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THE EVOLUTION OF STOCK MARKET EFFICIENCY OVER TIME: A SURVEY OF THE EMPIRICAL LITERATURE

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Abstract. This paper provides a systematic review of the weak-form market efficiency literature that examines return predictability from past price changes, with an exclusive focus on the stock markets. Our survey shows that the bulk of the empirical studies examine whether the stock market under study is or is not weak-form efficient in the absolute sense, assuming that the level of market efficiency remains unchanged throughout the estimation period. However, the possibility of time-varying weak-form market efficiency has received increasing attention in recent years. We categorize these emerging studies based on the research framework adopted, namely non-overlapping sub-period analysis, time-varying parameter model and rolling estimation window. An encouraging development is that the documented empirical evidence of evolving stock return predictability can be rationalized within the framework of the adaptive markets hypothesis.

Keywords. Adaptive markets hypothesis (AMH); Efficient markets hypothesis (EMH); Evolving return predictability; Stock markets; Weak-form EMH

1. Introduction

The term 'market efficiency', formalized in the seminal review of Fama (1970), is generally referred to as the informational efficiency of financial markets which emphasizes the role of information in setting prices.[1] More specifically, the efficient markets hypothesis (EMH) defines an efficient market as one in which new information is quickly and correctly reflected in its current security price.[2] In his first review paper, Fama (1970) outlines the classic taxonomy of information sets available to market participants and further classifies the EMH into the weak-form, semi-strong-form and strong-form. The present paper focuses on the weak-form version, which asserts that security prices fully reflect all information contained in the past price history of the market.[3] Even in this weak-form category, the huge body of literature can be further subdivided into at least two major groups.[4] The first strand of studies, which is the focus of our survey, tests the predictability of security returns on the basis of past price changes. More specifically, previous studies in this sub-category employ a wide array of statistical tests to detect different types of deviations from a random walk in financial time series, such as linear serial correlations, unit root, low-dimensional chaos, nonlinear serial dependence and long memory. The second group of studies examines the profitability of trading strategies based on past returns, such as technical trading rules (see the survey paper by Park and Irwin, 2007), momentum and contrarian strategies (see references cited in Chou *et al*., 2007).

In his seminal review, Fama (1970) surveys the empirical evidence for the weak-form, semi-strong-form and strong-form EMH. He gives relatively wider coverage to the first category. Empirical studies prior to 1970 generally employ serial correlation tests and technical trading rules, and their findings strongly suggest that stock markets are weak-form efficient. Two decades later, Fama (1991) conducts a second review of the market efficiency literature. Instead of focusing on past returns, he expands the coverage of weak-form EMH to tests of return predictability using other variables such as the dividend–price ratio, earnings–price ratio, book-to-market ratio and various measures of the interest rates. The tests for the semi-strong-form and strong-form EMH are renamed as event studies and tests for private information, respectively. His review shows mounting evidence of return predictability from past returns, dividend yields and a number of term-structure variables, but he argues that these findings might be spurious and should be met with scepticism.

More recently, Yen and Lee (2008) provide a chronological review of empirical evidence on the EMH over the last five decades. Their survey clearly demonstrates that the EMH no longer enjoys the level of strong support it received during the golden era of the 1960s, but instead has come under relentless attack from the school of behavioural finance in the 1990s. Besides the above broad review, there are other survey papers with a specific theme, for instance, (1) Fama (1998) surveys the empirical work on event studies, with a focus on those papers reporting long-term return anomalies of under- and over-reactions to information; (2) Malkiel (2003) and Schwert (2003) scrutinize those studies reporting evidence of statistically significant predictable patterns in stock returns; (3) Park and Irwin (2007) review the evidence on the profitability of technical trading rules in a variety of speculative markets, including 66 stock market papers published over the period from 1960 to 2004.

The recent discussion published in Malkiel *et al*. (2005) clearly indicates that there is no sign of compromise between proponents of the EMH and advocates of behavioural finance. In an attempt to offer reconciliation to the opposing camps, Lo (2004) notes that useful insights can be gained from the biological perspective and calls for an evolutionary alternative to market efficiency. In particular, he proposes the new paradigm of adaptive markets hypothesis (AMH) in which the EMH can co-exist alongside behavioural finance in an intellectually consistent manner. In this new hypothesis, market efficiency is not an all-or-none condition but is a characteristic that varies continuously over time and across markets. The main contribution of this paper is to provide a systematic review on the empirical literature of evolving weak-form stock market efficiency, which is consistent with the prediction of AMH.

Two recent papers further justify the need for our review. First, Ito and Sugiyama (2009) estimate the time-varying autoregressive coefficients by using a state space model and report that the developed US stock market exhibits varying degrees of efficiency over the sample period from 1955 to 2006. These authors claim that there is little literature that examines the degree of time-varying market inefficiency except Lo (2004). Section 5 shows that the use of a time-varying autoregressive model as a test of evolving efficiency was formalized by Zalewska-Mitura and Hall (1999) a decade ago, and this framework is widely adopted to examine the changing degree of informational efficiency in emerging stock markets. Second, Charles and Darné (2009b) provide an exclusive and extensive survey on the recent developments of the variance ratio (VR) tests. In their concluding remarks, these authors highlight the possible effect of structural changes on the VR tests, which they further note can be addressed using rolling sub-samples. Our survey in Section 6 complements their methodological review by highlighting empirical studies using rolling estimation windows to address the stability of return predictability over time.

The remainder of this paper is structured as follows. Section 2 discusses the AMH proposed by Lo (2004). The next four sections then survey the weak-form EMH literature that examines return predictability from past price changes, with an exclusive focus on the stock markets. It is worth noting that the number of empirical studies has grown tremendously, but survey papers after Fama (1970) have largely neglected this strand of literature. We classify the weak-form EMH literature based on the research framework adopted, namely (1) full sample (fixed parameter); (2) sub-samples (non-overlapping, fixed parameter); (3) full sample (time-varying parameter) and (4) rolling estimation windows (overlapping but fixed parameter in each window). Concluding remarks are given at the end of the paper.

2. The Adaptive Markets Hypothesis

The possibility that market efficiency does evolve over time is best described by Self and Mathur (2006, p. 3154), who write: ‘The true underlying market structure of asset prices is still unknown. However, we do know that, for a period of time, it behaves according to the classical definition of an efficient market; then, for a period, it behaves in such a way that researchers are able to systematically find anomalies to the behaviour expected of an efficient market.’ In this regard, the characteristics of the market microstructure, limits to arbitrage, psychological biases, noise trading and the existence of market imperfections are those potential factors that can give rise to periods of departure from market efficiency. At the macro level, it is not unreasonable to expect market efficiency to evolve over time due to changes in macro institutions, market regulations and information technologies. To accommodate the changing degree of market efficiency over time, Lo (2004) proposes a new version of the EMH derived from evolutionary principles. Our discussion on the AMH borrows heavily from Lo (2004, 2005).

With the issue of rationality in human behaviour at the heart of the controversy between the opposing camps of EMH and behavioural finance, Lo (2004) argues that valuable insights can be derived from the biological perspective and calls for an evolutionary alternative to market efficiency. More specifically, Lo (2004) proposes the new paradigm of AMH in which the EMH can co-exist alongside behavioural finance in an intellectually consistent manner. The AMH has taken years to formulate since the idea of viewing financial markets from a biological perspective is singled out by Farmer and Lo (1999) as one of the frontiers of research in finance. This evolutionary idea has been followed up by Lo (1999, 2002) and Farmer (2002), before it is formalized in Lo (2004) as the AMH and further elaborated in Lo (2005). It is interesting to note that the ideas underlying the AMH have been inspired by several bodies of literature: bounded rationality in economics, complex systems, evolutionary biology, evolutionary psychology and behavioural ecology. Though evolutionary economics is now an established branch in economics after the seminal work of Nelson and Winter (1982), the applications of evolutionary concepts in the financial contexts are limited. The AMH is a major breakthrough that offers not only reconciliation to the current controversy in finance, but also concrete implications to the practice of investment management.

By coupling Simon's (1955) notion of bounded rationality and 'satisficing' with evolutionary dynamics, Lo (2004) argues that many behavioural biases are in fact consistent with an evolutionary model of individuals learning and adapting to a changing environment via 'satisficing' heuristics. On the other hand, it is the impact of evolutionary forces on financial institutions and market participants that determines the efficiency of markets, and the performance of investment products, businesses and industries. Briefly, the precepts that guide the AMH as outlined in Lo (2005) are (1) individuals act in their own self-interest; (2) individuals make mistakes; (3) individuals learn and adapt; (4) competition drives adaptation and innovation; (5) natural selection shapes market ecology; and (6) evolution determines market dynamics. Despite its rather abstract and qualitative nature, the AMH offers a number of practical implications for portfolio management. First, the equity risk premium varies over time according to the recent stock market environment and the demographics of investors in that environment. Second, arbitrage opportunities do arise in the financial markets from time to time. Third, investment products undergo cycles of superior and inferior performance in response to changing business conditions, the adaptability of investors, the number of competitors in the industry and the magnitude of profit opportunities available. Finally, survival is ultimately the only objective that matters for the evolution of markets and financial technologies.

