

Pairs trading in the index options market^{*}

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Abstract

We test the Index options market efficiency by means of a statistical arbitrage strategy, i.e. pairs trading. Using data on five Stock Indexes of the Euro Area, we first identify any potential option mispricing based on deviations from the long-run relationship linking their implied volatilities. Then, we evaluate the profitability of a simple pair trading strategy on the mispriced options. Despite the signals of potential mispricing are frequent, the statistical arbitrage does not produce significant positive returns, thus providing evidence in support of Index Option market efficiency. The time-to-maturity of the options involved in the trade as well as financial market turbulence have a marginal effect on the eventual strategy returns, which are instead mostly driven by the moneyness of the options traded. Our results remain qualitatively unchanged if a stricter definition of reversion to the equilibrium is applied or when the long-run relationship is estimated on an (artificially derived) time series of options prices rather than on options' implied volatilities.

Keywords: pairs trading, option market efficiency

JEL Codes: G10, G12, C44, C55

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1. Introduction

We investigate the index option market efficiency through pairs trading, a specific kind of statistical arbitrage strategy.

The Efficient Market Hypothesis (EMH), as postulated by (Fama, 1970), claims that no abnormal return can be obtained on the market if information is fully disclosed.² Indeed, the agents able to identify mispriced securities will immediately exploit all the arbitrage opportunities, making them quickly disappear. Hence, the EMH is relatively easy to test: it can be disproved if it is possible to systematically identify and exploit arbitrage opportunities in order to obtain profits. In this paper we follow this approach and test for Index options market efficiency by verifying the absence of arbitrage opportunities. We do so by means of a statistical arbitrage approach, i.e. pairs trading, which requires the identification of pairs of assets whose prices commove and the setting of a trading rule to profit from prices divergences. This approach is typically applied to stocks. So, we first adapt the procedure of pairs formation to options, which are assets remarkably different (both financially and statistically) with respect to stocks. Once couples of options are created, and a stationary and mean-reverting relationship between them is established, a simple pair trading strategy is implemented whenever such relationship appears to be violated. A significant profitability of such trading strategy will be thus interpreted as evidence against the EMH.

In our application we use at-the-money one-month maturity (with a time-to-maturity ranging between 10 and 46 calendar days) Index options. This choice comes with several advantages. First, since the underlying is a synthetic representation of a stocks' portfolio, the final payoff is cash-settled rather than paid through an exchange of goods. Hence, no other transaction costs are incurred to cash-in the payoff, aside from those strictly deriving from the trade. Second, at-the-money options are the most informative in terms of volatility, as most of their value is driven by this component. This is very important for our application since the long-run equilibrium relationship between pairs of options is established through their (implied) volatilities. Last, short-term-maturity options are among the most liquid in the market, thus guaranteeing sufficient data for the empirical application.

Being the first applying pairs trading to test Index Options market efficiency, this paper represents a novel contribution to both the strands of literature dealing with option market efficiency, on the one hand, and with statistical arbitrage, and in particular pair trading, on the other. Both these strands of literature are briefly reviewed in Section 2 those two literatures. Section 3 outlines the methodology and the arbitrage strategy employed to test market efficiency, while Section 4 presents the dataset used, covering all dead call options on five European Stock Indexes during the period from May 2007 until the end of 2017. Finally, Section 5 discusses the robustness of the results and last Section concludes.

² The literature differentiates levels of market efficiency based on the definition of "available information" (Fama, 1991). In its Weak Form, the information is limited to the past history of prices; in its Semi-Strong Form all publicly available information is included; in its Strong Form all existing information, both public and private, is considered (Jensen, 1978).

2. Literature review

This work relies at the intersection of two distinct streams of literature: the one testing for Index option market efficiency and the one implementing statistical arbitrage strategies, such as pairs trading, which so far has been tested on stocks (and few other types of assets), but never on options.

Index options market efficiency can be tested by means of either model-based or model-free methodologies. The former approach involves the so called “joint hypothesis problem”, pointed out by Fama (1998). Indeed, when model-based tests are used, market efficiency and the appropriateness of the pricing model used are jointly tested, so that evidence of no efficiency may indeed be due to the (wrong) pricing model being used rather than disproof of the EMH. As a result, most of the previous contributions on Index options market efficiency amount to test the absence of arbitrage opportunities.³ Following the seminal paper by Stoll (1969), many contributions have tested the no-arbitrage relationships on the option market, with special focus on the US. For instance, Evnine and Rudd (1985) reported significant violations of the put-call parity and of the boundary conditions for the S&P100 option market, thus advocating market inefficiency. Many years after and working with S&P500 index options, Ackert and Tian (2001) reach the opposite conclusion. Concurrently, tests have been carried out on the European markets, by e.g. Capelle-Blancard and Chaudhury (2001) for the French index (CAC40) option market, Mittnik and Rieken (2000) for the German index (DAX) option market, Cavallo and Mammola (2000) and Brunetti and Torricelli (2005) for Italian index (Mib30) option market. They all conclude in favor of index option market efficiency highlighting the pivotal role of market frictions: if, on the one hand, arbitrage opportunities are frequent, on the other, they almost completely disappear once transaction costs are taken into account.

