RESEARCH ARTICLE

Delta-Normal Value at Risk Using Exponential Duration with Convexity for Measuring Government Bond Risk

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A bond is simply a debt that promises to repay the money with interest in the future. An issuer must pay the coupon regularly and repay the face value at the maturity date. Therefore, a bond is called fixed-income security. However, as with any investment, there is always some risk involved. Two significant bond risk investments are interest rate risk and credit risk. In this paper, we want to measure interest risk, which affects bond price movements. Exponential duration with convexity (EDC) will be applied to predict an accurate estimation of bond price caused by the interest rate change. Delta-normal value at risk (DN-VaR) is used to calculate risk based on the bond price estimation. We apply this method to four Indonesian Government Bonds with the code FR0053, FR0061, FR0073, and FR0074. The results show that by using traditional VaR and modified VaR, FR0053 has the smallest risk compared to others. According to EDC, the DN-VaR of FR0053 will decrease due to the interest rate change. The increase in interest rate gives less effect to the risk.

Keywords: value at risk, delta-normal, exponential duration, convexity, government bond

JEL Classification: G32

At the beginning of 2018, the global financial crisis occurred in almost all countries in the world. This was preceded by a trade war between America and China. Consequently, the global recession hit the world due to the cessation of economic activity. At the beginning of 2018, the Indonesian Minister of Finance has predicted that a crisis will also affect Indonesia. Since the beginning of 2018, all sectors experienced a decline, particularly in financial investment, as evidenced by the decrease in economic growth, slowing investment, and the fluctuating price in the Jakarta Composite Index (JCI), which greatly affected stock investment.

Samsi et al. (2018)with particular reference to the stock market, bank, and real estate. Using analysis of cointegration, parsimonious error correction model (PECM examined the financial crisis's effect on economic growth in ASEAN-5 by incorporating the sectoral stock market indices into the model. The results from the parsimonious error correction model showed that growth is affected by the global financial crisis.

The asset price bubble is known as one of the factors of the economic crisis. Some literature suggested that government bonds can rule out rational bubbles. Thepmongkol and Kaytanyaluk (2019) shed for Singapore's case, and the government bonds are keys to the effectiveness of such anti-bubble policy.

Financial investments allocate monetary resources ranging from risk-free to risky investments and expect a reasonable return that varies with risk (Singh, 2014). There is an opportunity for return (profit) in any investment, and there should be a possibility of loss (risk). Higher risk with a higher return is a general principle in finance. Investors, especially conservative investors, often choose bonds as their investments because bonds provide an element of stability. Although a bond is considered a less risky investment, some risks may happen in bond trading. One of the important bond risks is interest risk. A bond's price generally decreases when interest rates rise and increases when interest rates fall. Schuknecht et al. (2008) stated that a bond is a long-term security that gives the holder a right to the issuer's long-term debt. As a long-term investment, the longer a bond's maturity, the higher risk of significant fluctuations in its prices caused by changes in market interest rates (Vanguard Asset Management, 2015).

A bond has unique features compared to other investments. Valuing a bond depends on the structure of the bond. An issued bond has four characteristics: face value, coupon rate, coupon period, and maturity. When a bond is issued, the yield to maturity (YTM) will also be considered an essential factor in buying bonds. Bond price, yield to maturity, and risk of bond investment are influenced by interest rate.

Bonds are issued from various institutions, including governments, agencies, and companies. Government bonds are generally assumed to have low risk. Agencies and corporate bonds are in a good performance when issued by reputable companies and will be risky when issued by low rating companies. Therefore, invest in a government bond is more attractive to investors.

The main factors in government bond risk investment are interest rate fluctuation and inflation (Muharam, 2013; Yusuf & Prasetyo, 2019). Conventional risk measurement for determining government bond risk is using sensitivity analysis. This leads to the concept of duration, which measures the linear exposure, or slope, of the bond value to interest rate (Jorion, 2007). Duration is used to indicate how much the bond price will react to each percentage point of change.