With regard to the present context of evolving market efficiency, the second implication deserves further elaboration. Based on the evolutionary perspective, profit opportunities do exist from time to time. Though they disappear after being exploited by investors, new opportunities are continually being created as groups of market participants, institutions and business conditions change. This is consistent with the conjecture of Grossman and Stiglitz (1980) that sufficient profit opportunities must exist to compensate investors for the cost of trading and information gathering. In fact, Daniel and Titman (1999) have earlier highlighted the possible co-existence of EMH and behavioural finance by introducing the term 'adaptive efficiency'. These authors recognize the behavioural biases of most market participants but at the same time assume that other investors exist who can detect and profit from these biases by examining past price trends. More specifically, in a market that is adaptively efficient, profit opportunities do arise in historical data, but if investors learn from the past price history, these profit opportunities will gradually erode through time.[5]

A corollary of this implication is that market efficiency is not an all-or-none condition but is a characteristic that varies continuously over time and across markets. Lo (2005) argues that convergence to equilibrium, which is central to the EMH, is neither guaranteed nor likely to occur at any point in time. As such, it is incorrect to assume that the market must march inexorably toward some ideal equilibrium state or perfect efficiency. Instead, the AMH implies more complex market dynamics, such as cycles, trends, bubbles, crashes, manias and other phenomena that occur in the financial markets. Lo (2004, 2005) offers a concrete example by computing the rolling first-order autocorrelation for monthly returns of the Standard & Poor's (S&P) Composite Index from January 1871 to April 2003. His graphical plot reveals that the degree of efficiency, measured by the first-order autocorrelation coefficient, varies through time in a cyclical fashion with the surprising result that the US market is more efficient in the 1950s than in the early 1990s. The author claims that this finding is due to institutional changes in the stock market as well as the entry and exit of various market participants. Both studies do acknowledge that such cycles are not ruled out by the EMH in theory, but existing empirical implementation assumes markets are perpetually in equilibrium.

3. Full Sample Analysis with Fixed Parameter: Examining the Absolute Weak-form Stock Market Efficiency

The bulk of the weak-form EMH literature generally applies different types of past return-based predictability tests on the full sample period, as if market efficiency is a static characteristic that remains unchanged over different stages of market development. In their framework, the research question addressed is whether the stock market under study is or is not weak-form efficient in the absolute sense. We organize the existing empirical studies based on the nature of the temporal dependence their statistical tests are designed to detect. It is worth mentioning that in an earlier review paper Andreou *et al*. (2001) trace the development of various statistical models for speculative price data since the early 20th century, and these authors also cover the temporal dependence discussed here. As a whole, our survey reveals overwhelming evidence of predictable patterns from past returns, especially for emerging stock markets.

3.1 *Linear Serial Correlations*

Serial correlation tests and spectral analysis are the earlier tools employed in the weak-form EMH literature, pioneered by Fama (1965) and Granger and Morgenstern (1963), respectively. These statistical procedures are testing the least restrictive version of the random walk hypothesis, which is the Random Walk 3 model of Campbell *et al*. (1997) that only requires uncorrelatedness of price changes. Since the seminal work of Lo and MacKinlay (1988), the VR test has emerged as the primary tool for testing whether stock return series are serially uncorrelated. Charles and Darné (2009b) provide an exclusive and extensive survey on its recent developments. The VR test is based on the statistical property that if the stock price follows a random walk, then the variance of the k-period return is equal to k times the variance of the one-period return. Hence, the VR, defined as the ratio of the variance of the k-period return to k times the variance of the one-period return, should be equal to one for any holding period k, under the null hypothesis of serially uncorrelated stock returns. A notable recent innovation of the VR test includes non-parametric tests proposed by Wright (2000) based on signs and ranks of returns that follow exact distributions.

In empirical applications, it is customary to examine the VRs for several holding periods, and the verdict of non-random walk is proclaimed when one of the estimated VR statistics is significantly different from unity. However, this multiple comparison across all pre-selected holding periods can lead to over-rejection of the null hypothesis. To control for the overall test size, joint testing procedures have been proposed in the literature, among others by Richardson and Smith (1991), Chow and Denning (1993), Whang and Kim (2003), Chen and Deo (2006), Kim (2006) and Kim and Shamsuddin (2008). These multiple VR tests remain the firm favourites in the extant weak-form EMH literature. In contrast, despite numerous methodological refinements to existing serial correlation tests (see, for example, Lobato *et al*., 2002; Horowitz *et al*., 2006) and spectral-based tests (see, for example, Durlauf, 1991; Deo, 2000), we do not find any applications of these improved statistical tools on stock market data, with McPherson *et al*. (2005) and McPherson and Palardy (2007) being the only two studies identified.

The empirical studies in this group experience a phenomenal growth over the past five decades and it is impossible to give a full review here. Since Lim and Brooks (2006) provide a list of those papers published over the 1965–2005 period, our survey hence focuses on recent stock market efficiency studies that examine the uncorrelatedness of stock return series. Based on the non-exhaustive list in Lim and Brooks (2006), 57 of the total 92 papers conduct their efficiency tests on one single country, covering the stock markets of 25 countries. The remaining 35 papers perform comparative analysis, either on a regional basis or based on the classification of market status. In terms of empirical evidence, the findings are contradictory even for the same stock market under study, due to differences in methodologies employed or sample periods selected.

To provide a glimpse of this controversy, we use China as a case study, since the weak-form efficiency of its two stock exchanges in Shanghai and Shenzhen has been subjected to strict scrutiny, including the books by Groenewold *et al*. (2004) and Ma (2004). On one hand, Laurence *et al*. (1997), Liu *et al*. (1997), Long *et al*. (1999) and Lima and Tabak (2004) conclude that the Chinese stock markets are weak-form efficient as their stock returns do not exhibit linear serial correlations. These efficiency findings are quite surprising given the widely shared perception that the Chinese stock markets are highly speculative, driven mainly by market rumours and individual investor sentiments. At the other end of the spectrum, Mookerjee and Yu (1999) and Ma (2004) arrive at the conclusion that the same market is inefficient since their autocorrelation-based tests reject the random walk hypothesis. Though Groenewold *et al*. (2004) find evidence of significant linear serial correlations, they caution that their detected predictability could be spurious return autocorrelations induced by thin trading. Zhang and Li (2008) and Charles and Darné (2009a) add to this growing list of Chinese efficiency papers, but their applications of a battery of VR tests yield mixed findings.

The literature has continued to grow in the past three years albeit at a slower pace, with greater emphasis on emerging stock markets. Squalli (2006) examines the weak-form efficiency of two exchanges in the United Arab Emirates, the Dubai Financial Market (DFM) and the Abu Dhabi Securities Market (ADSM). Both exchanges are relatively young in age with their inauguration in year 2000. The results from VR tests consistently show that most of the economic sectors in DFM and ADSM are inefficient. Similar findings of serially correlated stock returns are also reported by Chakraborty (2006) and Hassan and Chowdhury (2008) for stock markets in Bangladesh and Pakistan. The recent methodological refinements to VR tests have prompted a number of studies to conduct a re-examination of the stock market data in Asia (Hoque *et al*., 2007; Kim and Shamsuddin, 2008), Europe (Smith, 2009), Middle East and Africa (Al-Khazali *et al*., 2007; Ntim *et al*., 2007; Smith, 2007, 2008; Lagoarde-Segot and Lucey, 2008). These recent studies do report evidence of weak-form efficiency for emerging stock markets, for instance Al-Khazali *et al*. (2007) for Bahrain, Egypt, Jordan, Kuwait, Morocco, Oman, Saudi Arabia and Tunisia; Smith (2007) for Israel, Jordan and Lebanon; Kim and Shamsuddin (2008) for South Korea, Taiwan and Thailand; Smith (2008) for Egypt, Nigeria, South Africa and Tunisia; Smith (2009) for Poland and Turkey. To conclude our survey, two observations are worth mentioning here: (1) though the VR tests have been widely accepted as the standard tool, there are still some recent papers which rely solely on the conventional autocorrelation tests (see Mollah, 2007; Mobarek *et al*., 2008); (2) the efficiency of developed markets receives relatively less attention, with Lovatt *et al*. (2007), Jirasakuldech *et al*. (2008) and Hung *et al*. (2009) among the few recent additions to the literature.

