Cat bond valuation using Monte Carlo and quasi Monte Carlo method

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The frequency of natural disasters is very small, but the loss of damage and the risks that must be borne is of enormous value. Recently, Catastrophe bond (CAT bond) has grown rapidly in financial markets to increase the coverage of environmental disasters and the resulting economic losses, insurance companies and reinsurers are barely covered. Catastrophe bond (CAT Bond) is one of the insurance-linked financial securities instruments that aim to transfer risk by insuring natural disaster events to the capital market. The model of natural disaster loss without a jump-diffusion process followed a model of geometric Brownian motion. We estimate and match each parameter in each model by using grid search and then we use the method of Monte Carlo and quasi-Monte Carlo to obtain numerical results for the CAT bonds pricing formulas. From this simulation, the Monte Carlo method has good enough accuracy and efficiency to valuates the CAT bond. Less then 500 iterations Monte Carlo have reached convergence in 1280.49 seconds. And quasi-Monte Carlo more efficient with less than 400 iterations have reached convergence in 30.89 seconds. Both methods have reached small enough MAPE. Based on the simulations carried out through this research, it was showed that the quasi-Monte Carlo method is better than the Monte Carlo method based on the value of Mean Absolute Percentage Error (MAPE) and running time.

1. Introduction

From year to year, there are many natural catastrophes in various regions with an increasing frequency. This results in even greater financial losses. The magnitude of this financial loss had a serious impact on the insurance and reinsurance industry and could lead to the bankruptcy of several insurance companies. Therefore, lack of capital due to high claims for natural disaster losses is a very serious problem for insurance and reinsurance companies. Catastrophe risk bonds (CAT bonds) are one of the most important insurance-linked financial securities [1]. A fixed amount of payment for capital market investors to cover high losses due to catastrophes. If the trigger event does not occur before the coupon is paid by the CAT bonds to the bondholder, the net investment income from the trust fund will be the gain from the insurance company on the difference between the coupon rate and the investment income. However, when a trigger event occurs, the coupon income or principal of the bondholder will lose partially or completely, this money will be paid from the SPV to the insurance company to cover the proposed catastrophe loss claim.

The structure of a bond’s cash flow is dependent on the triggering event. Thus, the main objective of CAT bonds is the transfer of risk from the insurance market and government...
baskets to financial markets [2]. CAT bonds allow relatively low-risk transfer costs compared to reinsurance with higher general reinsurance premiums [3]. In a previous study, Louberge et al. [4] applied the classic assumptions of the Black Scholes formula to the CAT bound before applied the compound Poisson process combined with a simple binomial interest rate model. Another option model proposed by Baryshnikov et al. [5] and Lee and Yu [6] are CAT bond models formed from a multiple Poisson process. Similarly, Vaugirard [7] [8] who also uses the Vasicek model [9] for interest rate movements and introduces a barrier options framework with a jump-diffusion process for the underlying physical index of the CAT bonds model.

Furthermore, in the research conducted by Bernacki and Kukla [10], they used a double stochastic Poisson process in valuing the zero-coupon and coupon CAT bonds. Prez-Fructuoso [11] developed a specific CAT bond model with index triggers for continuous times. Besides, Reshetar [12] attributes the risk-neutral pricing of insurance-related securities to a combination of an extreme risk of death with a risk of catastrophe. Lopez Cabrera and Hardle [13] examined the calibration of CAT bonds for the Mexican earthquake and produced a method for valuation of the CAT bound with a stochastic claim arrival process according to Hainaut [14].

In terms of a risk-neutral expectation of a random pay-off expressed the fair price of a financial derivative. In some cases, the expectation is explicitly computable, by a geometric Brownian motion, modeled on the Black Scholes formula for call options on assets. Besides using the Black-Scholes analytical solution, there are numerical methods to approach the Black-Scholes solution, the most popular one is the Monte Carlo method. Monte Carlo has been used by Boyle [15] to resolve option prices used pseudo-random numbers. A good review of the American-style derivatives method also can be found in Staum [16] and Chen [17], which reviews the improvement of the Monte Carlo method in financial engineering. Clewlow [18] solved a naive numerical method using the Monte Carlo simulation. Rostan [19] presents on the basic probabilistic Monte Carlo method for pricing European discrete barrier options and compound real options. In this paper, we present CAT bond valuation with an addition of three factors of the geometric Brownian motion using the Monte Carlo and quasi-Monte Carlo approach.