Value at risk (VaR) had been vastly expanded to measure credit risk in the last few years. Some researchers have provided theoretical models and empirical estimates of government bond risk by combining the VaR method and duration. Macaulay (1938) developed a seminal study of duration, popularly known as the Macaulay duration (MD). MD can be inaccurate for large interest rate changes, then Fisher and Weil (1971) added convexity to achieve a better approximation to bond pricing. Livingston and Zhou (2003, 2005) improved a new measure for duration, that was called exponential duration (ED), based on the change in the natural logarithm of value, and was proved as a more accurate measure to estimate bond price changes caused by an interest rate change, compared to MD. Knowles and Su (2005) concerned their research in measuring government bond portfolios using key-rate duration and delta-normal VaR. Su and Knowles (2010) calculated the VaR value using the mixture-normal method and measures the VaR and expected shortfall values on government bonds. Viceira (2012) measured bond risk based on the covariate of bond returns and stock returns. Obadovic et al. (2016) conducted research by calculating the VaR value of bonds with some significant levels using the delta-normal method. Maruddani and Hoyyi (2017) have been provided a comparison between MD, MD with convexity (MDC), ED, and exponential duration with convexity (EDC) for sensitivity analysis. It has been proven that EDC has less error value than other methods.

We highlight three important kinds of literature for explaining the novelty of this research. Knowles and Su (2005)three-factor model (level, slope, and curvature gave a method for measuring government bond risk using delta-normal value at risk by employing key-rate duration. Livingston and Zhou (2005) found out ED as a new method to determine bond duration. Maruddani and Hoyyi (2017) showed and concluded that EDC had a good performance in predicting the change of bond price based on interest rate fluctuation. EDC was proven to be an accurate method to predict bond price changes in case of high and extreme fluctuation interest rate changes.

This study will develop a method to measure delta-normal VaR by using EDC. This work gives new techniques and tools especially in global crises, which are price fluctuations that are very volatile and extreme. DN-VaR using MD, MDC, ED, and EDC is also compared for predicting risk in extreme interest rate changes. As an empirical test, we analyzed some Indonesian government bonds in 2020.

Theoretical Framework

Duration and Convexity

In 1938, the duration concept was introduced by Macaulay and Hicks. Duration is the average return time of funds and a good measure of bond prices' sensitivity to interest changes (Xu, 2020). Duration is defined as a technique used to measure the length of the stream of payment associated with a bond investment. Macaulay duration of bond P is defined mathematically by Ajlouni (2012)

$$\text{Duration} = D = \sum_{i=1}^{n} \frac{PV(CF)_t}{P} \times t \tag{1}$$

Bond price sensitivity to interest rate movements is calculated by using Modified Duration. The percentage change in bond price caused by the change in interest rate is defined as (Martellini et al., 2003)

$$D^* = \frac{D}{1+r} \tag{2}$$

where:

- t : the period which is the cash flow is expected to be received
- $PV(CF_t)$: the present value of cash flow for period t discounted at the YTM level (yield to maturity)
- P : the bond market price
- m : the number of coupon periods until maturity

Then we can estimate bond price based on duration uses the following equation:

$$\widehat{p_1} = P(1 - D^*\Delta r) \tag{3}$$

where:

- ΔP : price change in a bond = P_1 - P_0
- P : price of bond market
- r : bond interest rates
- Δr : the change in interest rates $r_1 = r_0$
- $\widehat{p_1}$: the new actual price estimation of the bond based on the MD

Duration is suitable for small interest change, because bond price is a nonlinear function. The approximation can be improved by adding convexity term in the calculation. Convexity is the second derivative of bond price to interest rate, and the formula is (Bodie et al., 2008)

$$\text{Convexity} = V = \frac{1}{P(1+r)^2}$$

$$= \sum_{t=1}^{n} \frac{(CF)_t}{P(1+r)^2} \times t(t+1) \tag{4}$$

Livingston & Zhou (2003, 2005) also stated that MD can be quite inaccurate for large changes in interest rates. Their papers suggested ED as the new method and showed that the techniques were more accurate than MD and MDC. Mathematical proof was provided and the empirical study on a 30-year par bond with 5% coupon rate proved that ED is the most accurate estimation to predict bond price based on interest rate change. Maruddani & Hoyyi (2017) completed the methods by providing EDC. The new formula has proved that EDC gave the smallest error and provided the same empirical study results.

