Dynamic Correlation Models

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Abstract
One of the inputs required by investors, seeking to hold efficient portfolios, is the correlation between the securities to be included in the portfolio. Correlation estimates are required in most applications in finance including asset pricing models, capital allocation, risk management and option pricing and hedging. This paper presents an overview of my PhD thesis that focused on developing and investigating innovative methods for estimating and forecasting correlation between financial asset returns. Firstly, the importance of correlation estimation in financial applications is examined focusing on a risk management application. Secondly, a traditional financial economics problem regarding the international financial market linkages is addressed based on a dynamic correlation structure. An application to the European bond markets volatility transmission mechanism is provided. Thirdly, an innovative methodology for forecasting correlation using the market prices of derivative instruments is developed.

1. Introduction

Uncertainty plays a central role in financial economics theory. In the core of every financial problem is the analysis of the behaviour of investors under uncertainty. Statistical and econometric methods are widely used in the modelling and analysis of financial markets in order to take into account uncertainty. The application of econometric methods in financial market data has formed a new discipline, called financial econometrics. An important topic in financial econometrics that has received significant attention in the finance literature is the modelling of the second moments of asset returns. Accurate estimates and good forecasts of asset return volatility and correlation are required in most financial applications including asset pricing, capital allocation, risk management, derivatives pricing and hedging. While a lot of research effort has been devoted in modelling volatility, understanding of correlation is relatively poor.

Traditionally, correlation has been modeled as a constant and unconditional variable. Over the years, practitioners have come to realize that correlation actually varies through time and several researchers have provided empirical evidence to support this view (e.g., Von Fustenberg and Jeon, 1989, Koch and Koch, 1991, Erb et al., 1994, Longin and Solnik, 1995). The recognition of the time-variability of correlation has motivated a continuously growing amount of research on a wide variety of dynamic correlation models.

This study focuses on the modelling of correlation between asset returns. Firstly, we investigate the importance of correlation estimation in the context of risk management
. More specifically, the effect of correlation mis-estimation on Value-at-Risk (VaR) calculation is investigated. Secondly, we explore the market factors influencing international financial market linkages taking into account the dynamic structure of conditional correlation. More specifically, we measure how and to what extent the volatility of a European bond market is affected by local shocks, regional shocks and world shocks. In addition to exploring the volatility transmission mechanism, the time-varying correlation structure between the European bond markets is investigated. Thirdly, we propose a new measure for forecasting correlation using the market prices of derivative instruments, called implied correlation index, which provides a market forecast of the future average correlation between the underlying assets of the portfolio. By applying this methodology to the Dow Jones Industrial Average index, the statistical properties and the forecasting performance of the implied correlation measure are examined.

A number of important results are drawn from this research. Firstly, the accurate estimation of correlation in an important task for risk managers since errors in correlation estimation affect significantly the VaR calculation. Secondly, by considering a dynamic correlation structure in the volatility transmission mechanism of the European bond markets, new evidence may be drawn regarding the links between these markets. Finally, correlation forecasts as implied by option prices are useful proxies of future correlation and contain additional information not included in traditional historical forecasts.

The paper is structured as follows. Section 2 explores the role of correlation modelling in financial economics. Section 3 presents a brief review of the related research work and the theoretical motivation of the thesis. Section 4 depicts the main research findings. Section 5 underlines the major conclusions of this study.

2. Correlation in financial economics

Correlation is one of the most important parameters that needs to be estimated in the context of Modern Portfolio Theory. The Capital Asset Pricing Model, CAPM, and the Arbitrage Pricing Theory, APT, (Campbell et al., 1997) use correlation as a measure of dependence between different financial instruments in order to arrive at an optimal portfolio selection. Surprisingly, correlation estimation has not received significant attention in the finance literature compared to other estimators such as volatility.

Over the last decades, increasingly sophisticated statistical methods have been built to capture the characteristics of volatility. The explosion in volatility modelling can be traced to the seminal work of Engle (1982) and Bollerslev (1986). Research in the area of volatility modelling has resulted to a wide variety of modelling techniques including autoregressive conditional heteroscedasticity (ARCH) and general autoregressive conditional heteroscedasticity (GARCH) models, stochastic volatility models, implied volatility as extracted from option prices or direct indicators of volatility such as ex post squared returns. Partial surveys of the volatility modelling literature can be found in the studies of Bollerslev et al. (1994), Ghysels et al. (1996) and Campbell et al. (1997).

