Exploring the Cox Ingersoll Ross (CIR) Interest Rate Model: A Comprehensive Analysis and Applications in Financial Modeling

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Abstract. This research comprehensively analyzes the Cox Ingersoll Ross (CIR) interest rate model and explores its application in financial modeling. The CIR model is widely used in finance to model interest rates and has proven to be a valuable tool for understanding and predicting interest rate dynamics. Through comprehensive analysis and exploration of the interest rate model, the CIR aims to deepen the concept of interest rates, analyze the application of the CIR model in various financial contexts, and provide deeper insight into the crucial role of interest rates in effective financial decision-making. This research method covers all the essential steps needed to explore the Cox Ingersoll Ross (CIR) Interest Rate Model in-depth, adopting a qualitative descriptive approach using deductive reasoning. The author will examine financial modeling. Several significant findings have been revealed with the results of research on implementing the CIR model to approximate interest rates. First, it was found that the interest rate approximation based on the CIR model shows quite good performance, mainly when applied to data whose fluctuations are not too large. Second, it is essential to note that in the context of actuarial interest rates used in research related to pension funding, stochastic interest rates, as described in the CIR model, better reflect the actual situation.

Keywords: CIR Model, Comprehensive, Modeling, Finance.

1 Introduction

A deep understanding of interest rates is critical in financial science and has significant implications for investment decision-making, risk management, and financial planning. In this context, the Cox Ingersoll Ross (CIR) Interest Rate Model is essential in forecasting interest rate movements. This research aims to investigate the CIR Interest Rate Model in-depth, analyze its fundamental principles, and explore the various applications of this model in financial modeling. The importance of understanding the dynamics of interest rates cannot be underestimated in finance. Interest rates influence nearly every aspect of economics and business, including asset value assessments, investment planning, risk management, and financial strategy. Therefore, interest rate modeling has become very important in understanding and forecasting changes in the economic and financial landscape.

Understanding interest rates is also a key element in actuarial mathematics courses. Actuaries have responsibilities for managing financial and financial risks in various contexts, including

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insurance, investment management, and retirement planning. Understanding interest rates is essential in discount calculations, investment assessment, risk management, and long-term financial planning. It is supported by Siregar, T. M., Ritonga, A., & Sianipar, L. S. Y. (2021). Using various numbers and symbols related to mathematics to solve economic problems in various contexts of daily life is very much needed. The Cox Ingersoll Ross (CIR) Interest Rate Model is one of the critical tools in modeling interest rate movements. This model was developed by John C. Cox, Jonathan E. Ingersoll, and Stephen A. Ross in 1985 and has become a valuable tool in describing interest rate fluctuations with a realistic mathematical approach. In line with the value of disaster reinsurance, there is an inverse relationship between the initial value of interest rates and the average interest rate in the long term, according to Chao, W. (2021).

The CIR model is based on the concept that interest rates vary in volatility over time. This model describes interest rates as a stochastic process governed by differential equations. Therefore, a deep understanding of the basic principles of this model is essential for practitioners and researchers in financial science, and Ghorbani, N., & Korzeniowski, A. (2020) said regarding CT Call Option prices in linear investment hedging for levels of stochastic interest modeled by the CIR Process. In addition to understanding the basic principles of the CIR model, it is also essential to explore the various applications of this model in a financial context. The CIR model has been used in various contexts, including bond valuation, forecasting future interest rates, interest rate risk management, and investment portfolio planning. Thus, this research will provide valuable insights for practitioners and researchers in financial modeling.

Financial modeling involves several vital components to provide a comprehensive picture of the financial situation, potential risks, and opportunities. In financial modeling, central elements such as financial data include information about historical and current financial situations, including assets, liabilities, income, and expenses, as well as other factors that impact financial decisions. Next, mathematical models describe the interactions between various financial variables. Forecasting and projection refer to attempts to predict future financial situations. Risk management also helps identify, measure, and control potential risks in a financial context. Irwansyah, I. P., Damuri, A., & Yudaningsih, N. (2022) supported the previous statement, saying that modeling school financial information systems uses design models. User experience for testing system functionality using a black box test scores 100% according to system functionality. Financial modeling plays a vital role in supporting decision-making related to investment and finance, which can then provide relevant conclusions. Based on the modeling results, recommendations and appropriate actions can be taken, which can then be evaluated through performance analysis.