As Bondarenko (2003) puts it, however, two different types of arbitrage opportunities can be identified: a “*Pure Arbitrage Opportunity*, i.e. a zero-cost trading strategy that offers the possibility of a gain with no possibility of a loss”, and a “*Statistical Arbitrage Opportunity*, i.e. a zero-cost trading strategy for which (i) the expected payoff is positive, and (ii) the conditional expected payoff in each final state of the economy is non-negative”. In both cases, the average payoff in each final state is non-negative. The main difference is thus the possibility of negative payoffs, which are allowed in the statistical arbitrage opportunity but not in the pure one. All the above-cited works on Index Option market efficiency test the absence of *pure* arbitrage opportunities. To the best of our knowledge, there is no evidence on the index option market efficiency based on *statistical* arbitrage.

Turning to statistical arbitrage, the most well-known application belonging to this approach is certainly pairs trading, which identifies assets whose prices share a similar behavior and tries to exploit deviations from this long-run equilibrium to make profits. Pairs trading has

³ The literature differentiates between cross-markets efficiency, which is based on tests of the joint efficiency of the option and the underlying market (by verifying the put-call parity and the lower-boundary conditions), and the internal option market efficiency, that aims to assess the existence of arbitrage opportunities within the very same option market (by verifying, e.g., box and butterfly spreads).

been implemented using a variety of approaches, which differentiate based on the way pairs are selected (Krauss, 2017). For instance, in distance approach assets are paired by minimizing the sum of squared deviation between normalized prices, while in cointegration approach, pairs are identified based on cointegration tests. Regardless of which of the approaches is used, the literature on pairs trading is largely and almost entirely applied to the stock market. Many works focus on the U.S. one, such as (Gatev, Goetzmann, & Rouwenhorst, 2006; Avellaneda & Lee, 2010; Do & Faff, 2010; Miao, 2014; Jacobs & Weber, 2015; Rad, Low, & Faff, 2016), but some further applications can be found to other stock markets, such as the European (Dunis & Lequeux, 2000), the Japanese (Huck, 2015), the Brazilian (Perlin, 2009; Caldeira & Moura, 2013), the Chinese (Li, Chui, & Li, 2014) and the Taiwanese one (Andrade, Di Pietro, & Seasholes, 2005).⁴

To sum up, the efficiency of the Index options market has so far been investigated using pure arbitrage strategies only, while statistical arbitrage, and in particular pairs trading, has been mostly applied to stock market.⁵ The only paper we are aware of that falls into the intersection of these literatures is Ammann and Herriger (2002), who apply a statistical arbitrage strategy to the Implied Volatilities of options on S&P500, S&P100 and NASDAQ Indexes. In their contribution, the authors estimate a stationary and long-run equilibrium relationship between the underlying indexes returns, which they then use to derive a valid mean-reverting relationship for the options' implied volatilities. This mean-reverting strategy is thus used to identify potential mispricing of the options. Using data from 1995 to 2000, they find that profits stemming from relative mispricing of options are indeed frequent, albeit they rarely survive once transaction costs and bid and ask spread are taken into account, concluding, consistently with most of the literature, in favor of index option market efficiency. This paper contributes to the still unpopulated literature testing the efficiency of the Index options market based on pairs trading, and proposes a small variation with respect to Ammann and Herriger (2002): the mean-reverting relationship is estimated directly on the implied volatilities, rather than indirectly derived from the one estimated on underlying index returns.

3. Methodology

We use statistical arbitrage, and in particular pairs trading, to test the Index options market efficiency. Among the different approaches proposed in the pair trading literature, we will rely on the cointegration approach, given its proved superiority in term of profitability (Huck & Afawubo, 2015; Rad, Low, & Faff, 2016; Blázquez, De la Orden, & Román, 2018). In this approach, the pairs of assets sharing a long-term equilibrium relationship are pinpointed

⁴ Examples of works applying PT to securities other than stocks include Girma and Paulson (1999) and Cummins and Bucca (2012), who focus on the “crack spread”, that is the difference between petroleum and its refined products futures prices. Simon (1999) works on the “crush spread”, namely the difference between soybean and its manufactured goods futures prices. Emery and Liu (2002) work with the “spark spread”, i.e. the difference between natural gas and electricity future prices.

