MODELING THE TERM STRUCTURE OF INTEREST RATES IN UKRAINE AND ITS APPLICATION TO RISK-MANAGEMENT IN BANKING

by

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Thesis Supervisor: ______________________ Professor Olesia Verchenko

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Abstract

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This work on the term structure of interest rates employs the Vasicek model (1977) to cover three important aspects. The first concerns the fitting of Ukrainian data to this model to see how good it approximates movements in the Ukrainian bond market. The second relates to the forecasting of future yield curve using the estimated parameters of the model. The third involves the use of Vasicek model to calculate two commonly accepted market risk measures for a portfolio of fixed income securities, value at risk and expected shortfall, using Monte Carlo simulation.

Data sample for this paper consists of Treasury bills and government bonds prices and yields to maturity for the period August 2010 to January 2011 collected from Ukrainian organized exchanges and over-the-counter market participants, downloaded from Bloomberg.

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Chapter 1

INTRODUCTION

Over the last two years the market of fixed income instruments in Ukraine has gone through substantial changes. Before the world financial crisis the market of fixed income securities in Ukraine was rather rudimentary and very slow. Only government bills and bonds market was active. Due to the fact that yields to maturity for sovereign debt of Ukraine were higher than in the developed markets of the EU and the USA, the interest from non-residents side was quite considerable. In the pre-crisis period the prices of five-year credit default swaps (CDS), which are a major tool to hedge against the sovereign debt default risk for investors, were relatively low for Ukraine, but during the crisis the CDS rates for Ukraine, as well as for other emerging economies, soared to more than 5,000 points (Bloomberg). This was a convincing evidence of the very high default risk that provoked non-residents to cut their investment into Ukrainian debt instruments and leave the market.

After the most severe times of the crisis passed, the economic and political situation began to recover and some signs of renewed economic growth became obvious. The new government came back to practice of issuing long-term government bonds and short-term T-bills to attract financial resources from private sector and from abroad.

Moreover, the major rating agencies such as Standard & Poor's, Fitch and Moody's have upgraded the credit ratings of Ukraine in 2010 from negative to stable outlook. This had an immediate impact on Ukraine 5-year CDS prices, which continue declining (Bloomberg).

The major holders of debt instruments are National Bank of Ukraine (NBU) and commercial banks (NBU official statistics). One has to mention the constantly growing interest of non-residents to the local market of fixed income instruments. This is a clear evidence of post-crisis recovery of investors' confidence and interest to the debt instruments issued by the Ukrainian government.

All these favorable changes have led to a surge in the development of the market of fixed income instruments in Ukraine. The major participants of this market are the government, central bank, commercial and investment banks, pension funds and large international mutual funds, who are most interested in constant analysis of its dynamics and who try to predict and estimate the possible risks associated with investing in it.

To analyze the bond market, economists and financial professionals conduct the research on the behavior of interest rates, i.e. the yields of fixed income securities. One of their main questions is about the link between the short term and long term interest rates, or, equivalently, the relationship between the maturity of bond instruments and their returns. The returns of fixed income instruments are also known as their yields to maturity (YTM), and the relation between these yields and the maturity of corresponding instruments is referred to as the term structure of interest rates or the yield curve.[1]

There are many benefits from a better comprehension of the yield curve dynamics. Understanding and modeling the term structure of interest rates plays a key role in the conduct of monetary policy, in forming the expectations about

[1] One of the most prevalent economic theories of term structure is the expectations theory, and it states that the long rates are the average of future expected short term rates. In the case of a decline in future expected short rates, one would observe the opposite situation with decline in long term rates (Mishkin, 2004). This theory suggests that the likelihood that yield curve is upward sloping is the same as that it is downward sloping.

future economic activity and inflation, in financing of public debt, the financial risk management associated with holding a portfolio of bonds, and the valuation of financial instruments. The term structure of interest rates contains information about market expectations and the risk premium that compensates bondholders for the risks exposure they face when holding debt securities: credit risk, market risk and liquidity risk (Ferrucci, 2003).

Furthermore, all bond market participants are very interested in being able to forecast interest rates dynamics. In particular, this ability is crucial for financial risk management purposes. If interest rates change unexpectedly, a financial institution might face the possibly negative change in value of its market portfolio, which might trigger the loss of investors' confidence. Financial institutions are thus interested in predicting future losses, and hence insuring themselves by making the appropriate capital provisions (using, for example, such generally accepted measure of market risk as value at risk (VaR)).

The goal of this paper is to analyze the yield curve dynamics for the Ukrainian bond market in the post-crisis period. In particular, we employ the prominent Vasicek (1977) model of short term interest rates to identify the relation between the short term and long term interest rates. This model starts with postulating a random process for short rates dynamics and derives the processes for all long term interest rates from the short rate process. First, we estimate the parameters of this model using the market data on bond prices. Then, we demonstrate how this model can be used to forecast the term structure, form the distribution of consequent portfolio gains/losses and make appropriate capital provisions. In particular, we show how to use the model to calculate two measures of market risk (value at risk and expected shortfall) for a portfolio of fixed income instruments using Monte Carlo simulations of future dynamics of short term interest rates.

The Vasicek model is one of the earliest models of the short rate but is still very actively used by both academic researchers and practitioners. The model is intuitively appealing and is relatively easy to use to derive bond prices and bond yields from it. Also, extensive literature (De Munnik et.al,1993; Longstaff, 1989) evidences that it produces a good fit to observed term structure, and our results are consistent with those documented in the literature.

