A COMPREHENSIVE REVIEW OF VALUE AT RISK METHODOLOGIES

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A Comprehensive Review of Value at Risk Methodologies*

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Abstract

In this article, we review the full range of methodologies developed to estimate the Value at Risk from standard models to recently proposed methodologies. For these methodologies, we present their relative strengths and weaknesses from theoretical and practical perspectives. From a practical perspective, the empirical literature shows that the approaches based on Extreme Value Theory and Filtered Historical Simulation are the best methods to estimate VaR. Additionally, the Parametric method under the skewed and fat-tail distributions provides results that are promising, especially when the assumption that the standardised returns are independent and identically distributed is abandoned and time variations are considered in the conditional high-order moments.

Keywords: Value-at risk, manage risk, EVT, parametric and non-parametric methods,
JEL Classification: G15, G24

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1. Introduction

Basel I, also called the Basel Accord, is the accord that was published in 1988 in Basel (Switzerland) by the Basel Committee on Bank Supervision (BCBS), involving the chairmen of the central banks of Germany, Belgium, Canada, France, Italy, Japan, Luxembourg, Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States of America. This accord provides recommendations on banking regulations with regard to capital risk, market risk and operational risk. The purpose of this accord is to ensure that the financial institutions have enough capital on account to meet obligations and absorb unexpected losses.

For a financial institution, measuring the risk it faces is an essential task. In the particular case of market risk, a possible method of measurement is the evaluation of losses likely to be incurred when the price of the portfolio's assets declines. This measurement is the purpose of the Value at Risk (VaR) methodology. The VaR of a portfolio tells us the maximum amount that an investor may lose over a given time horizon and with a given probability. Because the BCBS at the Bank for International Settlements required a financial institution to meet the capital requirements on the base VaR estimates, permitting them to use internal models to calculate their VaRs, this methodology has become a basic market risk management tool of financial institutions[1]. As a consequence, it is not surprising that the last decade has witnessed the growth of academic literature comparing alternative modelling approaches and proposing new models for VaR estimations, attempting to improve upon the existing ones.

Although the VaR concept is very simple to calculate, it is not easy. The methodologies initially developed to calculate the VaR of a portfolio are (i) the variance-covariance approach, also called the Parametric method, (ii) Historical Simulation (Non-parametric method) and (iii) Monte Carlo simulation, which is a Semi-parametric method. As is well known, all these methodologies, usually called standard models, have numerous shortcomings, which has led to the development of new proposals.

In the framework of Parametric approaches, the first model proposed to estimate VaR is Riskmetrics, which was proposed by J.P. Morgan (1996). The major drawback of this model is related to the normal distribution assumption for the financial returns. The empirical evidence shows that the financial returns do not follow a normal distribution. The second drawback of Riskmetrics has to do with the model used to estimate the conditional volatility of the financial return. The third drawback of the traditional parametric approach involves the assumption that

[1] When the Basel I Accord was concluded in 1988, no capital requirement was defined for the risk market. However, regulators soon recognised the risk to a banking system if insufficient capital was held to absorb the large sudden losses from huge exposures in capital markets. During the mid-90s, proposals were tabled for an amendment to the 1988 accord, requiring additional capital over and above the minimum required for credit risk. Finally, a market risk capital adequacy framework was adopted in 1995 for implementation in 1998. The 1995 Basel I Accord amendment provided a menu of approaches for determining the market risk capital requirements.

the return is independent and identically distributed (iid). There is substantial empirical evidence that the distribution of standardised financial returns is not iid (see Hansen (1994), Harvey and Siddique (1999), Jondeau and Rockinger (2003), Bali and Weinbaum (2007) and Brooks et al. (2005)).

Taking these drawbacks into account, the research in the framework of the Parametric method has moved in several directions. The first one involves searching for a more sophisticated volatility model that captures the characteristics observed in the volatility of the financial returns. The second line of research involves searching for other density functions that capture the skew and kurtosis of the financial returns. Finally, the third line of research considers that the higher-order conditional moments are time-varying.

In the context of the Non-parametric method, several Non-parametric density estimation methods have been implemented, with improvement on the results obtained by Historical Simulation. In the framework of the Semi-parametric method, new approaches have been proposed: (i) the Filtered Historical Simulation, proposed by Baronesi-Adesi et al. (1999); (ii) the CaViaR method, proposed by Engle and Manganelli (2004) and (iii) the conditional and unconditional approaches based on Extreme Value Theory. These two last methods, joint to the parametric approach under the skewed distributions and considering that higher-order conditional moments are time-varying, provide good estimations of the VaR.

In this article, we review the full range of methodologies developed to estimate the VaR from the standard models to recently proposed methodologies. For these methodologies, we present their relative strengths and weaknesses from theoretical and practical perspectives. The aim of this paper is to provide to a researcher in financial risk all the models and proposed developments to estimate the VaR, bringing such a researcher to the frontiers of knowledge in this field.

The rest of this paper is organised as follows. In the next section, we review a full range of methodologies developed to estimate the VaR. In subsection 2.1, we present a non-parametric approach. Parametric approaches are offered in subsection 2.2, and semi-parametric approaches are presented in subsection 2.3. In section 3, we present the empirical results obtained by the papers dedicated to comparing VaR methodologies. The last section includes the main conclusions.

2. Value at Risk Methods

The VaR of a portfolio is defined as the maximum potential loss that a portfolio can generate over a particular time horizon within a defined confidence level. The VaR is thus a conditional quantile of the asset return loss distribution.

Let $r_1, r_2, r_3,..., r_n$ be identically distributed independent random variables representing the financial returns. Use $F(r)$ to denote the cumulative distribution function, $F(r) = \Pr(r_t < r|\Omega_{t-1})$, conditionally on the information set Ω_{t-1} that is available at time *t*-1. Assume that $\{r_t\}$ follows the stochastic process:

$$\begin{gathered} r_t = \mu + \varepsilon_t \\ \varepsilon_t = z_t\sigma_t \quad z_t \sim iid(0,1) \end{gathered} \tag{1}$$

where $\sigma_t^2 = \mathrm{E}(z_t^2|\Omega_{t-1})$ and z_t has the conditional distribution function $G(z)$, $G(z) = Pr(z_t < z|\Omega_{t-1})$. The VaR with a given probability $\alpha \in (0,1)$, denoted by $\mathrm{VaR}(\alpha)$, is defined as the α quantile of the probability distribution of financial returns:

$$F(VaR(\alpha)) = Pr(r_t < VaR(\alpha)) = \alpha \qquad \text{or} \qquad VaR(\alpha) = \inf\{v|P(r_t \le v) = \alpha\}$$

This quantile can be estimated in two different ways: (1) inverting the distribution function of financial returns, $F(r)$, and (2) inverting the distribution function of innovations, $G(z)$. With regard to the latter, it is also necessary to estimate σ_t^2.

$$VaR(\alpha) = F^{-1}(\alpha) = \mu + \sigma_t G^{-1}(\alpha) \tag{2}$$

Hence, a VaR model involves the specifications of $F(r)$ or $G(z)$. The estimation of those functions can be performed using the following methods: (1) Non-parametric methods; (2) Parametric methods; and (3) Semi-parametric methods.

2.1 Non-parametric methods

The Non-parametric approaches seek to estimate the VaR of a portfolio without making strong assumptions about the distribution of the returns portfolio. The essence of these approaches is to let the data speak for themselves as much as possible and to use the recent empirical distribution of the returns –not some assumed theoretical distribution - to estimate the VaR.

All Non-parametric approaches are based on the underlying assumption that the near future will be sufficiently similar to the recent past such that we can use the data from the recent past to forecast the risk in the near future.

The Non-parametric approaches include (a) Historical Simulation and (b) Non-parametric density estimation methods.

2.1.1. Historical Simulation

Historical Simulation is the most popular Non-parametric approach. This method uses the empirical distribution of financial returns as an approximation for $F(r)$, so that in this method, $\mathrm{VaR}(\alpha)$ is the α quantile of the empirical distribution. To calculate the empirical distribution of financial returns, different sizes of samples can be considered.

The advantages and disadvantages of the Historical Simulation have been well documented by Down (2002). The two main advantages of the Historical Simulation approach are the following: (1) the method is very easy to implement, and (2) because this approach does not depend on parametric assumptions about the distribution of the return portfolio, they can accommodate wide tails, skewness and any other non-normal features observed in financial observations. The biggest potential weakness of this approach is that its results are completely dependent on the data set. If our data period was unusually quiet, Historical Simulation will often underestimate the risk. However, if our data period was unusually volatile, Historical Simulation will often overestimate the risk. In addition, Historical Simulation approaches are sometimes slow to reflect major events, such as the increases in risk associated with sudden market turbulence.

The first papers involving the comparison of VaR methodologies, such as those by Beder (1995), Mahoney (1995), Hendricks (1996), Beder (1996), Pritsker (1997), Smithson and Minton (1997), Jackson et al. (1998), Raaji and Raunig (1998), and Blanco and Blomstrom (1999), reported that the Historical Simulation performed at least as well as the methodologies developed in the early years, the Parametric approach and the Monte Carlo simulation. The main conclusion of these papers is that among the methodologies developed initially, no approach appeared to be better than the rest.

However, more recently, papers such as those by Abad and Benito (2012), Ashley and Randall (2009), Trenca (2009), Angelidis et al. (2007), Alonso and Arcos (2005), Gento (2001), Danielson and Vries (2000) have reported that the Historical Simulation approach produces inaccurate VaR estimates. By comparison with other recently developed methodologies such as the Historical Simulation Filtered, Conditional Extreme Value Theory, and Parametric approaches, as we become further separated from normality and consider volatility models more sophisticated than Riskmetrics, Historical Simulation provides a very poor VaR estimate.

2.1.2. Non-parametric density estimation methods

Unfortunately, the Historical Simulation approach does not best utilise the information we have. It also has the practical drawback that it only allows us to estimate VaR at discrete confidence intervals determined by the size of our data set[2]. The solution to this problem is to use the theory of Non-parametric density estimation. The idea behind Non-parametric density is

[2] Thus, if we have, e.g., 100 observations, it allows us to estimate VaR at the 95% confidence level but not the VaR at the 95.1% confidence level. The VaR at the 95% confidence level is given by the sixth largest loss, but the VaR at the 95.1% confidence level is a problem because there is no loss observation to accompany it.

to treat our data set as if it were drawn from some unspecific or unknown empirical distribution function. One simple way to approach this problem is to draw straight lines connecting the mid-points at the top of each histogram bar. Once we draw these lines, we can ignore the histogram bars and treat the area under the lines as if it were a probability density function (*pdf*) to estimate the VaR at any confidence level. However, we could draw smooth curves that overlap well, and so on. This approach conforms exactly to the theory of non-parametric density estimation, which leads to important decisions about the width of bins and where bins should be centred. These decisions can therefore make a difference in our results (for a discussion, see Butler and Schachter (1998) or Rudemo (1982)).

A kernel density estimator (Silverman (1986), Sheather and Marron (1990)) is a method for generalising a histogram constructed with the sample data. Where a histogram results in a density that is piecewise constant, a kernel estimator results in a smooth density. Smoothing the data can be performed with any continuous shape spread around each data point. As the sample size grows, the net sum of all the smoothed points approaches the true pdf, whatever that may be, irrespective of the method used to smooth the data.

The smoothing is accomplished by spreading each data point with a kernel, usually a pdf centred on the data point, and a parameter called the bandwidth. A common choice of bandwidth is that proposed by Silverman (1986). There are many kernels or curves to spread the influence of each point, such as the Gaussian kernel density estimator, the Epanechnikov kernel, the biweight kernel, an isosceles triangular kernel and an asymmetric triangular kernel. From the kernel, we can calculate the percentile or estimate of the VaR.

In the study by Chen and Tang (2005), we can find an assessment of the evolution of the statistical properties of the kernel. Huang (2009) uses the non-parametric kernel estimator technique on the tail distributions, in addition to undertaking a comparison among different methodologies to estimate the VaR. The empirical results show the accomplishment of a reliable estimation of VaR with kernel estimators, outperforming other existing methods. Brownlees and Gallo (2010) obtain similar results.

Kernel-based approaches can also be developed further in various ways. For example, Gourieroux and Jasiak (2001) use kernel-based pseudo-density methods to provide local approximations of an unknown density function and thus estimate the conditional VaR; Scaillet (2004) uses a broad class of dependency structures known as strong mixing to obtain kernel estimators for conditional EVT. These approaches are similar in spirit to Engle and Manganelli's conditional autoregressive VaR (CaViaR) approach.