⁵ See Hogan *et al.* (2004) for a review of statistical arbitrage applications to test market efficiency.

based on cointegration tests. Then, a simple trading strategy is implemented anytime deviations from the equilibrium are observed. However, applying cointegration to Index options rather than to stocks poses a major challenge, which is due to the fact that, by their own nature, options have a finite life. This implies that we may not have enough data to train the classical cointegration approach: in most of the applications the formation period employed to test for cointegration lasts one year. To overcome this problem, Ammann & Herriger (2002) rely on the returns of the underlying indexes. More specifically, after having pre-selected pairs of indexes that have highly correlated daily returns, they check the returns' stationarity, and then they estimate the long-run relationship linking Indexes' returns, rather than on Index Option prices. Finally, they use the obtained estimates to derive the corresponding long-run relationship that should hold between the volatilities of the paired Options. The idea is that, if the quotations of the underlying indexes are highly correlated, and the market is efficient in pricing similar risks, the volatilities of the options written on those indexes should share a relationship. If violations of such an equilibrium-relationship between volatilities are systematically observed, then market efficiency is disproved. We differ from Ammann & Herriger (2002) since we identify the potential mispricing based on the long-run relationship estimated on options' implied volatilities directly, rather than on the one estimated on underlying indexes' returns, and then applied to the volatilities. In doing so, we avoid to assume that the same relationship links the Indexes' returns and the Index Option volatilities.

The proposed methodology is thus structured as follows:

1. Check for stationarity: using data over the full sample, run ADF tests to check for stationarity of the options' implied volatilities (IV);
2. Using 1-year observations, which serve as estimation period, regress the IV_Y on the IV_X , for all options written on the pairs of indexes (Y, X), so as to obtain the estimates required to derive the Spread;
3. Moving to the following 6-month observations, which serve as trading period, compute the Spread, implement a simple trading strategy whenever a misprice is suspected, i.e. when the Spread significantly diverges from zero, and evaluate the profitability of this trading strategy;
4. Rolling regression: steps 2 to 3 are repeated shifting the sample one month ahead at each repetition, so as to evaluate the results independently of the starting point and to update the information set as time passes. Notice that this produces for each month in the sample (except the first and last 5), 6 overlapping trading strategies.

The profitability of this trading is thus evaluated by looking at the total number of trades opened, as well as the average number of days a position is kept opened and the average returns across the 6 different overlapping trading strategies. The statistical significance of the returns will be tested by means of the Newey-West statistics (Newey & West, 1987). Evidence of significant returns stemming from such trading will be thus interpreted as evidence against option market efficiency.

The next subsections describe steps 2 and 3 of the procedure in greater detail.

3.1 Estimation period

Using 1-year data, the following OLS regression is estimated:

$$IV_{t,Y} = \beta_0 + \beta_1 IV_{t,X} + \varepsilon_t \quad (1)$$

where:

- $IV_{t,Y}$ is the implied volatility of the option written on Index Y observed at day t
- $IV_{t,X}$ is the implied volatility of the option written on Index X observed at day t
- ε_t is the error term at time t
- β_0 is the intercept, that in this case simply acts as a scale parameter
- β_1 is the slope, measuring the linear relationship between the two implied volatilities

The estimate is performed for all possible pairs of indexes (Y, X).

Notice that using IV, which are typically stationary time series, allows a correct measurement of their association via OLS regression, as opposed to what happens when this approach is applied to stock prices, which typically are $I(1)$ time series.

3.2 Trading period

Each estimation period is followed by a six-months trading period, in which a simple pair trading strategy is implemented any time one of the options has an observed implied volatility that sufficiently deviates from the predicted value based on the estimates of model (1). The idea is that, when this divergence is detected, the agent could sell the relatively overpriced option and buy the other one so as to close the position whenever the two volatilities align again. If such a strategy is able to generate significant profits, the market efficiency in pricing relative risks is actually disproved.