2. Cat bonds structure
Figure 1 below is a simple CAT bound structure, this structure involves sponsors who can be played by insurance, reinsurance, or government companies. The sponsor will transfer the risk to the investor, who is willing to take the risk for the higher expected return. Special purpose vehicles (SPV) created for the transfer of risk to the capital market, which provides protection dan give benefit to sponsors and issue bonds to investors. The sponsor pays a premium in domestic exchange for guaranteed benefits that will be obtained by predetermined coverage if a disaster of a certain scale occurs and the investor buys a bond. SPV raises capital and invests the proceeds in safe and short-term securities held in trust accounts.

If the specified event which is covered by the contract does not happen during the term of the CAT bond time, the principal cost plus compensation cost will be received by the investor as catastrophic risk exposure. However, if during the risk-exposure period, a catastrophic risk event occurs and triggers specified in the bond contract, then among compensates will be received by the sponsor according to the CAT bond contract from the SPV. This results in a full principal or a partial to the investors [20].

There are three basic trigger types of CAT bonds [21]. The first trigger is Trigger indemnity. This trigger involves the actual loss of the bond-issuing insurance company. The second is the index trigger. This trigger is a value generated from the Property Claim Service (PCS) estimated loss. The investors would not have to worry about the insurer’s claims adjustment practices. and the third one is a parametric trigger. This trigger is based on a measurable natural hazard parameter. So the parameter for a hurricane bond would be the windspeed and for
Figure 1. CAT Bond Structure.

an earthquake, the bond would be the ground acceleration. The specified formula was formed by collecting data at multiple reporting stations to get some fit parameter.

3. Cat bonds model valuation
Changes in currency exchange rates at any time are denoted $dS_t$ is the change in the value of $S(t + 1)$ and $S_t$. The models follow a geometric Brownian motion. The return of a currency exchange rate is the change in the exchange rate at $t + 1$ and $t$ against the exchange rate at time $t$. The interest rate also changes in value following the mean-reverting process and follows the Vasicek model. The exchange rate models and the domestic and foreign interest rate models can be written as:

$$
\frac{dS_t}{S_t} = (r_1 - r_2)dt + \sigma_SS_t dW_S \\
\frac{dr_1}{r_1} = \kappa_1(\theta_1 - r_1)dt + \sigma_1 dW_1 \\
\frac{dr_2}{r_2} = \kappa_2(\theta_2 - r_2)dt + \sigma_2 dW_2.
$$

Where $\sigma_S, \sigma_1, \sigma_2$ are the volatilities, the long-term means for the domestic and foreign interest rate denote by $\theta_1$ and $\theta_2$, $\kappa_1$ and $\kappa_2$ be the mean reversion rates, and then $W_S, W_1,$ and $W_2$ are the Wiener process related by the correlation matrix:

$$
\begin{pmatrix}
1 & \rho_{1S} & \rho_{S2} \\
0 & 1 & \rho_{12} \\
0 & 0 & 1
\end{pmatrix}
$$

The zero-coupon domestic bond price take-home earnings of $1 at $T$ based on the Vasicek model is:

$$
B_1(t, T) = e^{\delta(t) - \gamma(\tau) r_1}
$$
where
\[ \gamma(\tau) = \frac{1}{\kappa_1} \left(1 - e^{(-\kappa_1 \tau)}\right) \]
and
\[ \delta(\tau) = \left[\left(\frac{\sigma_1}{2\kappa_1}\right)^2 - \theta_1\right] [B(\tau) - \tau] - \frac{\sigma_1^2}{4\kappa_1} B_1^2(\tau) \]

with \( \tau = T - t \). A similar formula is expressed for a zero-coupon foreign bond price, it fulfilled to replace the index 1 by 2.