2.2. Parametric method

Parametric approaches estimate the risk by fitting probability curves to the data and then inferring the VaR from the fitted curve. In the framework of Parametric approaches, the first model to estimate VaR was Riskmetrics, proposed by J.P. Morgan (1996). This model assumes that the return portfolio and/or the innovations of the return follow a normal distribution. Under this assumption, the VaR of a portfolio at an $\alpha\%$ confidence level is calculated as $VaR(\alpha)=\mu+\sigma_t G^{-1}(\alpha)$, where $G^{-1}(\alpha)$ is the α quantile of the standard normal distribution and σ_t is the conditional standard deviation of the return portfolio. To estimate σ_t, J.P. Morgan uses an Exponential Weight Moving Average Model (EWMA). The expression of this model is as follows:

$$\sigma_t^2=\left(1-\lambda\right)\sum_{j=0}^{N-1}\lambda^j\left(\varepsilon_{t-j}\right)^2 \tag{3}$$

where $\lambda=0.94$ and the window size (N) is 74 days for daily data.

The major drawbacks of Riskmetrics are related to the normal distribution assumption for financial returns and/or innovations. The empirical evidence shows that financial returns do not follow a normal distribution. The skewness coefficient is in most cases negative and statistically significant, implying that the distribution of the financial return is skewed to the left. This result is not in accordance with the properties of a normal distribution, which is symmetric. By the other hand , the empirical distribution of the financial return has been documented to exhibit a significantly excessive kurtosis (fat tails and peakness) (see Bollerlev (1987); Engle and González-Rivera (1991); Aït-Sahalia and Lo (1998); Theodossiou and Trigeorgis (2003); Poon and Granger (2003); Bali and Theodossiou (2007)). Consequently, the size of the actual losses is much higher than that predicted by a normal distribution.

The second drawback of Riskmetrics involves the model used to estimate the conditional volatility of the financial return. The EWMA model captures some characteristics of volatility, such as varying volatility and cluster volatility, but does not take into account the asymmetry and the leverage effect (see Black (1976), French et al. (1987) and Pagan and Schwert (1990)). In addition, this model is technically inferior to the family GARCH models to model the persistence of volatility.

The third drawback of the traditional Parametric approach involves the iid return assumption. There is substantial empirical evidence that the standardised distribution of financial returns is not iid (see Hansen (1994), Harvey and Siddique (1999), Jondeau and Rockinger (2003), Bali and Weinbaum (2007) and Brooks et al. (2005)).

Taking these drawbacks into account, the research in the framework of the Parametric method has moved in several directions. The first attempts searched for a more sophisticated volatility model that captures the characteristics observed in the volatility of financial returns. In this framework, three families of volatility models have been considered: (i) the GARCH family, (ii) Stochastic Volatility and (iii) Realised volatility. The second line of research investigated other density functions that capture the skew and kurtosis of financial returns. In this context, several density functions have been considered: (i) the Skewness *t*-Student Distribution of Hansen (1994), (ii) Beta Generalised Exponential of the Second Kind (EGB2) of McDonal and Xu (1995), (iii) Error Generalised Distribution (GED) of Nelson (1991), (iv) Skewness Error Generalised Distribution (SGED) of Theodossiou (2001), (v) t-Generalised Distribution of Mcdonald and Newey (1988), (vi) Skewness Generalised-t Distribution (SGT) of Theodossiou (1998), (vii) Inverse Hyperbolic Sign (IHS) of Johnson (1949) and (viii) a mix of normal functions. Finally, the third line of research considered that the higher-order conditional moments are time-varying.

In the framework of the Parametric method, following a different approach, McAleer et al. (2010a) proposed a risk management strategy that consists of choosing from among different combinations of alternative risk models to forecast the VaR. As the authors remark, given that a combination of forecast models is also a forecast model, this model is a novel method for estimating the VaR. Following such an approach, McAleer et al. (2010b) suggest using a combination of VaR forecasts to obtain a crisis robust risk management strategy. McAleer et al. (2011) present cross-country evidence to support the claim that the median point forecast of VaR is generally robust to a Global Financial Crisis.

2.2.1. Volatility models

The volatility models proposed in the literature to capture the characteristics of financial returns can be divided into three groups: (i) the GARCH family, (ii) the stochastic volatility models and (iii) realised volatility-based models. A brief summary of some of the most commonly used models applied to the VAR calculation are submitted in coming notes and in references related to studies in which they have been used.

(i) GARCH family

Engle (1982) proposed the Autoregressive Conditional Heterokedasticity (ARCH), which featured a variance that does not remain fixed but rather varies throughout a period. Bollerslev (1986) further extended the model by inserting the ARCH generalised model (GARCH). This model specifies and estimates two equations; the first depicts the evolution of the returns in accordance with the past returns, whereas the second patterns the evolving volatility of the returns. The most generalised formulation for the GARCH models is the GARCH (p,q) model represented by the following expression:

$$r_t=\mu_t+\varepsilon_t$$
$$\sigma_t^2=\alpha_o+\sum_{i=1}^{q}\alpha_i\varepsilon_{t-1}^2+\sum_{i=1}^{p}\beta_i\sigma_{t-1}^2 \quad (4)$$

One of the limitations facing the GARCH model is the need to impose restrictions on the parameters to guarantee that the variance is positive. In the GARCH(1,1) model, the parameters must comply with the restrictions $\alpha_o > 0, \alpha_1, \beta > 0$ and $\alpha_1 + \beta < 1$.

In most of the empirical applications conducted on financial series, the addition of the value $\alpha_1 + \beta$ is observed to be very close to the unit. By forcing the condition that the addition is equal to the unit, the integrated GARCH model (IGARCH) of Engle and Bollerslev (1986)[3] becomes:

$$\begin{gathered}\sigma_t^2 = \alpha_0 + (1-\beta)\varepsilon_{t-1}^2 + \beta\sigma_{t-1}^2 \\ \alpha_o,\ \beta > 0 \quad and \quad \beta < 1\end{gathered} \tag{5}$$

The conditional variance properties of the IGARCH model are not very attractive from the empirical point of view due to the very slow motion phasing out the impact of the shocks upon the conditional variance (volatility persistence). Nevertheless, the impacts that fade away have an exponential behaviour, which is how the fractional integrated GARCH model (FIGARCH) proposed by Baillie, Bollerslev and Mikkelsen (1996) behaves, with the simplest specification, FIGARCH (1,d,0), being:

$$\sigma_t^2 = \frac{\alpha_o}{1-\beta_1} + \left(1 - \frac{(1-L)^d}{(1-\beta_1 L)}\right) r_t^2 . \tag{6}$$

If the parameters comply with the setting conditions $\alpha_0 > 0,\ 0 \le \beta_1 < d \le 1$, the conditional variance of the model is most likely positive for all *t* cases. With this model, there is a likelihood that the r_t^2 effect upon σ_{t+k}^2 will trigger a decline over the hyperbolic rate while *k* surges.

An important innovation has focused on the power term by which the data are to be transformed. The presence of volatility clustering is by no means unique to the square returns of an asset price, as generally, the absolute changes in an asset's price will also exhibit volatility clustering. Higgins and Bera (1992) have introduced the Power GARCH model (PGARCH), wherein the power term by which the data are transformed is estimated within the model rather than being specified a priori. The expression of the PGARCH (1, 1) is as follows:

$$\begin{gathered}\sigma_t^{\delta} = \omega + \alpha\left|\varepsilon_{t-1}\right|^{\delta} + \beta\sigma_{t-1}^{\delta} \\ \omega > 0,\ \alpha \ge 0,\ \beta \ge 0 \ and \ \delta > 0\end{gathered} \tag{7}$$

Here, δ is equivalent to the Box-Cox transformation of σ_t.

The Taylor-Schwert (TS-GARCH) model proposed by Taylor (1986) and Schwert (1989) parameterises the conditional standard deviation as a distributed lag of the absolute

[3] The EWMA model is equivalent to the IGARCH model with the intercept α_0 being restricted to being zero, the autoregressive parameter β being set at a pre-specific value λ, and the coefficient of ε_{t-1}^2 being equal to 1-λ.

innovations and the lagged conditional standard deviation. The specification of the model TS-GARCH(1,1) is as follows:

$$\sigma_t = \alpha_o + \alpha_1 \left| \varepsilon_{t-1} \right| + \beta \sigma_{t-1}$$
$$\alpha_o > 0,\ \alpha_1, \beta > 0 \quad and \quad \alpha_1 + \beta < 1 \tag{8}$$

The previously mentioned models do not completely reflect the nature posed by the volatility of the financial times series because, although they accurately characterise the volatility clustering properties, they do not take into account the asymmetric performance of the yields before positive or negative shocks (leverage effect) (see Black (1976), French, Schwert and Stambaugh, (1987) and Pagan and Schwert (1990)).

Because previous models depend on the square or absolute value of the errors, the effect caused by positive innovations is the same as the effect produced by negative innovations of equal absolute value. Nonetheless, reality shows that in financial time series, the existence of the leverage effect is observed, which means that the volatility increases at a higher rate when yields are negative compared with when they are positive. To establish a pattern framework for the leverage effect, new non-linear GARCH formulations should be searched. In the next paragraph, there is a reference to the most commonly used formula in financial practice.

The Exponential GARCH model (EGARCH) of Nelson (1991) is formulated based on the conditional variance logarithm. The expression of EGARCH (1,1) is as follows:

$$log(\sigma_t^2) = \alpha_0 + \gamma \left(\frac{\varepsilon_{t-1}}{\sigma_{t-1}} \right) + \alpha_1 \left(\left| \frac{\varepsilon_{t-1}}{\sigma_{t-1}} \right| - \sqrt{\frac{2}{\pi}} \right) + \beta\, log(\sigma_{t-1}^2) \tag{9}$$
$$\alpha_1 + \beta < 1$$

Because this model is formulated upon the logarithm of the conditional variance, when compared with the GARCH (1,1) model, it does not require the specification of positiveness conditions over the estimated parameters.

In contrast, the Threshold GARCH model (GJR-GARCH) of Glosten, Jagannathan and Runkle (1993) is, similar to the GARCH model, formulated based on the variance but assumes that the ε_{t-1}^2 parameter depends on the sign of the shock. Thus, the GJR-GARCH(1,1) model has the following expression:

$$\sigma_t^2 = \alpha_o + \alpha_1 \varepsilon_{t-1}^2 - \gamma\, \varepsilon_{t-1}^2 S_{t-1}^- + \beta \sigma_{t-1}^2$$
$$S_{t-1}^- = 1 \quad for \quad \varepsilon_{t-1} < 0 \quad and \quad S_{t-1}^- = 0 \quad otherwiese \tag{10}$$
$$\alpha_o \geq 0,\ \alpha_1, \beta > 0\ and\ \ \alpha_1 + \beta < 1$$

The Threshold GARCH (TGARCH) model of Zakoïan (1994) extends TS-GARCH to allow for the conditional standard deviation to depend on the sign of the lagged innovations. The expression of TGARCH(1,1) is:

$$\sigma_t = \alpha_o + \alpha_1|\varepsilon_{t-1}| + \gamma\,\varepsilon_{t-1}S^{-}_{t-1} + \beta\sigma_{t-1}$$
$$S^{-}_{t-1} = 1 \quad for \quad \varepsilon_{t-1} < 0 \quad and \quad S^{-}_{t-1} = 0 \quad otherwiese \qquad (11)$$
$$\alpha_o \geq 0,\ \alpha_1, \beta > 0 \text{ and } \alpha_1 + \beta < 1$$

The Asymmetric GARCH model (AGARCH) of Engle (1990) patterns the asymmetric effects of the shocks starting from the GARCH model. The AGARCH(1,1) model is represented by:

$$\sigma^2_t = \alpha_o + \alpha_1\varepsilon^2_{t-1} + \gamma\varepsilon^2_{t-1} + \beta\sigma^2_{t-1}$$
$$\alpha_o \geq 0,\ \alpha_1, \beta > 0 \text{ and } \alpha_1 + \beta < 1 \qquad (12)$$

The model may be alternatively represented as follows:

$$\sigma^2_t = \alpha_o + \alpha_1(\varepsilon_{t-1} + \gamma)^2 + \beta\sigma^2_{t-1} \qquad (13)$$

where $\alpha_o > 0,\ \alpha_1 \geq 0$ and $\beta \geq 0$ readily ensure that the conditional variance is almost surely positive.