A definition of “sufficient deviation” is thus required. To this end, using the estimates of β_0 and β_1 obtained in the estimation period, we compute the *Spread*⁶ as:

$$Spread_t = IV_{t,Y} - \hat{\beta}_0 - \hat{\beta}_1 IV_{t,X} \quad (2)$$

The Spread is thus obtained as the out-of-sample residuals of model (1). Under stationarity of both variables involved in the simple linear regression model, in-sample residuals are also a stationary process, mean-reverting towards 0. We take advantage of this characteristic out-of-sample and detect a “significant” deviation of $Spread_t$, from its long-run value of 0, any time the following relationship is violated:

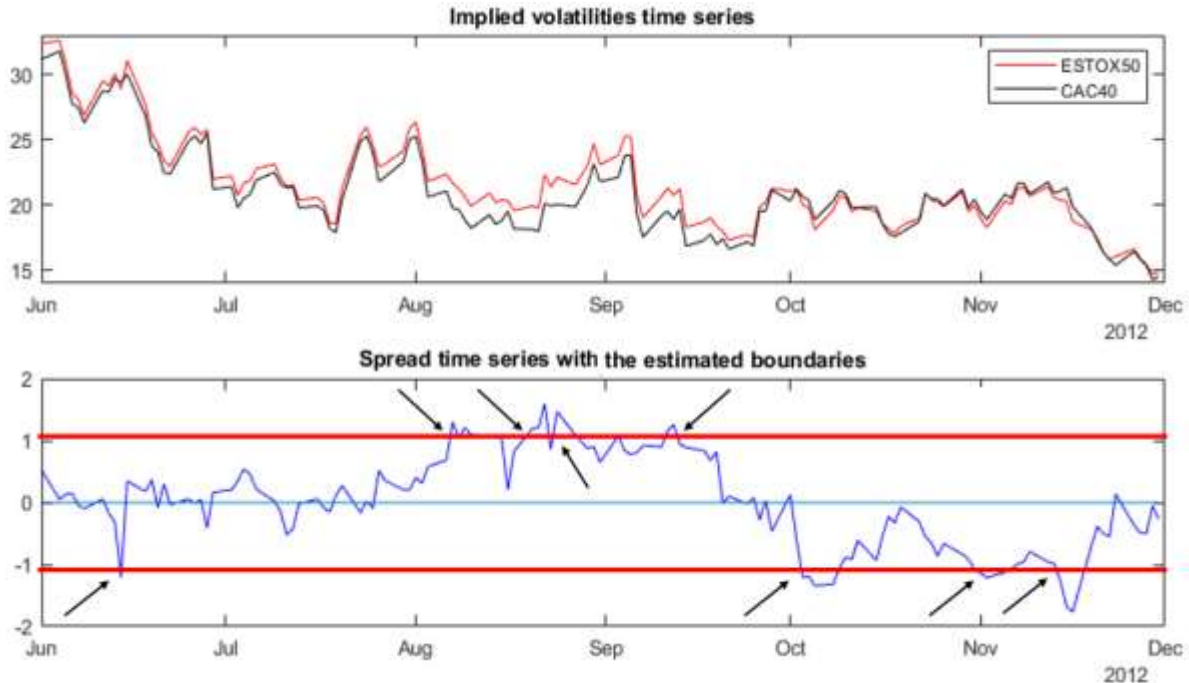
$$2\hat{\sigma} \geq Spread_t \geq -2\hat{\sigma} \quad (3)$$

where $\hat{\sigma}$ is the standard deviation of the residuals obtained in regression (1). All exits of the Spread from these boundaries will be interpreted as a misalignment of the options’ implied volatilities from their relationship as estimated in model (1), will be thus signaling a potentially profitable mispricing, and will hence trigger a trading strategy. As an example, the top panel of Figure 1 reports the time-series of the Implied Volatilities of one-month maturity ATM call options written on CAC40 and ESTOX50 Indexes, which clearly share the same pattern. The

⁶ This definition, including the estimated intercept, follows the one proposed by Vidyamurthy (2004).

spread between these implied volatilities, along with its $\pm 2\hat{\sigma}$ boundaries, are instead plotted in the bottom panel: the trading is triggered very time the spread exists the boundaries, as pointed by the arrows.

Figure 1 - Example of implied volatilities and Spread time series



Notes: The top panel reports the time-series of the Implied Volatilities of one-month maturity ATM call options written on CAC40 (black line) and ESTOX50 (red line) Indexes, between the 1st of July and the 31st of December 2012. The bottom panel reports the estimated spread between these two implied volatilities (in blue) and $\pm 2\hat{\sigma}$ boundaries (in red). The black arrows indicate when the trading is triggered.

Consistently with the practice established in the pair-trading literature, we set up two types of trading strategies: a “self-financing” strategy, in which the quantities traded in the two stocks are such that no initial capital investment is required, and a “beta-arbitrage” strategy, in which the quantities traded in the two stocks are determined as a function of the regression slope estimates.