As provided in Maruddani & Hoyyi (2017), the estimation for bond pricing using MDC, ED, and EDC consecutively are

$$\widehat{p_2} = P(1 - D^*\Delta r + V(\Delta r)^2) \tag{5}$$

$$\widehat{p_3} = P(\exp(D^*)\,\Delta r) \tag{6}$$

$$\widehat{p_4} = P(\exp(D^*)\exp\left(-\frac{D^{*2}}{2} + v\right)(\Delta r)^2) \tag{7}$$

where:

$\widehat{p_2}$: the new actual price estimation of the bond based on the MDC

$\widehat{p_3}$: the new actual price estimation of the bond based on the ED

$\widehat{p_4}$: the new actual price estimation of the bond based on the EDC

Delta-Normal Value at Risk

According to (Jorion, 2007) VaR summarizes the worst loss over a target horizon that will not be exceeded with a given level of confidence. The parametric approach calculates VaR based on considerable distributions, such as normal distribution. The delta-normal method is the most frequently used in this approach because of the simplest way to handle it.

The delta-normal method assumes that the return or percentage of price change from the financial market is normally distributed. The formula to calculate VaR for a single asset is:

$$VaR = Z_{(\alpha)}\sigma P\sqrt{t} \tag{8}$$

As stated above, the percentage price change caused by interest rate change can be calculated using modified duration, then the VaR by considering modified duration as (Obadovic et al., 2016):

$$VaR = PD^{*}Z_{(\alpha)}\sigma \tag{9}$$

where:

$Z_{(\alpha)}$: Z value for normal distribution at a significance level

σ : volatility or the standard deviation of bond price return

P : bond price

$\sqrt{t}$: holding period

D*: Modified Duration

Research Method

Type and Data Source

Bond data is taken from the IBPA website, www.ibpa.co.id. From 80 government bonds, we choose the bonds using three criteria: (a) give fixed-rate coupon; (b) publish bond market price data completely; (c) the return of price data is normally distributed, because of the assumption for DN-VaR. From the three criteria, we use four government bonds with fixed-rate coupons.

The four bonds are FR0053, FR0061, FR0073, and FR007. Weekly bond market price data was taken from the BCA website, www.bca.co.id from February 29, 2017 to February 17, 2020.

Methodology

This study measures the delta-normal VaR for a government bond portfolio build upon the EDC concept. In the first step, we focus on estimating bond price change based on EDC as a procedure to estimate price changes of a bond. This step is doing as follows: (a) calculate the duration of bond using Macaulay duration; (b) calculate MD as a tool for predicting the sensitivity of a bond; (c) calculate convexity for adding accuracy in MD, which is named as MDC; (d) calculate ED and EDC based on MDC for more exact price changes of a bond when the interest rate has high and extreme volatility.

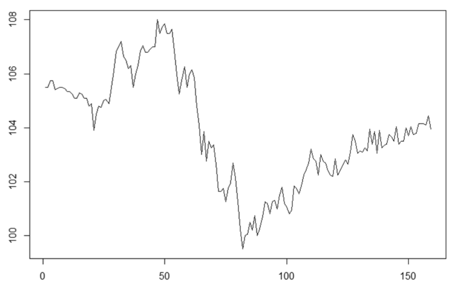
The second step focuses on predicting the bond risk using DN-VaR. The steps are as follows: (a) calculate the bond price return using compounded log return; (b) test the normality distribution of the return series using Kolmogorov-Smirnov test; (c) calculate each volatility of bond price using MD, MDC, ED, and EDC; (d) Calculate each DN-VaR for the four methods; and (e) compare the result and analyze FR0053, FR0061, FR0073, and FR007 risks.

