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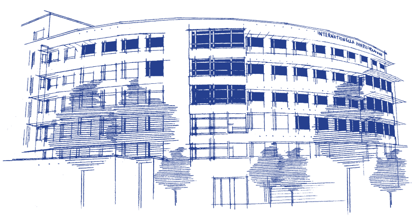
Assessing Distributional Properties of High-Dimensional Data

RASHID MANSOOR



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This doctoral thesis consists of five papers in the field of multivariate statistical analysis of high-dimensional data. Because of the wide application and methodological scope, the individual papers in the thesis necessarily target a number of different statistical issues.

In the first paper, Monte Carlo simulations are used to investigate a number of tests of multivariate non-normality with respect to their increasing dimension asymptotic (IDA) properties as the dimension p grows proportionally with the number of observations n such that $p/n \rightarrow c$ where c is a constant.

In the second paper a new test for non-normality that utilizes principal components is proposed for cases when $p/n \rightarrow c$. The power and size of the test are examined through Monte Carlo simulations where different combinations of n and p are used.

The third paper treats the problem of the relation between the second central moment of a distribution to its first raw moment. In order to make inference of the systematic relationship between mean and standard deviation, a model that captures this relationship by a slope parameter (β) is proposed and three different estimators of this parameter are developed and their consistency proven in the context where the number of variables increases proportionally to the number of observations. In the fourth paper, a Bayesian regression approach has been taken to model the relationship between the mean and standard deviation of the excess return and to test hypotheses regarding the β parameter. An empirical example involving Stockholm exchange market data is included. Then finally in the fifth paper three new methods to test for panel cointegration of high-dimensional data in the error correction framework are introduced.

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This thesis, is dedicated to the memory
of my dear father Muhammad Ismail
who passed away before this thesis
was completed.

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Jönköping October 22, 2013
Rashid Mansoor

Abstract

This doctoral thesis consists of five papers in the field of multivariate statistical analysis of high-dimensional data. Because of the wide application and methodological scope, the individual papers in the thesis necessarily target a number of different statistical issues. In the first paper, Monte Carlo simulations are used to investigate a number of tests of multivariate non-normality with respect to their increasing dimension asymptotic (IDA) properties as the dimension p grows proportionally with the number of observations n such that $p/n \to c$ where c is a constant. In the second paper a new test for non-normality that utilizes principal components is proposed for cases when $p/n \to c$. The power and size of the test are examined through Monte Carlo simulations where different combinations of n and p are used.

The third paper treats the problem of the relation between the second central moment of a distribution to its first raw moment. In order to make inference of the systematic relationship between mean and standard deviation, a model that captures this relationship by a slope parameter (β) is proposed and three different estimators of this parameter are developed and their consistency proven in the context where the number of variables increases proportionally to the number of observations. In the fourth paper, a Bayesian regression approach has been taken to model the relationship between the mean and standard deviation of the excess return and to test hypotheses regarding the β parameter. An empirical example involving Stockholm exchange market data is included. Then finally in the fifth paper three new methods to test for panel cointegration of high-dimensional data in the error correction framework are introduced.

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1 Introduction

Multivariate statistical analysis deals with the statistical analysis of data that comprise several measurements (variables) of a number of individuals or objects (observations). It is obvious that observing several variables gives us more information than observing only a single one. The multivariate approach allows us to explore the joint performance of the variables at hand and to assess the influence of each variable in the presence of others. There are many studies such as marketing research, where most business problems are multidimensional, studies on production processes, where a number of different measurements are taken on the same unit or studies on health and economy, etc. While the vast majority of the statistical research in the first half of the 1900s was set on univariate problems, the importance of developing methods for analysing multidimensional data was slowly becoming recognized. Scientists such as Pearson (1901), Hotelling (1933), and Fisher (1936) pioneered research on how to analyse multivariate data, in particular within classification problems. Other contributions include those by Wishart (1928), who derived the distribution of sample variances and covariances for multivariate normal samples, Wilks (1946), who provided procedures for additional tests of hypotheses on means, variances, and covariances, and Mahalanobis (1936) who developed distance measures with application areas such as outlier detection. From the mid-1950s and onwards, multivariate methods were recognized as a common and important part of the statistician's toolbox. Multivariate techniques were developed for applications in quality control, time series analysis, and regression analysis, which were previously restricted to univariate problems. While most of these methods are recognized as being well behaved for data of low dimensions, such as joint analysis of people's height, weight, and body mass index observed on a thousand individuals, recent attention has been devoted to cases where the numbers of variables and observations are proportional. In such cases the standard multivariate methods are usually not well behaved, which in turn produces biased estimates, and wrong conclusions are drawn about the data at hand.

