FURTHER EVIDENCE ON THE TIME-VARYING EFFICIENCY OF CRUDE OIL MARKETS

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ABSTRACT
In this paper, we apply the rolling sample Shannon entropy and the Symbolic Time Series Analysis to evaluate the dynamic of weak-form efficiency of the crude oil markets. Daily closing spot prices data for two worldwide crude oil benchmarks (West Texas Intermediate and Europe Brent) are used with a time window of 4 years. Our main findings support evidence that the degree of efficiency of crude oil market is time-varying. Moreover, the WTI market appears to be less efficient than the Europe Brent. We finally show that the crisis 1997-1998 adversely affected the efficiency degree in crude oil markets. Overall, the findings have several important policy and investment implications.

Keywords
crude oil markets, weak-form market efficiency, Asian financial crisis, Shannon entropy

JEL classification: G14; G15; C87

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1. Introduction

Crude oil is among the most important fossil fuels and serves as benchmark for the pricing of numerous financial instruments and oil-related products. Over the last decade, the crude oil markets have been characterized by strong upward drifts and wide fluctuations.[1] It is now common that this high volatility may arise from, among others, the imbalance between supply and demand, irregulars events related to weather, market conditions, economic growth, political aspects, investors' psychological expectations as well as other unforeseen events such as wars, embargoes and revolutions. The combined effect of these events, whatever the nature, may cause the price of crude oil to fluctuate without relation to its fundamental value. The degree of informational efficiency of crude oil markets may thus be substantially affected and varies through time.

The purpose of this article is to examine whether international crude oil markets are weak-form efficient over time as it is likely to be the case. This research question is motivated by the fact that empirical results regarding the dynamic behavior of crude oil prices appear to be controversial in the existing literature. Clear-cut conclusions would therefore allow us to accurately discuss the implications of the results on, for example, energy policies and portfolio management in presence of oil risk. According to Fama (1970, 1991), a market is said to be efficient if all available and relevant information is immediately and fully reflected in the asset prices. The information set is defined as anything that affects asset prices and is divided in three broad categories with respect to the efficient market hypothesis (EMH): past information (weak-form efficiency), public information (semi-strong form efficiency), and public and private information (strong-form efficiency). The validity of the EMH implies that market price forecasts are impossible because there are no accurate patterns to asset prices and that no investor can take advantage of the available information to make abnormal profits.

Only a few studies have empirically questioned the efficient behavior of international crude oil markets. Green and Mork (1991) investigate the efficiency of crude oil markets (monthly prices of Mideast Light and African Light/North Sea crudes) by testing whether the price of a futures contract on crude oil is an efficient predictor of the *ex-post* spot price at the time of merchandise delivery and find evidence of predictability in oil prices for the whole sample period 1978-1985. They also show the improvements of market efficiency when sub-sample periods are considered. Using Lagrange multiplier unit root tests with one and two endogenous structural breaks, Shambora and Rossiter (2007) evaluate the efficiency of crude oil futures market using the artificial neural network technique. Based on the prices of daily nearby crude oil futures contracts, the authors compare the profitability generated by the neural network model to three benchmark trading rules including buy and hold, technical analysis and random walk. Their results indicate that the artificial neural network model outperforms the others strategies, which suggests the inefficiency of crude oil futures market. Maslyuk and Smyth (2008) test the weak-form efficiency of weekly spot and futures prices of the WTI and Brent crude oils

[1] Crude oil markets have experienced an unprecedented boom period in the aftermath of the 1997-1998 financial crisis and the 2001 internet bubble burst. For example, the West Texas Intermediate (WTI) crude oil spot price closed at $20.74 per barrel on January 2002 and broke a record level of $133.93 per barrel on June 2008.

over the period 1991-2004. The authors cannot reject the efficient behavior of crude oil markets considered as both oil spot and futures prices can be characterized as a random walk process. Charles and Darné (2009) test the random walk hypothesis for two crude oil markets (WTI and Brent) over the period from June 1982 to July 2008.[2] Their results indicate that the Brent market behaves in accordance with weak-form market efficiency, whereas the WTI market seems to be inefficient over the sub-period 1994-2008. Lee and Lee (2009) examine the weak-form efficiency of total energy prices, and four other disaggregated energy prices (coal, oil, gas and electricity) in real terms for OCDE countries over the period 1978-2006. Their panel data stationarity tests allowing for sudden shifts in both level and slope show evidence against the weak-form efficiency for all energy prices, including oil prices.