The relationship between financial modeling and specific industries or sectors is essential because each industry has unique characteristics and dynamics that influence financial modeling. The specific challenges and requirements in financial modeling for specific industries vary widely. A deep understanding of the characteristics of the industry, relevant data, and applicable regulations is the key to success in modeling financial conditions and effective decision-making. Financial modeling tailored to the needs and risks of each industry will help companies and organizations face unique challenges and opportunities in their business. It was also stated by Koesnadi, I. (2019) and Fatmasari, F., & Sauda, S. (2020) that The commodity distribution flow financial system is needed to ensure the smooth distribution of commodities and the macroprudential policies issued by Bank Indonesia as the central bank which has full authority, play an essential role in maintaining Financial System Stability (SSK) in Indonesia according to Rusydiana, A. S., Rani, L. N., & Hasib, F. F. (2019).

Financial Modeling Software and Tools are essential in conducting financial analysis and creating mathematical models that understand financial conditions and make decisions based on data software used in financial modeling, such as Microsoft Excel, MATLAB, R, or Python. The choice of financial modeling software and tools must be tailored to the needs and complexity of the project. Often, a combination of multiple tools and programming languages is used to leverage the strengths of each. So, interest rates are one of the critical variables in the financial environment that significantly impact the value of assets and liabilities. Therefore, a deep understanding of interest rate movements is essential for companies, financial institutions, investors, and individuals in planning their finances. With the CIR Interest Rate Model as the primary analytical tool, this research aims to explore the concept of interest rates, analyze the application of the CIR model in various financial contexts, and provide deeper insight into the crucial role of interest rates in effective financial decision-making.

2 Method

This research method covers all the critical steps needed to explore the Cox Ingersoll Ross (CIR) Interest Rate Model in-depth, adopting a qualitative descriptive approach using deductive reasoning. The author will examine financial modeling. Data was obtained from a literature review of financial modeling models from government publication/report texts, government financial websites, official financial portals, scientific journals, and mass media articles relevant to the study topic. Analysis techniques regarding comprehensive applications in financial modeling are carried out in the following stages.

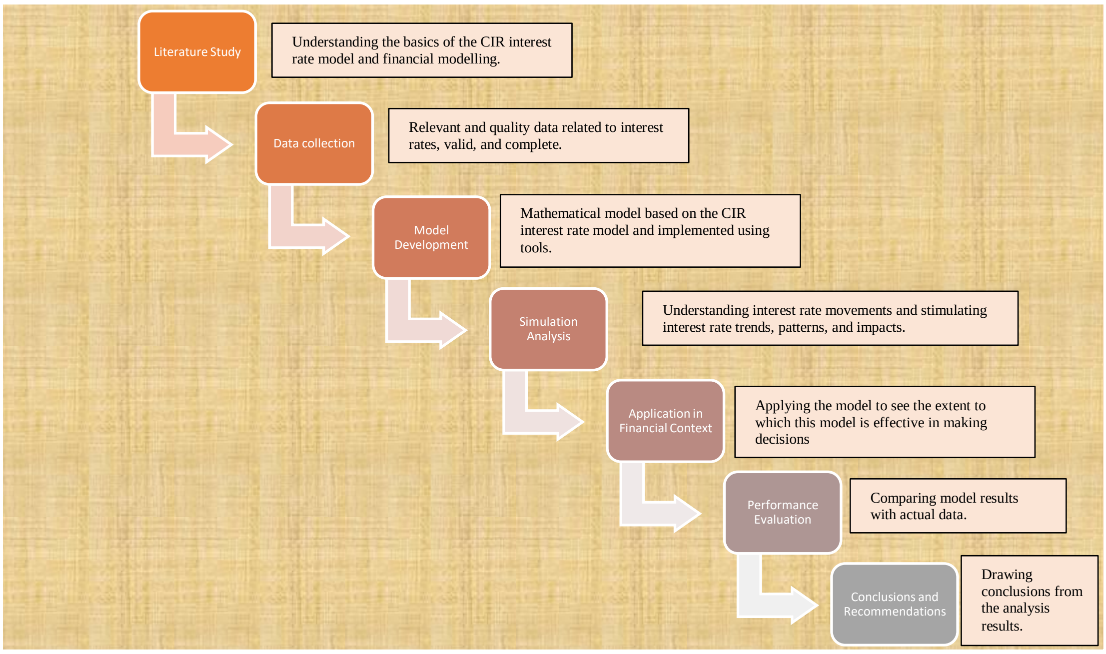

Fig. 1. Stages of Analysis Techniques.