The Asymmetric Power GARCH model (APGARCH) of Ding, Granger and Engle (1993) is an extension of the PGARCH model. The APARCH(1,1) model can be expressed as:

$$\sigma^{\delta}_t = \alpha_0 + \alpha_1(|\varepsilon_{t-1}| + \gamma\varepsilon_{t-1})^{\delta} + \beta\sigma^{\delta}_{t-1} \qquad (14)$$

where coefficients must conform with the following conditions:

$$\alpha_0 > 0,\ \alpha_1 \geq 0, \beta > 0, \delta > 0 \text{ and } -1 < \gamma < 1$$

The Quadratic GARCH model (QGARCH) of Sentana (1995) is another method to model the asymmetric effects of shocks on volatility. The QGARCH model is specified as:

$$\sigma^2_t = \alpha_0 + \alpha_1(\varepsilon_{t-1} + \gamma\sigma_{t-1})^2 + \beta\sigma^2_{t-1}$$
$$\alpha_0 > 0,\ \alpha_1, \beta > 0 \quad and \quad \alpha_1 + \beta < 1 \qquad (15)$$

The Square-Root GARCH model (SQR-GARCH) of Heston and Nandi (2000) also models the asymmetric effects. The SQR-GARCH(1,1) has the expression:

$$\sigma^2_t = \alpha_0 + \alpha_1(\gamma\sigma_{t-1} + \varepsilon_{t-1}/\sigma_{t-1})^2 + \beta\sigma^2_{t-1}$$
$$\alpha_0 > 0,\ \alpha_1, \beta > 0 \quad and \quad \alpha_1 + \beta < 1 \qquad (16)$$

Finally, Engle and Ng (1993) proposed two models. The first is the VGARCH, with the following expression in the simplest case:

$$\sigma^2_t = \alpha_0 + \alpha_1(\gamma + \sigma^{-1}_{t-1}\varepsilon_{t-1})^2 + \beta\sigma^2_{t-1}$$
$$\alpha_0 > 0,\ 0 < \beta < 1 \quad and \quad 0 < \alpha_1 < 1 \qquad (17)$$

The second is the Nonlinear Asymmetric GARCH (NAGARCH), with the expression of NAGARCH(1,1) being:

$$\sigma^2_t = \alpha_0 + \alpha_1(\varepsilon_{t-1} + \gamma\sigma_{t-1})^2 + \beta\sigma^2_{t-1}$$
$$\alpha_0 > 0,\ \alpha_1, \beta > 0 \quad and \quad \alpha_1 + \beta < 1 \qquad (18)$$

In all these models (EGARCH, GJR-GARCH, TGARCH, AGARCH, APARCH, QGARCH, VGARCH, SQR-GARCH, NGARCH), γ is the leverage parameter. A negative value of γ means that past negative shocks have a deeper impact on current conditional volatility than past positive shocks. Thus, we expect the parameter to be negative ($\gamma < 0$). The persistence of volatility is captured by the β parameter. In the particular case of the EGARCH model, the volatility of the return also depends on the size of the innovations. If α_1 is positive, the innovations superior to the mean have a deeper impact on current volatility than those inferior to the mean.

Finally, it must be pointed out that there are models that collect the leverage effect and the non-persistence memory effect. For example, Bollerslev and Mikkelsen (1996) insert the FIEGARCH model, which aims to account for both the leveraging effect (EGARCH) and the long memory (FIGARCH) effect. The simplest expression of this family of models is the FIEGARCH (1,d,0):

$$(1-\phi L)(1-L)^d log(\sigma_t^2) = \alpha_0 + \gamma\left(\frac{r_{t-1}}{\sigma_{t-1}}\right) + \alpha_1\left(\left|\frac{r_{t-1}}{\sigma_{t-1}}\right| - \sqrt{\frac{2}{\pi}}\right) \tag{19}$$

Even though there is a general consensus about the lack of normality shown by the yields, some authors have addressed the possibility of this issue as being due to the existence of structural changes. Therefore, the notion of volatility persistence could be matched with the high probability of a state of low (high) volatility, which may be followed by another state with low (high) volatility. One way to represent the changes in volatility persistence is to combine a Markow Regime-Switching model (Hamilton (1989)) with the GARCH-type models to achieve different values for the volatility persistence, depending on the state or regime.

Gray (1996) generalised the Hamilton model to model the regime changes within the GARCH model. Thus, the Markow switching GARCH (MS-GARCH (1,1)) is defined by:

$$\begin{gathered} r_t = \mu_{s_t} + \varepsilon_t = \mu_{s_t} + \sigma_t z_t \quad with \quad z_t \; iid \;\; N(0,1) \\ \sigma_t^2 = \omega_{s_t} + \alpha_{s_t}\varepsilon_{t-1}^2 + \beta_{s_t}\sigma_{t-1}^2 \end{gathered} \tag{20}$$

where s_t is a non-observable random variable that can take values 1,2,…K, which can be described by a Markov chain:

$$Prob(s_t = j | s_{t-1} = i, s_{t-2} = K) = Prob(s_t = j | s_{t-1} = i) = p_{ij} \tag{21}$$

for i,j=1,2,…,K. The s_t variables can be regarded as the state or regime of the process at the t moment. As occurs in the classic GARCH model, certain restrictions must be imposed on the coefficients to ensure that the variance will be eventually positive, and therefore, $\omega_{s_t} > 0, \alpha_{s_t} \geq 0,$ and $\beta_{s_t} \geq 0$.

Ané and Ureche-Rangau (2006) generalised the Asymmetric Power GARCH model of Ding, Granger and Engle (1993) by its definition within the change of the regime context. They introduced the Regime-Switching Asymmetric POWER GARCH model (RS-APARCH), assuming that each regime volatility follows the dynamics of APGARCH (1,1):

$$\sigma_{s_t}^{\delta_{s_t}} = \omega_{s_t} + \alpha_{s_t}\left(\left|\varepsilon_{t-1}\right| + \gamma_{s_t 1}\varepsilon_{t-1}\right)^{\delta_{s_t}} + \beta_{s_t 2}\sigma_{t-1}^{\delta_{s_t}} \tag{22}$$

where the coefficients must abide with the following conditions:

$$\omega_{s_t} > 0, \alpha_{s_t} \geq 0, \beta_{s_t} > 0, \delta > 0 \; and \; -1 < \gamma_{s_t 1} < 1$$

with $\gamma_{s_t,1}$ being the parameter responsible for the asymmetric answer.

The empirical applications found in the literature involving the Parametric models for VaR estimation are very extensive. An example can be taken from the research of Bali and Theodossiou (2007), which utilises 10 different GARCH specifications, stating that the best results are provided by the TS-GARCH and EGARCH models. González-Rivera et al. (2004) undertook a comparison between eleven different GARCH models. In addition to the comparison of results with other models (EWMA, SV, MA(20)), and although there is no evidence of an overpowering model, they concluded that asymmetric models produce better outcomes. The comparison analysis performed by Angelidis et al. (2007) also does not reach a conclusive result concerning any of the models. Others applications of the family of GARCH models can be found in the following studies: Haas et al. (2004), Li and Lin (2004), Carvalho et al. (2006), Sajjad et al. (2008), Chen, So and Lin (2009), Abad and Benito (2012) and Chen et al. (2011).

(ii) Stochastic Volatility Models

An alternative path to the GARCH models to represent the temporal changes over volatility is through the stochastic volatility (SV) models proposed by Taylor (1982, 1986). In these models, the volatility in *t* does not depend on the past observations of the series but rather on a non-observable variable, which usually is an autoregressive stochastic process. To ensure the positiveness of the variance, the volatility equation is defined according to the variance of the logarithm as in the EGARCH model.

The stochastic volatility model proposed by Taylor (1982) can be written as:

$$\begin{aligned} r_t &= \mu_t + \sqrt{h_t} z_t \quad z_t \sim N(0,1) \\ \log h_{t+1} &= \alpha + \phi \log h_t + \eta_t \qquad \eta_t \sim N(0, \sigma_\eta) \end{aligned} \tag{23}$$

where μ_t represents the conditional mean of the financial return, h_t represents the conditional variance, and z_t and η_t are stochastic white-noise processes.

The basic properties of the model can be found in Taylor (1986, 1994), Shephard (1996) and Ghyels et al. (1996). The main difference between the GARCH and SV models is the estimation method. In the GARCH model, the parameters can be estimated in a direct way by using maximum likelihood techniques. In contrast, in the SV model, the distribution of $z_t \left| \Omega_{t-1} \right.$ cannot be explicitly featured because h_t is not observable and cannot be recovered from the historical temporal series. As a result, the maximum likelihood techniques cannot be used to estimate the SV model parameters. Alternative processes have being proposed for its estimation: Taylor (1992, 1994) used the method of moments; Harvey and Shephard (1996) and Harvey et al. (1994) used a quasi-maximum likelihood approach; So et al. (1997a, 1997b) and Shephard (1994) used the expectation-maximisation (EM) algorithm and simulated EM algorithms, respectively; Danielson (1994) obtained simulated maximum likelihood estimates by the Monte Carlo method to evaluate the likelihood function; and Shephard (1993) and Jacquier et al. (1994) proposed a Bayesian approach. Regardless, there is no consensus as to which estimation method is the most accurate for the SV model.

As in the GARCH family, for the stochastic volatility models, alternative and more complex models have been developed to allow for the pattern of both the large memory and the leverage effect. In upcoming notes, some of these models are mentioned.

For the purpose of covering the leverage effect of volatility, Harvey and Shephard (1996) proposed the autoregressive asymmetric stochastic first-order volatility model, A-ARSV(1) using the following equations:

$$\begin{aligned} r_t &= \mu_t + \sqrt{h_t}\, z_t \\ log\, h_{t+1} &= \alpha + \phi\, log\, h_t + \sigma_\eta\, \eta_t \quad |\phi| < 1 \end{aligned} \tag{24}$$

where z_t and η_t are, respectively, random noises of the mean equation and the volatility logarithm equation, which comply with the following binomial and bi-variant distribution:

$$\begin{pmatrix} z_t \\ \eta_t \end{pmatrix} \sim iid\left(\begin{pmatrix} 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 & \delta\sigma_\eta \\ \delta\sigma_\eta & \sigma_\eta^2 \end{pmatrix} \right) \tag{25}$$

where δ denotes the correlation among the noises of the log-volatility equation and the mean equation and, therefore, the relationship between the variable r_t and the volatility variations one period ahead, h_{t+1}. Thus, if $\delta < 0$, negative values of z_t in the t period will tend to lead to positive values in η, which would entail a greater volatility in the $t+1$ period.

Another model that captures the leverage effect is the Threshold Stochastic Volatility model (THSV) proposed by So, Li and Lam (2002). A set of Bernoulli random variables, s_t, is defined by:

$$s_t = \begin{cases} 0 & if \quad r_{t-1} < 0 \\ 1 & if \quad r_{t-1} \geq 0 \end{cases} \tag{26}$$

The THSV(1,1) model is then given by the following:

$$\begin{aligned} r_t &= \mu_t + \sqrt{h_t}\, z_t \quad z_t \sim N(0,1) \\ log\, h_{t+1} &= \alpha_{s_{t+1}} + \phi_{s_{t+1}}\, log\, h_t + \eta_t \quad \eta_t \sim N(0, \sigma_\eta) \end{aligned} \tag{27}$$

as in the original formulation, z_t and η_t are stochastically independent. At time t-1, when there is an unexpected drop in price due to the presence of bad news, $r_t \leq 0$ and $s_t = 0$. In contrast, if there is good news at time *t-1*, then $r_t > 0$ and $s_t = 1$. Therefore, the value of s_t is determined by the sign of r_{t-1}. In the THSV model, the parameters α and ϕ switch between the two regimes corresponding to the rise and fall in asset prices.