Several studies have looked at the possibility of time-variations in the efficiency levels of international crude oil markets. Tabak and Cajueiro (2007) investigate the evolving efficiency hypothesis of WTI and Brent crude oil markets by means of the modified Hurst exponent and document the presence of time-varying degrees of long-range dependence in daily oil returns over the period 1983-2004. Moreover, crude oil markets have become more efficient through time and the WTI crude oil prices seem to be more weak-form efficient than the Brent prices. Alvarez-Ramirez et al. (2008) reach similar conclusions based on their study of time-varying autocorrelations for the Brent, WTI Cushing, and Dubai oil returns over the period 1987-2007. Their results typically indicate that crude oil markets exhibit short-term inefficient behavior, but they are becoming efficient over the long term. It is worth noting that the results presented in Tabak and Cajueiro (2007) is clearly inconsistent with the findings of Charles and Darné (2009), while the short-term predictability in oil return reported in Alvarez-Ramirez et al. (2008) is in line with the findings of Elder and Serletis (2008).

Our present study contributes to the above literature by assessing the time-varying degree of informational efficiency of crude oil markets through a combination of the Symbolic Time Series Analysis (STSA) and the modified Shannon entropy. Compared to other methods of efficiency assessment, this approach has the advantage of being simple to be implemented and appropriate for evaluating the information content of financial time-series. Its use also permits to compare the results across studies. Risso (2008) adopts this approach to examine the relationship between informational efficiency and financial market crashes, and confirms its suitability for testing the weak-form market efficiency.

We structure the remainder of this paper as follows. Section 2 introduces the empirical method and shows how it can be applied to model the time-varying efficiency in the crude oil markets. Section 3 presents data used. Section 4 reports and interprets the obtained results. Concluding remarks are provided in Section 5.

2. Econometric method

Whether a market is informationally efficient or not has direct consequences on the trading strategies and financing decisions of portfolio managers and financial managers operating in commodity markets. Here we investigate whether the actual

[2] The authors use a non-parametric variance ratio tests suggested by Wright (2000), and Belaire-Franch and Contreras (2004) as well as the wild-bootstrap variance tests developed by Kim (2006).

crude oil price at time *t* instantaneously and fully reflects all available information relevant for oil pricing. This market condition implies that the past pattern of oil price movements is inexploitable to forecast the future prices. Accordingly, oil returns are unpredictable and independently distributed under the risk-neutral agent assumptions (Fama, 1991).

We adopt a two-step procedure to test for the weak-form efficiency of crude oil markets. We first refer to the STSA techniques to symbolize the oil return series under consideration in order to detect their different dynamic patterns. We then employ the modified Shannon entropy to assess the quantity and inherent characteristics of information contained in each series. Specifically, the symbolization step consists of transforming oil return series of many possible values into symbolic series of a few distinct values. Following Risso (2008), we define two extreme symbolic dynamics for the crude oil return series such as:

$$if\begin{cases} r_t \succ 0 & s_t = 1 \\ r_t \leq 0 & s_t = 0 \end{cases} \qquad (1)$$

In the above expression, r_t and s_t denote oil return series at time *t* and its corresponding symbolic series respectively. Accordingly, the symbolic series is none other than a binary random variable that takes a value of one if the return is positive and zero otherwise, and zero being the breaking point between two symbols.[3] The sequences of 0s and 1s for the oil return series thus represent the successive decreases (referred to as "bear market") and successive increases (referred to as "bull market") in oil prices respectively.