3.2 *Unit Root*

The unit root test is another type of statistical test favoured by researchers in the weak-form EMH literature. Earlier studies generally employ conventional unit root tests, in particular the popular augmented Dickey–Fuller (ADF) test, and find that the log-levels of stock prices are non-stationary. They then conclude the markets under study are weak-form efficient. Since a review of previous findings has been provided by Lean and Smyth (2007), we limit our survey to recent empirical papers that adopt structural-break or panel unit root tests. The argument given in favour of the former is that if a structural break is present in the data, there is a possibility the break is interpreted as the existence of a unit root and hence will lead to under-rejection of the null hypothesis. The methodology has been further refined to allow for multiple structural breaks. On the other hand, panel unit root tests are justified on the grounds that univariate unit root tests have low power when the sample size is small, measured in terms of time span of the data rather than the frequency of observations.

Narayan and Smyth (2007) find that the price indices for stock markets in G7 countries contain a unit root, even after taking into account the presence of structural breaks in the trend. These G7 stock price indices only attain stationarity when Narayan (2008) employs the panel Lagrange multiplier (LM) unit root test with two structural breaks. Using univariate LM unit root tests with both one and two structural breaks, Lean and Smyth (2007) find that stock price indices in eight Asian countries follow a random walk process. This verdict is further supported by the panel LM unit root test with one break. However, when allowing for two structural breaks, the panel result instead suggests stock prices are mean reverting. Even the emerging Istanbul Stock Exchange is proclaimed as weak-form efficient by Ozdemir (2008) because its major price index is characterized by a unit root with two structural breaks. Narayan and Prasad (2007) apply three different panel unit root testing approaches on 17 European countries' stock price indices, and the null hypothesis of a unit root cannot be rejected in all cases. Using similar methodologies but with two more panel unit root tests, Narayan and Narayan (2007) also cannot reject the null of unit root in their sampled countries. To sum up, the consensus from the aforementioned studies is that there is a unit root in the logarithmic price level. This is not surprising as Campbell *et al.* (1997) note that stock returns have more attractive statistical properties than prices such as stationarity and ergodicity. Evidence of stationarity in stock prices only emerges when a panel LM unit root test with two structural breaks is employed (Lean and Smyth, 2007; Narayan, 2008).

Due to the lower power of the ADF unit root test in identifying stationarity when the underlying data generating process is characterized by a nonlinear process, Caner and Hansen (2001) propose a unit root test built on an unrestricted two-regime threshold autoregressive model. This newly developed threshold unit root test has been adopted by Narayan (2005, 2006) and Qian *et al.* (2008). The consensus from the above three studies is that the stock price indices under study exhibit threshold nonlinearity, with Narayan (2005) and Qian *et al.* (2008) reporting unit roots in both regimes, while Narayan (2006) documents a partial unit root regime in the US stock price index. Koustas *et al.* (2008) re-examine the US stock market data using a statistical framework in which the null hypothesis of a unit root is tested against the alternative of a globally stationary three-regime self-exciting threshold autoregressive (SETAR) process. Their results show the inner regime is characterized by a unit root while the two outer regimes are well captured by a stationary autoregressive process. This body of literature also employs unit root tests that allow the alternative hypothesis to incorporate nonlinear dynamics in the form of an exponential smooth transition autoregressive process (Hasanov, 2009a, b) and a transitional autoregressive process (Kim *et al.*, 2009). The applications of these nonlinear unit root tests consistently show strong evidence of mean reversion in stock prices. Despite all the methodological advances, Rahman and Saadi (2008) highlight that a unit root is a necessary pre-requisite for the random walk hypothesis but not a sufficient condition. More specifically, the presence of a unit root *per se* is not sufficient to imply a random walk since the return series must also be serially uncorrelated or serially independent.

3.3 *Nonlinear Serial Dependence*

Given that the assumption of normality is rather restrictive for financial time series, several authors criticize the use of autocorrelation-based procedures in testing the weak-form EMH. This is because all pure white noise series (i.e. a random walk with independent and identically distributed (i.i.d.) increments) are white noise (i.e. serially uncorrelated), but the converse is not true unless the series is normally distributed. Hinich and Patterson (1985) blame Jenkins and Watts (1968) and Box and Jenkins (1970) for blurring the definitions of whiteness and independence. According to Hinich and Patterson (1985), many early investigators implicitly assume the observed time series is generated from a Gaussian process and test for white noise using the correlation structure, hence ignoring possible nonlinear relationships between consecutive price changes. From a statistical perspective, the distinction between white noise and pure white noise is nontrivial when nonlinear dependence is present. It was pointed out three decades ago by Granger and Andersen (1978) that autocorrelation-based tests have no power against nonlinear processes with zero autocorrelation, such as the bilinear autoregressive, nonlinear moving average and threshold autoregressive processes. A misleading conclusion in favour of market efficiency could be delivered when the VR test statistics are insignificant. Motivated by this concern, the literature during the 1980s witnesses the development of new statistical tools capable of uncovering hidden nonlinear structures in previously observed serially uncorrelated stock market data (for early empirical evidence, see Hinich and Patterson, 1985; Brockett *et al.*, 1988; De Gooijer, 1989; Scheinkman and LeBaron, 1989).

It is worth mentioning that our literature survey reveals it is in fact the chaos theory, originated from the physical sciences, that caught the fancy of economists in the early 1980s. The issue of whether chaos exists in stock markets has generated much excitement because its presence suggests the potential of short-term return predictability and hence contradicts the weak-form EMH (for details, see the survey papers by LeBaron, 1994; Barnett and Serletis, 2000). On the other hand, Brock and Hommes (1998) show that chaos in stock prices can arise if heterogeneous expectations among traders are introduced into a standard asset pricing equilibrium model (for subsequent modifications and extensions to this type of heterogeneous beliefs model, consult the survey paper by Hommes and Wagener, 2009). Most of the early empirical papers employ the correlation dimension estimate proposed by Grassberger and Procaccia (1983) to detect low-dimensional chaotic dynamics in stock returns (see Scheinkman and LeBaron, 1989; Kohers *et al.*, 1997; Barkoulas and Travlos, 1998; Harrison *et al.*, 1999; Yadav *et al.*, 1999; Chappell and Panagiotidis, 2005).[6] Other complementary approaches adopted in the empirical literature are the dominant Lyapunov exponent (Yadav *et al.*, 1999) and the close returns test (Gilmore, 1993, 1996; McKenzie, 2001).

The consensus that emerges from the aforementioned studies, with the exception of Harrison *et al*. (1999), is the absence of low-dimensional chaos in stock return series. Instead, their further analysis on the same dataset reveals the existence of nonlinear serial dependence. This negative evidence on chaos still holds even when a larger sample size is used or a more advanced chaos test is employed. For instance, Abhyankar *et al*. (1995, 1997) utilize high-frequency intraday data as a means to increase the number of observations, but still their Lyapunov exponent point estimates indicate no conclusive evidence of chaos. On the other hand, significant methodological advancements have been made by Whang and Linton (1999) and Shintani and Linton (2004), who construct the standard error for the neural network Lyapunov exponent estimator, and hence provide a formal statistical test for chaos. Empirical studies applying the above refined framework to daily stock returns also reject the null hypothesis of chaos (see Serletis and Shintani, 2003; Shintani and Linton, 2004).

Given that the search for chaotic dynamics in stock market data remains an elusive goal, the initial enthusiasm among researchers has faded and their attention has since turned to nonlinear stochastic dependence. This has contributed to an explosive growth of nonlinearity tests to the extent that a full review is impossible (for a limited survey, see Granger and Teräsvirta, 1993; Patterson and Ashley, 2000; Tsay, 2005). Generally, the existing tests can be divided into two broad categories. The first group contains all the tests derived without a specific nonlinear alternative. Those widely adopted in extant stock market studies are the bispectrum test (Hinich, 1982), McLeod and Li's (1983) test, Tsay's (1986) test, the third-order moment test (Hsieh, 1989), the neural network test (Lee *et al.*, 1993), the Brock–Dechert–Scheinkman (BDS) test (Brock *et al.*, 1996) and the bicorrelation test (Hinich, 1996).[7] Despite their usefulness as general tests for nonlinearity, a rejection of the null hypothesis gives little clue on the actual type of nonlinear dynamics. The usual method for assessing their power properties is by means of Monte Carlo simulations (see, for example, Ashley *et al.*, 1986; Brock *et al.*, 1991, 1996; Hsieh, 1991; Lee *et al.*, 1993; Barnett *et al.*, 1997; Patterson and Ashley, 2000). The second category involves testing linearity against a well-specified nonlinear model, employing the LM, likelihood ratio or Wald test. The popular nonlinear alternatives considered in the literature are the SETAR-type nonlinearity (Petruccelli and Davies, 1986; Tsay, 1989; Chan and Tong, 1990; Hansen, 1999; Petruccelli *et al.*, 2009), smooth transition autoregressive type nonlinearity (Luukkonen *et al.*, 1988; van Dijk *et al.*, 1999; González and Teräsvirta, 2006) and the autoregressive conditional heteroscedasticity (ARCH) process (Engle, 1982; Lumsdaine and Ng, 1999; Blake and Kapetanios, 2007).