### 3.1. Call option price on foreign currency

We assume a risk-neutral for the forward contract of the exchange rate. An approximation of the forward exchange rate \( F(t, T) \) with conditional variance proposed by Hilliard et al [22], and the contact have zero expected drift. So, based on risk-adjusted, the covariances between the three state variables \( S_t, r_1, \) and \( r_2 \) given by:

\[ \nu^2(\tau) = \sigma_3^2(\tau) + \frac{\tau^3}{3} \left(\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}\right) + \tau^2 (\sigma_{1S} - \sigma_{2S}) . \]

The price of the forward exchange rate is
\[ C(t, T) = B_1(t, T) (F(t, T) N(d_1) - KN(d_2)) \] (4)

where the strike price is \( K \) and the cumulative probability distribution function \( N(.) \) for the standardized normal distribution,

\[ d_1 = \frac{\ln \left(\frac{F(t, T)}{K}\right) + \nu^2(\tau)}{\nu(\tau)} \]

and

\[ d_2 = d_1 - \nu(\tau). \]

By the interest parity, the forward exchange rates are
\[ F(t, T) = \frac{B_1(t, T)}{B_2(t, T)} S_t. \] (5)

### 3.2. Catastrophe index

Unger [23], have been modeled the loss index without any jump process, the index \( I_t \) by Property Claim Service (PCS) is the stochastic variable which is assumed to follow a geometric Brownian motion process as:

\[ dI_t = \alpha I_t dt + \sigma I_t dW_t \] (6)

where the rate damage appreciation is \( \alpha \), as measured by the PCS index over time and represents the volatility in the PCS index due to the small catastrophes and \( dW_t \) is the Winner process or the randomness.
CAT bond is triggered as the first time when the index $I_t$ reaches the trigger threshold $D$. We define the instant $\eta$ as:

$$\eta = t \geq 0, \text{ for } \text{Min } (I_t) \geq D.$$ 

At the maturity $T$ date, the cash flow of the CAT bond is total cash if there is an event of a catastrophe and not as long as the contract. Let $V$ be the face value of the CAT bond at maturity date $T$. If before the maturity date, the CAT bond is triggered, it is reduced by a proportion $\epsilon$. So, at the maturity date, the cash flow $(Z)$ is:

$$Z = F 1_{\eta > T} + (1 - \epsilon) F 1_{\eta < T}$$

where $1_{\eta > T}$ is the indicator function defined by:

$$1_{\eta < T} = \begin{cases} 1, & \text{untuk } \eta \leq T \\ 0, & \text{yang lainnya.} \end{cases}$$

By the sponsor’s point of view, the currency exchange risk has taken by adding the pay-off of a fence, the sponsor would setup because he does not want to assume this risk. Investor hopes to cover an appreciation of his currency against the American dollar, that is, against an increased growth in $S_t$. When the event of a catastrophe occurring that would force him to change his money in his currency the yield he would obtain from the SPV. Thus, the sponsor takes a long position on a call on his currency to fasten in the exchange rate at maturity date $T$, and will exercise it only if the exchange rate is unfavorable at the triggering time and if the CAT bond is triggered. The options pay-off with a strike price $K$ is:

$$(S_T - K)1_{S_T > K}1_{\eta < T}.$$  

The CAT bonds pay-off not subject to the exchange risk and adding the proportion $\frac{\epsilon V}{K}$ to this pay-off, so the total cash flow received by the CAT bondholder is express by:

$$Z = F - \epsilon F 1_{\eta < T} - \frac{\epsilon V}{K} (S_T - K)1_{S_T > K}1_{\eta < T}.$$  

3.3. The cat bond price

The general formula of CAT bond price is defined by:

$$L_{CAT} = E_Q [M(t, T)Z_{CAT}|F_t]$$  

where $D$ is a discount factor, define by:

$$M(t, T) = e^{-\int_t^T r_1(u)du}$$

and $Z_{CAT}$ is the CAT bond’s cash flow at maturity time $T$, defined by equation (7). By using this equation we obtain equation (8) as:

$$L_{CAT} = FB_1(t, T) \left[ 1 - \epsilon E_Q [1_{\eta < T}|F_t] - \frac{\epsilon F}{K} E_Q [(S_T - K)1_{S_T > K}1_{\eta < T}|F_t] \right]$$  