Given that the symbolic oil return generating process under the null hypothesis of weak-form efficiency can be considered as a Bernoulli process, the Shannon entropy (*H*) can be applied to evaluate the degree of uncertainty with which the sequences of 0s (1s) will occur. The more uncertain the realization of the sequences of 0s and 1s, the lower is the degree of return predictability. Concretely, let *p* be the probability of observing a sequence of oil price decreases (symbol 0) and (1 – p) the probability of observing a sequence of oil price increases (symbol 1), the measure of weak-form market efficiency is given by

$$H = -\frac{1}{\log_2(n)}\left[p\log_2(p) + (1-p)\log_2(1-p)\right] \qquad (2)$$

where $0\log_2 0 = 0$ by convention.

The expression in Equation (2) is the binary case of Shannon entropy with *n* being equal to 2. *H* is a concave function whose values are bounded between zero and one. The maximum value ($H = 1$) is obtained for $p = 0.5$ when the sequences of the symbolic series are completely random. In this case, the crude oil market is said to be efficient. The entropy reaches its minimum value ($H = 0$) for $p = 1$ or $p = 0$, indicating that a sequence of negative or positive oil returns occurs with certainty and as a result the crude oil market is inefficient. The probability of a sequence of

[3] Note that it is possible to define more than two symbols for the oil return series, but in this paper we are only interested in the combinations of negative and positive returns. Thus, zero serves as the convenient partition in the return series.

negative returns (positive returns) above 0.5 would mean a lower level of weak-form efficiency, and profitable opportunities can be exploited from using patterns in price changes. Note that the probability p is calculated by relating the number of sequences of 0s to the total number of distinct sequences over the whole period.

According to Risso (2008), the theoretical expression for H is defined as follows

$$H = \frac{-1}{\log_2(n)} \left(\sum_{i=1}^{n} p_i \log_2 p_i \right) \quad (3)$$

Where n is the total number of sequences and p_i is the probability of sequence i =1, 2, …, n. The total number of sequences is given by $n = 2^L$, where L is a length or a sequence of days.

In order to study the evolution of efficiency in crude oil markets, we use a rolling sample method. That is, we select a time-window of four years (1008 observations) and move it across the time by adding a new observation until the end of the entire sample while estimating the value of H for each time-window (Cajueiro and Tabak, 2004). By doing so, we obtain an efficiency index for each oil return series considered.

3. Data and stochastic properties

We consider daily closing spot prices of two crude oil benchmarks: Cushing West Intermediate (WTI), the reference crude oil for the USA, and Europe Brent, the reference crude for the North Sea. The closing prices were extracted from the US Energy Information Administration (EIA) website. Data for WTI crude oil index covers the period from January 02, 1986 to July 03, 2007, while they go from May 20, 1987 through July 03, 2007 for Brent crude oil index. The continuously compounded daily returns are computed by taking the differences in the logarithm of two consecutive prices. These return series are then transformed into symbolic series with two symbols (1 for positive returns, and 0 otherwise) before the Shannon entropy can be applied to construct the efficiency indices.

Table 1. Statistical properties of crude oil returns

	WTI	Brent
Mean	0.012	0.025
Median	0.056	0.000
Maximum	19.150	17.333
Minimum	-40.630	-36.121
Standard deviation	2.539	2.321
Skewness	-1.045	-0.830
Kurtosis	20.966	19.982
Jarque-Bera	72793***	62982***
$Q^2(10)$	1345***	1146***

Notes: Jarque-Bera and $Q^2(10)$ refer to the empirical statistics of the Jarque-Bera test for normality and the Ljung-Box test for autocorrelation applied to squared returns, respectively. *** denotes the rejection of the null hypothesis of normality and no autocorrelation at the 1% level.