Furthermore many of the statistical models depend on standard assumptions (e.g. normality, serial independence, homoscedasticity, moment restrictions, etc.) about the data; an appropriate statistical model is one whose major assumptions are suitable for the data analysed. When the distributional assumptions are violated, subsequent analyses will differ from those expected and can produce misleading inferences. However, while the problem has not suffered from lack of attention in cases where n is large relative to p, little, if any, attention has been given to cases when n is fixed and p increases or p/n increases simultaneously towards a constant c where $0 \leq c < 1$ and $c > 1$.

This thesis is concerned with the intersection of these two problems.

2. High-Dimensional Data

While it was almost impossible to analyse data of higher dimension than, say, five, before the introduction of the PC, we nowadays often face problems involving the analysis of very large datasets. Some examples include econometric panel datasets where one may have weekly observations of 50-100 companies over a 5-year period, the investigation of risk and return across a large number of heterogeneous assets in finance, or an analysis of surveys where budget constraints frequently will restrict the sample size n to be low compared to p. The traditional multivariate methods are, however, usually not well behaved in cases where p is large compared to n. A common requirement of an estimator is that of consistency, i.e. that an estimated parameter should converge to the unknown true value as the number of observations increase. But in situations where p is comparable to n the asymptotical properties are more realistically described through the mode where the ratio between p and n tends towards a constant, i.e. $p/n \to c$, $0 < c < 1$. In such cases the traditional assumptions are violated and the statistic at hand will usually not converge to its true parameter. For example, the standard estimator of the inverse covariance matrix is well known to degenerate when p grows proportionally with n (Girko, 1995; Serdobolskii, 1985). Other examples include methods for hypothesis tests of linear restrictions, which typically depend on fixed dimension asymptotics (Muirhead, 1982; Rao, 1973; Fujikoshi, 1970, 1988) and will hence not be well behaved under conditions where p increases. Hence there is a need to develop new statistical methods that remain well behaved also under more general asymptotic conditions. Although the influence of high-dimensional data has been noticed in many different directions of multivariate statistical inference, the problem has not yet been clearly cited in the literature, and the development of descriptive and inferential methods for such data is still a great challenge to research in statistics.

The development of increasing dimension analysis (IDA) was pioneered by Kolmogorov in the early 1970s to be followed by a number of important contributions, including problems of estimating the inverse covariance matrix (Girko 1975, 1990, 1995; Serdobolskii 1985, 2000, 2008), estimation of high-dimensional expected value vectors (Serdobolskii, 2008), hypothesis testing (Srivastava, 2007), discriminant analysis (Serdobolskii, 2008; Pavlenko and Von Rosen, 2001). Some other contributions include Yin et al. (1988), Jonsson (1982), and Silverstein and Bai (1995), who derived limits for eigenvalues.

A somewhat different problem arises when p is larger than the number of observations n such that $p/n \to c$ where $c > 1$. Such cases are seen in many statistical applications and are common in fields such as biological sciences and financial studies. For example, data from DNA micro arrays may involve thousands of gene expression levels measured in relatively few subjects. The methodological problem in this setting is how to extract the useful information from the data when the dimension of the data p is larger than the number of observations n. In such situations there is an option of using data reduction methods and present a system having many degrees of freedom by imposing restrictions on the covariance structures. Factor analysis, principal components analysis, and discriminant analysis are some of the techniques that can be used for dimensionality reduction.