The rich and expanding theoretical literature continues to supply empiricists with advanced nonlinear statistical tools for testing the random walk hypothesis. A list of those empirical studies published over the 1985–2005 period is provided by Lim *et al*. (2006). All their listed 42 papers report overwhelming evidence of nonlinear serial dependence across international stock markets with different market structure mechanisms, indicating that the observed feature is a stylized fact of stock data. More recently, Patterson and Ashley (2000) introduce a 'nonlinearity toolkit' that provides convenient access to a selection of the best tools available for statistically detecting nonlinearity in the generating mechanism of a given time series.[8] The battery of nonlinearity tests included in the toolkit are the Engle LM test (Engle, 1982), Hinich bispectrum test (Hinich, 1982), McLeod and Li's (1983) test, Tsay's (1986) test, Hinich bicorrelation test (Hinich, 1996) and the BDS test (Brock *et al.*, 1996). Due to its convenience, this 'nonlinearity toolkit' has been adopted by recent studies to re-examine the weak-form efficiency of stock markets. For instance, Panagiotidis (2005, 2009) finds strong evidence of nonlinear dependence in the returns of major stock indices traded in the Athens Stock Exchange. Subsequent applications in other stock markets by Lim *et al.* (2008b), Alagidede and Panagiotidis (2009b) and Lim and Brooks (2009a) consistently show that nonlinearity is a stylized fact of stock return series.

3.4 *Long Memory*

Long memory is characterized by an autocorrelation function that decays at a hyperbolic rate or, equivalently, an infinite spectrum at zero frequency. Mandelbrot (1971) argues that the presence of long memory implies less than perfect arbitraging and the resulting prices do not follow a random walk process. Empirically, Greene and Fielitz (1977) are perhaps the first to investigate whether stock returns exhibit such persistent statistical dependence. Using the classical rescaled range (R/S) analysis proposed by Hurst (1951), these authors find strong evidence of long memory in the daily returns of their sampled 200 US common stocks. Though subsequent studies using the same methodology lend further support to the findings of Greene and Fielitz (1977), Lo (1991) argues that the distribution of the classical R/S statistic is not well defined and is sensitive to higher frequency serial correlation. With these shortcomings in mind, Lo (1991) constructs a new test called the modified R/S test that accounts for the presence of short-term dependence, and re-examines the earlier claim of widespread evidence of long memory. In contrast with prior findings, none of the modified R/S statistics in his study are statistically significant at the 5% level in any sample period or sub-period for daily and monthly US stock index return series. In recent years, the rescaled variance (V/S) statistic developed by Giraitis *et al.* (2003) has emerged as a competing statistical test for detecting long memory (for applications, see Cajueiro and Tabak, 2005b; Assaf, 2006, 2008).

An alternative approach to detect long memory in the financial economics literature is the direct estimation of an autoregressive fractionally integrated moving average model, denoted as ARFIMA(p, d, q), where d is the fractional differencing parameter (for details on fractionally integrated processes, consult the survey paper by Baillie, 1996). Under this approach, a process exhibits long memory when $d \neq 0$, and the sign of d will determine the nature of the process. More specifically, for $d \in (0, 0.5)$, the sum of the autocorrelations diverges to infinity and the ARFIMA process is said to exhibit persistent behaviour. On the other hand, the sum of the autocorrelations converges to zero for $d \in (-0.5, 0)$ and the long memory is called anti-persistent. Various procedures have been proposed to estimate this fractional differencing parameter, but the semi-parametric GPH test (Geweke and Porter-Hudak, 1983) and the local Whittle estimator developed by Robinson (1995) remain popular in empirical applications.

In another development, the now rapidly expanding interdisciplinary field of *econophysics* has witnessed a resurgence of interest in long memory, but its focus is on the Hurst exponent (H), which is related to the fractional differencing parameter by the equality $d = H - 0.5$.[9] Our review of recent stock market studies shows that various methods have been used to extract the Hurst exponent, such as the R/S analysis (Cajueiro and Tabak, 2005c; Batten *et al.*, 2008), V/S analysis (Cajueiro and Tabak, 2005b), detrended fluctuation analysis (Oh *et al.*, 2008; Serletis *et al.*, 2008), detrending moving average (Serletis and Rosenberg, 2009), wavelet analysis (Kyaw *et al.*, 2006; Brooks *et al.*, 2008) and the generalized Hurst exponent approach (Di Matteo *et al.*, 2005). In a recent paper, Rea *et al.* (2008) conduct a simulation study into the properties of 12 different estimators of the Hurst exponent and fractional differencing parameter in long memory time series (see also references cited therein). These authors show that not all estimators of long memory are created equal, and their simulation results provide useful guides to researchers on the appropriate choice of estimators.

Unlike the overwhelming support for nonlinear serial dependence, the evidence of significant long memory in stock return series is far from pervasive. Cheung and Lai (1995) and Hiemstra and Jones (1997) extend the analysis of Lo (1991) to 1952 US common stocks and 18 major stock market indices, respectively. In most cases, however, the modified rescaled range statistic cannot reject the null hypothesis of no long memory at the conventional significance level. Their conclusion is further reinforced by the GPH spectral regression. Other studies with negative evidence include Barkoulas and Baum (1996), Jacobsen (1996), Kilic (2004), Ma *et al.* (2006), Elder and Serletis (2007), Batten *et al.* (2008), Granero *et al.* (2008), Oh *et al.* (2008) and Serletis *et al.* (2008). Using a battery of four different statistical tests, Sadique and Silvapulle (2001) find evidence of long memory in the weekly stock returns for four of their seven sampled markets. Such mixed findings are also reported for stock markets in the Middle East and North Africa region (Assaf, 2006; Maghyereh, 2007), Central Europe (Kasman *et al.*, 2008) and major developed countries (Gil-Alana, 2006; Assaf, 2008). Nevertheless, this voluminous literature does contain papers with significant evidence of long memory (see Barkoulas *et al.*, 2000; Limam, 2003; Cajueiro and Tabak, 2005b; Christodoulou-Volos and Siokis, 2006; Kyaw *et al.*, 2006; Serletis and Rosenberg, 2009).

3.5 *Other Statistical Contributions*

The development of new statistical tests in the econometrics literature has been advancing rapidly, along with their empirical applications. We highlight in this section two groups of time series analytic tools yet to be adopted in the extant stock market studies, except by the developers of the tests themselves. First, several test statistics have been proposed for testing whether stock returns are martingale difference sequence, or equivalently, whether stock prices follow a martingale process (see Hinich and Patterson, 1992; Domínguez and Lobato, 2003; Kuan and Lee, 2004; Hong and Lee, 2005; Escanciano and Velasco, 2006a, b). Statistical tests of martingale difference sequence are designed to capture linear and nonlinear serial dependence in mean, but they do not impose any restrictions on the dynamics in conditional variance and other higher-order conditional moments.[10,11] Second, given that an i.i.d. process is time reversible, testing for time reversibility (TR) provides an alternative means to examine the random walk behaviour of stock prices.[12] Though suggestion on how to test for TR was alluded to as early as Brillinger and Rosenblatt (1967), a formal statistical test was developed only three decades later by Ramsey and Rothman (1996). Motivated by this time-domain TR test, Hinich and Rothman (1998) derive its frequency-domain counterpart based on the bispectrum and Lim *et al*. (2008a) generalize the test to the next polyspectral measure using the trispectrum. Chen *et al*. (2000), Chen (2003), Racine and Maasoumi (2007) and Psaradakis (2008) provide additional TR tests to the literature.

4. Non-overlapping Sub-samples with Fixed Parameter: Addressing the Effect of Major Events on Weak-form Market Efficiency

It is evident from our survey in Section 3 that the bulk of the literature focuses on testing whether a market is or is not weak-form efficient. However, a number of studies argue that it is more important to understand the underlying factors that lead a market to become efficient. The present section reviews this strand of literature that addresses the effect of some postulated factors on market efficiency by means of non-overlapping sub-samples. We organize the existing empirical studies based on their predetermined events. In general, the findings from these country-by-country sub-period studies are inconclusive, especially when the adopted statistical tests either reject or do not reject the null hypothesis of a random walk in both sub-periods of pre- and post-changes. Nevertheless, the research framework adopted does show that these investigators are aware of the non-static characteristic of market efficiency.