A number of factors complicate the task of developing models for estimating and forecasting correlation. Firstly, correlation between asset returns, like volatility, is not directly observable. The traditional approach proposes the estimation of the correlation matrix from data on daily asset returns while more recent techniques use higher frequency data to estimate realized correlations (see Andersen et al., 2001a, 2001b). Secondly, traditional techniques assumed that correlation is constant over time. However, a number of studies document that correlation actually varies over time and increases during periods of high volatility and turmoil (King and Wadhwani, 1990, Erb et al., 1994, Ramchand and Susmel, 1998, Ang and Chen, 2002). Thirdly, as the number of asset increases, the estimation of the correlation matrix becomes problematic.

Following the recognition of the time-variability of correlation, a wide variety of correlation models has been developed in the literature. Two questions arise from the plethora of correlation models. Firstly, how important is correlation estimation in financial applications and secondly, which of the correlation models provides the best forecast of future correlation to be used as an input in financial applications. A series of studies have dealt with the second question by evaluating the forecasting performance of correlation models in the context of various financial applications. For example, Elton and Gruber (1973) and Chan et al. (1999) in the context of asset allocation, Beder (1995) and Alexander and Leigh (1997) in the context of risk management, Gibson and Boyer (1998) and Byström (2002) in the context of option pricing. However, the evidence about which is the best correlation model is far from being conclusive. Furthermore, since most applications require forecasts of both volatility and correlation, evaluating the forecasting performance of correlation independently of volatility is extremely difficult. Surprisingly, the first question concerning the importance of correlation estimation remains unanswered. The first part of the thesis attempts to answer this question by investigating the effect of correlation mis-estimation on the induced VaR error.

The success of the ARCH and GARCH methodology in modeling the time-varying variances of asset returns in the univariate case has motivated many researchers to extend these models to the multivariate dimension. The basic multivariate GARCH model called vec GARCH is provided by Bollerslev et al. (1988). They extend the GARCH representation to a vectorized conditional variance-covariance matrix in a multivariate setting. However, the estimation and application of this model in the financial context requires further restrictions. In most multivariate GARCH models it is difficult to verify that the conditional variance covariance matrix is positive definite as well as to impose the appropriate restrictions during the optimization of the log-likelihood function. As a result, it is often assumed that correlation is time-invariant in order to simplify the estimation procedure. Bollerslev (1990) pointed out that under the assumption of constant correlation the maximum likelihood estimate of the correlation matrix is equal to the sample correlation matrix. As the sample correlation matrix is always positive definite, the optimization requires that only the conditional variances are positive definite.

More recently, a number of researchers have developed a new class of multivariate GARCH models that take into account the time-variability of correlation explicitly (e.g. Engle, 2002, and Tse and Tsui, 2002). Although these models allow for the correlation matrix to be time-varying, they model the conditional variances individually as univariate GARCH processes without allowing the past innovations and variances of one variable to influence the conditional variance of the other variables. A common application of the multivariate GARCH methodology is to the modeling of the volatility transmission mechanism between international equity markets, interest rates, currencies etc. Most existing studies on volatility spillovers assume that correlation is constant (e.g. Booth et al., 1997, Laopodis, 2002, Miyakoshi, 2003) or model separately the conditional variances of each variable in a univariate setting and use the squared residuals of one variable as an explanatory variable of the volatility process of the other variable (e.g. Bekaert and Harvey, 1997, Ng, 2000). We deal with this issue in the second part of the thesis by studying the volatility transmission mechanism in the European bond markets using a dynamic correlation structure.

Most correlation models use just past observed values of the variables under examination as the relevant information set. An alternative source of information that can be used for forecasting future correlation are option prices. Option prices have been widely used in order to obtain implied volatility, i.e. the market forecast of the underlying asset volatility. Latane and Rendleman (1976) were the first to show evidence in favor of this approach and motivated further research on the issue of implied volatility. The apparent benefits that can be obtained by using the information contained in option prices provide the motivation for using the notion of "implied" correlation as an estimate of future correlation.

Only a limited number of studies have used option prices to derive implied correlation measures and only for currency options. Bodurtha and Shen (1995), Siegel (1997), Campa and Chang (1998), and Lopez and Walter (2000) derive option-implied correlations using currency and cross-currency option data and study the forecasting performance of these estimates. They find that implied correlations are useful for forecasting future currency correlations. Moreover, a number of option pricing formulas for products such as quantos, exchange options, rainbow options require correlation estimates. By using the observed options prices and inverting the option-pricing formula, a market correlation forecast can be derived. The main limitation of this approach relates to the limited number and trading (usually OTC) of such products. Concluding, the market forecast of future correlation as implied by option prices is an appealing measure and, interestingly, its properties have not been studied in the literature. The third part of the thesis proposes an innovative methodology for the derivation of implied correlation measures.