3. Distributional Properties

Knowledge of the theoretical distribution that best approximates the underlying distribution of a random variable is crucial for deciding what statistical models are appropriate to use for those specific data. An appropriate statistical model is one whose fundamental assumptions are suitable for the data analysed. When the underlying assumptions are inappropriate, the actual distribution of the common point estimators or test statistics will differ from that expected. For example, most of the economic data consist of time series and there are very often temporal correlations in the model error terms corresponding to successive time periods. This is known as autocorrelation and the reason might be omitted variables or misspecification of the dynamic process. There is a large amount of literature on autocorrelation tests where several single-wise and system-wise autocorrelation tests have been developed. For example, tests for autocorrelated errors of univariate models were proposed by Ljung and Box (1978) and the BG test by Breusch (1978) and Godfrey (1978). Further development was made by Hosking (1980), Edgerton and Shukur (1999), and Holgersson (2004), where multivariate versions of autocorrelation tests were suggested. Similarly, another standard assumption is that of homoscedasticity. Homoscedasticity means that the disturbance variance should be constant at each observation. Violation of this assumption is called heteroscedasticity. A number of methods have been suggested for testing heteroscedasticity. For example, Doornik (1996) examined certain properties of a test for multivariate heteroscedasticity suggested by Kelejian (1982), while Holgersson and Shukur (2004) proposed a system-wise test for heteroscedasticity. Another common test was developed by White (1980). An additional way to characterize a distribution is through its third and fourth central moments, i.e. the coefficients of skewness and kurtosis. A somewhat different way to characterize the distributional properties of a multivariate dataset is through the link between different moments. In case there exists, for example, a linear relationship between the mean values and the standard deviations, then the distribution of the multivariate random variable may be characterized by a lower number of parameters than otherwise.

While significance tests for assessing distributional properties such as those discussed above are well established in cases where n is large relative to p, little attention has been given to cases when n is fixed and p increases or p/n increases simultaneously towards a constant c where $0 \le c < 1$. This thesis considers assessing distributional properties of different types in high-dimensional settings.

Multivariate Normality of High-Dimensional Data

"*It is not enough to know that a sample could have come from a normal population; we must be clear that it is at the same time improbable that it has come from a population differing so much from the normal as to invalidate the use of 'normal theory' tests in further handling of the material*." (*E. S. Pearson, 1930*)

Normality is one of the most common assumptions in the development and use of statistical methodology. The importance of normality is due to the fact that many of the statistical methods are strongly dependent on this assumption and require an effective test procedure to detect possible non-normality. The violation of the assumption of normality and its effect on standard statistical procedures date back before Bartlett's (1935) paper on the *t*-test. A number of well-known tests can be found in D'Agostino (1982) and Srivastava and Mudholkar (2003). These are usually based on (i) sample skewness and kurtosis measure, (ii) the characteristic function, or (iii) other characterizations of the normal distribution.

Also multivariate techniques frequently assume multivariate normality. Hopkins and Clay (1963), Mardia (1970), and Conover and Iman (1980) in their simulation studies highlight the importance of the multivariate normality assumptions, demonstrating that many of them lack robustness when they are applied to non-multivariate data. In recent times new approaches for testing multivariate normality have been recommended by Bowman and Foster (1993), Henze and Wagner (1997), and Romeu and Ozturk (1993), and multivariate extensions of tests by Shapiro and Wilk (1965) using order statistics was suggested by Royston (1983) and Srivastava and Hui (1987). Other authors, for example Mardia (1970), Srivastava (1984), and Lütkepohl and Theilen (1991), developed tests using multivariate skewness and kurtosis for detecting multivariate normality. These are of particular interest partly since they are simple to conduct and partly because they are commonly used and included in standard software.