4.1 *The Opening of Domestic Stock Market to Foreign Investors*

In the wake of the movement toward financial liberalization in developing countries, some researchers explore the issue of whether the opening of these emerging markets to foreign investors has any positive effect, by examining the state of informational efficiency before and after the official date of liberalization. This inquiry is even more pertinent after the 1997 Asian financial crisis given that there is much discussion in policy circles to reverse the previous liberalization measures by imposing some form of capital controls (see Kim and Singal, 2000a, b). The empirical evidence drawn from a wide set of emerging markets on this subject matter is rather inconclusive. Using data from 20 developing countries and VR tests, Kim and Singal (2000a, b) find that stock markets in general become efficient after their policymakers allow the participation of foreign investors. Füss (2005) reaches similar conclusion for seven Asian emerging stock markets, i.e.

India, Indonesia, South Korea, Malaysia, the Philippines, Taiwan and Thailand. The statistical results in Basu *et al*. (2000) provide weak support to the efficiency benefit of stock market opening. In contrast, Groenewold and Ariff (1998) and Kawakatsu and Morey (1999a, b) report that their sampled emerging markets are weak-form efficient even before the actual market opening date. The Athens Stock Exchange is also reported to be efficient before liberalization by Laopodis (2003, 2004). On the other hand, Maghyereh and Omet (2002) conclude that financial liberalization has no effect on market efficiency, as the Amman Stock Exchange remains inefficient after liberalization.

4.2 *The Adoption of an Electronic Trading System*

One major reform that has been undertaken by stock exchanges around the world in recent decades is the replacement of physical trading floors by computerized trading systems. For instance, Jain (2005) assembles the announcement and actual introduction dates of electronic trading by the leading stock exchanges of 120 countries. His survey reveals a strong trend toward full automation of trading, where the leading stock exchanges in 101 of the 120 sampled countries have introduced fully automated and transparent electronic trading systems within the last 25 years. Against this backdrop, a number of studies examine the efficiency effect brought by the shift to computerized trading systems. Naidu and Rozeff (1994) find that the autocorrelations of returns tend to decrease after the adoption of an electronic trading system by the Singapore Stock Exchange. However, such evidence of efficiency benefit is not supported by subsequent studies on other stock exchanges. For instance, Freund *et al*. (1997) apply the rescaled range analysis on the Toronto Stock Exchange, but conclude that the introduction of the Computer-Assisted Trading System does not appear to have a material effect on the weak-form efficiency of Toronto Stock Exchange. Similarly, the rescaled range analysis by Freund and Pagano (2000) reveals that varying levels of automation in the New York Stock Exchange do not coincide with a significant change in the level of market efficiency.

4.3 *The Implementation of a Price Limits System*

After the October 1987 crash, the circuit breaker system in the form of price limits has been one of the popular regulatory mechanisms. It becomes almost ubiquitous after the outbreak of the Asian financial crisis, as many stock exchanges around the world have some forms of limit rules in place (see Kim and Yang, 2004, Table 2). Chen *et al*. (2005) note that most of the recent academic literature criticizes this policy tool for its impediment to market efficiency, notably in preventing prices from efficiently reaching their equilibrium level. On the empirical front, a number of studies formally explore the efficiency implication of implementing a price limits system. For instance, using 30 active individual stocks traded on the Korea Stock Exchange, Lee and Chung (1996) find that the rejection of the weak-form EMH is overridden after adjusting the effects of the price limits on stock price movements, suggesting that the market would be efficient if it were not for the price limits system. In another study involving the South Korean stock market, Ryoo and Smith (2002) divide the sample into five sub-periods with different daily price limit regimes and the VR test results reveal that the imposed price limits prevent stock prices from following a random walk process. However, when the limits are relaxed, the market as a whole approaches a random walk. This is consistent with the findings reported earlier by Chang and Ting (2000) for the Taiwan stock market in which the authors find that when the limits increase from 3% (31 October 1987 to 12 November 1988) to 5% (19 November 1988 to 7 October 1989) and to 7% (13 October 1990 to 6 January 1996), the first-order autocorrelation decreases from approximately 50% to 23% and to 19%.

4.4 *The Occurrence of a Financial Crisis*

The occurrence of a market crash or financial crisis is another possible contributing factor of market inefficiency. This is because investors are generally swamped by panic in that chaotic financial environment, and this would adversely affect their ability to price stocks efficiently. Motivated by this concern, Hoque *et al*. (2007) examine the weak-form efficiency of eight emerging Asian stock markets using VR tests for the pre-crisis (1990–1997) and post-crisis (1998–2004) periods. Their results show that the crisis has no significant effect on the degree of efficiency, with six of the Asian markets (Hong Kong, Indonesia, Malaysia, Philippines, Singapore and Thailand) remaining inefficient even after the crisis, while the opposite occurs for South Korea. Taiwan is the only market that records improved efficiency from the pre-crisis to post-crisis period. Using three different types of multiple VR tests and weekly data for nine Asian stock markets, Kim and Shamsuddin (2008) divide their sample into sub-sample I (1990–1996) and sub-sample II (1998–2005) in order to separate the effect of the 1997 financial crisis. The three statistical tests consistently show that the stock markets of Hong Kong, Japan and Taiwan remain efficient even after the crisis. However, for the other six markets, the effect of the financial turmoil is difficult to discern given that no consensus could be reached by the three multiple VR tests employed.

4.5 *The Changes in Regulatory Framework*

Antoniou *et al*. (1997) argue that changes in the regulatory environment would have significant impact on the efficiency of the underlying stock market. Using daily data on the Istanbul Stock Exchange Composite Index, these authors examine market efficiency on a yearly basis for the period from 1988 to 1993. Their results show that changes in the regulatory structure from late 1989 have led the Istanbul Stock Exchange to become efficient since the year 1991. Hence, they conclude that an efficient market is brought about by providing a regulatory framework that encourages participation in the market, removes institutional restrictions on trading, and ensures investors have access to high quality and reliable information. Groenewold *et al*. (2004) postulate that changes in the regulation governing the direct involvement of banks in the stock market would have significant effect on market efficiency given the traditional and dominant role of the banks in the Chinese financial system. To address this question empirically, the authors test the weak-form efficiency of the Chinese stock market over three different sub-periods in which banks are subjected to different regulations. The empirical results support their conjecture; in particular, market efficiency suffers when banks are excluded from the stock market during the sub-periods of 1 July 1996 to 31 December 1999, but there is improvement in efficiency when banks are readmitted during 1 January 2000 to 29 March 2001.

On 19 February 2001, the Chinese government relaxe the share tradability restriction, where local investors with foreign currency accounts were permitted to trade the B-shares. Lu *et al*. (2007), Fifield and Jetty (2008) and Hung (2009) explore the effect of the above regulatory policy change on the weak-form efficiency of Chinese stock markets, by applying a battery of VR tests on both sub-periods of pre- and post-deregulation. Lu *et al*. (2007) find that the opening of the B-share markets to domestic Chinese investors exerts positive impact on market efficiency. Fifield and Jetty (2008) obtain a similar finding of improved efficiency in the sub-period of post-deregulation, which they attribute to reduced information disadvantage of foreign investors and a more rapid dissemination of information among investors. The result from the sub-period analysis in Hung (2009) also shows that the A-share market of Shenzhen and B-share markets of both exchanges in Shanghai and Shenzhen become efficient after the deregulation of B-share markets.

4.6 *Technological Advances*

Gu and Finnerty (2002) analyse the evolution of market efficiency in the US stock market using 103 years of daily data (1896–1998) for the Dow Jones Industrial Average. Given that there have been significant changes in the last 50 years, particularly advances in information technology and the growing ability of investors to use relevant information promptly and rationally for their investments, the authors argue that these factors would reduce the level of autocorrelation and hence move the market toward efficiency. To test their hypothesis, Gu and Finnerty (2002) compute the first-order autocorrelation between daily returns for each individual year using VR, serial correlation and runs tests. Their results reveal that for most years from 1941 to the mid 1970s, the market is not weak-form efficient with high levels of autocorrelation. Compared to the first 35 years of the sample period where autocorrelation fluctuates moderately around a very low level, this increasing trend of autocorrelation from 1896 to the mid 1970s appears inconsistent with the hypothesis put forward, suggesting that technological advances do not have the dominant effect on the level of market efficiency for the first three quarters of the 103 years. However, the autocorrelation experiences a sharp decline since the late 1970s, indicating that the market has evolved and attained efficiency during the last two decades, which the authors attribute to advances in information technology and investors' experience. Subsequently, Gu (2004) tests the same hypothesis on a different stock exchange. Using the VR test to examine the evolution of the level of autocorrelation in daily returns of the NASDAQ Composite Index from 1971 to 2001, the author finds that the market only attains weak-form efficiency in the last 10 years.