Having briefly described the related research work and the theoretical motivation of the thesis, the following section depicts the main objectives of this research and the adopted research approach.

3. Development and use of dynamic correlation models in financial applications

Three important aspects of correlation modelling are examined. Firstly, the importance of correlation estimation in the context of risk management is investigated. Secondly, a model for volatility transmission that captures the dynamic correlation structure is examined. Thirdly, a method for extracting information about correlation from derivative products is proposed.

The main objectives of the first part of the thesis are the following. Firstly, the relationship between correlation estimation and VaR calculation is investigated. Understanding this relationship is a necessary prerequisite for measuring market risk accurately. Correlation is one of the parameters that needs to be estimated so as to implement any parametric VaR model. Any bias in the measurement of correlation between the portfolio assets will yield an erroneously calculated VaR. Despite the plethora of correlation estimators proposed in the literature, the correlation mis-estimation is inevitable. More importantly, in periods of market stress, where VaR is supposed to be used for, the correlations deviate significantly from the estimated values (see Boyer et al, 1999, Rebonato and Jäckel, 2000, and Bhansali and Wise, 2001, for a discussion of cases where the statistical techniques can not provide accurate estimates of correlation).

A number of studies compare VaR models that use different multivariate volatility models. Their results indicate that different correlation estimators yield significantly different VaR figures. However, the evidence about which is the best correlation estimator within a VaR framework is far from being conclusive. This study takes a different route. Accepting that any correlation model estimates the (unknown) 'true' correlation with some error, the question "Does it matter which (false) correlation estimator shall we use for VaR purposes?" arises. We address this question by examining whether there is a systematic relationship between correlation mis-estimation and the induced VaR mis-calculation. This is important for effective risk management. For instance, in the case that there is such a relationship, the VaR model error issue (due to correlation mis-estimation) becomes important; the risk manager should look for the method that estimates correlation with the lowest possible error. On the other hand, if no such systematic relationship exists, the risk manager can switch between the existing correlation estimators without affecting in a significant way his (already) mis-calculated VaR. Then, he can focus on identifying the effect of other sources of model error on his VaR calculation.

The methods for calculating VaR are described in the first part of the thesis and analytical expressions for the sensitivity of VaR calculation to correlation errors are derived. The relationship between correlation estimation and VaR calculation is further examined using a simulation setup. First, a semi-parametric approach that considers a general class of unbiased correlation estimators is developed; correlation estimation errors are simulated from an assumed normal distribution. Then, the effect of mis-estimating correlation on VaR is studied parametrically by applying specific correlation estimators (moving average, exponentially weighted moving average and GARCH-type models) to simulated data. Both approaches are implemented using specific linear and non-linear portfolios containing options. VaR is calculated with variance-covariance (delta-normal and delta-gamma), and Monte Carlo simulation methods.

The objective of the second part of the thesis is the development and application of a multivariate GARCH model that captures the volatility transmission and the dynamic correlation structure in the European bond markets. Most approaches for modeling volatility spillovers assume conditional time-invariant correlations in order to simplify the estimation procedure (see Booth et al., 1997, Laopodis, 2002, Miyakoshi, 2003). However, several studies (e.g. Erb et al., 1994, and Longin and Solnik, 1995, amongst others) provide evidence that support the time-variability of correlation. The second part of the thesis builds upon the methodology developed by Darbar and Deb (2002) and models volatility spillovers assuming a time-varying conditional correlation structure. While most of the previous studies have focused on the interaction between a single pair of countries, we investigate the influence of two major market factors, regional and world, to both Euro and non Euro area national bond markets within the European region. We focus on the relationships between bond markets that, relative to equity markets, are less studied in the literature (see Ilmanen, 1995, Clare and Lekkos, 2000, Driessen et al., 2003). Furthermore, extending the sample period beyond the launch of Euro in January 1999, allows us to test how the bond markets interdependence has changed after this major event.

More specifically, the second part of the thesis examines the volatility transmission mechanism from the US bond market and the aggregate Euro area bond market to twelve individual European bond markets. A bivariate EGARCH model with a dynamic conditional correlation structure that deals with US effects as exogenous is used. Empirical results on the price and volatility spillovers from both the aggregate Euro area bond market and the US bond market to the individual European markets are presented. Moreover, we examine the dynamic correlation structure between the individual European bond markets and the aggregate Euro area / US bond market. Finally, we test whether the US effects are correctly modeled as exogenous and whether the price and volatility spillovers as well as the dynamic correlation structure between the European bond markets has changed significantly after the European Monetary Union (EMU).