More specifically, if $Spread_t > 2\hat{\sigma}$, the option written on index Y is suspected to be overpriced with respect to option written on index X . Therefore, in the self-financing strategy, one unit of option written on index Y is sold and at the same time the option written on X is bought in the amount affordable under the proceeds from the previous sale. In the beta-arbitrage strategy, one unit of option written on Y is sold and the quantity bought of option on X equals to the amount bought in the self-financing strategy multiplied by $\hat{\beta}_1$ (the idea is that the amount in euros spent for option written on X is equal to $\hat{\beta}_1$ times the price of option Y). Both positions are then unwounded when the $Spread$ reverts within the estimated boundaries. Finally, all the open positions are forcibly closed when the end of the trading period is reached or when the options get to maturity (to reduce the sensitivity of the results to the natural decline of the options prices when approaching expiration, the positions are closed two days before maturity).

Conversely, if $Spread_t < -2\hat{\sigma}$, the option written on Y is suspected to be underpriced with respect to the option written on X , so that the trading scheme is exactly the opposite. In the self-financing strategy, one unit of option written on X is sold and with the proceeds from the sale the affordable amount of option on Y is bought. In the beta-arbitrage strategy, one unit of option on X is sold and the quantity of option written on Y will be the same bought in the self-financing strategy divided by $\hat{\beta}_1$. As above, all the positions are closed when the *Spread* reverts within the estimated boundaries, or when the maturity of the option and/or the end of the trading period is reached.

To reduce the sensitivity of our results to the natural decline of the options prices when approaching expiration, all positions are forcibly closed two trading days before maturity. Each transaction payoff and the final returns are computed once the initial trade is unwound and will depend on the relative price of the traded options. Notice that returns can be interpreted as excess returns only in the self-financing strategy since no initial investment is needed. Instead, in the beta-arbitrage strategy the payoff when the trade is initiated depends on $\hat{\beta}_1$ and affects the final outcome of the transaction.

4. Empirical application

In this section we first present the dataset used and then the results obtained in terms of profitability of the pair trading strategy described above.

4.1 Data

The empirical application relies on daily data spanning the period from the 1st of May 2007 until the 31st of December 2017, for a total of 2784 days, and referring to five Stock Indexes of the Euro Area, namely:

- CAC 40 (Cotation Assistée en Continu), quoted on the Paris Bourse;
- DAX 30 (Deutscher Aktienindex), quoted on the Frankfurt Stock Exchange;
- FTSE 100 (Financial Times Stock Exchange 100 index), quoted on the London Stock Exchange;
- FTSE MIB (Financial Times Stock Exchange Milano Indice di Borsa), quoted on the Milan Stock Exchange;
- ESTOX 50 (Euro STOXX 50): leading stock index for the Eurozone, covering 50 stocks from 11 Eurozone countries (Austria, Belgium, Finland, France, Germany, Ireland, Italy, Luxembourg, Netherlands, Portugal and Spain).

The advantage of focusing on options written on Indices is that, given that the underlying is a synthetic representation of a stocks' portfolio, the final payoff is cash-settled rather than paid through an exchange of goods. Hence, no other transaction costs are incurred to cash-in the payoff, aside from those strictly deriving from the trade.

For each Index, we use the following data, all retrieved from Thomson Reuters DataStream⁷:

- Stock Index Prices;
- Options Prices of all the Call options written on the index, along with their maturities and strike prices⁸;
- Implied Volatilities of the at-the-money 1-month maturity Call Options written on the index.

For each day in the sample and for each underlying Index, we select the at-the-money (ATM henceforth) call options. We focus on ATM options since most of their market value is related to volatility, so that they are the most informative in this sense. This is very important for our application since the long-run equilibrium relationship between pairs of options is established directly through their (implied) volatilities.

Among the ATM options, we then select the one with the shortest maturity, since short-term-maturity options are among the most liquid in the market. In doing so, we exclude those with a residual life equal or less than 10 days, with the twofold aim to guarantee the possibility of trading on that option and to reduce the sensitivity of the results to the natural decline of the options prices when approaching expiration. This leaves us with ATM one-month options whose time-to-maturity ranges between 11 days (corresponding to at least 7 trading days) and 46 days (corresponding to at least 32 trading days).

Finally, we select the one whose strike price is as close as possible to the value of the underlying Index. If two series are found to have the same absolute distance between strike and Index price, we exclude the one with higher strike price, so as to maintain the one more conservative in terms of final payoff.⁹

We thus end up, for each day in our sample, with one single ATM one-month call option for each of the underlying indexes considered.¹⁰

⁷ Through a deep analysis of the data and with the support of the data provider, many recording errors have been corrected directly on Thomson Reuters DataStream. Most of such issues were due to the same identification code being attributed to more than one series at different points in time.