This paper is organized as follows. Chapter 2 reviews the existing literature on term structure models and the approaches to their estimation. Chapter 3 overviews the methodology, discusses the Vasicek model, value at risk and expected shortfall concepts. Chapter 4 describes the data. Chapter 5 presents the empirical results. Chapter 6 concludes with a discussion of policy implications, as well as suggests perspectives for future research on this important topic.

Chapter 2

LITERATURE REVIEW

Since this work aims at modeling the term structure of interest rates in Ukraine, it is natural to provide a brief overview of the existing literature on different approaches to estimation of the term structure of interest rates and issues associated with it. First, we concentrate on the theoretical approaches used in the literature to model the term structure of interest rates. Second, we consider the literature that deals with models that are used to study the term structure and their estimation. Third, we review the papers devoted to the specification of Vasicek model and different techniques used to estimate the parameters of this model, that are further used to demonstrate the application of Vasicek model results to financial risk management.

There has been developed a lot of theoretical approaches to model the term structure of interest rates. When trying to explain the link between the short-term and long-term interest rates both academics and practitioners raise the question what should be modeled?

Early approaches to estimate the term structure aimed at modeling the bond prices dynamics. However, they did not result in a better understanding of the shape of the yield curve. There has not been elaborated any framework that could capture the behavior of interest rates based on the bond prices evolution (Cox et.al, 1985).

The next step was to develop the interest rate models that represented the stochastic evolution of a given interest rate, usually the short rate (yield on a very short-term instrument). Then, all bond prices can be expressed in terms of the short-rate process parameters, and all longer-term rates are functions the current short rate level and model parameters. In particular, the valuation approach based on these models relies on the solving a partial differential equation derived from the underlying stochastic process for the short rate. This equation is solved analytically or numerically for the prices of the bonds and thereafter the bond yields are derived from these prices. As a result one gets the set of bond yields for different maturities and constructs the yield curve (Vasicek, 1977).

As an alternative to these approaches it was later suggested to consider the stochastic process for the entire term structure of interest rates by taking all yields or all forward rates available from the market. Although this approach looks intuitively appealing, since it might provide wider scope of the yield curve modeling, the models of this class become very sophisticated and the estimation techniques are very complex. Therefore practitioners dealing with the term structure of interest rates try to employ the models that combine both the consistency with the current yield curve and the relative simplicity of models' parameters estimation (Hull et al., 1990).

Overall these three approaches are interrelated in the process of modeling the term structure of interest rates.

Theoretical and empirical literature divides models of the term structure of interest rates into two broad classes: equilibrium models and no-arbitrage models. The first class of models is based on the derivation of the term structure from the given economic assumptions. These models rely on the specific initial presumptions about the economic variables and then derive a stochastic process for the short-term interest rate dynamics to use it for further construction of the yield curve. Thus, the output from the equilibrium models is the initial term structure of interest rates. Herewith the major drawback of this category of models is that they do not automatically fit the current yield curve. The no-arbitrage models overcome this shortcoming by taking the current yield curve as an input and choosing the parameters to capture the behavior of interest rates in the future. In this respect the latter models look more attractive from the point of view of consistency with the current yield curve (Gibbons, 1993).

Another important classification of yield curve models is done by dividing them into single and multi-factor models. The idea behind these models is that the yield curve movements are governed by a set of various factors (Heath et al., 1992).

Wilson (1994) decomposes the dynamics of the yield curve into three independent factors:

- shift of the yield curve, i.e. a parallel movement of all the interest rates, which explains the major portion of the rates volatility;

- a situation when long-term and short-term interest rates move in opposite directions;

- a situation when the intermediate rates move in the opposite direction to both short-term and long-term rates.

The significance of two latter factors in explaining the term structure dynamics is not high comparing to the first one. Since the first factor generally explains the movements of interest rates at most, the one factor models have gained a broad popularity among practitioners. However, this does not imply that the entire term structure is governed by the parallel movements, but simply that it is sufficient to explain the link between the short-term and long-term interest rates by employing only one single source of uncertainty.

One-factor models contain only one underlying driving force for the interest rate process. One of the earliest and the most famous one-factor equilibrium model is the Vasicek (1977) model of short-term rate. This model postulates the stochastic process for short-term rate and derives a general form of the yield curve.

Among many term structure models this model attracts attention of practitioners due its relative simplicity in estimation and possibility to easy calculate bond prices and yields. This model is still actively employed in the majority of researches conducted in the area of term structure modeling and bond pricing. It remains to be the benchmark core model for these purposes (Gibbons, 2001).

A lot of studies on the term structure of interest rates were conducted in developed countries like USA, Japan, Germany and others. In these studies the authors mainly used Treasury bill and government bond yields since such securities are deemed to have low or no default risk.

However, estimating the term structure of interest rates in most emerging markets such as Ukraine is quite problematic because of the relatively small market size.

Choudhry (2004) suggests that for modeling the yield curve in emerging markets one should incorporate the equilibrium models of interest rates, since they account for an absence of reliable market data, which often happens in developing capital markets. He also finds that Vasicek model performs rather well in fitting the current yield curve to the one observed from the market.

Chapter 3

METHODOLOGY

In this work we estimate the Vasicek model for the market of fixed income instruments in Ukraine.