The objective of the third part of the thesis is the development of an innovative methodology for forecasting correlation using the market prices of derivative instruments. Since option prices reflect the market's view and expectations, they arguably contain useful information not included in historical data. We extend the methodology used for constructing implied volatility indices to derive an index for implied correlation from option prices. The derived correlation index has three important advantages compared to alternative measures. It reflects the market view, it is a forward looking measure and has a constant forecasting horizon.

The proposed methodology can be applied to options on any portfolio of assets. For the construction of the implied correlation measure, market prices of the portfolio option as well as individual options on each one of the portfolio constituents are required. By applying this methodology to index options, the derived implied correlation measure is the market forecast of the future level of diversification in the market portfolio represented by the index during the specified forecast horizon. Finally, this new measure, called implied correlation index, provides the market forecast of future average correlation between asset returns.

The proposed methodology is applied to the DJIA index options prices and the statistical properties and the dynamics of the proposed implied correlation measure are examined. More specifically, we study the time-series properties of the implied correlation index and whether several stylized facts reported in the literature for correlation are also present in the implied correlation index. Moreover, the forecasting performance of the implied correlation index as a proxy of future realized correlation index is assessed. Both unbiasedness and orthogonality tests are conducted using a simple historical measure as the alternative forecast.

Having described the objectives of the thesis and the adopted research approach, the next sections briefly presents the main research findings.

4. Research findings

This section will try to draw together the evidence from the particular components of the thesis. Although the thesis has dealt with only a small fraction of the numerous issues involved with correlation modeling and its application, we have managed to establish some important results in this area.

In the first part of the thesis we examine explicitly the systematic relationship between errors in estimating correlation and the resulting error in calculating VaR (VaR Percentage Error, VPE). The results of this study are similar for both the semi-parametric and parametric analysis. We find that VPE is significantly sensitive to mis-estimating correlation; as the correlation estimation error increases, the VaR mis-calculation increases. This holds for both linear and option portfolios where VaR is calculated by either variance-covariance or Monte Carlo simulation methods. Therefore, the choice of a model that estimates correlation with the lowest possible error is important for risk managers. An additional result of this study is that as the level of the 'true' correlation decreases, the sensitivity of VPE to correlation errors increases. This implies that the calculated from linear portfolios VaR will be more sensitive to correlation errors for well diversified linear portfolios. In the case of option portfolios, this implies that the correlation bias effect increases as the correlation between the underlying assets decreases.

Moreover, the correlation bias effect to VaR depends also on the options moneyness level, and the time-to-maturity. The results show that the option portfolio VaR is more sensitive to correlation errors in the case that the portfolio contains short-maturity in-the-money options. This result is not welcomed by the risk manager, since most of the options trading activity is concentrated on short-expiry, near-the-money options. Finally, our results indicate that the VaR sensitivity to correlation mis-estimation depends on the method that is employed to calculate VaR. Using Monte Carlo simulation rather than variance-covariance methods increases this sensitivity. Therefore, the accuracy of VaR results obtained from Monte Carlo simulation should be verified via various backtesting methods. Furthermore, it is well known that for linear portfolios the risk manager is in principle indifferent between using variance-covariance and Monte Carlo simulation methods; the calculated via Monte Carlo simulation VaR converges to the calculated via variance-covariance VaR. However, since the correlation bias effect on VaR depends on the employed method, the use of Monte Carlo simulation should be avoided even for small linear portfolios, if possible.

The second part of the thesis is concerned with the modeling of the volatility transmission mechanism between asset returns allowing for a time-varying correlation structure. The methodology is applied to the European bond markets. The results of this research suggest that significant price and volatility spillovers exist between the aggregate Euro area bond market and the individual European bond markets both within and outside the Euro area. The second moment interdependencies are far more pronounced and reciprocal than the first moment interdependencies. Moreover, the own market effects are significant in the price and volatility process of most European bond markets. In most of these markets local and regional shocks have an asymmetric impact in the bond market volatility process. While this is a well-documented stylized fact for stock market returns, it has not been extensively investigated for bond market returns.

Moreover the results of our analysis indicate that the world market factor of US has a significant influence in the individual European bond market volatility process. While the US market returns influence the European bond market returns in a limited number of cases, the US bond market volatility is a significant factor in explaining the individual European bond market volatilities in almost all cases. However, both domestic and regional effects to the European bond market returns and volatility are more pronounced compared to US effects. The introduction of Euro has significantly affected the price and volatility transmission mechanism in both Euro area and non Euro area bond markets. In most European bond markets, the price and volatility spillover coefficients from and to the aggregate Euro area index have significantly increased after this major event. Furthermore, the correlation levels among the European countries have increased and become more stable after the introduction of Euro.