Descriptive statistics for all the daily return series are reported in Table 1. It is observed that daily return series have several features in common as far as the third and fourth moments are considered. More precisely, they are negatively skewed and have large kurtosis coefficients, compared to the levels of a normal distribution. This confirms the fact that the normality is clearly rejected according to the Jarque-Bera test statistics. We also test for serial correlations using the Ljung-Box Q statistics of order 10 based on the squared returns, and the results do not reject the null hypothesis of autocorrelations, meaning that there are some predictable patterns in daily oil returns.

Table 2. Results of unit root tests and stationarity analysis

	WTI	Brent
ADF	-41.36***	-37.85***
PP	-66.65***	-77.43***
KPSS	0.3154	0.2387

Notes: ADF is the Augmented Dickey-Fuller (1979) unit-root test statistics. PP is the Phillips-Perron (1988) unit-root test statistics. KPSS is the Kwiatkowski, Phillips, Schmidt and Shin (1992) stationarity test statistics. *** denotes the rejection of the null hypothesis at the 1% level.

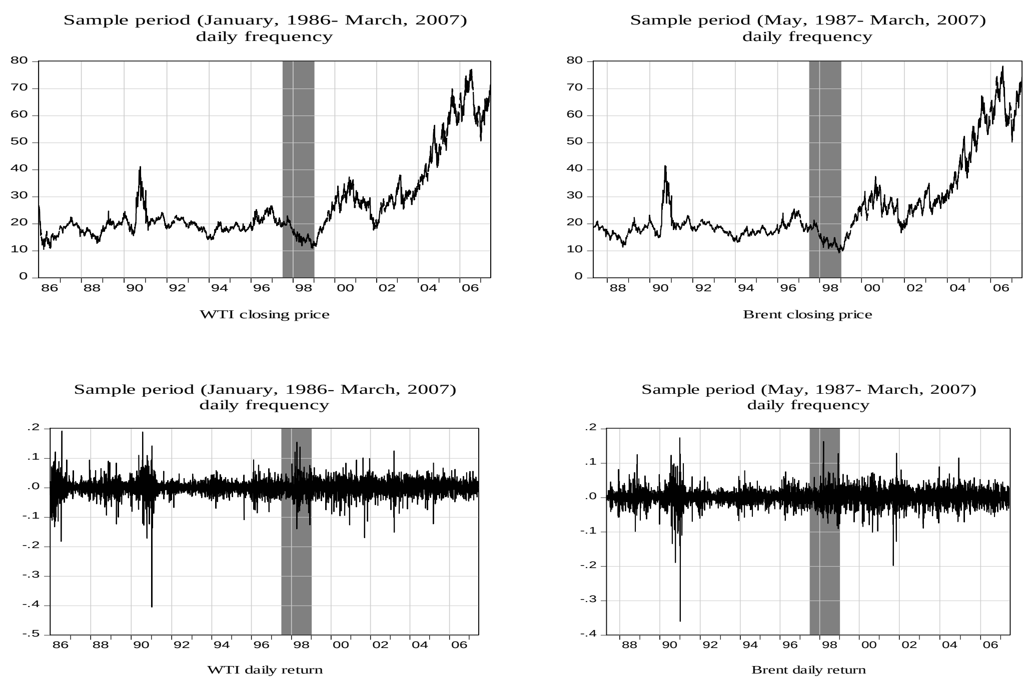

Figure 1. Time-variations of daily crude oil spot prices and returns

Table 2 presents the obtained results of some commonly used stationary tests: the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski, Phillips, Schmidt and Shin (KPSS) stationarity test.[4] Both ADF and PP tests reject hypothesis of unit root for all the daily returns, meaning that crude oil return time series are governed by an *I(0)* process which have no long-range memory. For the KPSS test, the results reveal that we cannot reject the null hypothesis of stationarity at the 1% level for all the return series.