The measures of multivariate skewness and kurtosis proposed by Mardia (1970) are defined as follows:

$$\beta_{1,M} = E\left[(\mathbf{X}_i - \boldsymbol{\mu})'\boldsymbol{\Sigma}^{-1}(\mathbf{X}_j - \boldsymbol{\mu})\right]^3 \text{ and } \beta_{2,M} = E\left[(\mathbf{X}_i - \boldsymbol{\mu})'\boldsymbol{\Sigma}^{-1}(\mathbf{X}_i - \boldsymbol{\mu})\right]^2, \qquad (1)$$

where $\mathbf{X}_i$ and $\mathbf{X}_j$ are identically and independently distributed. The sample analogies are given by

$$b_{1,M} = n^{-2}\sum_{i=1}^{n}\sum_{j=1}^{n} r_{ij}^3 \text{ and } b_{2,M} = n^{-1}\sum_{i=1}^{n} r_i^4 \text{, where}$$

$$r_i^2 = \left[\left(\mathbf{X}_i - \bar{\mathbf{X}}\right)' \mathbf{S}^{-1}\left(\mathbf{X}_i - \bar{\mathbf{X}}\right)\right]^2,\ r_{ij} = \left[\left(\mathbf{X}_i - \bar{\mathbf{X}}\right)' \mathbf{S}^{-1}\left(\mathbf{X}_j - \bar{\mathbf{X}}\right)\right],$$

$$\bar{\mathbf{X}} = n^{-1}\sum\nolimits_{i=1}^{n}\mathbf{X}_i \text{ and } \mathbf{S} = n^{-1}\sum\nolimits_{i=1}^{n}\left(\mathbf{X}_i - \bar{\mathbf{X}}\right)\left(\mathbf{X}_i - \bar{\mathbf{X}}\right)'.$$

Jarque and McKenzie (1995) suggested a combination of these two measures by

$$D_M = D_{1,M} + D_{2,M}^2 \text{ where } D_M \xrightarrow{L} \chi^2_{(p(p+1)(p+2)/6+1)}. \qquad (2)$$

A second class of measures of multivariate skewness and kurtosis was proposed by Lütkepohl and Theilen (1991). Let $\mathbf{L}$ denote the Cholesky decomposition of $\mathbf{S}$ such that

$\mathbf{S} = \mathbf{L}'\mathbf{L}$. Then define $b_{1,L} = (n/6)\sum_{j=1}^{p}\left(n^{-1}\sum_{i=1}^{n} z_{ij}^{3}\right)^{2}$ and $b_{2,L} = (n/24)\sum_{j=1}^{p}\left(n^{-1}\sum_{i=1}^{n} z_{ij}^{4} - 3\right)^{2}$ for $j = 1,..., p$, where $\mathbf{Z}_i = (z_{1i},...,z_{Pi})' = \mathbf{L}^{-1}\left(\mathbf{X}_i - \bar{\mathbf{X}}\right)$. Under the null hypothesis of normality the following asymptotic distribution holds:

$$D_L = b_{1,L} + b_{2,L} \xrightarrow{L} \chi^2_{2p}. \qquad (3)$$

The composite statistics D_M and D_L are frequently used in applied statistics to test for non-normality and are also included in many statistical software. The small sample properties of the tests have been investigated through simulation studies by, among others, Holgersson and Shukur (2001) and Doornik and Hansen (2008). While these investigations involved cases of fixed *p*, we here investigate the size and power properties of these tests with respect to their IDA properties, i.e. when *p* increases together with *n*, say $p/n \to c$, $0 < c < 1$. It has been exposed in this thesis that Mardia's (1970) and Srivastava's (1984) tests are inconsistent for some distributions, while Lütkepohl and Theilen (1991) in contrast are consistent for all the non-normal settings used in this thesis. One reason may be that the degrees of freedom of Mardia's (1970) tests increase quickly with the increase in dimension and tests based on a chi-square distribution with many degrees of freedom often have low power. The other reason might be that Mardia's (1970) measures of multivariate skewness and kurtosis both require the inversion of sample covariance matrices. For high-dimensional data the sample covariance matrices may be degenerate and their inversion may be unstable, which in turn may lead to biased analyses. If the dimension is larger than the number of observations, inversion of the sample covariance matrices will be impossible. Based on the above discussion, the Lütkepohl and Theilen (1991) test is used as a benchmark, and a test that utilizes principal components is proposed to test for non-normality when the number of dimensions is larger than the number of observations $(p > n)$, and also when the number of observations is larger than the dimension $(n > p)$ and p increases asymptotically along with n. This is further discussed in Paper 2.