The third part of the thesis firstly describes the theoretical background for the derivation of the average implied correlation index from index option prices. An empirical application using the Dow Jones Industrial Average index option prices is provided. The univariate time-series properties and seasonalities of the index are examined as well as the relationship between the correlation index and both the underlying index changes and the volatility index changes. Furthermore, a number of stylized facts about correlation emerging from the literature are tested for the implied correlation index. And, the forecasting performance of the implied correlation index as a forecast of realized correlation index is assessed.

The results document a significantly positive first-order autocorrelation of the correlation index levels and a significant negative first order autocorrelation of the correlation index changes. The reported correlation persistence is in line with previous evidence on the autocorrelation structure of return correlations. The correlation index varies substantially over time. No intraweek pattern is identified in the time series of the correlation index changes. Moreover, the correlation index tends to increase when markets move down as well as during high volatile periods.

This study also investigates whether several stylized facts reported in the literature for correlation are also present in the implied correlation index. DJCIX levels exhibit a significant positive autocorrelation up to 41 lags. In addition, an asymmetric response of correlation index movements to the underlying index innovations is documented. Negative shocks in the underlying index are accompanied with increases in the implied correlation index. A similar significant relationship is not documented for positive returns of the underlying index. Furthermore, the results of this study indicate that high volatile periods are accompanied by increased correlations. Rather remarkably, the examination of the dynamic structure between the correlation and volatility index indicates that current and past changes in the stock returns correlation Granger cause stock market volatility changes rather than volatility changes Granger cause correlation changes.

Regarding forecast performance, the implied correlation index is found to be an upward biased forecast of the realized correlation index. However, in comparison to a historical estimate of the correlation index, the implied correlation index exhibits a stronger relationship to future realized correlation index and it is orthogonal to the information set. Based on this evidence, the implied correlation index appears to be a useful proxy of future correlation that contains additional information non included in historical correlation forecasts.

5. Conclusions

The aim of this research has been threefold: first to underline the importance of correlation in finance theory and practice, second to present the application of dynamic correlation models in financial decision making and thirdly to develop an innovative methodology for forecasting future correlation. This section summarizes the main objectives and implications of the thesis.

By examining the systematic relationship between errors in estimating correlation and the resulting error in calculating VaR we find that the choice of a model that estimates correlation with the lowest possible error is important for risk managers. Moreover, we find that the sensitive of VaR mis-calculation to correlation errors also depends on the level of portfolio diversification and, in the case of option portfolios, on the moneyness level and the time-to-maturity. In particular, the correlation bias effect is more pronounced for short-maturity in-the-money options. Furthermore, the results indicate that the calculated via Monte Carlo simulation VaR is more sensitive to correlation mis-estimation.

The second part of the thesis investigates the magnitude and changing nature of the volatility spillovers from the aggregate Euro area bond market and the US bond market to twelve individual European bond markets. The econometric methodology used to model the volatility transmission mechanism allows us to investigate the price and volatility transmission mechanism as well as the time-varying correlation structure between the individual European bond markets and the aggregate Euro area bond market index. Evidence is provided for the existence of short-run dynamic relationships between the individual European bond markets and the aggregate Euro area bond market in terms of both price and volatility spillovers. The price and volatility spillover processes as well as the correlation structure have significantly changed for a number of European bond markets after the introduction of Euro. Finally, the US bond market significantly influences the individual European bond markets in terms of both price and volatility spillovers.

The third part of the thesis is concerned with the development of a general methodology for deriving implied correlation measures from option prices. An implied correlation index is constructed from DJIA option prices and its dynamics and time-series properties are examined. The empirical results of this study indicate that the correlation index constructed to reflect the future average level of correlation between the DJIA constituent stock returns is well behaved. Negative innovations in the stock index returns have a significant negative association with contemporaneous changes in the implied correlation index. Interestingly, a similar significant relationship is not found for positive stock index innovations. Furthermore, this study documents a significant positive relationship between stock return correlations and volatility changes. These results are in line with previous findings that correlations increase in bear or high volatile markets limiting the benefits of diversification when they are needed most. Finally, the evidence of this study suggests that the implied correlation index is a useful proxy for future correlation. Despite of being a biased forecast of future realized correlation, it exhibits a strong relationship with future realized correlation compared with an alternative historical measure.

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