With regards to the long memory pattern, Harvey (1998) and Breidt et al. (1998) independently proposed the stochastic volatility model with long memory, where the volatility logarithm follows an ARFIMA (1,d,0) process. The model, denoted LMSV(1,d,0), is represented by:

$$\begin{aligned} r_t &= \mu_t + z_t\sqrt{h_t} \\ (1-\phi L)(1-L)^d \log(h_t) &= \alpha + \sigma_\eta \eta_t \end{aligned} \tag{28}$$

Some applications of the SV model to estimate the VaR can be found in Fleming and Kirby (2003), Lehar et al. (2002), Chen et al. (2011) and González-Rivera et al. (2004). In the context of the Parametric method, Fleming and Kirby (2003) compare the GARCH models with the stochastic autoregressive volatility models (SARV). They find that the GARCH model and SARV models perform comparably in a test of the conditional VaR estimate. Lehar et al. (2002) compared option pricing models using two families of volatility models: the GARCH models and SV models. The comparison of these models was conducted in terms of their ability to forecast the VaR of derivative assets. They found that there were no differences between the volatility models employed. González-Rivera et al. (2004) presented a comparison among fifteen different volatility models (GARCH and SV) and found that the SV model had the best performance in estimating the VaR. Chen et al. (2011) compared the performance of two stochastic volatility models, SV and the THSV, with a wide range of the GARCH family of volatility models: GARCH, IGARCH, GJR-GARCH EGARCH, and EWMA model. The comparison was conducted in two different samples. They found that the SV and the THSV models joined with the EWMA models had the worst performances in estimating the VaR.

(iii) Realised Volatility

The origin of the realised volatility concept is certainly not recent. Merton (1980) had already mentioned this concept, showing the likelihood of the latent volatility approximation by the addition of *N* intra-daily square yields over a *t* period, thus implying that the addition of square yields could be used for the variance estimation. Taylor and Xu (1997) showed that the daily realised volatility can be easily crafted by adding the intra-daily square yields. Assuming that a day is divided into equidistant *N* periods and if $r_{i,t}$ represents the intra-daily yield of the i-interval of day $_t$, the daily volatility for day *t* can be expressed as:

$$\left[\sum_{i=1}^{N} r_{i,t}\right]^2 = \sum_{i=1}^{N} r_{i,t}^2 + 2\sum_{i=1}^{N}\sum_{j=i+1}^{N} r_{j,t} r_{j-i,t} \tag{29}$$

In the event of yields with ¨zero¨ mean and no correlation whatsoever, then $E\left[\sum_{i=1}^{N} r_{i,t}^2\right]$ is a consistent estimator of the daily variance σ_t^2.

Andersen et al. (2001a, 2001b) upheld that this measure significantly improves the prediction compared with the standard procedures, which just rely on daily data.

Although financial yields clearly exhibit leptokurtosis, the standardised yields by realised volatility are roughly normal. Furthermore, although the realised volatility distribution poses a clear asymmetry to the right, the distributions of the realised volatility logarithms are approximately Gaussian (Pong et al (2004)). In addition, the long-term dynamics of the realised volatility logarithm can be inferred by a fractionally integrated long memory process. The theory suggests that realised volatility is a non-skewed estimator of the volatility yields and is highly efficient. The use of the realised volatility obtained from the high-frequency intra-daily yields allows for the use of traditional procedures of temporal times series to create patterns and forecasts.

A problem raised by the realised volatility framework is the election of the optimum frequency. The size of the chosen interval of time is a key factor in estimating the volatility as it is an essential parameter due to its reflection of different market member perceptions and actions in the short and long terms. Generally, the intra-daily data are available in a range of frequencies that span from 1 to 30 minutes. There are some methods of correction. The most commonly used is the optimal frequency following the methodology of Hansen and Lunde (2006) and Zhang et al (2005). Both articles show enough evidence of the high efficiency of this correction model. Bandi and Russel (2005a, 2006) minimized the error function using its derivative. These authors estimated and empirically proved that a sample with a frequency equal to 15 minutes would be enough to estimate its volatility. Due to the frequency selection being a restriction and the absence of an overwhelming consensus, the best choice to pick the optimum frequency, as other authors have mentioned, would be realised from computing the realised frequency for different frequencies.

Recent empirical results from the RV literature show two typical features in volatility, which are the asymmetric effect on volatility caused by previous returns and the long-range dependence of volatility. The former issue has been investigated by Bollerslev and Zhou (2006), Bollerslev et al. (2006), Bollerslev et al. (2011), Chen and Ghysels (2010), Martens et al. (2009) and Patton and Sheppard (2009), among others. With respect to the latter point, the autoregressive fractionally integrated model has been used by Andersen et al. (2001a, 2001b and 2003), Koopman et al. (2005) and Pong et al. (2004), among others, whereas other studies have used the heterogeneous autoregressive model of Corsi (2009) to approximate the hyperbolic decay rates associated with long memory models.

Here, we present some of the most representative realised volatility models. Pong et al. (2004) justified the need of an ARMA pattern to seize the realised volatility processes. They showed that the addition of the two AR(1) processes could capture the persistent performance of the realised volatility in a better way than just a single AR(1) process. Because the addition of the two AR(1) processes is equivalent to one ARMA(2,1), the model or pattern to explain the dynamics of realised volatility is represented by:

$$(1-\phi_1 L-\phi_2 L^2)(\ln RV_t-\mu)=(1-\delta_1 L)u_t \qquad (30)$$

Andersen et al. (2001a, 2001b and 2003) proposed an autoregressive fractionally integrated long memory model of movable means (ARFIMA) to capture the long-range dependence within the realised volatility processes. They also verified, as previously stated, that the algorithm of realised volatility describes a roughly normal distribution. The mathematical expression of the ARFIMA(1,d_{RV},1) model for the logarithm of realised volatility has the following expression:

$$\left(1-\psi_1 L\right)\left(1-L\right)^{d_{RV}}\left(\log(RV_t)-\mu\right)=\left(1+\delta_1 L\right)u_t \qquad (31)$$

where d_{RV} is the fractionally differentiating parameter and u_t is the distributed error according to the N(0, σ_u^2) distribution.

Müller et al. (1997) proposed the heterogeneous interval ARCH (HARCH) process for different time intervals of different sizes. The HARCH process is able to reproduce long memory volatility. Similar to most of the ARCH processes, the HARCH model is based on the square of the change of prices. The HARCH(n) model is defined by the equations:

$$r_t=\sigma_t\varepsilon_t$$
$$\sigma_t^2=c_o+\sum_{j=1}^{n}c_j\left(\sum_{i=1}^{j}r_{t-1}\right)^2 \qquad (32)$$

where ε_t follows a normal distribution with mean zero and variance 1 and the parameters comply with the conditions c_o>0, c_n>0 y $c_j \geq 0$ for $j=1,\ldots, n-1$. The equation of the variance is a linear combination of the added squared returns.

The HARCH process belongs to the ARCH family but differs from other ARCH processes due to its consideration of the volatility of the return changes upon different-sized intervals compared with the ARCH processes in which the time intervals are always the same size. In the HARCH (2) model case, the variance equation can be expressed as:

$$\sigma_t^2=c_o+c_1 r_{t-1}^2+c_2(r_{t-1}+r_{t-1})^2=c_o+(c_1+c_2)r_{t-1}^2+c_2 r_{t-2}^2+2c_2 c_o r_{t-1} r_{t-2} \qquad (33)$$

The HARCH (2) process can be identified with an ARCH (2) ordinary process except for the last term. In the ARCH processes what matters is the absolute value of the returns, whereas the sign of those returns is also paramount in the HARCH process: two consecutive changes on the returns with the same size and same direction have a larger contribution to the variance than two processes of the same size with opposite signs. The process HARCH is similar to a Markov chain.

The authors generalised the HARCH model by imposing onto the volatility a dependence on the volatility of the previous period:

$$\sigma_t^2 = c_o + \sum_{j=1}^{n}\sum_{k=1}^{j} c_{jk}\left(\sum_{i=k}^{j} r_{t-1}\right)^2 + \sum_{i=1}^{q} b_i \sigma_{t-1}^2 \qquad (34)$$

where $c_o > 0$, $c_{jk} \geq 0$ for $j=1,\ldots,n$ $k=1,\ \ldots,j$; $b_i \geq 0$ for $i=1,\ \ldots,\ q$.

This formulation accounts for all the cases for HARCH (c_{jk}=0 except c_{j1}) as well the ARCH and GARCH (c_{jk}=0 but c_{jj}) processes. The last term denotes the GARCH process. In addition, the HARCH model can be depicted as a special case of the Quadratic ARCH (QARCH of Sentana (1995)).

Corsi (2004) extended the HARCH model of Müller and proposed a model that can be explained as a combination of different components of realised volatilities with daily, weekly and monthly frequencies to adjust the pattern of long memory volatility because changes in the short and long terms also affect the return values. The short run-volatility is explained by the volatility of the previous period and by the expected volatility in the medium and long terms for the same period.

$$\ln RV_t^d = \beta_o + \beta_d(\ln RV_{t-1}) + \beta_w(\ln RV_{t-5;t-1}) + \beta_m(\ln RV_{t-22;t-1}) + \varepsilon_t \qquad (35)$$

where

$$ln RV_{t+1-k;t} = \frac{1}{k}\sum_{j=1}^{k} ln RV_{t-j} \qquad (36)$$

which means that for the long-term volatility component case ($\ln RV_{t-22:t-1}$), the volatility is calculated using a first-order autoregressive process with the realised volatility mean of the last 22 days. The previous expression can be estimated using minimum ordinary squares.

(vi) Empirical results of volatility models in VaR

This section lists the results obtained from the researches regarding the comparison of volatility models in terms of the VaR.

Overall, the EWMA model provides inaccurate VaR estimates. In a comparison with other volatility models, the EWMA model had the worst performance in estimating the VaR (see Chen et al. (2011), Abad and Benito (2012), Ñiguez (2008), Alonso and Arcos (2006), González-Rivera et al. (2004) and Huang and Lin (2004) among others).

The performance of the GARCH models strongly depends on the assumption about the distribution of the returns. Overall, under a normal distribution, the VaR estimates are not very accurate. However, when asymmetric and fat-tail distributions are considered, the results improve considerably.

There is scarce empirical evidence of the relative performance of the stochastic volatility models against the GARCH models in terms of the VaR (see Fleming and Kirby (2003), Lehar et al. (2002), Chen et al. (2011), Gonzalez-Rivera et al. (2004) and Ghen et al. (2011)). Fleming and Kirby (2003) compared a GARCH model with a SARV. They found that both models had comparable performances in terms of the VaR. Lehar et al. (2002) compared option pricing models in terms of VaR using two family models: GARCH and SV. They found that in terms of their ability to forecast the VaR, there are no differences between these volatility models. Chen et al. (2011) compared the performance of two stochastic volatility models, SV and the THSV, with a range wide of GARCH family volatility models: the GARCH, IGARCH, GJR-GARCH EGARCH, and EWMA models. The comparison was conducted on two different samples. They found that the SV, THSV and EWMA models had the worst performances in estimating the VaR. However, in a similar comparison, Gonzalez-Rivera et al. (2004) found that the SV model had the best performance in estimating the VaR. In general, with some exceptions, the evidence suggests that SV models do not improve the results obtained by the family of GARCH models.

The models based on the realised volatility work quite well to estimate the VaR (see Asai et al. (2011), Bownless and Gallo (2010), Clements et al. (2008), Giot and Laurent (2004) and Andersen et al. (2003)). Some papers show that an even simpler model (such as an autoregressive) combined with the assumption of the normal distribution for the returns yields reasonable VaR estimates.

In terms of forecasting volatility, there are many papers in the literature showing that the models based on realised volatility are superior to the GARCH models. However, not many papers report comparisons with regard to their ability to forecast VaR. Brownless and Gallo (2011) compared several RV models with a GARCH and EWMA model and found that the models based on RV outperformed both EWMA and GARCH models. Along this same line, Giot and Laurent (2004) compared several volatility models: EWMA, APARCH, and RV. The models are estimated with the assumption that the returns follow either normal or skewed *t*-Student distributions. They found that under a normal distribution, the RV model performed the best. However, under a skewed *t*-distribution, both APARCH and RV models provided very close results. These authors emphasised that the superiority of the models based on the realised volatility over the GARCH family is not as obvious when the estimation of the latter assumes the existence of asymmetric and leptokurtic distributions.

There is scarce empirical evidence on the performance of fractional integrated volatility models to estimate the VaR. Examples of papers that report comparisons of these models can are those by So and Yu (2006) and Beltratti and Morana (1999). The first paper compared, in terms of VaR, a FIGARCH model with a GARCH and IGARCH model. It was found that the GARCH model provided more accurate VaR estimates. In a similar comparison that included the EWMA model, So and Yu (2006) found that FIGARCH could not outperform GARCH. The authors concluded that although their correlation plots displayed some indication of long memory volatility, this feature is not very crucial in determining the proper value of VaR.

However, in the context of the realised volatility models, there is evidence that models that capture long memory in volatility provide accurate VaR estimates (see Andersen et al. (2003) and Asai et al. (2011)). The model proposed in this last paper captured long memory volatility and asymmetric features.