Results and Discussions

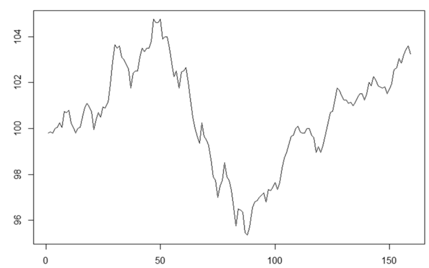
The bonds used in this study are government bonds series FR (Fixed Rate) with a coupon period of every six months. The parameters of each bond can be seen in Table 1. The movement of bond market price and market return are displayed as graphs in Figures 1 and 2. Figure 1 shows that the historical data is dramatically up and down, but the four graphs show the same pattern each time. It can be shown that from the second quarter of 2018 until the end of 2018, the bond prices had a descending pattern to the lowest point. At the beginning of 2019, bond prices began to move up slowly. It was caused by the global financial crisis in 2018. Fortunately, Indonesia was able to survive and show stable economic growth. However, in Figure 2, the return of bond market price shows stationer movement in constant mean but volatile in

Table 1. *Government Bond Data*

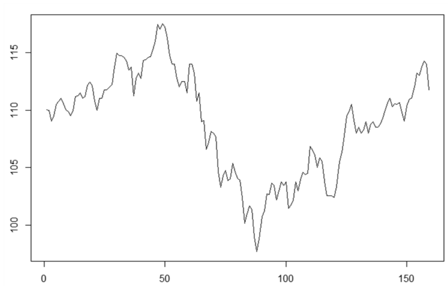
Parameter	Bond Code			
	FR0053	FR0061	FR0073	FR0074
Outstanding Value	98,537,793	102,72,000	66,217,000	47,831,140
Coupon	8.25%	7%	8.75%	7.5%
Listing date	09 July 2010	24 May 2011	06 August 2015	10 November 2016
Maturity date	15 July 2021	15 May 2022	15 May 2031	15 August 2032



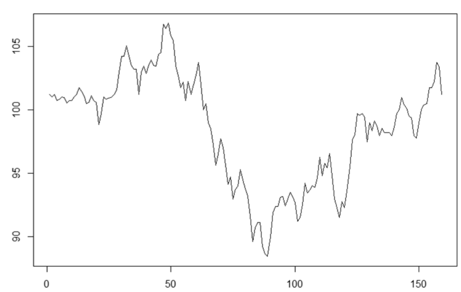
FR0053



FR0061



FR0073



FR0074

Figure 1. Graphs of Bond Market Price Movements

Table 2. *Statistics Descriptive for Bond Market Price Data*

Bond Code	Minimum	Maximum	Mean
FR0053	99.50	108.00	103.82
FR0061	95.35	104.75	100.52
FR0073	97.65	117.50	108.75
FR0074	88.45	106.85	98.44

Table 3. *Kolmogorov-Smirnov Test*

Bond Code	D Value	*p-value*
FR0053	0.079593	0.2695
FR0061	0.061571	0.5871
FR0073	0.076897	0.3076
FR0074	0.052701	0.7725

Table 4. *Return Data Volatility*

Bond Code	Return
FR0053	0.004423
FR0061	0.004075
FR0073	0.009431
FR0074	0.010073

Table 5. *Duration and Convexity*

Bond Code	Macaulay Duration	Modified Duration	Convexity
FR0053	7.43452	6.86791	282.58
FR0061	7.84899	7.33550	317.99
FR0073	8.89817	8.18222	441.91
FR0074	9.57434	8.90636	495.81