Mean-standard Deviation Ratio of Large Data Sets

Datasets involving a large number of variables frequently involve parameter restrictions, in the sense that the distribution of the data is expressed using a parameter of lower dimension than the data. In such cases one may either use the information of possible parameter restrictions to reduce the dimension of data or to make inference on the parameter restrictions themselves. Relevant questions may involve the functional form of parameter restrictions or their numerical value. An important case involves financial economic theories in which it is stated that the higher the risk an investor is willing to take, the higher is the potential return from the investment. Hence there is an explicit relation between the expected values and standard deviations across a large number of variables. References include Osteryoung et al. (1977), Lopes et al. (1993), and Sharpe (1966), who investigated the ratio of mean value to standard deviation. In order to make inferences of the systematic relationship between mean and standard deviation values, a model that captures the relationship between standard deviations and the mean values may be applied. A link between the standard deviation and mean of a set of variables $X_1,...,X_n$ may be defined as follows:

$$\mu_i = \beta\sigma_i, \tag{4}$$

where $\mu_i = E[X_{it}]$, $\sigma_i = \sqrt{E[X_{it} - \mu_i]^2}$, $i = 1,...,n,\ t = 1,...,T$ and $-\infty < \mu_i < \infty$, $0 < \sigma_i < \infty$. Methods to consistently estimate the beta parameter in (4) are proposed in the thesis. Specifically, if $\{\bar{X}_j\}_{j=1}^n$ and $\{S_j\}_{j=1}^n$ denote the set of sample means and standard deviations, it may be shown that the following estimators are consistent:

$$\hat{\beta}_k = \frac{\sum_{i=1}^{n} w_i^k \bar{x}_i s_i}{\sum_{i=1}^{k} w_i^k \bar{x}_i s_i^2}, \quad k = 1,\ 2,\ 3.$$

Apart from consistency, there is also an issue of how to make inference on the beta parameter, e.g. to test whether or not it is equal to zero. While this is not straightforward to do in the standard frequentist way, Bayesian methods will be of great potential. Specifically, it may be shown that the joint posterior pdf β and σ_δ, which is given by

$$p(\beta, \sigma_\delta \mid \bar{X}_i, \sigma_i) \propto p(\beta, \sigma_\delta)\, p(\bar{X}_i \mid \sigma_i, \beta, \sigma_\delta), \tag{5}$$

facilitates estimation of the marginal posterior pdf of β. This is defined as follows:

$$p(\beta \mid \bar{X}_i, \sigma_i) = \int_0^\infty p(\beta, \sigma_\delta \mid \bar{X}_i, \sigma_i)\, d\sigma_\delta. \tag{6}$$

Of particular interest is to test if the β coefficients for two independent segments, or sub-samples, are equal, i.e. $H_0 : \beta_d = 0$ vs $H_1 : \beta_d \neq 0$. Details are given in Papers 3 and 4.