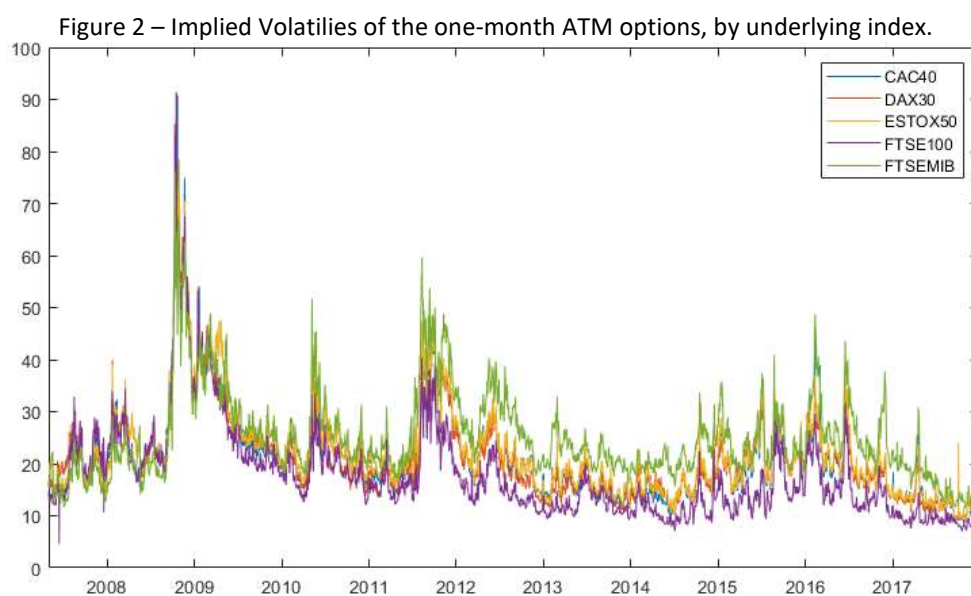
⁸ FTSE 100 call options prices are in pound sterling, while all others are quoted in euros. The corresponding daily GB Sterling/Euro FX exchange rate is thus used to convert in euros the prices of options on FTSE 100. The identifying number of each series is 6239 for CAC 40, 12158 for DAX 30, 11939 for ESTOX 50, 9501 for FTSE 100 and 7303 for FTSE MIB. In DataStream missing values on option prices are replaced with the previous day observation.

⁹ In the selection process, we further exclude all call options with non-standard maturity, i.e. with a maturity settled in a different day from the third Friday of the month, as well as some calls presenting two series for the same strike price. For these reasons, we excluded one option on the CAC 40, one option on the ESTOX 50 and six options on the FTSE 100.

¹⁰ Notice that the ATM one-month call option selected in a certain day, in which a trade is maybe opened, is not necessarily the same ATM one-month call option selected in another day. This means that it might happen that the call selected for the day a trading is opened does not coincide with the one selected for the day the same trade is closed. Thus, in order to have the prices of the traded option in both the day in which the trade is triggered and in the day in which the trade is closed, needed to compute the actual profits obtained trading an option, we needed to store, for each selected option, the entire time-series of the prices. As a result, we actually end up with 2784 (one for each day in our sample) option prices time-series.

4.2 Preliminary analyses

The time series of the implied volatilities of one-month maturity ATM options written on the selected Indexes are represented in Figure 2. Two major shocks are distinctly common to all series, namely the outburst of the global Financial Crisis at the end of 2008 and the Sovereign Debt Crisis at the end of 2011, both having brought instability (i.e. higher volatility) to the European Financial Market. The series however share a very similar pattern also outside these two extreme events, so the possibility of finding strong relationships between the IV of the five underlying indexes seem quite high.



Note: The figure reports the time series of the Implied Volatility of the at-the-money 1-month maturity call options written on the following stock market indexes: CAC40, DAX 30, FTSE 100, FTSE MIB, ESTOX 50, from 1st of May 2007 until the 31st of December 2017.

The similarity of the Implied Volatilities across the five underlying indexes is further confirmed by the degree of variability, which is very similar across the series (see panel A of Table 1) and the quite high level of correlation (panel B of Table 1 - Descriptive statistics, correlation and ADF test: one-month ATM options Implied Volatilities, by underlying Index Table 1), which never falls below 0.75.¹¹

Table 1 - Descriptive statistics, correlation and ADF test: one-month ATM options Implied Volatilities, by underlying Index

Panel A – Option Implied Volatilities					
	CAC 40	DAX 30	ESTOX 50	FTSE 100	FTSE MIB

¹¹ In pairs trading applications the initial set of potential pairs is often artificially narrowed to highly correlate (for instance, Miao, 2014, and Ammann & Herriger, 2002, pre-select pairs of stocks with correlation greater than 0.95). In our application none of the pairs has been excluded, thus avoiding the need of setting an arbitrary threshold for correlation.