This is one-factor equilibrium model that relies on the volatility of the short rate and incorporates a mean reversion feature which is indifferent to price trends similar to that of stock prices, i.e., interest rates tend to revert back to the long-run level over time. This model of the yield curve contains the constant parameters and a constant volatility in the short rate. Hereafter, one often assesses the actual parameters using the historical data.

The Vasicek model (1977) presumes that the term structure of interest rates at time t is r(t), which follows the mean-reverting process of the form (Promchan, 2007):

$$dr(t) = \kappa(\theta - r(t))dt + \sigma dz(t) \tag{1.1}$$

where,

dr is a small change in the short rate caused by a change in time (dt) which contains a drift back to the mean level θ at the rate of κ;

κ is the speed of mean reversion, it shows how long a factor returns to its long term rate. Mean reversion represents the persistence of an impact of new economic information or some shock on the economy;

dz (t) includes uncertainty, which is represented by the Brownian motion. The short-term rate r is deemed to be the immediate rate at time t and can be used for continuous compounding;

θ is the parameter which represents the process that implies a mean-reverting feature in the Vasicek model and one may treat it as the equilibrium level of the short-term interest rate, around which it evolves with some probability. If the interest rate is below its long term value θ, the expected change in interest rate is positive and vice versa. Hence, the short-term interest rate will tend to rise (fall). It moves toward its long-term value fast if it is far from it and when the parameter κ (speed of return to the long term mean value) is high. It is assumed that the volatility of the short rate follows a normal distribution. An obvious shortcoming of the Vasicek model is that the interest rate can take a negative value (Promchan, 2007).

The logic of the Vasicek approach to bond pricing is related to the problem faced by a bond market-maker who tries to hedge against interest rate risk, i.e. the unfavorable movements in interest rates (McDonald, 2006). The model assumes that a bond is a general function of the short-term interest rate that follows a particular mean-reverting process represented by equation (1.1.).

In this one-factor model bond value is determined by the short-term rate. A bond value $P_\tau[r(t)]$ in a risk-neutral economy discounted at time t with a maturity of τ and a face value 1 can be expressed as follows:

$$P_\tau[r(t)] = \tilde{\mathrm{E}}_t\left[\exp\left(-\int_t^{t+\tau} r(s)ds\right)\right] \tag{1.2}$$

$\tilde{\mathrm{E}}_t$ is the expectation with respect to the risk-neutral stochastic process.

One can estimate the spot rate from the following equation:

$$dr(t) = \kappa\left[\tilde{\theta} - r(t)\right]dt + \sigma d\tilde{Z}(t) \tag{1.3}$$

Now calculated expected yields can be used to find the bond value:

$$P_r\left[r(t)\right] = \exp\left(\frac{1-e^{-\kappa\tau}}{\kappa}\left[R_\infty - r(t)\right] - \tau R_\infty - \frac{\left(1-e^{-\kappa\tau}\right)^2}{4\kappa^3}\sigma^2\right) \tag{1.4}$$

The yield to maturity (YTM) of a bond is presented as $R_t(t) = -\frac{-\ln P_\tau\left[r(t)\right]}{\tau}$ and implies:

$$R_\tau(t) = R_\infty + \frac{1-e^{-\kappa\tau}}{\kappa\tau}\left[r(t) - R_\infty\right] + \sigma^2\frac{\left(1-e^{-\kappa\tau}\right)^2}{4\kappa^3\tau} \tag{1.5}$$

With an increase of maturity from $\tau \longrightarrow \infty$, the YTM converges to:

$$\lim_{\tau \longrightarrow \infty} R_\tau(t) = R_\infty = \tilde{\theta} - \frac{\sigma^2}{2\kappa^2} \tag{1.6}$$

Equation (1.5) ensures positive interest rates at all maturities with the simple parameter restrictions being the following:

$\kappa > 0$, $R_\infty > 0, \sigma > 0$ and $r(t) > 0$.

In this work we estimate the equation (1.5) which is the empirical model for the Vasicek yield curve.

To estimate the parameters of the model we use a nonlinear optimization procedure by minimizing the sum of square errors and by choosing the parameters κ, R_∞ and σ such that they provide the lowest mean squared error:

$$\min_{R_\infty,\kappa,\sigma} \sum_{i=1}^{n} \left[P_{i,\tau}(c,t) - P_{i,\tau}^{*}(c,t) \right]^2 \quad \text{for bond i at time t} \qquad (1.7)$$

Since $P_{i,t}(c,t)$ is the market bond price, $P_{\tau}^{*}(c,t)$ is the price given by model when:

$$P_{\tau}^{*}(c,t) = \sum_{j=1}^{K} c_j P_{\tau_j}[r(t)] \qquad (1.8)$$

c is the bond cash flow vector;

$c = (c_1,\dots,c_K)$

τ represents the corresponding payment dates;

$\tau = (\tau_1,\dots,\tau_K)$

$P_{\tau_j}[r(t)]$ are the prices of the discount bond provided by the Vasicek model.

Equation (1.8) for the price can be estimated for each trading day.

This estimation is done using Matlab software by employing the grid-search algorithm for each trading days' yield curve.

The standard practice in the literature is to estimate the Vasicek model by cross section. The model is applied to each trading day to fit that day's yield curve and to get the corresponding parameters. This procedure is called the static estimation.