The standard call option price in the currency was given in equation (4). So, we obtain equation (9) as:

$$L_{CAT} = FB_1(t, T) \left[ 1 - \epsilon \left( 1 + \frac{C(t, T)}{KB_1(t, T)} \right) E_Q [1_{\eta < T}|F_t] \right].$$  

Then, trigger probability $E_Q [1_{\eta < T}|F_t]$ can solve by using equation (6) with strike $D$. 
4. Monte Carlo and quasi-Monte Carlo simulation
We use daily federal fund rate and BI rate and USD-IDR currency data for 2016 until 2018 data. We plot the log return of each data in Figure 2 until Figure 4. From these data, we estimate their parameters using a grid search algorithm. Parameters of each model are presented in the following Table 1. Monte Carlo uses in this paper by generating standard random normal

![Figure 2. Daily log-return Federal fund rate.](image)

![Figure 3. Daily log-return BI rate.](image)

![Figure 4. Daily log-return exchange rate USD-IDR.](image)

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \( \kappa_1 \) | 5.574 | \( \kappa_2 \) | 1.631 |
| \( \theta_1 \) | 1.751 | \( \theta_2 \) | 0.500 |
| \( \sigma_1 \) | 1.802 | \( \sigma_2 \) | 2.238 |
| \( \sigma_S \) | 0.012 |
We simulate the Brownian motion with Monte Carlo. From equation (4) we get the forward contracts price on foreign currency with strike price $K = 10000$, $S_0 = 13485$, $r_1(0) = 4.12\%$, $r_2(0) = 1.06\%$. Figure 5 shows the value of the long-term forward contact in the call option for the USD-IDR currency. This forward contact assumes risk-neutral to cover every loss and expects the profit to be received at the end of the contract period.

We simulate the CAT bond price in equation (10) by using the Monte Carlo method. The result of each iteration present in Table 2. Table 2 gives information that CAT bond price with Monte Carlo reaches convergence in 500 iterations with MAPE $4.1 \times 10^{-9}$. This error is
computed by comparing the analytic solution with the Monte Carlo approach. The result of this simulation shows that Monte Carlo has expensive computation, which means that the running time need long running time. In Table 3, the quasi-Monte Carlo method reaches convergence in each pair base after 200th, 200th, 200th and 100th iterations. It is shown that quasi-Monte Carlo fastest convergent than Monte Carlo. In the quasi-Monte Carlo approach, large base pairs converge faster than small base pairs.

### Table 3. CAT bond price under quasi-Monte Carlo method.

| Iteration | Black-Scholes | BP (2 and 3) | BP (2 and 157) | BP (157 and 2) | BP (157 and 359) |
|-----------|---------------|--------------|----------------|---------------|------------------|
| 10        | 176789254.9   | 0            | 548315735.07   | 548315737.07  | 828585170.45     |
| 25        | 176789254.9   | 98956807.81  | 0              | 0             | 472181055.57     |
| 50        | 176789254.9   | 176789255.04 | 0              | 0             | 0                |
| 75        | 176789254.9   | 264783627.22 | 176789255.04   | 176789257.04  | 241617983.37     |
| 100       | 176789254.9   | 176789255.04 | 0              | 0             | 176789245.04     |
| 200       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 300       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 400       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 500       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 600       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 700       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 800       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 900       | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |
| 1000      | 176789254.9   | 0            | 176789245.04   | 176789245.04  | 176789245.04     |