Mean	21.59	21.14	22.23	17.75	24.98
St. Deviation	8.95	8.70	8.85	8.91	8.30
Min	8.34	9.05	8.84	4.62	10.36
Median	19.65	19.11	20.32	15.40	23.04
Max	90.74	89.41	78.49	91.41	76.24
Panel B – Correlation across Option Implied Volatilities					
	CAC 40	DAX 30	ESTOX 50	FTSE 100	FTSE MIB
CAC 40	1	0.97	0.98	0.95	0.87
DAX 30		1	0.97	0.94	0.86
ESTOX 50			1	0.94	0.89
FTSE 100				1	0.75
FTSE MIB					1
Panel C – ADF tests on Implied Volatilities					
	CAC 40	DAX 30	ESTOX 50	FTSE 100	FTSE MIB
ADF – with drift test statistics					
pvalue				0.0083	
ADF – with trend and drift test statistics					
pvalue					

Notes: The table reports the main descriptive statistics for the Implied volatilities of one-month maturity ATM call options over the entire sample period (panel A), the Pearson Correlation Coefficient across the Implied Volatilities (panel B), and the t-statistics, and associated p-values, of the ADF test with drift only and with trend and drift, by underlying Index.

The Augmented Dickey-Fuller test for stationarity are then run on the implied volatilities. The ADF was run setting a maximum lag length equal to 15 and with both drift-only and drift and trend specifications. In all cases, the null for the presence of unit-root null is rejected a 95% confidence level. The IV are thus stationary time-series highly correlated across each other and apparently following a similar pattern over time, which we are going to exploit in the pair trading statistical arbitrage. If such trading strategy is able to produce significant profits, then EMH can be disproved.

4.3 Main Results

Table 2 reports the results of the self-financing and the beta-arbitrage trading strategies, implemented over the trading period spanning from the 1st of May 2008 until the 31st of December 2017 (data from the 1st of May 2007 till 30th of April 2008 are used in the first estimation period).

To begin with, the number of trades realized (column 13 of Table 2) is quite high, meaning that during the sample period under analysis the spread kicked the estimated boundaries, thus signaling potential mispricing on the market, in many occasions.¹² The vast majority of

¹² These figures are cumulative across the six overlapping portfolios, so some trades might be double counted. Yet, even assuming that all trades are common across the six portfolios, the overall number of suspected mispricing would still be pretty high (equal to $11191/6 = 1865$ trades). Considering that the trading days in our sample are 2419 (2784 -365), this figure would suggest an average of nearly 1 trade every day ($2419/1865=1.30$).

these trades(88%), which on average remain opened for 4 days, close because the *Spread* reverts within the boundaries, while the rest are forcibly closed either because the options involved in the trade expire (8%) or because the end of the trading period is reached (3%).

Despite the number of suspected mispricing is quite high, the average returns eventually obtained implementing the self-financing strategy (which are directly interpreted as excess returns since this strategy does not require initial investment) are indeed pretty low, on average around 0.8%, and not statistically significant, as shown in column (1) of Table 2. The corresponding extra-profit is equal to 9.30€, but again this is far from being statistically significant. Dissecting the result by the pairs of underlying indexes on which the traded options are written, we find that option pairs trading proved to be significantly profitable in 6 cases out of the 20 possible couples, with excess returns ranging from 4.3% (for the couple FTSEMIB-CAC40, corresponding to 15.60 € in terms of average profit) to as much as 13.6% (for the FTSEMIB-DAX30 couple, corresponding to an average profit of 56.60€). In all other cases, the strategy does not provide significant returns, and in 4 cases it even leads to statistically significant negative returns, all of which include the FTSE100, which points towards the required exchange rate conversion in Euro as playing as an additional source of friction.

The beta-arbitrage strategy differs from the self-financing strategy only in terms of traded quantities, so that the number of transactions and the closure reasons are unaffected. Recall however that, since in this case an initial investment is needed, the obtained returns cannot be interpreted as excess returns. The average returns observed across all pairs are still positive but much higher if compared to the one obtained implementing the self-financing strategy (7.3% on average against 0.8%).¹³ Nonetheless, consistently with the results for the self-financing strategy, the average return is not statistically significant. Moreover, looking at the returns by pairs, statistically significant positive returns survive only for the pairs written on FTSEMIB and on the ESTOX50.