3 Results and Discussion

3.1 Cox Ingersoll Ross (CIR) Interest Rate Model

The CIR interest rate model, an abbreviation of Cox, Ingersoll, and Ross, was introduced in 1985. It is one of many mathematical models used in finance to describe the behavior of interest rates. The CIR model is designed as an equilibrium model, reflecting the interest rate that will reach equilibrium in the long run. One of the main features of the CIR model is its ability to ensure that interest rates are always favorable. The CIR model recognizes that interest rates cannot fall below zero in the long run. The form of the CIR Model equation is:

$$dr(t) = k(\theta - r(t)dt + \sigma\sqrt{r(t)}\, dW(t) \quad (1)$$

With a value of k > 0, $\theta > 0, and\ \sigma > 0$

r(t) = Interest rate at time t
k = Speed r(t) returning towards θ
θ = Long-term average interest rates
σ = Votality of interest rates
W(t) = Wiener process

Let X(t) be a defined stochastic process

$$dx(t) = \mu_t dt + \sigma_t dW(t) \quad (2)$$

Since μ_t is the drift term, σ_t is the diffusion part, and W(t) is the Wiener process, so the function f (X(t),t) is also a stochastic process that has the form of a differential equation.

$$df(X(t),t) = \frac{\partial f}{\partial x}\, dx(t) + \frac{1}{2}\frac{\partial^2 f}{\partial x^2}\,\mathrm{dt} + \frac{\partial f}{\partial t}\,\mathrm{dt} \qquad (3)$$

Equation 3 can be written in integral form as follows:

$$f(X(t),t) - f(x(0),0) = \int_0^T \frac{\partial f}{\partial x}\,\mathrm{dx}\ (\mathrm{t}) + \int_0^T \left(\frac{1}{2}\frac{\partial^2 f}{\partial x^2} + \frac{\partial f}{\partial t}\right) dt \qquad (4)$$

If the equation is defined as function:

$$f\big(t, r(t)\big) = e^{kt} r(t) \qquad (5)$$

Based on equations (1), (2), (3) dan (4) so, it can be written as follows:

$$df\ \big(t, r(t)\big) = f_t\big(t, r(t)\big)dt + f_r\ \big(t, r(t)\big)dr\ (t) + \frac{1}{2}\ f_r\ \big(t, r(t)\big)dt$$

$$d\big(e^{kt} r(t)\big) = ke^{kt}\, r(t)dt + e^{kt} dr(t) + \frac{1}{2}.0$$

$$= ke^{kt} r(t)dt + e^{kt}(k - \big(\theta - r(t)\big)dt + \sigma\sqrt{r(t)}\mathrm{dW(t)})$$

$$= ke^{kt}\, r(t)dt + k\theta e^{kt}\, dt - ke^{kt}\, r(t)dt + \sigma e^{kt}\sqrt{r(t)}\, dW(t)$$

$$= k\theta e^{kt} + \sigma\, e^{kt}\sqrt{r(t)}\, dW(t) \qquad (5)$$

Then the equation (5) is integrated from t to t+1. With the difference between t+1 and t is Δt, we will get

$$e^{k(t+1)}\, r(t+1) - e^{kt}\, r(t) = \int_t^{t+1} k\theta\, e^{ku}\, du + \int_t^{t+1} \sigma\, e^{ku}\sqrt{r(u)}\, dW(u)$$

$$= k\theta\ \frac{1}{k}\ \big(e^{k(t+1)} - e^{kt}\big) + \int_t^{t+1} \theta\, e^{ku}\sqrt{r(u)}\, dW\ (u)$$

$$e^{k(t+1)}\, r(t+1) = e^{kt}\, r(t) + \theta\ \big(\, e^{k(t+1)} - e^{kt}\,\big) + \int_t^{t+1} \sigma\ e^{ku}\sqrt{r(u)}\, dW(u) \qquad (6)$$

After that, both sides of equation (6) are multiplied with $e^{-k(t+1)}$ to obtain the following solution:

$$r(t+1) = e^{k(t-(t+1)}\, r(t) + \theta\ \big(1 - e^{k(t-(t+1))}\,\big) + \int_t^{t+1} \sigma\ e^{-k(t+t+1-u}\sqrt{r(u)}\, dW(u) \quad (7)$$

