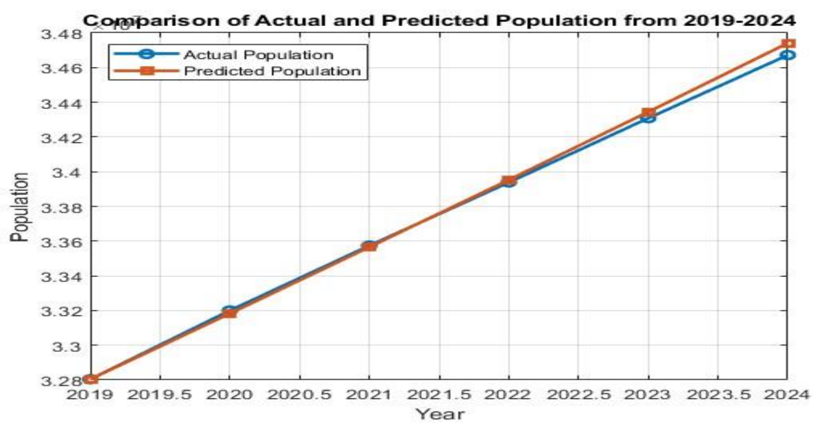

Figure 2: Actual and predicted population size (2019-2024) using computed growth rate from Newton Raphson Method

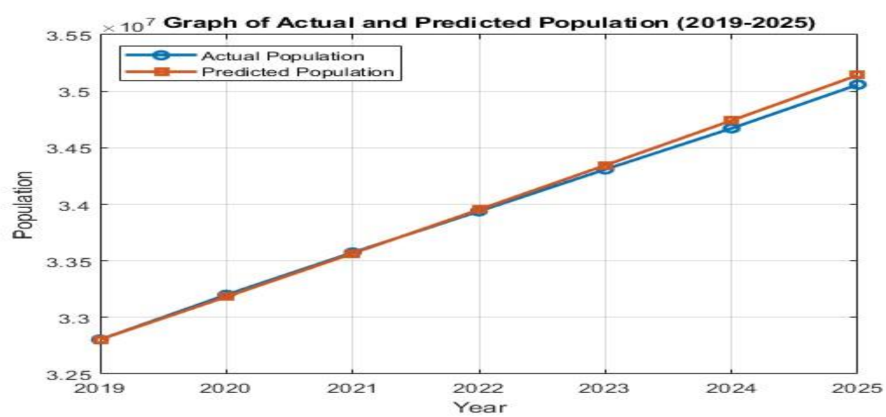

Figure 3: Graphs of actual and predicted population (2019-2025) using computed growth rate from Newton Raphson Method

Table 2 underscores the exceptional precision achieved by the Newton-Raphson method in forecasting Malaysia's population dynamics, as evidenced by the negligible deviations between the predicted and actual population values. This high degree of accuracy highlights the method's capability in addressing complex nonlinear relationships inherent in demographic trends. The analysis leveraged a constant annual growth rate of 0.011474, derived iteratively using the Newton-Raphson technique. This iterative computation ensured the rapid convergence of the growth rate parameter, allowing for precise calibration within the context of an exponential growth model.

By employing this calibrated growth rate, the study accurately predicted Malaysia's population trajectory for the period spanning 2019 to 2025. The minimal discrepancies observed validate the robustness of the Newton-Raphson method in capturing the multifaceted influences on population dynamics, such as fertility rate variations, migration patterns, and mortality rate fluctuations. The precision of the results also reflects the method's sensitivity in optimizing nonlinear algebraic equations to align with real-world data trends.

The findings further demonstrate the Newton-Raphson method's practical utility in demographic modelling, particularly in scenarios where traditional approaches fail to accommodate complex or irregular growth patterns. This methodological rigor not only enhances the reliability of population projections but also provides a computationally efficient framework for policymakers and researchers to model and anticipate demographic changes under diverse socio-economic and environmental conditions.

The application of a constant growth rate effectively approximates the complex interplay of demographic factors, such as fertility, mortality, migration, and socio-economic conditions, within the model's constraints. To quantify the method's precision further, the magnitude of accumulated error can be estimated using relative error techniques. These techniques involve computing the ratio of the absolute difference between predicted and actual values to the actual values, providing a normalized measure of error across different years. Such an evaluation offers deeper insights into the consistency and reliability of the Newton-Raphson method when applied to real-world demographic data.

By integrating relative error analysis, this study emphasizes the Newton-Raphson method's potential as a powerful tool for demographic forecasting, enabling researchers and policymakers to make informed decisions with confidence in the model's predictive accuracy.

Table 3: Relative error of the estimated population size

Year	Population	Predicted population	Relative error (%)
2019	32,804,020	32,804,202	-
2020	33,199,993	33,182,581	0.052446
2021	33,573,874	33,565,511	0.024909
2022	33,938,221	33,952,859	0.043131
2023	34,308,525	34,344,678	0.10538
2024	34,671,895	34,741,018	0.19936
2025	35,058,048	35,141,932	0.23927

These data have been trained on all the data up to the month of October in the year 2023.

The results described in Table 3 talk about a gradual increase in relative error over the years, which proves a slight discrepancy in predicting population values and the actual population. This trend however was modestly kept below 0.25% as it continued to exhibit the high accuracy of the predictive model. Such a tiny error margin made it possible for the Newton-Raphson method to lend robustness in approximating the dynamics of population under very slight deviation from real data. It is observed that there was no relative error for the year under consideration, since the value served as the baseline population figure for this study as per the methodology of this study, where initial population estimates served as the anchor of subsequent runs of the model time. Continuous delivery of the method, however, also seen in the very small relatively errors in years that were considered "observed," could only buttress this claim. The findings shown in Table 3 place the Newton-Raphson method as the best and most reliable for population estimation. This capability of capturing trends with high precision-in spite of all possible nonlinearity and multifactorial influences-should suit the formulation of models involved in very complicated demographics. Thus, we recommend the adoption of this method in estimating the future population of Malaysia in 2025. Its relevance to address a methodological gap and being computationally fast and efficient can be a very useful tool for policymakers and researchers modelling population growth in dynamic and uncertain environments.

7 CONCLUSION

Accurate estimate of population size in Malaysia is of great importance in informed government planning, socio-economic development and sustainable resource management. Population modelling would require strong numerical techniques which must be able to address all the complexities inherent in demographic dynamics, most of them nonlinear, and directly influenced by fertility rates, mortality trends, urbanization and migration patterns. This study employs the Newton-Raphson iterative optimization method to solve non-linear equations derived from exponential growth models for population estimation and hence demonstrated its usefulness as a computational tool for demographic forecasting. MATLAB programming supported the Newton-Raphson method by offering the necessary environment for efficient computation, visualization, and validation of results. But then, it allows for just approximate population estimates, and the same method performed superbly with observed population data for the years 2023 and 2024. The fact that people considered the entire year before the two mentioned years continued to speak for itself of the advantages in the method, including rapid convergence and high precision, which are vital in population analysis. This approach also predicts future demographic events, such as when Malaysia will attain a particular population number by iteratively estimating unknowns from the exponential growth equation. This would strategically position Malaysia for effective wealth distribution and long-term planning of policy development. Future studies could incorporate post-2024 population data as they become available to validate and refine the model's accuracy, and assess the long-term impact of COVID-19 on demographic trends. However, findings affirm that advanced numerical methods must therefore be integrated into all computational tools like MATLAB for improved reliability and accuracy in population modelling.

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