Alternative approach is to estimate the parameters of Vasicek model using time series analysis. However, as the empirical literature (De Munnik et.al,1993) suggests to use this technique one needs to estimate the Vasicek parameters by employing the historical market short term interest rates. This approach is not appropriate for Ukraine, since there is no benchmark for short-term rate in Ukraine so far.

After estimating the model parameters using daily data for the period from August 2010 to January 2011, one can then use them to forecast the bond prices. Hereafter the estimated yield can be compared to observed market yields and one is able to get mean absolute percentage errors:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|P_{it} - P^{*}{}_{it}\right| \Big/ P_{it} \tag{1.9}$$

It provides the average difference between the actual market yields and the fitted values.

Furthermore, since we have a random process for interest rate, we can use it for simulation of future short rates and determine the shape of the distribution. Once we have this distribution, we can compute value at risk (VaR) using Monte Carlo approach. Given the portfolio of fixed-income securities held by financial institution, we can calculate the future value of a portfolio and calculate prices along with a change of portfolio value. In this work we calculate VaR and expected shortfall (ES) as an alternative measure of market risk.

Hull (2007) defines value at risk in the following way: "We are X percent certain that we will not lose more than V dollars in the next N days." Here the two crucial inputs for the analysis are the confidence level (X percent) and the time horizon (N days). In this paper we use 99% confidence interval to make a forecast for 1 day ahead, as it is recommended by Basel Committee on Banking Supervision (BIS, 2006).The output is the value at risk (V dollars) for the portfolio of financial assets.

However, like all statistical tools, VaR has its limits (Artzner et al., 1997). This measure does not indicate the severity of loss beyond the threshold, hence the alternative risk measures were introduced. The major of them is the expected shortfall (ES), also known as the expected tail loss (ETL), formalized by Acerbi and Tasche (Acerbi et al., 2001), which measures the expected value of portfolio returns given that some threshold (usually the Value at Risk) has been exceeded.

Within the Monte Carlo approach one does not calculate variance and covariance among risk factors, but takes the simulation rout and specifies the probability distribution of the risk factor, which may differ from normal. With each run of simulations the risk factor takes a different value and a portfolio yields a different outcome. After the substantial number of simulations is conducted one obtains a distribution of portfolio values and is able to derive value at risk of this portfolio and expected shortfall as well.

Chapter 4

DATA DISCRIPTION

To estimate the parameters of Vasicek (1977) model we use the daily data on the prices and yields to maturity of fixed-income instruments from Ukrainian organized exchanges (UX and PFTS) and from over-the-counter market participants' obtained from Bloomberg. Our data sample consists of the daily bond quotes for the period of August 2010 – January 2011. For each day of observation we have 22 bonds with different time to maturities that were traded in the market.

The descriptive statistics of data on the fixed-income securities is presented in Table 1.

Table 1. Descriptive statistics on daily bond trading data

Days to maturity	Mean	SD	Min	Max
12-163	7,99%	1,04%	6,13%	9,48%
26-177	8,21%	1,24%	6,11%	13,86%
33-184	8,23%	1,20%	6,30%	9,99%
47-198	8,25%	1,05%	6,60%	9,99%
89-240	8,39%	1,03%	6,89%	10,08%
110-261	8,53%	1,18%	6,89%	10,83%
117-268	8,37%	1,50%	1,38%	13,91%
138-289	8,81%	1,08%	7,35%	10,56%
198-349	9,15%	1,04%	7,35%	11,13%
237-388	9,88%	1,12%	7,76%	11,24%
271-422	10,16%	1,08%	8,47%	11,77%
327-478	10,92%	1,36%	9,21%	22,22%
418-569	11,45%	0,69%	10,21%	13,23%
446-597	11,58%	0,65%	10,45%	13,50%
467-618	11,62%	0,61%	10,46%	13,47%
621-772	11,90%	0,61%	10,71%	13,46%
670-821	12,05%	0,61%	11,05%	13,98%

Table 1. Descriptive statistics on daily bond trading data - Continued

782-933	12,53%	0,77%	11,04%	13,99%
905-1056	12,75%	0,69%	11,34%	14,00%
989-1140	12,99%	0,73%	10,99%	14,01%
1027-1178	13,47%	0,62%	11,99%	14,25%
1061-1212	13,47%	1,31%	12,00%	14,34%

EMPIRICAL RESULTS

Estimation of the Vasicek (1977) model reveals that this model generally captures the behaviour of the observed yields of the bonds on Ukrainian market, but not always. For some days one observes not sufficient capability of the Vasicek yield curve to fit the observed term structure of interest rates (see FigureC1-Figure C5).

The estimated parameters of the Vasicek model are very volatile across time (Figure 1). We can conclude that the most volatile are mean levels for interest rates. Frequently they soar to very high level and sometimes they are close to initial short-term interest rates. Herewith the speeds of convergence (kappa) to these mean levels are very low. Also the volatility of short term rates proves to be very clustered.