Along this line, Níguez (2008) compared the ability to forecast the VaR of different GARCH family models, GARCH, AGARCH, APARCH, FIGARCH and FIAPARCH, and EWMA, and found that the combination of asymmetric models with fractional integrated models provided the best results.

In the context of the GARCH family models, there is evidence that the Markov-Switching GARCH outperforms the GARCH models (see Li and Lin (2004) and Sajjad et al. (2008)). But, there may not be such evident superiority if the GARCH models considers asymmetric and fat-tail distributions.

Although this evidence is somewhat ambiguous, the asymmetric GARCH models seem to provide better VaR estimations than the symmetric GARCH models. Evidence in favour of this hypothesis can be found in studies by Bali and Theodossiuo (2007), Abad and Benito (2012), Chen et al. (2011), Mittnik and Paolella (2000), Huang and Lin (2004), Angelidis et al. (2007), and Giot and Laurent (2004). In the context of the models based on realised volatility, the asymmetric models also provide better results (see Asai et al. (2011)). Some evidence against this hypothesis can be found in Angelidis et al. (2007).

Finally, some authors state that the assumption of the distribution of the returns, not the volatility models, is actually the important factor for estimating VaR. Evidence supporting this issue is found in the study by Chen et al. (2011).

2.2.2. Density functions

As previously mentioned, the empirical distribution of the financial return has been documented to be asymmetric and exhibit a significant excess of kurtosis (fat tail and peakness). Therefore, assuming a normal distribution for risk management and particularly for estimating the VaR of a portfolio does not produce good results. Under this assumption, the size of the losses will be much higher than those predicted by a normal distribution.

As the *t*-Student distribution has fatter tails than the normal distribution, this distribution that has been commonly used in finance and risk management, particularly to model conditional asset return (Bollerslev (1987)).

In the context of VaR methodology, some applications of this distribution can be found in studies by Cheng et al. (2011), Abad and Benito (2012), Polanski and Stoja (2010), Angelidis et al. (2007), Alonso and Arcos (2006), Guermat and Harris (2002), Billio and Pelizzon (2000), and Angelidis and Benos (2004). The empirical evidence of the performance of this distribution in estimating VaR is ambiguous. Some papers show that the *t*-Student distribution performs better than the normal distribution (see Abad and Benito (2012), Polanski and Stoja (2010), Alonso and Arcos (2006), and So and Yu (2006)[4]). However, other papers, such as those by Angelidis et al. (2007), Guermat and Harris (2002), Billio and Pelizzon (2000), and Angelidis and Benos (2004), report that the *t*-Student distribution overestimate the proportion of exceptions.

The *t*-Student distribution can often account well for the excess kurtosis found in common asset returns, but this distribution does not capture the skewness of the return. Taking this into account, one direction of research in risk management involves searching for other distribution functions that capture these characteristics.

In this context of VaR methodology, several density functions have been considered: (i) the Skewness *t*-Student Distribution (SSD) of Hansen (1994), (ii) Exponential Generalized Beta of the Second Kind (EGB2) of McDonal and Xu (1995), (iii) Error Generalised Distribution (GED) of Nelson (1991), (iv) Skewness Error Generalised Distribution (SGED) of Theodossiou (2001), (v) *t*-Generalised Distribution of Mcdonald and Newey (1988), (vi) Skewness *t*-Generalised distribution (SGT) of Theodossiou (1998) and (vii) Inverse Hyperbolic Sign (IHS) of Johnson (1949). Herein, we describe each of these distributions:

(i) Skewness t-Student distribution (SSD) of Hansen

To allow for skewness in the shape of the conditional return density, Hansen (1994) defined the SSD as:

$$f(z_t|v,\eta)=\begin{cases} bc\left[1+\dfrac{1}{\eta-2}\left(\dfrac{bz_t+\alpha}{1-\eta}\right)^2\right]^{-(\eta+1)/2} & if \quad z_t<-\left(\dfrac{a}{b}\right) \\ bc\left[1+\dfrac{1}{\eta-2}\left(\dfrac{bz_t+\alpha}{1+\eta}\right)^2\right]^{-(\eta+1)/2} & if \quad z_t\geq-\left(\dfrac{a}{b}\right) \end{cases} \tag{37}$$

The constant a, b, and c are fixed as:

[4] This last paper shows that *t*-Student at 1% performs better in larger positions, although it does not in short positions.

$$a = 4\lambda c\left(\frac{\eta-2}{\eta-1}\right) \qquad b^2 = 1+3\lambda^2 - a^2 \qquad c = \frac{\Gamma\left(\frac{\eta+1}{2}\right)}{\sqrt{\pi\left(\eta-2)\Gamma\left(\frac{\eta}{2}\right)\right)}}$$

where $z_t=(r_t - \mu_t)/\sigma_t$ are the standardised returns, $\Gamma(.)$ is the Gamma function, λ is the skewness parameter, and η is a tail-thickness parameter. These parameters satisfy $|\lambda| < 1$ and $\eta > 2$.

(ii) Beta Exponential Generalised of the Second Kind (EGB2)

The EGB2 was proposed by Mcdonald and Xu (1995). The EGB2 probability density function is:

$$EGB2(z_t; p; q) = C\frac{e^{p(z_t+\delta)/\theta)}}{\left(1+e^{p(z_t+\delta)/\theta)}\right)^{p+q}} \tag{38}$$

where $z_t=(r_t - \mu_t)/\sigma_t$ are the, standardised returns, $C = 1/\left(B(p,q)\theta\right)$, $\delta = \left(\Psi(p) - \Psi(q)\right)\theta$, $\theta = 1/\sqrt{\Psi^{'}(p) + \Psi^{'}(q)}$, p and q are positive scaling constants, $B(.)$ is the beta function, and $\Psi(x) = d\ln\Gamma(x)/dx$ and $\Psi^{'}(x) = d\Psi(x)/dx$ are the psi function and its first derivative, respectively. The EGB2 is symmetric for equal values of p and q, positively skewed for values of $p > q$, and negatively skewed for values of $p < q$. The EGB2 converges to the normal distribution for infinite values of p and q.

(iii) Error Generalised (GED)

The GED was proposed by Nelson (1991). The density of a GED random variable that normalised z_t to have a mean of zero and a variance of one is given by:

$$f(z_t) = \frac{\eta}{\lambda\, 2^{(1+1/\eta)}\Gamma(1/\eta)} exp\left\{-\left(\frac{1}{2}\right)\left|\frac{z_t}{\lambda}\right|^{\eta}\right\} \qquad -\infty < z < \infty, \quad 0 < \eta < \infty \tag{39}$$

where $z_t=(r_t - \mu_t)/\sigma_t$ are the standardised returns, $\Gamma(.)$ is the Gamma function, $\lambda \equiv \left[2^{(-2/v)}\Gamma\left(\frac{1}{\eta}\right)/\Gamma\left(\frac{3}{\eta}\right)\right]^{0,5}$, and η is a positive parameter, or the degrees of freedom governing the thickness of the tail parameter. When $\eta < 2$, the distribution has thinner tails than the normal. For $\eta = 2$, it is exactly a normal distribution with mean 0 and standard deviation σ, whereas for $\eta > 2$, the distribution has an excess kurtosis relative to the normal distribution. For real asset return data, we expect $\eta < 2$.

(iv) Skewness Generalised Error (SGED)

The SGED was proposed by Theodossiou (2001). The SGED probability density function is

$$f(z_t|\lambda,k)=\frac{C}{\sigma}exp\left(-\frac{|z_t+\delta|^k}{\left(1+sign(z_t+\delta)\lambda\right)^k\theta^k}\right) \tag{40}$$

where

$$C=k/\left(2\theta\Gamma(1/k)\right) \qquad \delta=2\lambda AS(\lambda)^{-1} \qquad \theta=\Gamma(1/k)^{0.5}\Gamma(3/k)^{-0.5}S(\lambda)^{-1}$$
$$\delta=2\lambda AS(\lambda)^{-1} \qquad S(\lambda)=\sqrt{1+3\lambda^2-4A^2\lambda^2}$$

$z_t=(r_t\ -\mu_t\ )/\sigma_t$ are the standardised returns, λ is a skewed parameter $[\lambda]<1$, k is the kurtosis parameter, and *sign* denotes the sign function.

(v) t-Generalised Distribution (GT)

The GT was proposed by McDonald and Newey (1988). The density of a GT random variable that normalises z_t to have a mean of zero and a variance of one is given by:

$$f(z_t|\lambda,h,k)=\frac{k\Gamma(h)}{2\lambda\Gamma(1/k)\Gamma(h-1/k)}\left\{1+\left(\frac{|z_t|}{\lambda}\right)^k\right\}^{-h} \tag{41}$$

where $\lambda>0$, $k>0$, $h>0$ and $-\infty<z_t<\infty$. Note that this function is a reparameterisation of the usual form of the generalised *t* distribution (see, for example, Johnson *et al*. (1995)) with p replaced by *k*, $1/(p+q)$ replaced by *h* and $\left(\sigma\, q^{1/p}\right)$ replaced by λ (for $\sigma>0$, $p>0$ and $q>0$).

(vi) Skewness t-Generalised Distribution (SGT)

The SGT introduced by Theodossiou (1998) is a skewed extension of the generalised *t* distribution that was originally proposed by McDonald and Newey (1988). The SGT is a distribution that allows for a very diverse level of skewness and kurtosis, and it has been used to model the unconditional distribution of daily returns for a variety of financial assets. Furthermore, SGT incorporatesseveral well-known distributions, such as the GT (McDonald and Newey (1988)), SSD of Hansen (1994), SGED of Theodossiou (2001), normal distribution, uniform distribution, GED of Nelson (1991) and *t*-Student distribution.

The SGT probability density function for the standardised residual is:

$$f(z_t|\lambda,\eta,k)=C\left(1+\frac{|z_t+\delta|^k}{\left((\eta+1)/k\right)\left(1+sign(z_t+\delta)\lambda\right)^k\theta^k}\right)^{-\frac{\eta+1}{k}} \tag{42}$$

where

$$C=0,5k\left(\frac{\eta+1}{k}\right)^{-\frac{1}{k}}B\left(\frac{\eta}{k},\frac{1}{k}\right)^{-1}\theta^{-1} \qquad \theta=\frac{1}{\sqrt{g-\rho^2}} \qquad \rho=2\lambda B\left(\frac{\eta}{k},\frac{1}{k}\right)^{-1}\left(\frac{\eta+1}{k}\right)^{\frac{1}{k}}B\left(\frac{\eta-1}{k},\frac{2}{k}\right)$$

$$g=(1+3\lambda^2)B\left(\frac{\eta}{k},\frac{1}{k}\right)^{-1}\left(\frac{\eta+1}{k}\right)^{\frac{1}{k}}B\left(\frac{\eta-1}{k},\frac{3}{k}\right) \qquad \delta=\rho\theta$$

λ is the skewness parameter, $|\lambda|<1$; η is a tail-thickness parameter, $\eta>2$; k is a peakedness parameter, k>0; $sign$ is the sign function; B(.) is the Beta function; δ is the Pearson's skewness; and the mode of f(z_t); $z_t=(r_t-\mu_t)/\sigma_t$ is the standardised residual.

The skewness parameter λ controls the rate of descent of the density around the mode of z_t. In the case of positive skewness ($\lambda>0$), the density function is skewed to the right. In contrast, the density function is skewed to the left with negative skewness ($\lambda<0$).

(vii) Inverse Hyperbolic sine (IHS)

The IHS was proposed by Johnson (1949). The IHS probability density function is

$$IHS(z_t|\lambda,k)=-\frac{k}{\sqrt{2\pi\left(\theta^2+(z_t+\delta)^2\right)}}\times exp\left(-\frac{k^2}{2}\left(ln\left((z_t+\delta)+\sqrt{\theta^2+(z_t+\delta)^2}\right)-(\lambda+ln(\theta))\right)^2\right) \tag{43}$$

where $\theta=1/\sigma_w$, $\delta=\mu_w/\sigma_w$, $\sigma_w=0.5(e^{2\lambda+k^{-2}}+e^{-2\lambda+k^{-2}}+2)^{0.5}(e^{k^{-2}}-1)$, μ_w and σ_w are the mean and the standard deviation, respectively, of $w=\sinh(\lambda+x/k)$, *sinh* is the hyperbolic sine function, and *x* is a standard normal variable. Note that the negative value of *k* results in more leptokurtic distributions.