4.7 *Other Non-overlapping Sub-samples Studies*

Hinich and Patterson (1995, 2005) argue that previous evidence of nonlinearity is not identifiable over long stretches of time, but instead it is only present in limited sub-samples of the data. To test their hypothesis, these authors apply the bicorrelation test in equal-length non-overlapping sub-samples to detect epochs of transient nonlinear dependence in a discrete-time pure white noise process. Using eight component stocks of the Dow Jones Industrial Average, they find that the detected nonlinear serial dependence is at best episodic in nature. Subsequent applications on other stock markets further support their conjecture (see Ammermann and Patterson, 2003; Bonilla *et al.*, 2006; Romero-Meza *et al.*, 2007; Lim, 2008b; Lim *et al.*, 2008b). Given that the above moving sub-samples framework is able to identify the time periods when detected nonlinear dependencies occur, some of these studies proceed to pinpoint the associated events. For instance, Lim (2008b) is able to identify major political and economic events that contribute to the short bursts of significant nonlinear serial dependence in the Malaysian stock market. This approach of associating nonlinear dependence with major events by means of non-overlapping sub-samples has also been adopted by Romero-Meza *et al*. (2007) and Lim *et al*. (2008b) for the stock markets of Chile and 10 developing Asian countries, respectively.

5. Full Sample Analysis with Time-varying Parameter: Tracking the Changing Degree of Weak-form Market Efficiency over Time

A major criticism of those non-overlapping sub-samples studies lies in their assumption that the movement toward market efficiency will take the form of a discrete change in the underlying parameter at the predetermined breakpoint. In this regard, it is more reasonable to expect market efficiency to change through time, but this dynamic characteristic could not be captured in arbitrarily chosen sub-samples. Motivated by this concern, an emerging literature employs a state space model to capture the time-varying weak-form stock market efficiency.

Emerson *et al*. (1997) represent the first stock market study that estimates a time-varying parameter model using the Kalman filter technique to track the changing degree of market efficiency over time. In their model, the time-varying autocorrelation coefficients are used to gauge the changing degree of return predictability, and hence evolving weak-form market efficiency. If the market under study becomes more efficient over time, the smoothed time-varying estimates of the autocorrelation coefficient will gradually converge toward zero and become insignificant. This framework is later formalized by Zalewska-Mitura and Hall (1999) as ‘test for evolving efficiency’ to provide a quantitative measure of the timing and speed of the movement toward efficiency.

Given that the emerging markets in Bulgaria and Hungary are still in the early stages of their development, Emerson *et al*. (1997) and Zalewska-Mitura and Hall (1999) argue that it is not sensible to address the issue of whether the stock markets in these transition economies are efficient or not. Indeed, it is hardly credible for newly established stock exchanges to be born efficient since it takes time for the price discovery process to become known. However, as market participants become more experienced and the market system becomes better developed over time, the level of efficiency in these infant markets will gradually improve. Hence, the more relevant research question is whether they are becoming more efficient, but this cannot be answered by classical steady-variable approaches that assume a fixed level of market efficiency throughout the entire estimation period. Using their proposed test for evolving efficiency, the above two studies are able to depict the time paths taken by their sampled stock markets toward a higher level of efficiency.

The test for evolving efficiency is subsequently adopted to track the evolving efficiency of other stock markets in the Central and Eastern European transition economies that have just emerged out of the former communist bloc (see, for example, Rockinger and Urga, 2000, 2001; Zalewska-Mitura and Hall, 2000; Schotman and Zalewska, 2006). Rockinger and Urga (2000) argue that this approach appears to be the only way since there is no observable variable for emerging markets that can be used to quantify the improvement in informational efficiency. Hence, it is not surprising that the test for evolving efficiency literature has expanded to include stock markets in Africa (Jefferis and Smith, 2004, 2005), China (Li, 2003a, 2003b), Jordan (Maghyereh, 2005) and the high-technology stocks in Europe (Pierdzioch and Schertler, 2007). In a parallel development, Kvedaras and Basdevant (2004) develop a time-varying VR statistic, and subsequently apply the methodology to track the changing degree of stock market efficiency in Estonia, Latvia and Lithuania. Though all the aforementioned studies focus on emerging markets, Ito and Sugiyama (2009) report that even the developed US stock market exhibits varying degrees of market efficiency from 1955 to 2006.

As discussed earlier, the advantage of a time-varying parameter model over non-overlapping sub-samples is that the former depicts market efficiency as a continuous process. Because of this, the time-varying framework can throw additional light on those events that are responsible for market inefficiency. More specifically, in those non-overlapped sub-samples studies, the specific event of interest (such as financial liberalization, trading systems automation, the implementation of a price limits system and financial crisis) is selected *a priori*. Instead, the time-varying framework first let the data detect those periods of inefficiency, and then investigators can proceed to identify the associated events.[13] For instance, Rockinger and Urga (2000) conduct careful inspection of anecdotal evidence from stock market characteristics, economic and political events to explain those periods of inefficiency in the four stock markets of Central and Eastern European transition economies, namely Czech Republic, Hungary, Poland and Russia. Li (2003a) use non-quantifiable changing characteristics of the markets such as market liquidity, information disclosure mechanism and regulation enforcement at different points of time to make inferences on the inefficiency of the Chinese stock markets. Jefferis and Smith (2005) relate the changing degree of weak-form efficiency at different stages of development to market turnover, market capitalization and institutional characteristics of seven African stock markets – Egypt, Kenya, Mauritius, Morocco, Nigeria, South Africa and Zimbabwe. Maghyereh (2005) first tracks the evolution of market efficiency in Amman Stock Exchange from 1 January 1999 to 30 August 2002, and then observes whether there is any structural shift toward zero in the autocorrelation coefficients around the date of electronic trading system adoption on 27 March 2000.

6. Rolling Estimation Windows with Fixed Parameter in Each Window: Measuring the Persistence of Deviations from a Random Walk over Time

Another group of studies applies existing weak-form EMH tests in rolling estimation windows.[14] Examples are the rolling VR tests (Tabak, 2003; Kim and Shamsuddin, 2008; Hung, 2009), rolling ADF unit root test (Phengpis, 2006), rolling bicorrelation test (Lim, 2007; Todea and Zoicas-Ienciu, 2008), rolling parameters of ARCH models (Degiannakis *et al.*, 2008; Alagidede and Panagiotidis, 2009a) and rolling Hurst exponent (Costa and Vasconcelos, 2003; Cajueiro and Tabak, 2004b, 2005d, 2006, 2008; Zunino *et al.*, 2007). The application of a rolling window essentially captures the persistence of stock price departures from a random walk benchmark over time. In fact, in his illustration of the AMH, Lo (2004, 2005) computes the rolling first-order autocorrelation for monthly returns of the S&P Composite Index. Timmermann (2008) notes that incomplete learning effects, structural changes in the return generating process and exogenous events can cause return predictability to evolve through time.[15]

Apart from the main finding of time-varying weak-form efficiency in stock markets, the rolling windows approach allows previous studies to gain additional insight. The present section highlights four issues addressed by this emerging literature.

6.1 *Assessing the Relative Weak-form Efficiency of Stock Markets*

Given that the literature is occupied with testing the absolute version of market efficiency, it is not surprising to learn that little is known about differences in the degree of efficiency across markets and what characteristics are associated with a higher level of informational efficiency, even after more than four decades of empirical investigations. Campbell *et al.* (1997), Lo and MacKinlay (1999) and Lo (2008) have repeatedly argued that perfect efficiency is an idealization that is unattainable in practice. Citing the work of Grossman and Stiglitz (1980), these three studies point out that if markets are perfectly efficient, there is no profit earned by information gathering, in which case there will be little reason to trade and markets will eventually collapse.[16] Hence, there must be sufficient profit opportunities or inefficiencies to compensate investors for the cost of trading and information gathering. Hence, Campbell *et al.* (1997, p. 24) offer the notion of relative efficiency, which is the efficiency of one market measured against another, for example the New York Stock Exchange versus the Paris Bourse, futures versus spot markets, or auction versus dealer markets.

The merit of this concept has witnessed the emergence of a group of studies that examines market efficiency in the relative rather than absolute sense (see the survey paper by Lim and Brooks, 2009b). In this literature, the degree of market efficiency is measured based on (1) how much private firm-specific information is incorporated into stock prices, using the market model R-square statistic (Morck *et al.*, 2000), the private information trading measure (Llorente *et al.*, 2002) and the probability of information-based trading (Easley *et al.*, 1997); (2) how quickly market-wide information is capitalized into stock prices using the price delay measure of Hou and Moskowitz (2005); (3) how closely stock prices follow a random walk using the weak-form EMH tests[17] and the pricing errors derived by Hasbrouck (1993). The growing importance of this literature has motivated the World Bank's Financial Sector Development Indicators project to construct a composite indicator for comparing the efficiency of stock markets around the world.