Equation (7) is the solution to equation (1). The recursive solution for r(t+1) is obtained as the value one step before r(t). Given Δt = (t+1)-t. So equation (7) can be written in the form of a transition equation as follows:

$$r(t+1) = r^{k(t-(t+1)}\, r(t) + \theta\left(1 - e^{k(t-(t+1)}\right) + \epsilon\,(t+1)$$

With

$$\epsilon\,(t+1) = \int_t^{t+1} \sigma\, e^{-k(t+1)-u} \sqrt{r(u)}\, dW(u) \qquad (8)$$

After getting the solution of the CIR model, look for the average and variance. The mean reversion properties of the CIR model can be proven by calculating the average of the CIR model. The average CIR model is obtained by calculating the expectations.

$$E[r(t+1)] = E\left[e^{-k\Delta t}\, r(t) + \theta\,(1 - e^{-k\Delta t}) + \int_t^{t+1} \sigma\, e^{-k((t+1)-u)} \sqrt{r(u)}\, dW\,(u)\right] \qquad (9)$$

Because the expectation value of this Ito integral is 0, then equation (9) becomes

$$E[r(t+1)] = E[e^{-k\Delta t}\, r(t) + \theta\,(1 - e^{-k\Delta t})]$$

$$E[r(t+1)] = e^{-k\Delta t}\, r(t) + \theta\,(1 - e^{-k\Delta t}) \qquad (10)$$

Equation (10) is the average of the CIR model. By taking the value $t \to \infty$ we will get $lim_{t\to\infty}\, E[r(t+1)] = \theta$. So it is proven that the CIR model has mean reversion properties because the long term average θ which is the mean reversion level.
Next, the variance of the CIR model will be calculated. To calculate the variance, assume the function X(t) = f(t,r(t))) = e^{kt}r(t) as in equation (3).

$$dX(t) = k\theta e^{kt}\, dt + \sigma\, e^{kt} \sqrt{r(t)}\, dW(t)$$

$$= k\,\theta e^{kt}\, dt + \sigma\, e^{\frac{kt}{2}} \sqrt{X(t)}\, dW(t) \qquad (11)$$

In the same way as when calculating the expectation from the CIR model, we get:

$$X(t) - X(0) = \int_0^t k\theta\; e^{ku}\, du + \int_0^t \sigma\; e^{\frac{ku}{2}} \sqrt{X(u)}\, dW(u)$$

$$X(t) = r(0) + \theta\,(\,e^{kt} - 1\,)$$

Until we get:

$$E[X(t)] = r(0) + \theta\,(\,e^{kt} - 1\,) \qquad (12)$$

Using Ito's theorem we can calculate:

$$d\left(X^2(t)\right) = 2X(t)dX(t) + (dX(t))^2$$

$$= 2X(t)\left[k\theta e^{kt}\,dt + \sigma\, e^{\frac{kt}{2}}\sqrt{X(t)}\,dW(t)\right] + \left[\theta e^{kt}\,dt + \sigma\, e^{\frac{kt}{2}}\sqrt{X(t)}\,dW(t)\right]^2$$

$$= 2k\theta\, e^{kt}\, X(t)dt + 2\sigma e^{\frac{kt}{2}} X^{\frac{3}{2}}(t)dW(t) + \sigma^2\, e^{kt}\, X(t)dt \qquad (13)$$

Next, integrate on both sides of the equation:

$$X^2(t) = X^2(0) + (2k\theta + \sigma^2)\int_0^t e^{ku}\, X(u)d(u) + 2\sigma \int_0^t e^{\frac{ku}{2}}\, X^{\frac{3}{2}}(u)dW(u) \qquad (14)$$

Calculate the expectation from equation (14). Because the expectation of the Ito integral is zero, we get:

$$E\,[X^2(t)] = E\left[X^2(0) + (2k\theta + \sigma^2)\int_0^t e^{ku}\, X(u)d(u)\right]$$

$$= X^2(t) + (2k\theta + \sigma^2)\int_0^t e^{ku}\, X(u)d(u)$$

Substitute the equation

$$E\,[X^2(t)] = r^2(0) + (2k\theta + \sigma^2)\int_0^t e^{ku}\left(r(0) + \theta\,(e^{ku} - 1)\right)d(u)$$

$$= r^2(0) + (2k\theta + \sigma^2)\left[\frac{r(0)}{k}(e^{kt} - 1) + \frac{\theta}{2k}(e^{2kt} - 1) - \frac{\theta}{k}(e^{kt} - 1)\right]$$

$$= r^2(0) + \frac{1}{k}(2k\theta + \sigma^2)(r(0) - \theta)(e^{kt} - 1) + \frac{\theta}{2k}(2k\theta + \sigma^2)(e^{2kt} - 1)$$