Cointegration of High-Dimensional Data

It was an important improvement in econometrics when it was established that if the ordinary least square (OLS) residuals from a regression between integrated variables of the same order are stationary, this may lead to superconsistent estimates of the coefficients. Granger (1981) named the concept cointegration; it was further developed by Engle and

Granger (1987). Several methods have been developed to test for cointegration. The most popular tests for cointegration are the residual-based cointegration tests by Engle and Granger (1987), Johansen (1988), and Stock and Watson (1988). All these univariate procedures lack statistical power and therefore the analysis of cointegration in the panel data setting has been a rich area of study in recent years and there has been an emergent interest in testing for panel cointegration in economic and financial variables. Panel cointegration tests are categorized into a first and a second generation of procedures, where the first generation assumes independence across the units in the panel. Along these lines, Pedroni (2004) and Kao (1999) generalized the residual-based cointegration tests by Engle and Granger (1987) and Phillips and Ouliaris (1990). Larsson et al. (2001) adapted the system approach of Johansen (1988), which in contrast to the above-mentioned residual-based testing procedure is able to detect multiple cointegration in the panel. McCoskey and Kao (1998) suggested a test for the null of panel cointegration. All these aforementioned tests do not take account of cross-sectional dependency. However the assumption of zero-independent cross-sectional dependency is in many contexts a highly restrictive one. Therefore a second generation of approaches takes account of cross-sectional dependency in the panel cointegration testing. These include, for example, the tests proposed by Bai and Kao (2006), Banerjee and Carrion-i-Silvestre (2006), Gengenbach et al. (2006), Groen and Kleibergen (2003), Nelson et al. (2005), Pedroni and Vogelsang (2005), and Westerlund (2005). However, these methods are only considered for the case when the number of cross-sectional units (N) is much smaller than the number of time period (T). Furthermore many studies fail to reject the null hypothesis of no cointegration, even in cases where the theory suggests strong cointegration. One reason for this failure may be that most residual-based cointegration tests require that the short-run adjustment process is equal to the long-run adjustment process. Banerjee et al. (1998), Kremers et al. (1992), and Mantalos and Shukur (1998) showed that its failure could cause a significant loss of power for residual-based cointegration tests.

In this thesis a different approach to test for panel cointegration in high-dimensional data is developed using the combining *p*-value approach, which was introduced to the panel unit root literature by Maddala and Wu (1999) and Choi (2001). A Fisher (1932) type of test is proposed, defined as

$$P = -2\sum_{i=1}^{N}\ln(p_i) \sim \chi^2_{(2N)}, \tag{7}$$

where p_i denotes the *p*-value of the test statistic for each cross-sectional unit *i*. Similarly Stouffer et al. (1949) proposed a test known as the inverse normal test defined as:

$$Z = \frac{1}{\sqrt{N}}\sum_{i=1}^{N}\Phi^{-1}(p_i) \overset{L}{\rightarrow} N(0,1), \tag{8}$$

where $0 \le p_i \le 1$ and $\Phi^{-1}(p_i)$ is a standard normal variable. Yet another test proposed by Choi (2001) is defined as:

$$P_m = -\frac{1}{\sqrt{N}} \sum_{i=1}^{N} \left(\ln(p_i) + 1 \right) \xrightarrow{L} N\left(0,1\right). \tag{9}$$

The key interest is to investigate the asymptotic properties of these three tests as N grows proportionally to T, i.e. we investigate the size and power properties of these tests with respect to their IDA properties. This is discussed in detail in the fifth paper.

4. Summary of the Articles

Article 1: Assessing Normality of High-Dimensional Data

In the first paper Monte Carlo simulations are used to investigate the properties of three tests of multivariate non-normality proposed by Mardia (1970), Srivastava (1984), and Lütkepohl and Theilen (1991) with respect to their increasing dimension analysis (IDA) properties. Since the effects of non-normality within normal-theory based inference of multivariate data may be serious if the dimension p of data is proportional to the sample size n, it is important that tests of the normality assumption remain well behaved in such settings. It is argued that a good test should be consistent in the sense that the likelihood to reject a false H_0 increases as the number of observations increases in all kinds of asymptotic settings including cases when (i) p is fixed and n increases, (ii) n is fixed and p increases, and (iii) n and p increase simultaneously, since all three cases concern an increasing amount of information (i.e. $np \to \infty$). The Mardia and Srivastava tests are shown to be inconsistent against some distributions whereas the test of Lütkepohl and Theilen in contrast is consistent against all non-normal distributions used in the paper. The final conclusions are that when testing for multivariate non-normality in high-dimensional data, the Lütkepohl and Theilen test with simulated critical values should be applied, while the tests by Mardia and Srivastava should be used with caution unless $n \gg p$.