In the emerging literature of evolving market efficiency, Cajueiro and Tabak (2004a, c, 2005a) are able to rank their selected stock markets using the medians of those computed rolling Hurst exponents. Specifically, given that the rolling window approach produces thousands of Hurst exponents for each market, the above studies argue that it is impossible to compare all of them, and they advocate the use of means, medians or other statistical measures of those computed Hurst exponents in order to compare the degree of efficiency across stock markets. The medians are selected as the preferred choice based on the findings that the Hurst exponents are not normally distributed. Lim and Brooks (2006) and Lim (2007) instead argue that a more appropriate indicator for building efficiency ranking is the percentage of sub-samples with a significant test statistic, where a higher percentage indicates more frequent stock price deviations, and hence a lower degree of informational efficiency. This is because the fundamental objective of using rolling window estimation is to measure how often the random walk hypothesis is rejected by the test statistic over the full sample period. Using their proposed framework in the context of the rolling bicorrelation statistic, both studies are able to compare the degree of weak-form efficiency among their sampled stock markets. For instance, with a wide coverage of 23 developed and 27 emerging stock markets, Lim and Brooks (2006) find that the degree of weak-form market efficiency varies widely across countries, and developed markets in general are more efficient than emerging ones.

6.2 *Identifying the Events that Coincide with Periods of Weak-form Market Inefficiency*

A number of studies employ the rolling window framework to identify the events that coincide with those time periods when the underlying stock return series deviate from a random walk. For instance, Costa and Vasconcelos (2003) attribute the movements of the Hurst exponents toward 0.5 as a consequence of the economic plans adopted by the Brazilian government, i.e. the Cruzado plan in February 1986, Collor Plan in March 1990 and Real Plan in July 1994. To incorporate the possibility of market inefficiency at shorter time scales, Alvarez-Ramirez *et al*. (2008) investigate the time-varying long-range dependence of the Dow Jones Industrial Average and S&P 500 Composite Index. The authors find that the US stock market approaches a random walk after the year 1972, which coincides with the end of the Breton Woods system. Using the rolling Hurst exponent, Cajueiro *et al*. (2009) assess whether the stock market liberalization measures introduced by the Greek government in the beginning of the 1990s has any effect on the underlying stock market efficiency. The authors find that there is a significant decrease in the degree of weak-form market inefficiency immediately after the liberalization date.

The rolling VR test statistic has also been adopted for a similar purpose. To complement their earlier non-overlapping sub-samples analysis, Kim and Shamsuddin (2008) also apply the multiple VR tests in rolling windows to determine whether the detected structural shifts in the multiple VR test statistics coincide with the 1997 financial crisis. The authors conclude that the crisis does not coincide with a significant change in the level of market efficiency for most of the Asian stock markets, with Singapore and Thailand being the exceptional cases that attain efficiency after the crisis. Hung (2009) further examines the efficiency effect of the relaxation of investment restriction on the Chinese B-share markets using the rolling VR tests. The author finds that market efficiency deteriorates immediately after the policy change, which contradicts his earlier result from the non-overlapping sub-period analysis and those reported by Lu *et al*. (2007) and Fifield and Jetty (2008). Instead, market efficiency improves after the trading of A-shares is opened to international institutional investors under the Qualified Foreign Institutional Investor scheme on 1 December 2002, which Hung (2009) claims is because the liberalization measure alleviates the difficulties for foreign investors to access information about Chinese companies.

6.3 *Determining the Impact of Postulated Factors on the Degree of Weak-form Market Efficiency*

As discussed in Section 4, the research design of previous non-overlapping sub-samples studies focuses on testing whether the random walk hypothesis can be rejected in those predetermined sub-periods of pre- and post-changes. It is not surprising to learn that most of these studies are not able to discern the effect of their postulated factors on stock market efficiency, in particular when the adopted statistical tests either reject or do not reject the null hypothesis of a random walk in both sub-periods. In this regard, if the research framework departs from the traditional focus of absolute market efficiency and instead employs the concept of relative efficiency, it is then possible to examine the efficiency impact of a particular factor. A number of studies do capitalize on the ability of the rolling window approach to infer the degree of market efficiency. For instance, Cheong *et al*. (2007) employ the median of their computed rolling Hurst exponents to compare the efficiency of the Malaysian stock market in four sub-periods of pre-crisis, crisis, USD pegged and post-crisis. The authors report that the highest inefficiency occurs during the Asian financial crisis period, followed by pre-crisis, post-crisis and US dollar pegged period.

Lim *et al*. (2008c) empirically examine the effect of the 1997 financial crisis on the efficiency of eight Asian stock markets, applying the rolling bicorrelation test statistic for the three sub-periods of pre-crisis, crisis and post-crisis. On a country-by-country basis, their results demonstrate that the crisis adversely affects the efficiency of most Asian stock markets, with Hong Kong being the hardest hit, followed by the Philippines, Malaysia, Singapore, Thailand and South Korea. However, most of these markets recover in the post-crisis period in terms of improved market efficiency. Their findings for Malaysia are consistent with those reported by Cheong *et al*. (2007), in which the highest inefficiency occurs during the crisis, followed by the pre-crisis and post-crisis periods.

The rolling bicorrelation statistic is then adopted by Lim (2008a) to disentangle the sectoral impact of the Asian financial crisis on the Malaysian stock market. Dividing their sample period into pre-crisis, crisis, USD pegged and post USD pegged period, the author finds that the highest inefficiency occurs during the crisis period for all eight economic sectors except tin and mining. The capital controls introduced by the Malaysian government do help to stabilize the stock market and could be credited, though not wholly, for the improvement in market efficiency during the USD pegged period for all the seven crisis-stricken sectors. The degree of market efficiency further improves in the final sub-period during which capital controls are lifted by the authorities. The same approach is later adopted by Lim and Brooks (2009c) to address the hypothesis that the implementation of a price limits system has an adverse effect on market efficiency. Using the stock markets from China, South Korea and Taiwan as case studies, the authors report the rolling bicorrelation test results for those selected sub-periods with different price limit regimes. In general, their statistical findings do not provide empirical support to the widely held claims that restrictive price limits and price limits *per se* are jeopardizing market efficiency.

6.4 *Exploring the Cross-country Determinants of Weak-form Market Efficiency*

The advantage of an empirical measure of relative efficiency is that it permits further exploration of the underlying factors associated with higher efficiency, extended from a single-country sub-period study to a broader multi-country investigation via cross-sectional or panel regression. For instance, the stock price synchronicity measure of Morck *et al*. (2000), in particular the average market model R-square statistic, has inspired extensive studies on stock market efficiency (for a survey, see Lim and Brooks, 2009b). Apart from comparing the degree of country-level market efficiency, this group of studies further explores the underlying determinants for the cross-country differences in stock price co-movement. Those identified significant factors include the degree of private property rights protection (Morck *et al*., 2000), public investor protection (Morck *et al*., 2000), stock market liberalization (Li *et al*., 2004), corporate transparency (Jin and Myers, 2006), securities laws (Daouk *et al.*, 2006), short sales restrictions (Bris *et al.*, 2007) and insider trading laws (Beny, 2007; Fernandes and Ferreira, 2009).

Motivated by the above literature, Lim and Brooks (2009d) further explore the factors that are responsible for the cross-country variation in the degree of stock price deviations from a random walk over time. Using the rolling bicorrelation test, the authors find evidence that the aggregate stock price indices of 50 countries do experience varying degrees of nonlinear departures from a random walk over the common sample period of 1995–2005. More specifically, stock markets in economies with low per capita GDP in general experience more frequent price deviations than those in the high income group. Further analysis consistently shows that the negative relation between the degree of stock price deviations and per capita GDP can largely be attributed to low income economies providing weak protection for private property rights. The proxy for private property rights protection remains significant even after controlling for other competing explanations such as public investor protection, corporate transparency and stock market openness. This piece of evidence suggests that secure private property rights are both a necessary and sufficient condition for ensuring stock prices move more closely to a random walk.

Lim and Brooks (2009d) argue that a strong private property rights institution is crucial for attracting the participation of arbitrageurs, as these investors will not trade if they expect to be unable to keep their profits. In fact, the critical role of arbitrageurs in restoring price deviations and keeping the market efficient has been the cornerstone of modern financial economics. Hence, the lack of arbitrage trading in low income economies due to weak private property rights protection will leave their stock price deviations uncorrected for long periods of time. Their results further reinforce the findings of Morck *et al.* (2000) on the importance of strong private property rights institutions for the stock market to perform its informational role efficiently. Both studies show that weak protection is associated with persistent stock price deviations from a random walk and a high degree of stock price synchronicity, respectively. A recent paper by Lagoarde-Segot (2009) examines, among other things, the impact of financial reforms on the time-varying informational efficiency of 28 emerging stock markets over the sample period 1996–2007. The significant determinants of market efficiency identified by their panel regressions are domestic market capitalization, financial sector development, international portfolio equity flows, the enforcement of insider trading regulations, and the automation of trading systems.