(viii) Mixture of Normal Distributions

Finite mixture models, particularly discrete mixtures of normal (MN) models, are an attractive class of non-normal models for the purpose of modelling financial asset returns. These models have been studied across different disciplines (e.g., Everitt and Hand (1981), Titterington et al. (1985) and McLachlan and Peel (2000)). One of the most appealing features of the MN models for modelling asset returns is their ability to capture leptokurtic, skewed and multimodal characteristics of the asset returns.

A general univariate normal mixture GARCH model, generalising earlier specifications such as those of Vlaar and Palm (1993) and Wong and Li (2001), has been proposed by Haas et al. (2004) and Alexander and Lazar (2006) and further investigated by Alexander and Lazar (2005), Ausín and Galeano (2007), Bertholon et al. (2006), Haas et al. (2006), Bauwens and Rombouts (2007), Wu and Lee (2007) and Giannikis et al. (2008).

(viii.a) Unconditional Mixed Normal Distribution

A random variable y is said to have a univariante (finite) normal mixture distribution if its unconditional density is given by

$$f(y)=\sum_{j=1}^{k}\lambda_j\phi(y;\mu_j,\sigma_j^2) \qquad (44)$$

where $\lambda_j>0,\ j=1,....,k,\ \sum_{j=1}^{k}\lambda_j=1$ are the mixing weights and

$$\phi(y;\mu_j,\sigma_j^2)=\frac{1}{\sigma_j\sqrt{2\pi}}exp\left\{-\frac{1}{2}\left(\frac{y-\mu_j}{\sigma_j}\right)^2\right\},\quad j=1,.....k$$

are the component densities. The normal mixture has finite moments of all orders with the expected value and variance given by

$$\mu=E(y)=\sum_{j=1}^{k}\lambda_j\mu_j \qquad (45)$$

$$var(y)=\sum_{j=1}^{k}\lambda_j(\sigma_j^2+\mu_j^2)-\left(\sum_{j=1}^{k}\lambda_j\mu_j\right)^2 \qquad (46)$$

(viii.b) Conditionally Heteroskedastic MN Processes

A time series $\{\varepsilon_t\}$ is generated by a k-component mixed normal GARCH(p,q) process or, in short, MN-GARCH, if the conditional distribution of ε_t is a k-component MN with zero mean that is

$$\varepsilon_t|\Psi_{t-1}\sim MN(\lambda_1,.....\lambda_k,\mu_1,.....\mu_k,\sigma_{1,t}^2,.......\sigma_{k,t}^2) \qquad (47)$$

where Ψ_t is the information set at time t and $\lambda_i\in(0,1),\ i=1,.....,k,\ \ \sum_{i=1}^{k}\lambda_i=1$. By imposing $\mu_k=-\sum_{i=1}^{k-1}(\lambda_i/\lambda_k)\mu_i$ on the mean of the k_{th} component, guarantees that ε_t has a zero mean.

Furthermore, the $k\times1$ vector of component variances, denoted by σ_t^2, evolves according to

$$\sigma_t^{(2)}=\alpha_0+\sum_{i=1}^{q}\alpha_i z_{t-i}^2+\sum_{j=1}^{p}\beta_j\sigma_{t-j}^{(2)} \qquad (48)$$

where $\sigma_t^{(2)} = [\sigma_{1,t}^2, \sigma_{2,t}^2, ..., \sigma_{k,t}^2]$; $\alpha_i = [\alpha_{i,1}, \alpha_{i,2}, ..., \alpha_{i,k}]$; $i = 0, ..., q$, are $k \times 1$ vectors: and β_j, $j = 1, ..., p$ are $k \times k$ matrices with typical elements, $\beta_{j,mn}$. The assumptions $\alpha_0 > 0, \alpha_i \geq 0, i = 0, ..., q,$ and $\beta_j \geq 0,\ j = 0, ..., p,$ correspond to non-negative conditions of Bollerslev (1986) for a normal GARCH model.

Then, the conditional variance of r_t is

$$\text{var}(r_t) = \sum_{j=1}^{k} \lambda_j (\sigma_{j,t}^2 + \mu_{j,t}^2) - \left(\sum_{j=1}^{k} \lambda_j \mu_{j,t} \right)^2 \tag{49}$$

(ix) Empirical results of the skewed distributions

Some applications to estimate the VaR of skewed distributions and a mixture of normal distributions can be found in Cheng et al. (2011), Polanski and Stoja (2010), Bali and Theodossiou (2008), Bali et al. (2008), Haas et al. (2004), Zhang and Cheng (2005), Haas (2009), Ausín and Galeano (2007), Xu and Wirjanto (2010) and Kuester et al. (2006).

These papers raised some important issues. First, regarding the normal and *t*-Student distributions, the skewed and fat-tail distributions seem to improve the fit of the financial data (see Bali and Theodossiou (2008), Bali et al. (2008), and Bali and Theodossiou (2007)). Consistently, some studies found that the VaR estimate obtained under skewed and fat-tailed distributions provides a more accurate VaR than those obtained from a normal or *t*-Student distribution. For example, Cheng et al. (2011) compared the ability to forecast the VaR of a normal, *t*-Student, and *SSD* of Hansen (1994) and GED. In this comparison, the skewed *t*-Student and GED distributions provide the best results. Polanski and Stoja (2010) compared the normal, *t*-Student, SGT and EGB2 distributions and found that just the latter two distributions provide accurate VaR estimates. Bali and Theodossiou (2007) compared a normal distribution with the SGT distribution. Again, they found that the SGT provided a more accurate VaR estimate.

Additionally, a mixture of normal distributions, *t*-Student distributions or GED distributions provided a better VaR estimate than the normal or *t*-Student distributions (see Hansen (1994), Zhang and Cheng (2005), Haas (2009), Ausín and Galeano (2007), Xu and Wirjanto (2010) and Kuester et al. (2006)). These studies showed that in the context of the Parametric method, the VaR estimations obtained with models involving a mixture with a normal distributions (and *t*-Student distributions) are generally quite precise.

2.2.3. Higher-order conditional time-varying moments

The traditional parametric approach for conditional VaR assumes that the distribution of returns standardised by conditional means and conditional standard deviations is iid. However, there is substantial empirical evidence that the distribution of financial returns standardised by conditional means and volatility is not iid (see Hansen (1994), Harvey and Siddique (1999), Jondeau and Rockinger (2003), Bali and Weinbaum (2007) and Brooks et al. (2005)). Earlier studies also suggested that the process of negative extreme returns at different quantiles may differ from one another (Engle and Manganelli (2004), Bali and Theodossiou (2007)).

Thus, taking the above into account, the earlier studies developed a new approach to calculate conditional VaR. This new approach considered that the higher-order conditional moments are time-varying (see Bali et al. (2008), Polanski and Stoja (2010) and Ergun and Jun (2010)).

Bali et al. (2008) introduced a new method based on the SGT with time-varying parameters. They allowed higher-order conditional moment parameters of the SGT density to depend on the past information set and hence relax the conventional assumption in the conditional VaR calculation that the distribution of standardised returns is iid. Following Hansen (1994) and Jondeau and Rockinger (2003), they modelled the conditional high-order moment parameters of the SGT density as an autoregressive process. The maximum likelihood estimates show that the time-varying conditional volatility, skewness, tail-thickness, and peakedness parameters of the SGT density are statistically significant. In addition, they found that the conditional SGT-GARCH models with time-varying skewness and kurtosis provided a better fit or returns than the SGT-GARCH models with constant skewness and kurtosis. In their paper, they applied this new approach to calculate the VaR. The in-sample and out-of-sample performance results indicated that the conditional SGT-GARCH approach with autoregressive conditional skewness and kurtosis provided very accurate and robust estimates of the actual VaR thresholds.

In a similar study, Ergun and Jun (2010) considered the SSD distribution of Hansen (1994), which they called the ARCD model, with a time-varying skewness parameter. They found that the GARCH-based models that take conditional skewness and kurtosis into account provided an accurate VaR estimate. Along this same line, Polanski and Stoja (2010) proposed a simple approach to forecast a portfolio VaR. They employed the Gram-Charlier expansion (GCE) augmenting the standard normal distribution with the first four moments, which are allowed to vary over time. The key idea was to employ the GCE of the standard normal density to approximate the probability distribution of daily returns in terms of the cumulants.[5] This approach provides a flexible tool for modelling the empirical distribution of financial data, which, in addition to volatility, exhibit time-varying skewness and leptokurtosis. This method provides accurate and robust estimates of the realised VaR. Despite its simplicity, their dataset

[5] Although in different contexts, approximating the distribution of asset returns via the GCE has been previously employed in the literature (e.g., Jarrow and Rudd (1982), Baillie and Bollerslev (1992), Jondeau and Rockinger (2001), Leon et al. (2005) and Christoffersen and Diebold (2006)).

outperformed other estimates that are generated by both constant and time-varying higher-moment models.

All previously mentioned papers compared their VaR estimates with the results obtained by assuming skewed and fat-tail distributions with constant asymmetric and kurtosis parameters. They found that the accuracy of the VaR estimates improved when time-varying asymmetric and kurtosis parameters are considered. These studies suggest that within the context of the Parametric method, techniques that model the dynamic performance of the high-order conditional moments (asymmetry and kurtosis) provide better results than those considering functions with constant high-order moments.

2.3. Semi-parametric methods

The Semi-parametric methods combine the Non-parametric approach with the Parametric approach. The most important Semi-parametric methods are Volatility-weight Historical Simulation, Filtered Historical Simulation (FHS), CaViaR method and the approach based on Extreme Value Theory.

2.3.1. Volatility-weight Historical Simulation

Traditional Historical Simulation does not take any recent changes in volatility into account. Thus, Hull and White (1998) proposed a new approach that combines the benefit of Historical Simulation with volatility models. The basic idea of this approach is to update the return information to take into account the recent changes in volatility.

Let $r_{t,i}$ be the historical return on asset *i* on day *t* in our historical sample, $\sigma_{t,i}$ be the forecast of the volatility[6] of the return on asset *i* for day *t* made at the end of *t-1*, and $\sigma_{T,i}$ be our most recent forecast of the volatility of asset *i*. Then, we replace the return in our data set, $r_{t,i}$, with volatility-adjusted returns, as given by:

$$r^*_{t,i} = \sigma_{T,i} r_{t,i} / \sigma_{t,i} \qquad (50)$$

According to this new approach, the VaR (α) is the α quantile of the empirical distribution of the volatility adjusted return ($r^*_{t,i}$).

This approach directly takes into account the volatility changes, whereas the Historical Simulation approach ignores volatility changes. Furthermore, this method produces a risk estimate that is appropriately sensitive to current volatility estimates. The empirical evidence presented by Hull and White (1998) indicates that this approach produces a VaR estimate superior to that of the Historical Simulation approach.

[6] To estimate the volatility of the returns, several volatility models can be used. Hull and White (1998) proposed a GARCH model and the EWMA model.

2.3.2. Filtered Historical Simulation

Filtered Historical Simulation was proposed by Barone-Adesi et al. (1999). This method combines the benefits of Historical Simulation with the power and flexibility of conditional volatility models.

Suppose we wish to use Filtered Historical Simulation to estimate the VaR of a single-asset portfolio over a 1-day holding period. In implementing this method, the first step is to fit a conditional volatility model to our portfolio return data. Barone-Adesi et al. (1999) recommended an asymmetric GARCH model. The realised returns are then standardised by dividing each one by the corresponding volatility, $z_t = (\varepsilon_t / \sigma_t)$. These standardised returns should be independent and identically distributed and therefore be suitable for Historical Simulation. The third step consists of bootstrapping a large number L of drawings from the above sample set of standardised returns.

Assuming a 1-day VaR holding period, the third stage involves bootstrapping from our data set of standardised returns: we take a large number of drawings from this data set, which we now treat as a sample, replacing each one after it has been drawn and multiplying each such random drawing by the volatility forecast 1 day ahead:

$$r_{t+1} = \mu + z^{*}\sigma_{t+1} \qquad (51)$$

where z^{*} is the simulated standardised return. If we take M drawings, we therefore obtain a sample of M simulated returns. With this approach, the VaR(α) is the α% quantile of the simulated return sample.

The recent empirical evidence shows that this approach works quite well in estimating the VaR (see Barone-Adesi and Giannopolous (2001), Barone-Adesi et al. (2002), Zenti and Pallotta (2001), Pritsker (2001), and Giannopoulos and Tunaru (2005)). With regards to other methods, Zikovic and Aktan (2009), Angelidis et al. (2007), Kuester et al. (2006) and Marimoutou et al. (2009) provide evidence that this method is the best for estimating the VaR. However, other papers indicate that this approach is not better than any others (see Nozari et al. (2010) and Alonso and Arcos (2006)).