Article 2: Using Principal Components to Test Normality of High-Dimensional Data

In this paper a test that utilizes principal components to test for non-normality is developed. A simulation study was conducted to investigate the size and power properties of the test in the high-dimensional setting, i.e. (i) when the number of dimension p is greater than the number of observations n and (ii) when n is greater than p and in both cases p increases asymptotically along with n. In this study principal component analysis is used to reduce the dimension of the data. The size and power of the test using Monte Carlo critical values and chi-square critical values are investigated. Based on the result of a simulation study, the test is seen to have good overall size and power properties and detects non-normality in all the cases, i.e. when p is fix and n increases and when p and n increase simultaneously. Hence the proposed D_L^* test is recommended to be used for non-normality in high-dimensional settings.

Article 3: Estimating Mean-Standard Deviation Ratios of Financial Data

This paper treats the problem of the relation between the second central moment of a distribution to its first raw moment. The key interest is the reciprocal of the coefficient of variation, where, according to the theory of finance, an investor is compensated by increased expected returns for taking higher risks (i.e. variance of the investments returns), which is represented by the ratio of the mean value to the standard deviation. In most cases these applications have involved the problem of making inference of the relation between the mean and the standard deviation of a single variable. In this context, however, there is a systematic relation between the standard deviations and mean values of a large number of heterogeneous variables. In order to make inference of the systematic relationship between the mean values and standard deviations, a model that captures this relationship by a slope parameter (β) is proposed and three different estimators of this parameter developed. Their consistencies are proven in the context where the number of variables is proportional to the number of observations. An empirical study is conducted on the stocks of Stockholm Stock Exchange between June 1995 and June 2010 and the population divided into three segments depending on the market capitalization value. It is seen that the beta parameter is heterogeneous across the three segments.

Article 4: A Bayesian Approach for Estimating Mean-Standard Deviation Ratios of Financial Data

In this paper a Bayesian regression approach has been taken to model the relationship between the mean and the standard deviation of the excess return. This paper derives procedures for statistical inference, in particular interval estimation and hence hypothesis testing, for assessing whether two population segments, e.g. Large Cap and Small Cap stocks, have equal risk/return ratios. It is shown that hypothesis testing of the possible difference between return-to-risk ratios of two market segments can easily be conducted by Bayesian credible intervals. Specifically, a vague prior is used, which facilitates the use of previously proposed frequentist results with the important enhancement of inference methods. Hence a simple but yet comprehensive tool is available for investors to quantify and compare risk rewards of different markets. The use of the method is demonstrated through an empirical investigation of the Small Cap and Large Cap segments of the Stockholm Stock Exchange.

Article 5: Testing for Panel Cointegration in High-Dimensional Data in the Presence of Cross-Sectional Dependency

This paper proposes some new methods to test for panel cointegration in the error correction framework in high-dimensional data. These new panel tests are based on different *p*-value combinations (used in, for example, panel unit root testing in Choi, 2001) of the single equation cointegration test in the error-correction framework suggested by Kanioura and Turner (2005). The paper uses a Wald statistic that is defined through the combination of individual *p*-values, and by means of Monte Carlo simulations the size and power properties of the tests are investigated when the number of cross-sectional units

(N) and the number of time periods (T) increase simultaneously, i.e. $N/T \to c$, where c is a constant. Moreover, the effect of cross-sectional dependency caused by a single common factor is investigated and it is shown that by applying a simple demeaning procedure any common factor over the cross- sectional dimension will be removed through mathematical cancellation. Based on the simulated results the Z-test first proposed by Stouffer et al. (1949) is the one recommended to be used in real applications. The demeaned version of this test is robust to cross-sectional dependency caused by a common factor. Furthermore it has the best power properties among the suggested *p*-value combinations and we recommend this test to be used in the high- dimensional setting.

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