### Table 4. Comparation of MAPE

| Iteration | Monte Carlo | BP (2 and 3) | BP (2 and 157) | BP (157 and 2) | BP (157 and 359) |
|-----------|-------------|--------------|----------------|---------------|------------------|
| 10        | 370.84346612| 131.845688   | 67.75776371    | 67.75776383   | 78.66371965      |
| 25        | 381.21099809| 78.652949    | 224.7692548    | 224.7692566   | 62.55901146      |
| 50        | 15.179349789| 7.91E − 08   | 148.8850337    | 148.8850339   | 219.1997636      |
| 75        | 18.89613528 | 56.120851    | 17.33808368    | 17.33808212   | 198.7302309      |
| 100       | 51.40932697 | 33.232558    | 7.91E − 08     | 1.21E − 06    | 26.83108582      |
| 200       | 1.291967946 | 5.21E − 08   | 243.965529     | 243.9655313   | 7.90E − 07       |
| 300       | 34.77344061 | 5.21E − 08   | 1.21E − 06     | 7.90E − 07    | 7.90E − 07       |
| 400       | 1.51323542  | 5.21E − 08   | 1.21E − 06     | 7.90E − 07    | 7.90E − 07       |
| 500       | 4.17E − 09  | 5.21E − 08   | 7.91E − 08     | 1.21E − 06    | 7.90E − 07       |
| 600       | 4.17E − 09  | 5.21E − 08   | 7.91E − 08     | 1.21E − 06    | 7.90E − 07       |
| 700       | 4.17E − 09  | 5.21E − 08   | 7.91E − 08     | 1.21E − 06    | 7.90E − 07       |
| 800       | 4.17E − 09  | 5.21E − 08   | 7.91E − 08     | 1.21E − 06    | 7.90E − 07       |
| 900       | 4.17E − 09  | 5.21E − 08   | 7.91E − 08     | 1.21E − 06    | 7.90E − 07       |
| 1000      | 4.17E − 09  | 5.21E − 08   | 7.91E − 08     | 1.21E − 06    | 7.90E − 07       |
Table 4 provides information that the Monte Carlo method has more small error value than quasi-Monte Carlo, for a large number of iterations. Meanwhile, for small iterations, the quasi-Monte Carlo has a smaller error value. This basis choice in the quasi-Monte Carlo also affects the error value obtained. Base pairs 2 and 3 have the smallest error value of $7.91 \times 10^{-9}$, while the base pairs 157 and 3 have an error value of $7.90 \times 10^{-7}$. Small bases have a smaller error value than large bases.

Table 4. Running time in second.

| Iteration | Monte Carlo | Quasi-Monte Carlo |
|-----------|-------------|-------------------|
| 10        | 3.411.507   | 0.503672          |
| 25        | 7.921.373   | 0.170277          |
| 50        | 3.314.869   | 0.503061          |
| 75        | 8.730.034   | 1.380.036         |
| 100       | 1.362.396   | 1.949.132         |
| 200       | 4.806.289   | 7.110.434         |
| 300       | 6.909.087   | 1.046.789         |
| 400       | 9.900.008   | 1.300.345         |
| 500       | 1.280.491   | 17.400.235        |
| 600       | 1.891.023   | 2.051.678         |
| 700       | 2.955.908   | 2.309.877         |
| 800       | 4.022.060   | 27.100.357        |
| 900       | 5.990.689   | 29.241.321        |
| 1000      | 7.508.871   | 3.089.723         |

Table 5 provides information that the computation time of the quasi-Monte Carlo approach is much more efficient than the Monte Carlo approach, so the quasi-Monte Carlo method for CAT bond valuation by taking into account the USD-IDR exchange rate is relatively better and more efficient than the Monte Carlo method.

5. Conclusion

We solve a CAT bonds valuation model without a jump-diffusion process and subject to the risk of the domestic and foreign interest rate and currency exchange rate. Those three stochastic factors, the domestic and foreign interest rates, and the exchange rate models followed geometric Brownian motion. We choose Monte Carlo and quasi-Monte Carlo Simulation in numerical computations, and they obtain good accuracy. In terms of running time, it has expensive computation. The quasi-Monte Carlo approach converges faster at the 400th iteration, while the Monte Carlo method converges at the 500th iteration. Quasi-Monte Carlo computation time is much shorter than the Monte Carlo method approach, for 1000 quasi-Monte Carlo iterations takes 30.89723 seconds, while Monte Carlo takes 7508.871 seconds. The choice of prime number base for quasi-random sequences has an effect on the randomness of the sequences formed, it can also affect the convergence and MAPE values. Van Der Corput’s quasirandom sequence with base 2 and 3 converges in the 400th iteration with MAPE values $5.12 \times 10^{-8}$, base 2 and 157 and bases 157 and 2 converge in the 300th iteration with MAPE values $7.191 \times 10^{-8}$ and $1.21 \times 10^{-6}$ and bases 157 and 359 converge on the 200th iteration with a MAPE value of $7.9 \times 10^{-7}$.
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