We show, in Figure 1, the time-variations of daily crude oil prices and returns. We observe obvious signs of price and return persistence which are interrupted by some periods of strong movements, suggesting the potential of conditional heteroscedasticity in times series of oil returns. The darker region coincides with the advent of the Asian financial crisis. Moreover, the normal probability plots and the histograms against normal distribution graphs show that all the daily returns exhibit asymmetry and fat tails. Our preliminary results are in line with previous findings reported in, among others, Hung et al. (2008), and Aloui and Mabrouk (2010).

4. Empirical results

The estimation of the Shannon entropy over different rolling time-windows from the moment 1 to T (total number of observations) allows us to obtain a time-varying H series, which is our measure of efficiency. We summarize the descriptive statistics of Shannon entropy exponent for WTI and Brent crude oil markets in Table 3, and use the median to compare the levels of efficiency across markets.

Table 3. Summary statistics of the modified Shannon entropy

	WTI	Brent
Mean	0.9936	0.9940
Median	0.9935	0.9939
Maximum	0.9972	0.9979
Minimum	0.9899	0.9894
Standard deviation	0.0016	0.0018
Skewness	0.1365	0.1048
Excess kurtosis	2.4375	2.2226
Jarque-Bera	71.8921***	111.0282***

Notes: Jarque-Bera refers to the empirical statistics of the Jarque-Bera test for normality. *** denotes the rejection of the null hypothesis at the 1% level.

As we can see, the minimum of Shannon entropy exponent is equal to 0.9894 for Brent market and 0.9899 for WTI market. The maximum of Shannon entropy exponent is higher for Brent index than for WTI index. On average, both crude oil markets are not weak-form efficient since the means of the respective Shannon

4 The ADF and PP tests are based on the null hypothesis of a unit root, while the KPSS test examines the null of no unit root. In Table 3 we only report the results under the assumption of no intercept. Similar results are obtained with intercept and/or linear trend, but they are not reported here for concision purpose. The lag length of the ADF test regressions is selected using the Schwarz Information Criteria (SIC) and the bandwidth for the PP test regressions is set using a Bartlett Kernel.

entropies are below the unity (i.e., price discovery on crude oil markets is totally random). Furthermore, WTI efficiency measure appears to be less volatile than the Brent as indicated by their respective the standard deviations (0.18% for Brent versus 0.16% for WTI). The magnitude of the skewness and kurtosis coefficients indicate that both series depart from a normal distribution. Indeed, the positivity of the skewness coefficient shows that both series are asymmetrically distributed with a longer right tail. Excess kurtosis is less than 3 and significant for WTI and Brent indices. All these signs of non-normality are confirmed by the results of the Jarque-Bera test as well as the normal probability plots (against normal distribution) and the Kernel density function plots of the estimated Shannon entropy exponents for both WTI and Brent indices, as shown in Figure 2. Effectively, large and permanent deviations from normality characteristics are observed for both time series, which typically reveals that our estimated efficiency measure evolve in a non-normal manner.