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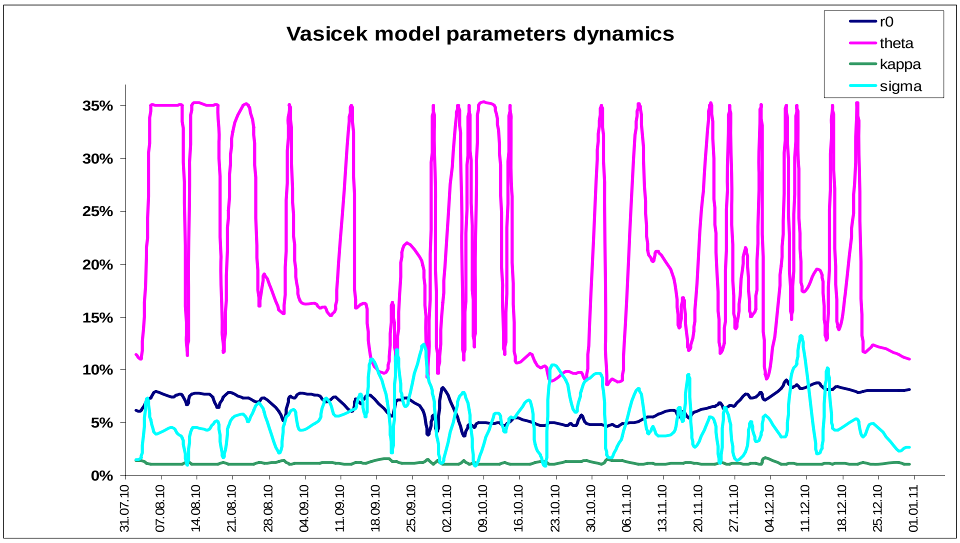

Figure 1. Vasicek model parameters dynamics

The goodness of fit of Vasicek model measured by the mean average percentage error (Figure 2) seems to be consistent with what we have expected and with what is described in the literature on this topic. MAPE falls in range between 2% and 6%, which is pretty bearable from the point of view of application of this model for policy recommendations.

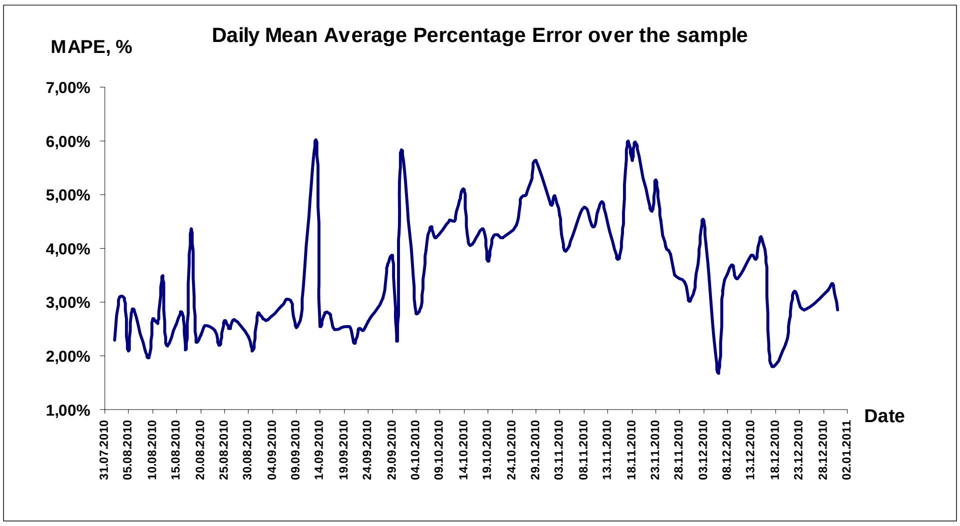

Figure 2. Daily Mean Average Percentage Error (MAPE) over the sample

The simulated future short term rates based on the estimated Vasicek model parameters are depicted in Figure 3.

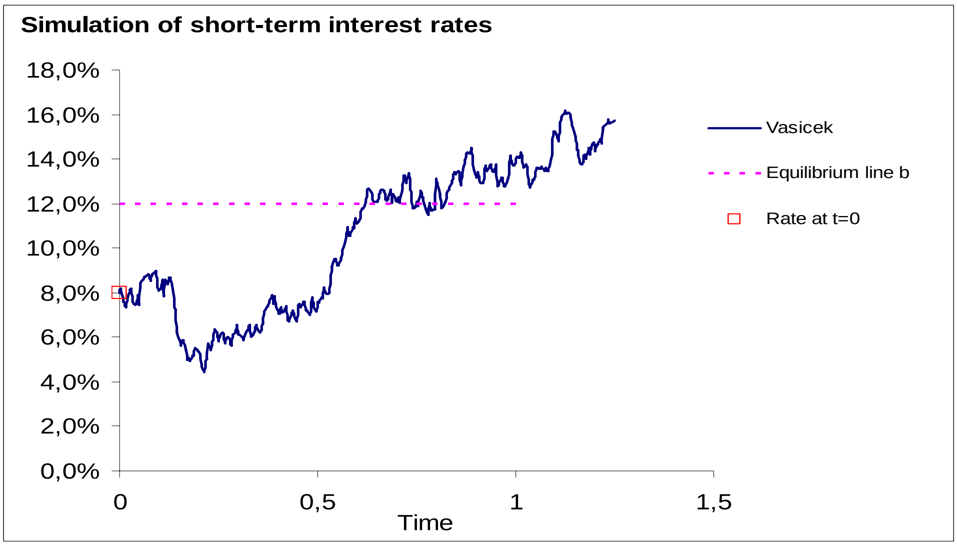

Figure 3. Monte Carlo Simulation of short-term interest rates

The distribution of short term rates obtained from Monte Carlo Simulation, as well as calculated VaR for 99% confidence interval and expected shortfall are presented in Figure 4.