Then it can be calculated

$$E\,[r^2(t)] = e^{-2kt}\, E\,[X^2(t)]$$

$$= e^{-2kt}\,[r^2(0) + \frac{1}{k}(2k\theta + \sigma^2)(r(0) - \theta)(e^{kt} - 1) + \frac{\theta}{2k}(2k\theta + \sigma^2)(e^{2kt} - 1)]$$

$$= e^{-2kt}\, r^2(0) + \frac{1}{k}(2k\theta + \sigma^2)(r(0) - \theta)(e^{-kt} - e^{-2kt}) + \frac{\theta}{2k}(2k\theta + \sigma^2)(1 - e^{-2kt})]. \qquad (15)$$

Through equation (10) and equation (15) the variance of the CIR model can be calculated

$$Var\left(r(t)\right) = E\,[r^2(t)] - (E\,[r(t)])^2$$

$$= r(0)\left(\frac{\sigma^2}{k}\right)(e^{-kt} - e^{-2kt}) + \theta\left(\frac{\sigma^2}{2k}\right)(1 - e^{-2kt})^2 \qquad (16)$$

3.2 Data Collection

The process of collecting interest rate data is an essential first step in financial analysis and financial planning. Interest rates in Indonesia from 2000 to 2021 experienced significant fluctuations, especially in the 2000-2005 and 2010-2021 periods. The interest rate table is as follows:

Table 1. Interest Rates

Year	IR (%)	Year	IR (%)
2000	14,53	2011	6,50
2001	17,62	2012	6,50
2002	12,93	2013	5,75
2003	8,31	2014	7,50
2004	7,43	2015	7,75
2005	12,75	2016	7,50
2006	9,75	2017	4,75
2007	8,00	2018	6,00
2008	9,25	2019	5,00
2009	8,75	2020	3,75
2010	6,50	2021	3,50

Source: Bank Indonesia

Based on the table above, the phenomenon of interest rates in Indonesia during this period can be explained: 2000-2005: In early 2000, Bank Indonesia (BI) set a reference interest rate of 17% to deal with the economic crisis that occurred at that time. However, in 2001-2002, BI lowered interest rates to around 4-5% to encourage economic recovery. In 2003-2005, BI raised interest rates again to around 9-13% to stabilize the exchange rate and control inflation.

2010-2013: At the beginning of this period, BI raised the benchmark interest rate to 6.5% to stabilize the exchange rate and control inflation. However, in 2012-2013, BI lowered interest rates to encourage higher economic growth. 2014-2015: In this period, BI raised the benchmark interest rate to 7.5% to stabilize the exchange rate and control inflation, especially after pressure on the exchange rate and trade balance deficit. 2020-2021: During this period, BI lowered the benchmark interest rate to 3.5% to encourage economic growth affected by the COVID-19 pandemic and control inflation, which is still low. Sari, S., & Ratno, F. A. (2020) said that interest rates have a positive and insignificant effect on the independent variable Economic Growth, shown through Gross Domestic Product, and must be more active in introducing sharia funding to the community. Ardiansyah, A., Jibril, H. T., Kaluge , D., & Karim, K. (2019).

In managing interest rates, BI continues to implement monetary policy oriented towards exchange rate stability and inflation and supporting economic growth. BI is also intensifying coordination with the government and other financial institutions to ensure the stability and smooth running of the financial system as a whole. The following is supported by a picture of the interest rate trend for 2000-2001.