Table 6. *Delta-Normal VaR*

Bond Code	Traditional VaR		Duration Based VaR	
	VaR (IDR)	VaR (%)	VaR (IDR)	VaR (%)
FR0053	667,841,974,609.36	0,68%	4,586,681,097,816.00	4.65%
FR0061	843,333,099,333.71	0.82%	6,186,271,607,187.74	6.02%
FR0073	1,176,535,193,719.82	0.02%	10,469,004,896,769.60	0.16%
FR0074	911,775,884,904.55	0.02%	8,120,602,577,459.57	0.17%

variance. World economic turmoil has greatly affected Indonesia. Several extreme return values also occurred throughout the period. The summary of data from 2017 to early 2020 is presented in Table 2. It is provided the statistics descriptive for Bond Market Price.

Results from the testing Normality Distribution for return data using the Kolmogorov-Smirnov gives the result in Table 3. As we can see in the p-value result that all the return series are shown as Normal Distribution.

The volatility for return data is presented in Table 4. As shown in Table 4, we can see that FR0074 has the most volatile return data. As a pre-conclusion, we can say that FR0074 is the riskiest bond.

Duration is a method that investor can use to estimate the sensitivity of a bond's price to interest rates change. Table 5 provide the value of MD, modified duration, and convexity.

Based on Table 5, the MD for FR0053 is 7.43452. It means that bond's investor needs 7.43452 years (in average) to receive the cash flows from a bond. Expecting the sensitivity of a bond can calculate by using MD; for example, the modified duration of FR0053 is 6.86791. It means that if the interest rate rises by 1% overnight, the bond's price is expected to drop by 6.86791%. Table 5 shows positive convexity for all bonds. Positive convexity leads to more

Table 7. *Delta-Normal VaR*

Interest Rate Changes	New Interest Rate	MD	MDC	ED	EDC
FR0053					
-5 %	3.25 %	6.253162 %	4.880580 %	6.561915 %	3.052264 %
-3 %	5.25 %	5.613794 %	4.736044 %	5.719744 %	4.342197 %
-1 %	7.25 %	4.974427 %	4.663777 %	4.985660 %	4.835333 %
0 %	8.25 %	4.654743 %	4.654743 %	4.654743 %	4.654743 %
1 %	9.25 %	4.335059 %	4.663777 %	4.345790 %	4.214756 %
3 %	11.25 %	3.695692 %	4.736044 %	3.788042 %	2.875727 %
5 %	13.25 %	3.056324 %	4.880580 %	3.301877 %	1.535862 %
FR0061					
Interest Rate Changes	**New Interest Rate**	**MD**	**MDC**	**ED**	**EDC**
-5 %	2.00 %	8.230628 %	6.373103 %	8.690091 %	3.669111 %
-3 %	4.00 %	7.347150 %	6.148354 %	7.504279 %	5.501766 %
-1 %	6.00 %	6.463672 %	6.035980 %	6.480277 %	6.260587 %
0 %	7.00 %	6.021933 %	6.021933 %	6.021933 %	6.021933 %
1 %	8.00 %	5.580194 %	6.035980 %	5.596007 %	5.406295 %
3 %	10.00 %	4.696716 %	6.148354 %	4.832400 %	3.542877 %
5 %	12.00 %	3.813238 %	6.373103 %	4.172992 %	1.761912 %
FR0073					
Interest Rate Changes	**New Interest Rate**	**MD**	**MDC**	**ED**	**EDC**
-5 %	3.75 %	22.278253 %	17.239319 %	23.801843 %	7.252115 %
-3 %	5.75 %	19.691010 %	16.324649 %	20.208808 %	13.174319 %
-1 %	7.75 %	17.103768 %	15.867314 %	17.158165 %	16.361571 %
0 %	8.75 %	15.810147 %	15.810147 %	15.810147 %	15.810147 %
1 %	9.75 %	14.516526 %	15.867314 %	14.568035 %	13.891692 %
3 %	11.75 %	11.929283 %	16.324649 %	12.368901 %	8.063407 %
5 %	13.75 %	9.342041 %	17.239319 %	10.501739 %	3.199745 %
FR0074					
Interest Rate Changes	**New Interest Rate**	**MD**	**MDC**	**ED**	**EDC**
-5 %	3.25 %	24.538099 %	18.851940 %	26.501877 %	6.948490 %
-3 %	5.25 %	21.513918 %	17.652393 %	28.591315 %	13.696763 %
-1 %	7.25 %	18.489738 %	17.052620 %	23.926242 %	17.591461 %
0 %	8.25 %	16.977648 %	16.977648 %	21.887425 %	16.977648 %
1 %	9.25 %	15.465558 %	17.052620 %	20.022341 %	14.721167 %
3 %	11.25 %	12.441378 %	17.652393 %	16.755416 %	8.026737 %
5 %	13.25 %	9.417197 %	18.851940 %	14.021535 %	2.851624 %