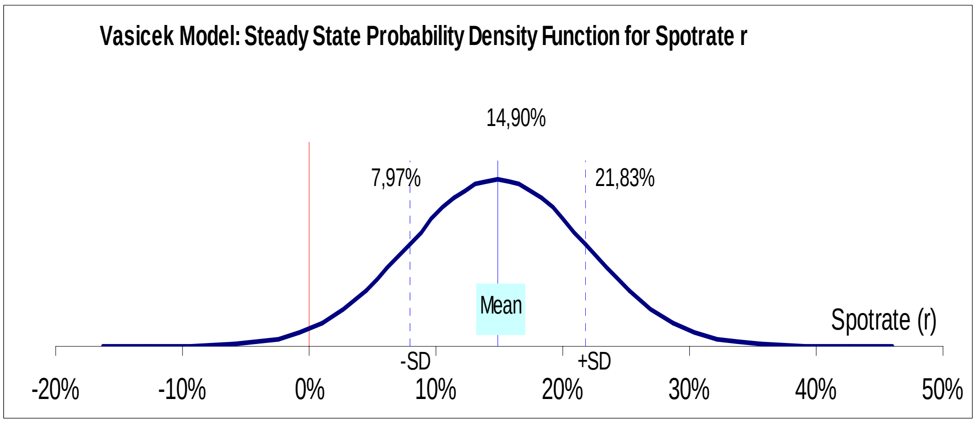

Figure 4. Vasicek Model: Steady State Probability Density Function for spot rate

Chapter 6

CONCLUSIONS

This work on the term structure of interest rates employs the Vasicek model (1977) to cover several important aspects.

The first concerns the fitting of Ukrainian yield curve to this model to see how good it approximates movements in the Ukrainian bond market. In general, Vasicek model shows plausible results as measured by the mean average percentage error for each trading day, which happens to be in the appropriate range of 3%-6%. This makes this model applicable for the purposes of policy recommendations, primarily to forecast the interest rates evolution using the parameters of Vasicek model.

The second involves the use of Vasicek model for financial risk-management purposes. In this work we demonstrate how to use the parameters of Vasicek model to calculate two commonly accepted market risk measures for a portfolio of fixed income securities, value at risk and expected shortfall, using Monte Carlo simulation. This methodology can be used by any financial institution in its daily trading activities to predict possible financial losses associated with unfavorable movements in the short-term interest rate. Having reliable forecasts of future developments of interest rates a financial institution can make the corresponding capital requirements to prevent these financial losses and thus keep a high confidence of investors.