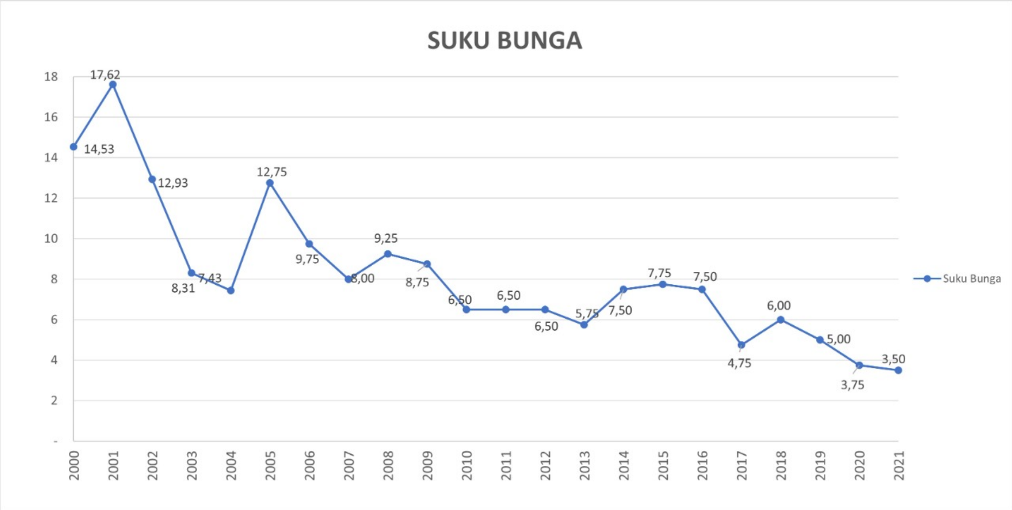

Fig. 2. Interest Rate Trend 2000-2001 (Source: Bank Indonesia)

3.3 Parameter Estimation ($\hat{\alpha}$, $\hat{\mu}$, and $\hat{\sigma}^2$)

Parameter estimation is a process for estimating population parameter values from a given data sample. In the context of the CIR model, there are three parameters to be estimated, namely $\hat{\alpha}$ (alpha-hat), $\hat{\mu}$ (mu-hat), dan $\hat{\sigma}^2$ (sigma-squared hat).
$\hat{\alpha}$ refers to the estimate of the alpha parameter (α) which represents the shift (intercept) of the regression line or model, and $\hat{\mu}$ refers to the average estimate of a sample taken from the population. This estimate is valid when we want to know the population mean based on the sample we have, while $\hat{\sigma}^2$ is an estimate of the population variance based on the sample we have. These estimates are used in various statistical analyses, including hypothesis testing and confidence interval calculations. Based on the derivative of the previous equation, estimates of $\hat{\alpha}$, $\hat{\mu}$, and $\hat{\sigma}^2$ so we obtained:

$$\hat{\alpha} = -\frac{1}{\Delta t}\ln\left[\frac{n\sum_{t=1}^{n} r_t\, r_{t-1} - \sum_{t-1}^{n} r_t \sum_{t=1}^{n} r_{t-1}}{n\sum_{t-1}^{n}(r_{t-1})^2 - \left(\sum_{t=1}^{n} r_{t-1}\right)^2}\right]$$

$$\hat{\mu} = \frac{\sum_{t-1}^{n} r_t\, e^{-\hat{\alpha}\Delta t}\sum_{t=1}^{n} r_{t-1}}{n\left(1-e^{-\alpha\Delta t}\right)}$$

$$\hat{\sigma}^2 = \frac{1}{n}\sum_{k=1}^{n}\frac{\left(r_t - \left(\hat{\mu}\left(1-e^{-\hat{\alpha}\Delta}\right)+e^{-\hat{\alpha}\Delta} r_{t-1}\right)\right)^2}{\left(\frac{1}{\alpha} r_{t-1}\left(e^{-\hat{\alpha}\Delta}-e^{-\hat{\alpha}\Delta}\right)+\frac{\hat{\mu}}{2\alpha}\left(1-2e^{-\hat{\alpha}\Delta}+e^{-2\hat{\alpha}\Delta}\right)\right)} \quad (17)$$

3.4 Retirement Benefits

The retirement benefits are then allocated to each year of service of the retirement participant so that they can be funded by contributions called accrual benefits (b_X). The amount of benefit accrual for each year of work is

$$b_x = \frac{B_r}{S_r} s_x \quad (18)$$

S_r is the total salary until before retirement and s_x is the participant's salary when he is x years old.