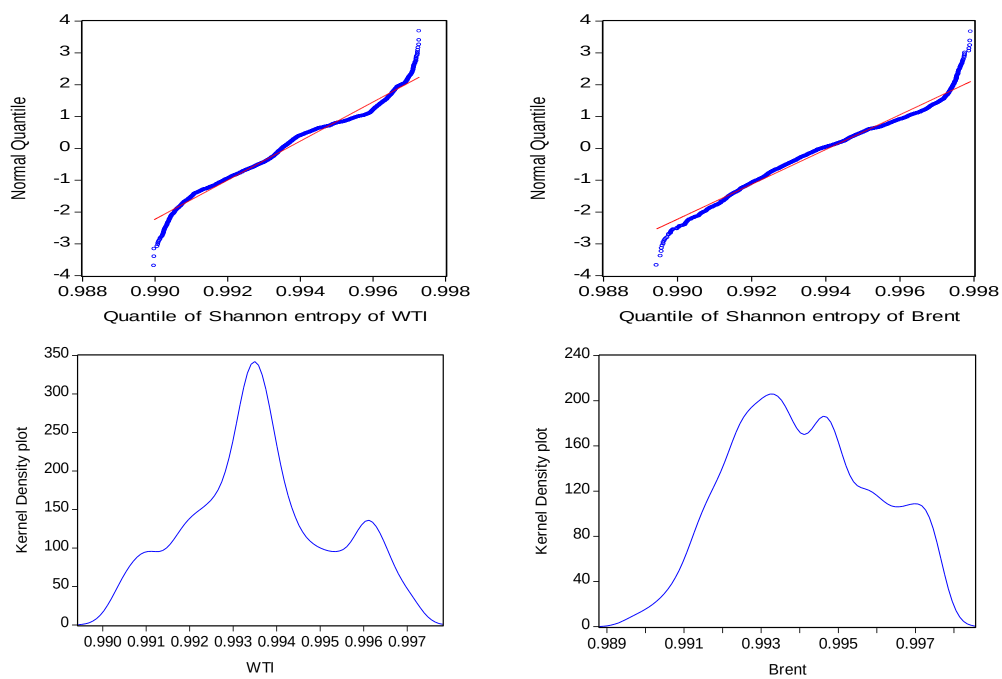

Figure 2. Normal probability and Kernel density plots of the Shannon entropy

The rejection of normal distributions of the Shannon entropy exponents requires us to perform several nonparametric tests in order to confirm our assessment that the Brent market behaves more efficiently according to Fama (1970, 1991)'s weak-form efficiency form than the WTI market, and thus to insure the robustness of relative efficiency comparison between studied markets. Note that the use of a nonparametric statistics approach also makes the economic interpretations of our findings meaningful and without any spurious bias. We apply nonparametric tests to compare the medians of the informational efficiency measure between WTI and Brent markets, and the results are reported in Table 4. As we can see, the null hypothesis of equality of medians is strongly rejected at the 1% level. This finding leads us to conclude that over the study period the median of the entropy value (*H*) is statistically larger for the Brent market than for the WTI market, or equivalently the Brent market is more efficient than the WTI one.

The difference observed in the level efficiency between two crude oil markets can be explained by the market-specific factors. Indeed, the Brent market is more international in nature and more representative of the world oil market, which typically suggests that it may contain a more important amount of information flow than does the WTI market. According to this factor, investors can execute hedging operations with ease in Brent market, and thus exploitable return-predictability opportunities will disappear quickly. By contrast, the WTI market might be exposed to significant speculation activities which deviate oil prices far from their efficient levels. In a recent study, Cifarelli and Paladino (2010) test the impact of speculative activity on the WTI oil price dynamics, and assess that this market is not a fundamentals-driven market.

Table 4. Tests of equality of medians

	Med. Chi-square	Adj. Med. Chi-square	Kruskal-Wallis	Kruskal-Wallis (tie-adj.)	Van der Waerden
WTI	2549.828	2541.362	3827.703	3827.704	3828.074
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Brent	3886.704	3876.897	3740.129	3740.129	3657.731
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)

Notes: This table reports the empirical statistics of several nonparametric tests for the equality of medians. The associated p-values are given in parenthesis. The use of these tests are indeed motivated by the fact our efficiency measures estimated from the modified Shannon entropy do not follow a normal distribution.

We are now interested in the evolving feature of crude oil market efficiency. For this we present in Figure 3 the time-paths of the Shannon entropies for WTI and Brent markets. A graphical comparison is given in Figure 4. Recall that these efficiency measures are estimated using a 4-year time-window and a time span of five days. As it can be observed, the efficiency dynamics is not similar for the two crude oil markets considered. In addition to the market microstructure reason we have mentioned above, this difference may be also explained by the matter of storage tank capacity and logistic infrastructure (Horsnell and Mabro, 1993). For instance, high levels of inventories at Cushing, due for example to uncertainties about the supply-demand conditions, tend to depress the price of the WTI crude oil market relative to the Brent market. Moreover, as noted by Charles and Darné (2009), the North American Free Trade Agreement (NAFTA) plays an important role for efficiency of crude oil market, but it has contributed to increase the efficiency level for Brent market and not for the WTI.