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APPENDIX A

Figure A1. Ukraine 5-year CDS.
Source: Bloomberg

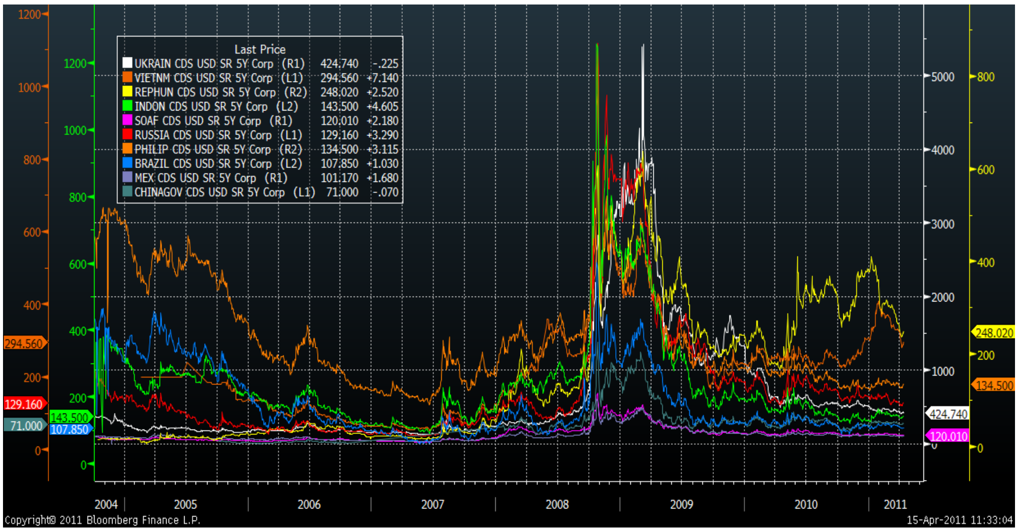

Figure A2. Emerging markets 5-year CDS.
Source: Bloomberg

APPENDIX B

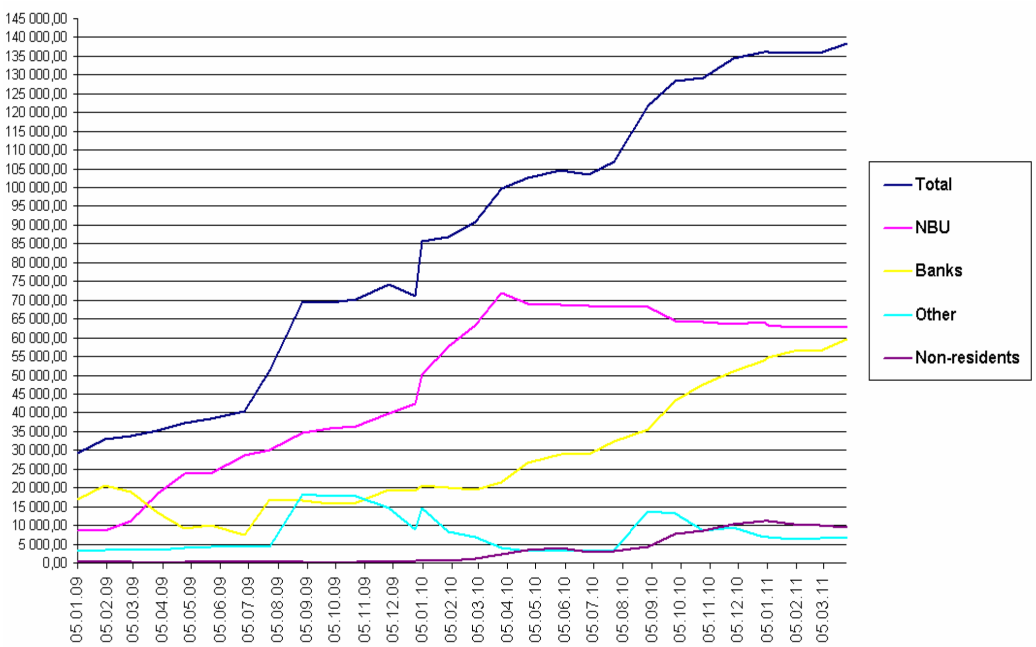

Figure B1. Government securities in circulation by principal debt in UAH millions, years 2009-2011