significant increases in bond prices. Under normal market conditions, the higher the coupon rate or yield, the lower a bond's degree of convexity. The FR0074 has the longest MD, the highest modified duration, and convexity. Therefore, FR0074 is the most sensitive bond caused by interest rate movement.

Livingston and Zhou (2003, 2005), Knowles and Su (2005) three-factor model (level, slope, and curvature, Ajlouni (2012)both, time structure of a bond and interest rate risk. The study concludes that, as a measure of the time structure of a bond, duration has four properties: (1, and Maruddani and Hoyyi (2017) employed modified duration to estimate price because it can be an indicator of vulnerability of investment to changing interest rates. Jorion (2007) suggested modified duration as a tool for calculating delta-normal VaR (DN-VaR); thus, we can use bond return as the risk factor. The following is DN-VaR calculation based on equations (8) and (9) at a 95% significance level, for a week investment. The results are shown in Table 6, which give higher risk prediction by using duration VaR. According to the two methods, the best bond to invest in is FR0053 because it has the smallest VaR.

Bond price change caused by interest rate fluctuation is derived from equations (3), (5), (6), and (7). Based on the estimated bond price, predicted DN-VaR which be affected by the interest rate fluctuation can be estimated. The DN-VaR values will vary according to the change of interest rate. Table 7 provides some numerical DN-VaR estimates for four different bonds by the four methods: MD, MDC, ED, and EDC. For example, FR0053 is a bond with a 5% annual coupon rate. Table 7 shows the prediction of DN-VaR based on the shifts of interest rate. According to Maruddani and Hoyyi (2017), the preferable method is EDC. DN-VaR calculated by using EDC decrease affected by the interest rate change. For FR0053, if the interest rate falls by 500 basis point, then DN-VaR drop from 4.654743% to 3.052264%. At the same time, the interest rate rises to 500 basis point, the DN-VaR drop from 4.654743% to 1.535862%.

In general, comparing the four bonds indicates that FR0074 is the riskiest investment because the DN-VaR is the most sensitive shift due to interest rate fluctuations. Also, FR0053 is the most preferred bond to invest in.

Conclusion

This paper develops a procedure for predicting delta-normal value at risk (DN-VaR) using bond price estimation based on interest rate change. The calculation for predicting bond price is based on EDC methods. A bond is a sensitive investment affected by interest rate fluctuation. The bond price will rise by decreasing the interest rate. Otherwise, estimating the bond's sensitivity is appropriate by using EDC. Then EDC is used to calculate the bond price estimation effect by the interest rate change. DN-VaR is predicted according to bond price estimation. For some Indonesian government bonds (FR0053, FR0061, FR0073, FR0074), DN-VaR by EDC will fall, even if the interest rate falls or rises. However, the decreasing risk because of decreasing interest rate is less affected by increasing rate interest. Among the four bonds, the most recommended bond is FR0053, because it is the most robust on risk due to the interest rate change.

Acknowledgment

This research was funded by The Ministry of Education and Culture through PTUPT Research Scheme in 2020.

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