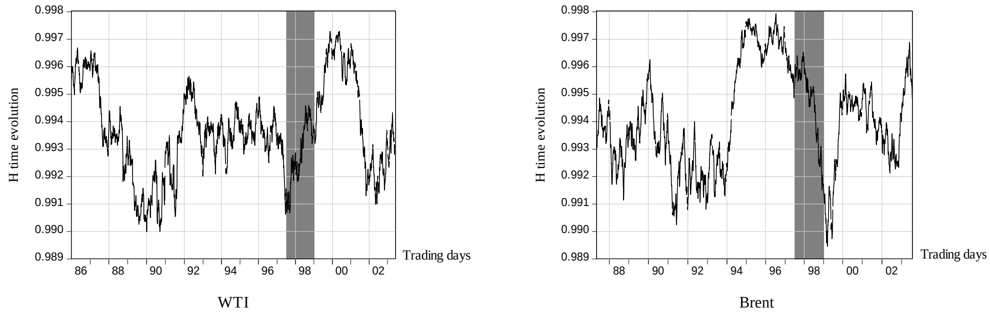

Figure 3. Time-paths of daily efficiency measure

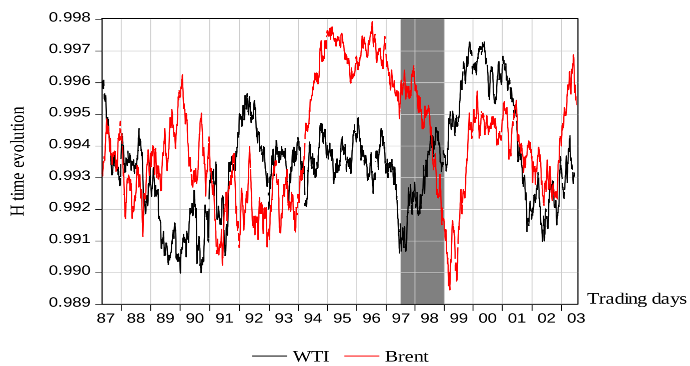

Figure 4. Comparison of evolving market efficiency

Further, a careful inspection of Figure 3 indicates that the efficiency measures of crude oil markets considered have some characteristics in common. We first observe a sudden drop in their efficiency measure in August 1990, which coincides obviously with the Iraqi Invasion of Kuwait. In September 2001 and March 2003, the WTI and Brent crude oil market efficiency attains its lowest level, and one would think that this result is due to increasing uncertainties caused by the September 11, 2001 terrorist attacks and the USA military action in Iraq (Gulf war) respectively. The devastating Asian financial crisis of 1997-1998 seems also to significantly decrease the weak-form efficiency degree of both crude oil markets. Our approach also permits us to examine this proposition by implementing a logit model where the Asian financial crisis event is represented by a binary variable (y_i) that takes the value of one during the crisis period (from July 2, 1997 to December 31, 1998) and the value of zero otherwise. The latent binary variable y_i^* is modeled as follows

$$y_i^* = \alpha + \beta H_i + \varepsilon_i \tag{4}$$

where H_i is the efficiency measure and ε_i is an error term.

The observable variable y_i is given by

$$y_i = \begin{cases} 1 & \text{if } y_i^* \succ 0 \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

The logit model can thus be represented as

$$P(y_i = 1) = \frac{1}{1 + e^{-(\alpha + \beta H_i)}} = \frac{e^{(\alpha + \beta H_i)}}{1 + e^{(\alpha + \beta H_i)}} \tag{6}$$

Table 5 reports the results of the logit model which show a negative link between the degree of week-form efficiency and the 1997-1998 Asian financial crisis.[5] Effectively, the probability of crisis increases with the decline in the efficiency measure. This result may be explained by the impacts of increased market uncertainties following the devaluation of the Thai baht, which in turn rose up the instability and the volatility of crude oil markets. The sudden withdrawal of foreign portfolio investments and increased informational asymmetries were also the factors that reduce the level of market efficiency and disrupt the oil market functioning.