2.3.3. CAViaR Model

Engle and Manganelli (2004) proposed a conditional autoregressive specification for the VaR. This approach is based on a quantile estimation. Instead of modelling the entire distribution, they proposed modelling the quantile directly. The empirical fact that the volatilities of stock market returns cluster over time may be translated quantitatively in that their distribution is autocorrelated. Consequently, the VaR, which is tightly linked to the standard deviation of the distribution, must exhibit similar behaviour. A natural way to formalise this characteristic is to use some type of autoregressive specification. Thus, they proposed a conditional autoregressive quantile specification that they called the CAViaR model.

Let x_t be a vector of time *t* observable variables and β_α a p-vector of unknown parameters. Finally, let $q_t(\beta) \equiv q_t(x_{t-1}, \beta_\alpha)$ be the α quantile of the distribution of the portfolio return formed at time *t-1*, where we suppress the α subscript from β_α for notational convenience.

A generic CAViaR specification might be the following:

$$q_t(\beta) = \beta_0 + \sum_{i=1}^{q} \beta_i q_{t-i}(\beta) + \sum_{j=1}^{r} \beta_j l(x_{t-j}) \qquad (52)$$

where *p= r+q+1* is the dimension of β and l is a function of a finite number of lagged observable values. The autoregressive terms $\beta_i q_{t-i}(\beta)$ *i=1,..,q* ensure that the quantile changes "smoothly" over time. The role of $l(x_{t-j})$ is to link $q_t(\beta)$ to observable variables that belong to the information set. A natural choice for x_{t-1} is lagged returns.

In the context of the CAViaR model, different autoregressive specifications can be considered:

- Symmetric absolute value (SAV):

$$q_t(\beta) = \beta_0 + \beta_1 q_{t-1}(\beta) + \beta_2 |r_{t-1}| \qquad (53)$$

- Asymmetric slope (AS):

$$q_t(\beta) = \beta_0 + \beta_1 q_{t-1}(\beta) + \beta_2 (r_{t-1})^+ + \beta_3 (r_{t-1})^- \qquad (54)$$

- Indirect GARCH(1,1) (IG):

$$q_t(\beta) = (\beta_0 + \beta_1 q_{t-1}^2(\beta) + \beta_2 (r_{t-1})^2)^{1/2} \qquad (55)$$

- Proportional symmetric adaptive (PSA):

$$q_t(\beta) = q_{t-1} + \beta_1 (|r_{t-1}| - q_{t-1})^+ + \beta_2 (|r_{t-1}| - q_{t-1})^- \qquad (56)$$

Chen et al. (2011) proposed a non-linear dynamic quantile family as a natural extension of the AS model. They defined the upcoming models as follows:

- Threshold CAViaR (T-CAViaR)

$$q_t(\beta) = \begin{cases} \beta_1 + \beta_2 q_{t-1}(\beta) + \beta_3 |r_{t-1}| & si \quad r_{t-1} \le u \\ \beta_4 + \beta_5 q_{t-1}(\beta) + \beta_6 |r_{t-1}| & si \quad r_{t-1} > u \end{cases} \qquad (57)$$

- Threshold Indirect GARCH (T-IG)

$$q_t(\beta) = \begin{cases} \left[\beta_1 + \beta_2 q_{t-1}^2(\beta) + \beta_3 r_{t-1}^2\right]^{1/2} & si \quad r_{t-1} \le u \\ \left[\beta_4 + \beta_5 q_{t-1}^2(\beta) + \beta_6 r_{t-1}^2\right]^{1/2} & si \quad r_{t-1} > u \end{cases} \qquad (58)$$

In both models, *u* represents the threshold value, although the authors indicated that they chose *u*=0.

The parameters of the CAViaR models are estimated by regression quantiles, as introduced by Koenker and Basset (1978). They showed how to extend the notion of a sample quantile to a linear regression model.

Bao et al. (2006) showed that CAViaR models are quite satisfactory in a stable period but that their performance is less satisfactory in a volatile period. Polanski and Stoja (2009) showed this method does not provide accurate estimations. Koretas and Zarangas (2005) conducted a comparison of several CAViaR models but did not reach any conclusive result. Chen et al. (2011) compared three CAViaR models (SAV, AS and T-CAViaR) with other alternative models (GARCH-N, GARCH-*t*, GJR-GARCH, IGARCH, Riskmetric). At the 1% confidence level, the T-CAViar model performs better than any other model

2.3.4. Extreme Value Theory

The Extreme Value Theory (EVT) approach focuses on the limiting distribution of extreme returns observed over a long time period, which is essentially independent of the distribution of the returns themselves. The two main models for EVT are (1) the block maxima models (BM) (McNeil (1998)) and (2) the peaks-over-threshold model (POT). The second is generally considered to be the most useful for practical applications due to the more efficient use of the data at the extreme values. In the framework of the POT models, there are two types of analysis: the Semi-parametric models built around the Hill estimator and its relatives (Beirlant et al. (1996), Danielson et al. (1998)) and the fully Parametric models based on the Generalised Pareto distribution (Embrechts et al. (1999)). In the upcoming sections each one of these approaches is described.

2.3.4.1. Block Maxima Models (BMM)

This approach involves the splitting of the temporal horizon into blocks or sections, taking into account the maximum values in each period. These selected observations form extreme events, also called a maximum block.

The fundamental BMM concept shows how to accurately choose the length period, n, and the data block within that length. For values greater than n, the BMM provides a sequence of maximum blocks $M_{n,1}, \ldots, M_{n,m}$ that can be adjusted by a generalised distribution of extreme values (GEV). The maximum loss within a group of n data is defined as $M_n=\max(X_1, X_2, \ldots X_n)$. For a group of identically distributed observations, the distribution function of M_n is represented as:

$$P(M_n \leq x) = P(X_1 \leq x, \ldots, X_n \leq x) = \prod_{i=1}^{n} F(x) = F^n(x) \qquad (59)$$

The asymptotic approach for $F^n(x)$ is based on the maximum standardised value

$$Z_n = \frac{M_n - \mu_n}{\sigma_n} \tag{60}$$

where μ_n and σ_n are the location and scale parameters, respectively. The theorem of Fisher and Tippet establishes that if Z_n converges to a non-degenerated distribution, this distribution is the generalised distribution of the extreme values (GEV). The algebraic expression for such a generalised distribution is as follows:

$$H_{\xi,\mu,\sigma}(x) = \begin{cases} \exp(-(1+\xi(x-\mu)/\sigma)^{-1/\xi} & \xi \neq 0 \; y \quad (1+\xi(x-\mu)/\sigma) > 0 \\ \exp(-e^{-x}) & \xi = 0 \end{cases} \tag{61}$$

where $\sigma > 0$, $-\infty < \mu < \infty$, and $-\infty < \xi < \infty$. The parameter ξ is known as the shape parameter of the GEV distribution, and $\eta = \xi^{-1}$ is the index of the tail distribution, H. The prior distribution is actually a generalisation of the three types of distributions, depending on the value taken by ξ.

- Gumbel (ξ =0) type I family. It has light extremes, not heavy extremes.

$$\Lambda(x) = \exp(-e^{-(x-\mu)/\sigma}) \qquad \forall x \in \Re \tag{62}$$

- Fréchet (ξ >0) type II family. This distribution is particularly useful for patterning financial returns as it has very heavy tails.

$$\Phi_{\xi,\mu,\sigma}(x) = \begin{cases} \exp(-(x-\mu)/\sigma)^{-1/\xi} & x \geq \mu \\ 0 & x < \mu \end{cases} \tag{63}$$

- Weibull (ξ <0) type III family. This distribution is used when the extremes are lighter (softer) than those from normal distribution, and thus, it is not particularly useful for applications related to financial yields (returns).

$$\Psi_{\xi,\mu,\sigma}(x) = \begin{cases} \exp(-(x-\mu)/\sigma)^{1/\xi} & x < \mu \\ 1 & x > 0 \end{cases} \tag{64}$$

The ξ, σ and μ parameters are estimated using maximum likelihood.

The VaR expression for the Gumbel and Fréchet distribution is as follows:

$$VaR = \begin{cases} \mu_n - \dfrac{\sigma_n}{\xi_n}(1-(-n\ln(\alpha))^{-\xi_n}) & to \quad \xi > 0 \quad (Fréchet) \\ \mu_n - \sigma_n \ln(-n\ln(\alpha)) & to \quad \xi = 0 \quad (Gumbel) \end{cases} \tag{65}$$

In most situations, the blocks are selected in such a way that their length matches a year interval and *n* is the number of observations within that year period.

This method has been commonly used in hydrology and engineering applications, although it is not very suitable for financial times series due to the cluster phenomenon largely observed in financial returns.

2.3.4.2. Peaks over Threshold Models (POT)

The POT model is generally considered to be the most useful for practical applications due to the more efficient use of the data for the extreme values. In the context of this model, we can distinguish between two types of analysis: (a) the fully Parametric models based on the Generalised Pareto distribution (GPD) and (b) the Semi-parametric models built around the Hill estimator.

2.3.4.2.a. Generalised Pareto Distribution

Among the random variables representing financial returns $\left(r_1, r_2, r_3, \ldots, r_n\right)$, we choose a low threshold *u* and examine all values (*y)* exceeding *u*: $\left(y_1, y_2, y_3, \ldots, y_{N_u}\right)$, where $y_i = r_i - u$ and N_u are the number of sample data greater than *u*. The distribution of excess losses over the threshold *u* is defined as:

$$F_u(y) = P(r - u < y \mid r > u) = \frac{F(y+u) - F(u)}{1 - F(u)} \tag{66}$$

Assuming that for a certain *u*, the distribution of excess losses above the threshold is a Generalised Pareto Distribution, $G_{k,\xi}(y) = 1 - \left[1 + \frac{k}{\xi} y\right]^{-1/k}$, the distribution function of returns is given by:

$$F(r) = F(y+u) = [1 - F(u)]G_{k,\sigma}(y) + F(u) \tag{67}$$

To construct a tail estimator from this expression, the only additional element we need is an estimate of $F(u)$. For this purpose, we take the obvious empirical estimator $(u - N_u)/u$. We then use the historical simulation method. Introducing the historical simulation estimate of $F(u)$ and setting $r = y + u$ in the equation, we arrive at the tail estimator

$$F(r) = 1 - \frac{N_u}{n}\left[1 + \frac{k}{\xi}(r-u)\right]^{-1/k} \qquad r > u \tag{68}$$

For a given probability $\alpha > F(u)$, the VaR estimate is calculated by inverting the tail estimation formula to obtain

$$VaR(\alpha) = u + \frac{\xi}{k}\left[\left[\frac{n}{N_u}(1-\alpha)\right]^{-k} - 1\right] \tag{69}$$

None of the previous Extreme Value Theory-based methods for quantile estimation yield VaR estimates that reflect the current volatility background. These methods are called *Unconditional Extreme Value Theory* methods. Given the conditional heteroscedasticity characteristic of most financial data, McNeil and Frey (2000) proposed a new methodology to estimate the VaR that combines the Extreme Value Theory with volatility models, known as the

Conditional Extreme Value Theory. These authors proposed GARCH models to estimate the current volatility and extreme value theory to estimate the distributions tails of the GARCH model shocks.