7. Conclusion

The predictability of stock returns on the basis of past price changes has been extensively investigated given its direct implication on weak-form market efficiency. The vast majority of the literature implicitly assumes the level of market efficiency remains unchanged throughout the estimation period. However, the possibility of temporal instability in the underlying economic relations has received increasing attention from economists (see, for example, Stock and Watson, 2003). This applies equally to the issue of return predictability, where our present survey shows that there is an expanding literature which challenges the assumed static characteristic of market efficiency by means of non-overlapping sub-period analysis, time-varying parameter model and rolling estimation window. An encouraging development is that the documented empirical evidence of evolving stock return predictability can be rationalized within the framework of the AMH proposed by Lo (2004, 2005).

On the methodological front, Anatolyev (2009) formalizes the sequential testing procedures to control the overall size of the tests, focusing on whether the null hypothesis of non-predictability holds throughout the sample period. Another novelty is that their sequential testing tools not only permit investigators to track the evolution of predictability over time in a historical sample, but also to conduct further testing as new observations begin to arrive. Though their retrospective and monitoring tests consider the directional accuracy test (Pesaran and Timmermann, 1992) and excess profitability statistic (Anatolyev and Gerko, 2005), Anatolyev (2009) notes that their framework can also be extended to other predictability tests such as the autoregressive coefficient and the BDS statistic. Their subsequent empirical application is able to track the dynamics of the level of predictability in 10 Eastern European stock markets.

We highlight here four related strands of literature that are not included in our survey. First, while this paper focuses exclusively on the stock markets, the issue of time-varying return predictability has also been addressed in other asset markets (see, for example, Yilmaz, 2003; Cajueiro and Tabak, 2007). Second, researchers have recently begun to examine the structural stability of the parameters in traditional predictive regression models of aggregate stock returns (see, for example, Paye and Timmermann, 2006; Rapach and Wohar, 2006; Lettau and Nieuwerburgh, 2008; Hjalmarsson, 2009). Their evidence suggests that the predictive ability of financial variables varies markedly over time. Third, the weak-form market efficiency is generally interpreted in terms of the existence of significant time series predictability. However, the implications of temporal dependence on market efficiency, in particular return autocorrelations, are still very much debated (see Boudoukh *et al.*, 1994). An alternative approach is to measure the speed of stock price adjustment since an efficient market is characterized as one in which the stock price responds to new information accurately and in a timely manner. For instance, Chelley-Steeley (2001, 2003, 2005, 2008) and Chelley-Steeley and Lucey (2008) estimate the price adjustment coefficient of the partial adjustment model with noise proposed by Amihud and Mendelson (1987). The above model is estimated using the Kalman filter, and their results show that the speed with which prices adjust to new information is time-varying. Fourth, proponents of the EMH always dismiss negative empirical evidence on the grounds that those detected stock market predictable patterns do not give rise to profitable investment strategies (see Malkiel, 2003). In the profitability literature, several recent studies examine the stability of technical trading profits over time, and they find that the positive excess returns identified in the 1970s and 1980s have declined substantially in the mid-1990s (see Menkhoff and Taylor, 2007; Park and Irwin, 2007; Neely *et al.*, 2009). Neely *et al.* (2009) note that these empirical regularities are consistent with the AMH.

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Notes

1. Another two distinct but interrelated types of financial market efficiency are: (1) operational efficiency which focuses on the level of costs in carrying out transactions on the exchange; (2) allocational efficiency, measuring the extent to which capital is efficiently allocated to the most productive sectors in the economy.
2. Other definitions have been proposed by Rubinstein (1975, 2001), Jensen (1978), Beaver (1981), Black (1986), Dacorogna *et al.* (2001), Malkiel (2003), Timmermann and Granger (2004) and Milionis (2007).
3. The information set is expanded to include publicly available information and privately held information under the semi-strong-form and strong-form EMH, respectively.
4. Fama (1991) later reclassifies the weak-form EMH as tests for return predictability, and this will include another group of literature that examines return predictability using financial variables such as the dividend–price ratio, earnings–price ratio, book-to-market ratio and various measures of the interest rates (recent studies include Boudoukh *et al.*, 2008; Campbell and Thompson, 2008; Cochrane, 2008; Lettau and Nieuwerburgh, 2008; Welch and Goyal, 2008; Hjalmarsson, 2009).
5. In the forecasting literature, temporary forecastability (Timmermann and Granger, 2004) and temporary market inefficiencies (Park and Irwin, 2007) are two leading explanations given for the counterintuitive positive forecasting results of technical trading rules during certain time periods.
6. One of the limitations of the correlation dimension is the lack of statistical theory for hypothesis testing, and this gap has been filled by Brock *et al.* (1996) who develop asymptotic distribution theory for statistics based on the correlation dimension. However, the null hypothesis for the BDS test is i.i.d. and hence does not provide a direct test for chaos. Even though the test is designed to have high power against deterministic chaos, various simulations show that it also has good power to detect linear dependence and nonlinear stochastic processes (see Brock *et al.*, 1991, 1996; Hsieh, 1991).
7. Some of these tests are continually being refined over the years, which include the BDS test (Kočenda and Briatka, 2005; Genest *et al.*, 2007), the bispectrum test (Hinich *et al.*, 2005; Hinich, 2009; Rusticelli *et al.*, 2009) and the bicorrelation test (Wild *et al.*, 2008).
8. The toolkit can be downloaded from Richard Ashley's website at http://ashleymac.econ.vt.edu/. Ashley and Patterson (2006) further illustrate the usefulness of this

toolkit in nonlinear model identification using the *p*-values of those included statistical tests.

9. Similarly, there is no evidence of temporal dependence between observations widely separated in time if $H = 0.5$. On the other hand, $0.5 < H < 1$ indicates that the series is somewhat persistent, while there is evidence of long memory with anti-persistent behaviour if $0 < H < 0.5$. Different tools from statistical physics have been adopted to shed new light on the scaling properties of stock returns (see the survey paper by Di Matteo, 2007).
10. A white noise process is not necessarily a martingale difference sequence because it may have a non-zero conditional mean. Examples are the bilinear autoregressive and nonlinear moving average processes which have zero autocorrelation, yet they are not martingale difference sequence because both processes can be predicted nonlinearly using its own past history.
11. On the other hand, a random walk with i.i.d. increments (i.e. a pure white noise process) is a martingale process, but a martingale process may not be a random walk. For instance, though the volatility of an ARCH process is time-varying and predictable, it is a martingale difference sequence because the conditional mean is zero.
12. A time series is time reversible if the probabilistic structure of the series going forward is identical to that in reverse time; otherwise, it is time irreversible.
13. This approach of event detection is commonly used to determine whether large price movements are linked to public news releases (see, for example, Cutler *et al.*, 1989; Fleming and Remolona, 1997; Kaminsky and Schmukler, 1999; Fair, 2002, 2003).
14. It is worth highlighting that the recursive estimation strategy has also been adopted to determine the persistence of deviations from a random walk, but it is relatively less popular (see de Lima, 1998; Self and Mathur, 2006). Perhaps this is because the recursive technique does not differentiate whether the time-varying test statistics are due to a change in the underlying process or an increase in the power of the test arising from adding observations recursively.
15. He proposes an adaptive forecast combination approach which employs rolling windows to estimate the model parameters and select the forecasting model. Using the US stock returns as an illustration, the proposed approach is able to identify relatively short-lived periods with return predictability. His findings suggest that though stock returns are not predictable most of the time, there are episodes of local predictability.
16. Slezak (2003) further shows that as long as irrational investors exist and there is a positive cost to becoming fully rational, then irrational agents will persist and their trades will cause predictability in equilibrium. Under these conditions, even perfectly weak-form efficient markets are impossible.
17. In the context of weak-form EMH, recently used measures of relative efficiency are the absolute value of the autocorrelation coefficient (some recent studies include Alexander and Peterson, 2008; Chordia *et al.*, 2008; Boehmer and Kelley, 2009; Boehmer and Wu, 2009), the absolute deviation from one of variance ratio (see Chordia *et al.*, 2008; Griffin *et al.*, 2008; Boehmer and Kelley, 2009) and the magnitude of the Hurst exponent (see Eom *et al.*, 2008a, b; Zunino *et al.*, 2008).

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