Table 5. 1997-1998 Asian financial crisis and weak-form efficiency

Variable	Coefficient	Std. Error	z-Statistic	P-value
Panel A: WTI crude oil market				
α	371.151	35.866	10.348	0.0000
β	-376.069	36.124	-10.410	0.0000
Probability (LR stat.)				0.0000
Panel B: Brent crude oil market				
α	163.584	24.163	6.7697	0.0000
β	-166.320	24.317	-6.8395	0.0000
Probability (LR stat.)				0.0000

Notes: α and β are the estimated coefficients associated with the constant and the efficiency measure, respectively. The probability (LR stat.) is the probability associated with the likelihood ratio statistics.

Summarizing all, our empirical results show the evolving feature of crude oil market efficiency, but the extent to which the weak efficiency improves over time cannot be confirmed. They are also not in line with those of Tabak and Cajueiro (2007) because we find that the Brent crude oil market is more weak-form efficient than the WTI market. Following the suggestions of previous studies, we also think that market deregulation, storage and logistic infrastructure are candidate factors for explaining the difference in the degree of efficiency across markets. Indeed, all these factors appear to be less favorable for WTI market than for Brent market. For instance, Charles and Darné (2009) show that the effects of market deregulation on

[5] Lim et al. (2008), Risso (2008), and Mensi (2012) obtain similar results for other financial markets.

the efficiency of WTI market over the sub-period 1984-2008 were not effective. For their part, Horsnell and Mabro (1993) explain this result by the fact that the WTI crude oil price is significantly affected by its storage tank capacity and its logistic infrastructure. Finally, Lee and Lee (2009) report that all energy markets (coal, gas, oil, and electricity) they consider are inefficient due essentially to the lack of arbitrages opportunities.

5. CONCLUSION

A vast literature has documented the importance of the efficiency market hypothesis with respect to the actions of both investors and policymakers. In this paper we shift our focus to the examination of the efficiency hypothesis in the crude oil markets by adopting a new approach which combines the Symbolic Time Series Analysis with the Shannon entropy. Using daily oil returns for WTI and Brent crude oil indices, we find that the efficiency degree of both crude oil markets varies through time, but the Brent market is more efficient than the WTI index according to Fama (1970, 1991)'s weak-form efficiency. Moreover, the efficiency measure of the Brent market tends to decline when we approach the end of the estimation method, while the WTI market experiences increases in the efficiency degree (see, Figure 5). Furthermore, we show evidence of a negative link between the Asian financial crisis and the level weak-form efficiency in the crude oil markets.

Our conclusions have several practical implications for commodity portfolio management, forecasting crude oil market volatility shocks, and hedging crude oil market risks. That is, over the periods with higher degree of market efficiency, the crude oil prices can be reasonably viewed as accurate signals for capital allocation and pricing of oil-related products and derivatives instruments. Individual and professional investors managing global portfolios with exposure to oil price risk may believe that their funds are directed to the most productive uses. Further, a strategy of randomly diversifying across securities and market sectors with little or no information cost would generate higher benefits than any other strategies relying on larger information set and execution costs. Inversely, the periods of lower market efficiencies, being found to be quite persistent in our study, give rise to exploitable opportunities and significant speculative activities in both spot and futures markets for oil. An investor can, for example, make excess returns by appropriately buying/selling crude oil when its price is below/above the fundamental value.

ACKNOWLEDGEMENTS

The first author, Chaker Aloui, would like to thank the Deanship of Scientific Research at King Saud University represented by the research center at CBA for supporting this research financially.

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