3.5 CIR Model Estimation of Interest Rates

To begin implementing the CIR model to approximate interest rates, the first step must be to collect data on the interest rates currently prevailing in the market by substituting the Milstein time interval method [0, T].

$$r_t = r_{t-1} + \alpha(\mu - r_{t-1})\Delta t + \sigma\sqrt{r_{t-1}}\big(W(\tau_t) - W(\sigma_{t-1})\big) + \frac{1}{4}\sigma^2\left((W(\tau_t) - W\tau_{t-1})^2 - \Delta t\right) \quad (19)$$

3.6 Implementation of The CIR Model for a Period of Five, Ten, and 20 Years.

To see whether the CIR model is good enough to approximate interest rates, Yunizar, E. D. (2019) said that the Jackknife method is appropriate when applied to Bank Indonesia's interest rate data, and the CIR model is effectively used to calculate interest rates. According to Rinanti, N. V. (2019). For a period of 5 years, starting from January 2000 to January 2005 with the following estimated results:

Table 2. CIR Model Parameter Estimation Results

Parameter Estimation	Year	α^	μ^	σ^
Results	5 years	0.5115	0.0821	0.0832
	10 years	0.5012	0.0784	0.0802
	20 years	0,5231	0.0831	0.0853

The estimated parameters are used to design an interest rate approach path through the Milstein simulation process. Based on the table 2, the pattern of interest rate movements produced by the CIR model in this approach shows reasonably good agreement with the actual movement of the data. The CIR model effectively approximates interest rates over five, ten, and 20 years using parameters estimated from the same data. However, the movements do not fully reflect the actual movements from the data.

The implementation results that have been carried out produce several significant conclusions regarding using the CIR model in this context. First, the CIR model is more suitable for data with relatively low fluctuations. It shows that this model is more efficient in dealing with interest rates that do not experience drastic or volatile changes.

Second, it should be noted that the CIR model still provides adequate results when used to estimate interest rates in the following year, even though it uses parameters estimated based on the previous year's data. It means the model can provide reasonably accurate estimates of future interest rates, even if the model parameters are calculated from past data.

Furthermore, these results also confirm that the more data used to estimate the parameters of the CIR model, the better the results of the approach will be for future data. Therefore, the collection of extensive and representative data has the potential to increase model precision and produce more precise estimates of future interest rates. It also shows the importance of ongoing data collection and applying relevant modeling techniques to understand and forecast changes in interest rates.

Conclusions

1. Implementing the CIR model to approximate interest rates has revealed several significant findings. First, it was found that the interest rate approximation based on the CIR model shows quite good performance, mainly when applied to data whose fluctuations are not too large. This high level of accuracy is reflected in the small error produced by the model, which shows that the pattern of interest rate movements produced by this approach is almost comparable to the actual movement of interest rates in the market.
2. Second, it is essential to note that in the context of actuarial interest rates used in research related to pension funding, stochastic interest rates, as described in the CIR model, better reflect the actual situation. This is because interest rates in the real economy constantly fluctuate according to changes in the country's economic conditions. Therefore, the CIR model can provide a more accurate picture of the ever-changing movements of interest rates, and this can become a strong basis in research related to pension funding management and planning.

References

[1] Ardiansyah, A., Jibril, H. T., Kaluge, D., & Karim, K. (2019). Permintaan Pembiayaan Murabahah Berdasarkan Tingkat Inflasi dan Suku Bunga BI Rate pada Bank Syariah di Indonesia. Bisma: Jurnal Bisnis dan Manajemen, 13(3), 172-180

[2] Chao, W. (2021). Valuing Multirisk Catastrophe Reinsurance Based on the Cox–Ingersoll–Ross (CIR) Model. Discrete Dynamics in Nature and Society, 2021, 1-8

[3] Fatmasari, F., & Sauda, S. (2020). Pemodelan Unified Modeling Language Sistem Informasi Enterprise Resource Planning. Jurnal Media Informatika Budidarma, 4(2), 429-436

[4] Ghorbani, N., & Korzeniowski, A. (2020). Adaptive risk hedging for call options under cox-ingersoll-ross interest rates. Journal of Mathematical Finance, 10(04), 697

[5] Irwansyah, I. P., Damuri, A., & Yudaningsih, N. (2022). Pemodelan Sistem Infomasi Keuangan Sekolah Menggunakan Model User Experience Design. TEMATIK, 9(1), 94-99

[6] Koesnadi, I. (2019). Pemodelan Informasi Keuangan Arus Distribusi Komoditas Dengan Metode Togaf

[7] Rinanti, N. V. (2019). Estimasi parameter model cox ingersoll ross menggunakan metode generalized least square (Doctoral dissertation, Universitas Islam Negeri Maulana Malik Ibrahim)