If the financial returns are a strictly stationary time series and ε follows a Generalised Pareto Distribution, denoted by $G_{k,\sigma}(\varepsilon)$, the conditional α quantile of the returns can be estimated as

$$VaR\,(\alpha) = \mu + \sigma_t G^{-1}_{k,\sigma}(\alpha) \qquad (70)$$

where σ_t^2 represents the conditional variance of the financial returns and $G_{k,\sigma}{}^{-1}(\alpha)$ is the α quantile of the Generalised Pareto Distribution, which can be calculated as:

$$G_{k,\sigma}{}^{-1}(\alpha) = u + \frac{\xi}{k}\left[\left[\frac{n}{N_u}(1-\alpha)\right]^{-k} - 1\right] \qquad (71)$$

2.3.4.2.b. Hill estimator

The parameter that collects the features of the tail distribution is the tail index, $\eta = \xi^{-1}$. Hill proposed a definition of the tail index as follows:

$$\hat{\eta}_H = \left[\frac{1}{u}\left(\sum_{i=1}^{u} log(r_i) - log\, r_{u+1}\right)\right]^{-1} \qquad (72)$$

where r_u represents the threshold return and u is the number of observations equal to or less than the threshold return. Thus, the Hill estimator is the mean of the most extreme u observations minus $u+1$ observation (r_{u+1}). Additionally, the associated quantile estimator is (see Danielson and de Vries (2000)):

$$VaR(\alpha) = r_{u+1}\left(\frac{1-\alpha}{u/n}\right)^{-1/\eta} \qquad (73)$$

The problem posed by this estimator is the lack of any analytical means to choose the threshold value of u in an optimum manner. Hence, as an alternative, the procedure involves using the feature known as Hill graphics. Different values of the Hill index are calculated for different u values; the Hill estimator values become represented in a chart or graphic based on u, and the u value is selected from the region where the Hill estimators are relatively stable (Hill chart leaning almost horizontally). The underlying intuitive idea posed in the Hill chart is that as u increases, the estimator variance decreases, and thus, the bias is increased. Therefore, the ability to foresee a balance between both trends is likely. When this level is reached, the estimator remains constant.

The existing literature addressing the EVT models to calculate the VaR is abundant. Regarding the BM models, Silva and Melo (2003) considered different maximum block widths, with the results suggesting that the extreme value method of estimating the VaR is a more conservative approach for determining the capital requirements than traditional methods. Byström (2004) applied both unconditional and conditional EVT models to the management of extreme market risks in the stock market and found that conditional EVT models provided particularly accurate VaR measures. In addition, a comparison with traditional (GARCH) approaches to calculate the VaR demonstrated EVT as being the superior approach for both standard and more extreme VaR quantiles. Bekiros and Georgoutsos (2005) conducted a comparative evaluation of the predictive performance of various VaR models, with a special emphasis on two methodologies related to the EVT, POT and BM. Their results reinforced previous results and demonstrated that some "traditional" methods might yield similar results at conventional confidence levels but that the EVT methodology produces the most accurate forecasts of extreme losses at very high confidence levels. Tolika et al. (2007) compared EVT with traditional measures (variance and covariance methods, Historical Simulation and Monte Carlo) and agreed with Bekiros and Georgoutsos (2005) on the outperformance of the EVT methods compared with the rest, especially at very high confidence levels. The only model that had a performance comparable with that of the EVT is the historical simulation model.

Some papers showed that unconditional EVT works better than the traditional Historical Simulation or Parametric approaches when a normal distribution for the returns is assumed and a EWMA model is used to estimate the conditional volatility of the return (see Danielsson and Vries (2000)). However, the unconditional version of this approach has not been profusely used in the VaR estimation because such an approach has been overwhelmingly dominated by the conditional EVT (see McNeil and Frey (2000), Ze-To (2008), Velayoudoum et al. (2009), and Abad and Benito (2012)). Recent comparative studies of VaR models, such as Nozari et al. (2010), Zikovic and Aktan (2009), and Gençay and Selçuk (2004), show that conditional EVT approaches perform the best with respect to forecasting the VaR.

Within the POT models, an environment has emerged in which some studies have proposed some improvements in certain aspects. For example, Brooks et al. (2005) calculated the VaR by a semi-nonparametric bootstrap using unconditional density, a GARCH(1,1) model and EVT. They proposed a Semi-nonparametric approach using a Generalised Pareto Distribution, and this method was shown to generate a more accurate VaR than any other method. Marimoutou et al. (2009) used different models and confirmed that the filtering process was important for obtaining better results. Ren and Giles (2007) introduced the media excessive function concept as a new way to choose the threshold. Ze-To (2008) developed a new conditional EVT-based model combined with the GARCH-Jump model to forecast extreme risks. He utilised the GARCH-Jump model to asymmetrically provide the past realisation of jump innovation to the future volatility of the return distribution as feedback and also used the EVT to model the tail distribution of the GARCH-Jump-processed residuals. The model is compared with the GARCH-*t* and conditional EVT-GARCH models and shows that the conditional EVT-GARCH-Jump model outperforms the GARCH and GARCH-*t* models. Chan and Gray (2006) proposed a model that accommodates autoregression and weekly seasonals in both the conditional mean and conditional volatility of the returns as well as leverage effects via an EGARCH specification. In addition, EVT is adopted to explicitly model the tails of the return distribution.

Finally, concerning the Hill index, some authors used the mentioned estimator, such as Bao et al. (2006), whereas others such as Bhattacharyya and Ritolia (2008) used a modified Hill estimator.

2.3.5. Monte Carlo (Semi-parametric)

The simplest Monte Carlo procedure to estimate the VaR on date t on a one-day horizon at a 99% significance level consists of simulating N draws from the distribution of returns on date $t+1$. The VaR at a 99% level is estimated by reading off element $N/100$ after sorting the N different draws from the one-day returns, i.e., the VaR estimate is estimated empirically as the α quantile of the simulated distribution of returns.

However, applying simulations to a dynamic model of risk factor returns that capture path-dependent behaviour, such as volatility clustering, and the essential non-normal features of their multivariate conditional distributions is important. With regard to the first of these, one of the most important features of high-frequency returns is that volatility tends to come in clusters. In this case, we can obtain the GARCH variance estimate at time t $\left(\hat{\sigma}_t\right)$ using the simulated returns in the previous simulation and set $r_t = \hat{\sigma}_t z_t$, where z_t is a simulation from a standard normal variable. With regard to the second item, we can model the interdependence using the standard multivariate normal or *t*-Student distribution or use copulas instead of correlation as the dependent metric.

Monte Carlo is an interesting technique that can be used to estimate the VaR for non-linear portfolios (see Estrella et al. (1994)) because it requires no simplifying assumptions about the joint distribution of the underlying data. However, it involves considerable computational expenses. This computational cost has been a barrier limiting its application into real-world risk containment problems. Srinivasan and Shah (2001) proposed alternative algorithms that require modest computational costs, and Antonelli and Iovino (2002) proposed a methodology that improves the computational efficiency of the Monte Carlo simulation approach of VaR estimates.

Finally, the evidence shown in the studies on the comparison of VaR methodologies agree with the greater accuracy of the VaR estimations achieved by methods other than Monte Carlo (see Abad and Benito (2012), Huang (2009), Tolikas et al. (2007) and Bao et al. (2006)).

3. Comparison of VaR methods

The empirical literature on VaR methodology is quite extensive. However, there are not many papers dedicated to comparing the performance of a large range of VaR methodologies.

In Table 1, we resume some papers. This table includes 20 papers. Basically, the methodologies that are compared in these papers are HS, FHS, the Parametric method under different distribution and the EVT-based approach. Only a few of the studies included other methods, such as the Monte Carlo, CaViaR, and the Non-Parametric density estimation methods, in their comparisons. For each benchmark article, we marked the methods included in the comparative exercise with a cross and shaded the method that provides the best VaR estimations. The approach based on the EVT is the best at estimating the VaR, and in 87.5% of the cases that include this method in the comparison, followed closely by FHS, in 71.4% of the cases.

The results yielded by the Parametric method should be paid attention to when considering that the conditional high-order moments are time-varying. The two papers that include this method in the comparison obtained a 100% outcome success (see Ergun and Jun (2010) and Polanski and Stoja (2010)). However, only one of these papers included EVT in the comparison (Ergun and Jun (2010).

Although not shown in the spread sheet, the VaR estimations obtained by the Parametric method within asymmetric and leptokurtic distributions and in a mixed-distribution context are also quite accurate (see Bali and Theodossiou (2008), Bali et al. (2008), Bali and Theodossiou (2007), Chen et al. (2011) and Polanski and Stoja (2010)), although this method does not seem to be superior to EVT and FHS (Kuester et al. (2006), Cifter and Özün (2007) and Angelidis et al. (2007)). Importantly, however, there are not many papers that include these three methods in the comparison.

Although there are not many works dedicated to the comparison of a wide range of VaR methodologies, the existing ones offer quite conclusive results. These results show that the approach based on the EVT and FHS is the best method to estimate the VaR. We also noted that the VaR estimates obtained by the Parametric method under the skewed and fat-tail distributions are promising results, especially when the assumption that the standardised returns is iid is abandoned and that the conditional high-order moments are considered to be time-varying.

Table 1. Overview of papers that compare VaR methodologies

	HS	FHS	RM	Parametric Approaches					ETV	CaViaR	MC	N-P
				N	T	SSD	MN	HOM				
Abad and Benito (2012)	x		x	x	x				x		x	
Ergun and Jun (2010)				x	x	x		x	x			
Nazori et al. (2010)		x							x			
Polansky and Stoja (2010)			x	x	x	x		x		x		
Brownless and Gallo (2010)	x		x	x								x
Huang(2009)	x			x							x	x
Marimoutou et al. (2009)	x	x		x					x			
Zikovic and Aktan (2009)	x	x		x					x			
Angelidis et al. (2007)		x		x	x	x			x			
Ozun et al. (2007)				x	x	x			x			
Tolikas et al. (2007)	x			x					x		x	
Alonso and Arcos (2006)	x	x		x	x							
Bao et al. (2006)	x	x	x						x	x	x	x
Bhattacharyya and Ritolia	x			x					x			
Kuester et al. (2006)	x	x		x	x	x	x		x			
Bekeiros et al. (2005)	x		x	x	x				x			
Gençay and Selçuk (2004)	x			x	x				x			
Gençay et al. (2003)	x			x	x				x			
Darbba, G. (2001)	x			x					x			
Danielson and Vries (2000)			x	x	x				x			

Note: In this table, we present some empirical papers involving comparisons of VaR methodologies. The VaR methodologies are marked with a cross when they are included in a paper. A shaded cell indicates the best methodology to estimate the VaR in the paper. The VaR approaches included in these paper are the following: Historical Simulation (HS); Filtered Historical Simulation (FHS); Riskmetrics (RM); Parametric Approaches estimated under different distributions, including the normal distribution (N), *t*-Student distribution (T), skewed *t*-Student distribution (SSD), mixed normal distribution (MN) and high-order moment time-varying distribution (HOM); Extreme Value Theory (EVT); CaViaR method (CaViaR); Monte Carlo Simulation (MC); and non-parametric estimation of the density function (N-P).

4. Conclusion

In this article, we review the full range of methodologies developed to estimate the VaR, from the standard models to the recently proposed methodologies. For these methodologies, we present their relative strengths and weaknesses from both theoretical and practical perspectives.

The performance of the parametric approach in estimating the VaR depends on the assumed distribution of the financial return and on the volatility model used to estimate the conditional volatility of the returns. With regard to the return distribution, the empirical evidence suggests that when asymmetric and fat-tail distributions are considered, the VaR estimate improves considerably. Regardless of the volatility model used, the results obtained by the empirical literature indicate the following. (i) The EWMA model provides inaccurate VaR estimates. (ii) The performance of the GARCH models strongly depend on the assumption of the distribution of the returns. Overall, under a normal distribution, the VaR estimates are not very accurate, but when asymmetric and fat-tail distributions are considered, the results improve considerably. (iii) Overall, with some exceptions, the evidence suggests that SV models do not improve the results obtained by the family of GARCH models. (iv) The models based on the realised volatility work quite well to estimate the VaR, outperforming the GARCH models estimated under a normal distribution. Additionally, Markov-Switching GARCH outperforms the GARCH models estimated under normality. In the case of the realised volatility models, some authors indicate that the superiority of this type of model compared with the GARCH family is not as strong when the GARCH models are estimated assuming asymmetric and fat-tail distributions for the returns. (v) In the framework of the GARCH family, the fractional-integrated GARCH models do not appear to be superior to the GARCH models. However, in the context of the realised volatility models, there is evidence that models that capture long memory in volatility provide more accurate VaR estimates. (vi) Although the evidence is somewhat ambiguous, asymmetric volatility models appear to provide a better VaR estimate than symmetric models.

Although not many works are dedicated to comparing a wide range of VaR methodologies, the existing ones offer quite conclusive results. The empirical literature shows that the approach based on the EVT and FHS is the best method to estimate the VaR. Regardless, it is important to note that the VaR estimates obtained by the Parametric method under the skewed and fat-tail distributions are promising results, especially when the assumption that the standardised returns is iid is abandoned and that the conditional high-order moments are considered to be time-varying.

To further the research, it would be interesting to explore whether in the context of an approach based on the EVT and FHS, considering asymmetric and fat-tail distributions to model the volatility of the returns could help improve the results obtained by these methods. Along this line, applying the realised volatility model and Markov-switching model may improve the results.

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