APPENDIX C

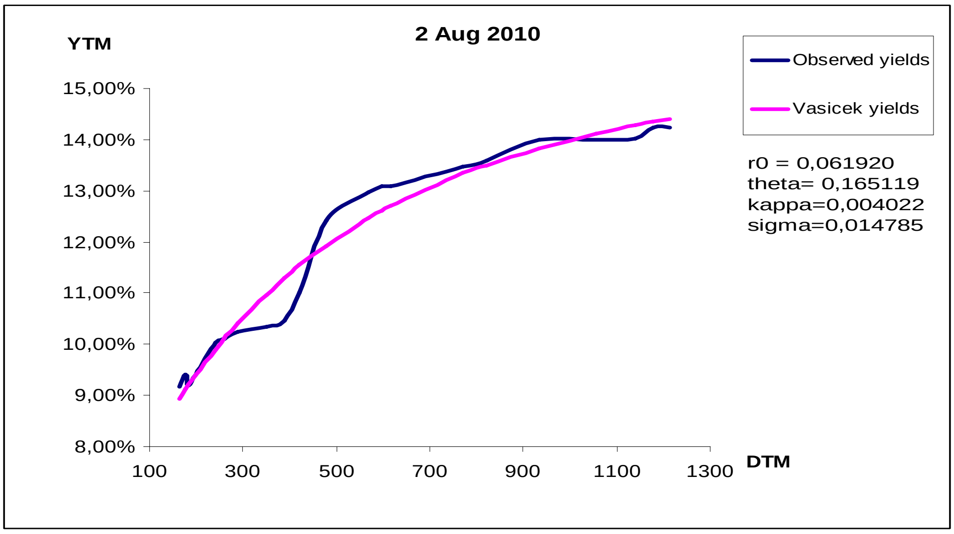

Figure C1. Yield curve for Ukrainian bonds as of 2 Aug 2010

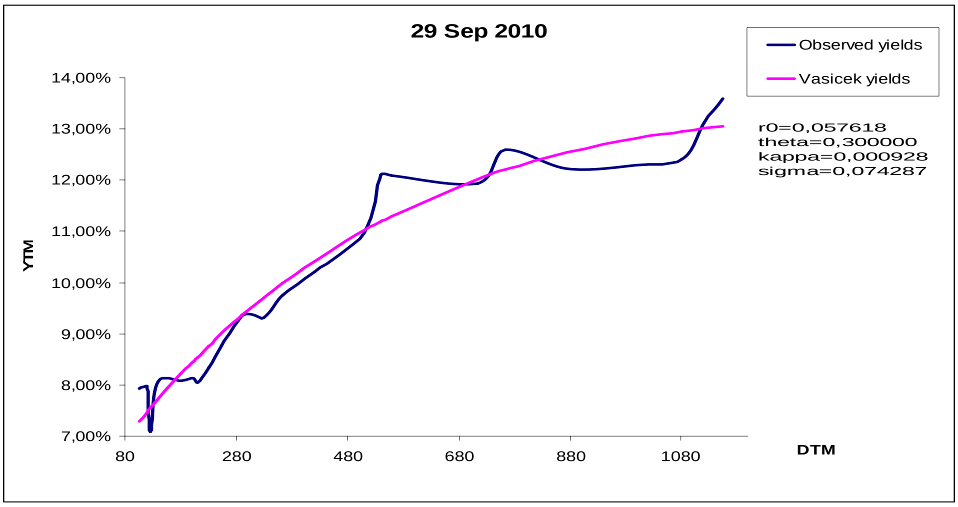

Figure C2. Yield curve for Ukrainian bonds as of 29 Sep 2010

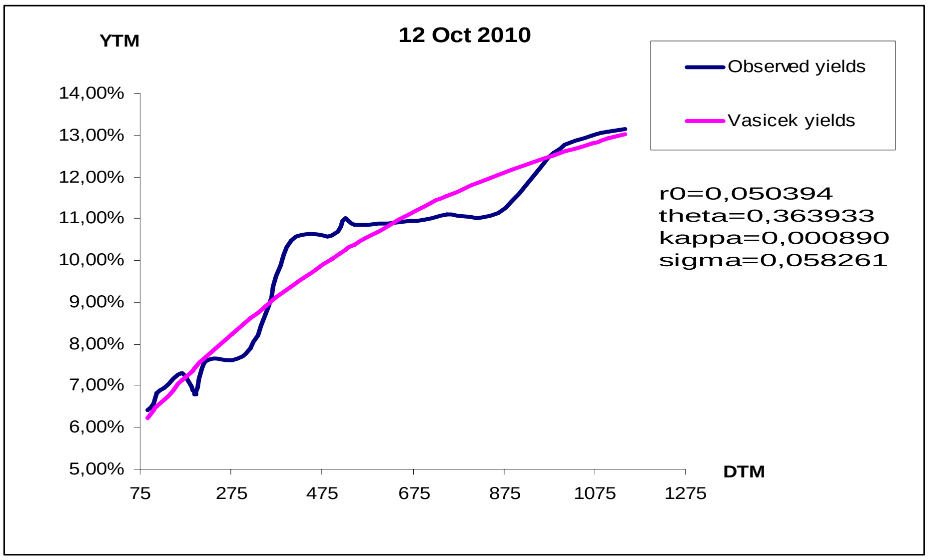

Figure C3. Yield curve for Ukrainian bonds as of 12 Oct 2010

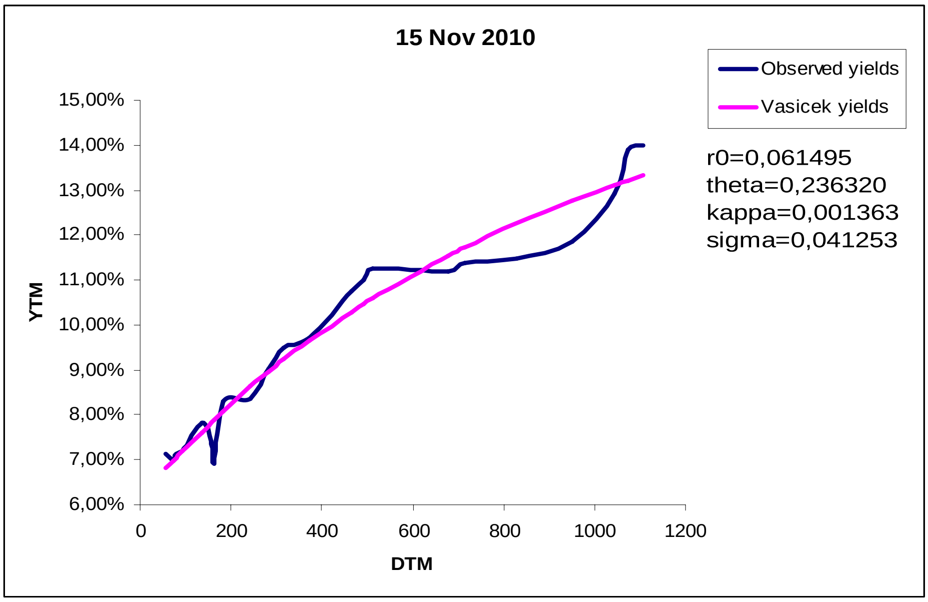

Figure C4. Yield curve for Ukrainian bonds as of 15 Nov 2010

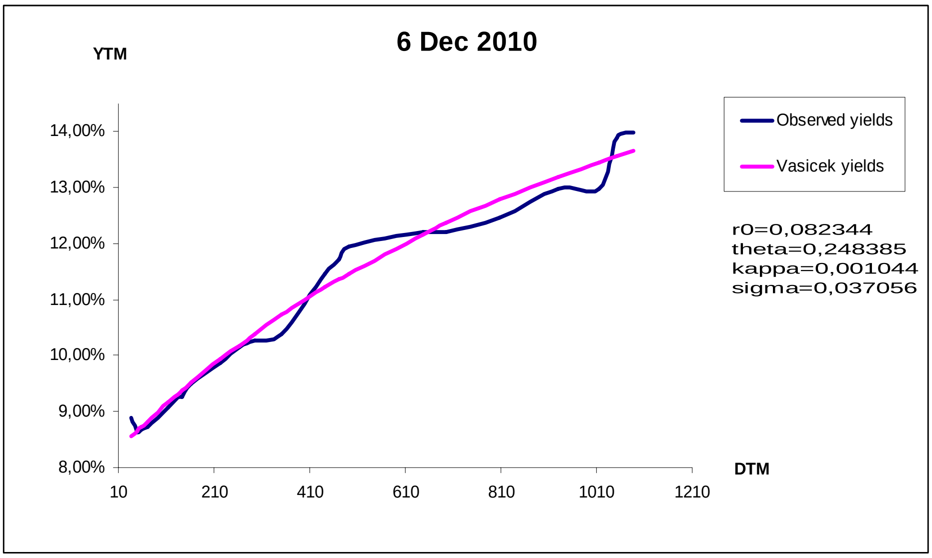

Figure C5. Yield curve for Ukrainian bonds as of 6 Dec 2010