All in all, despite the signals of potential mispricing are frequent, the statistical arbitrage does not produce significant positive expected returns, leading to the conclusion that there is no evidence against index option market efficiency. Notice that all the results presented so far are computed without taking transaction costs into account. Their inclusion in fact is likely to further reduce the profitability of the strategies, so our conclusion about index option market efficiency is reached under the most conservative condition.

¹³ The higher average return obtained is most likely due to the fact that the estimates obtained for beta are in most of the cases very close to one. In the beta-arbitrage strategy, one unit of option written on Y is sold and the quantity bought of option on X equals to the amount affordable under the proceeds from the previous sale multiplied by $\hat{\beta}_1$. If the estimates of $\hat{\beta}_1$ is very close to one, this means that the initial investment is very close to zero, which results in inflating the estimated final return.

Table 2 – Results for the option pairs trading self-financing and beta-arbitrage strategies, by pairs of underlying indexes.

	Self-financing strategy				Beta-arbitrage strategy returns				Closing			Average life	Total number of trades
	Average returns	NW stat	Average Profits (or losses)	NW stat	Average returns	NW stat	Average Profits (or losses)	NW stat	Boundary	Maturity	Trading period end		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)		
CAC40-DAX30	0.003	0.18	3.77	1.21	-0.510	-0.97	6.01*	1.93	0.82	0.14	0.04	5.33	468
CAC40-ESTOX50	-0.004	-0.64	-1.06**	-2.19	-1.701	-1.31	-1.00**	-2.13	0.97	0.02	0.01	2.60	525
CAC40-FTSE100	-0.042**	-2.59	-6.51***	-3.33	-0.834	-1.13	-6.25***	-3.08	0.86	0.09	0.05	4.31	538
CAC40-FTSEMIB	0.044***	3.46	31.02***	4.21	0.733	1.30	23.12***	2.81	0.88	0.08	0.04	3.99	560
DAX30-CAC40	0.007	0.39	5.18*	1.85	0.484	0.36	5.90**	2.06	0.82	0.13	0.05	5.51	448
DAX30-ESTOX50	0.005	0.40	1.35	0.89	-0.341	-0.50	2.89*	1.69	0.89	0.08	0.03	4.33	480
DAX30-FTSE100	-0.022	-1.32	-5.91**	-2.29	-0.256	-0.09	-6.42**	-2.12	0.88	0.09	0.03	4.17	653
DAX30-FTSEMIB	0.059***	2.93	39.66***	3.44	0.307	0.27	31.75**	2.62	0.85	0.11	0.04	4.72	570
ESTOX50-CAC40	0.006	0.87	0.34	0.66	-0.973	-1.62	0.64	1.23	0.97	0.02	0.01	2.57	560
ESTOX50-DAX30	0.023*	1.82	3.89**	2.23	-0.866	-0.94	6.34***	3.18	0.84	0.12	0.04	4.81	504
ESTOX50-FTSE100	-0.094***	-5.67	-12.34***	-5.95	-0.374	-1.47	-10.98***	-4.92	0.90	0.07	0.03	4.23	524
ESTOX50-FTSEMIB	0.051***	5.42	30.37***	5.14	0.551**	2.70	28.17***	3.97	0.92	0.05	0.03	3.58	683
FTSE100-CAC40	-0.037**	-1.85	-2.32	-1.10	-0.501	-0.89	-4.22**	-2.01	0.83	0.12	0.05	4.74	507
FTSE100-DAX30	-0.013	-0.86	-4.05	-1.61	0.013	0.03	-6.10**	-2.31	0.86	0.10	0.04	4.22	747
FTSE100-ESTOX50	-0.065***	-3.65	-4.70***	-2.86	2.328	0.95	-5.44***	-3.31	0.89	0.08	0.03	4.31	519
FTSE100-FTSEMIB	0.008	0.32	16.64	1.21	-0.702*	-1.87	6.03	0.41	0.84	0.12	0.05	4.69	597
FTSEMIB-CAC40	0.043***	3.49	15.60***	2.96	0.192	0.61	15.55**	2.41	0.92	0.05	0.03	3.34	539
FTSEMIB-DAX30	0.136***	6.16	56.60***	5.35	2.410	1.31	60.36***	4.10	0.87	0.10	0.03	4.43	547
FTSEMIB-ESTOX50	0.054***	5.64	19.67***	5.00	0.464**	2.67	22.86***	4.49	0.94	0.03	0.03	3.05	683
FTSEMIB-FTSE100	-0.024	-0.96	-9.77	-0.82	0.824	0.52	0.54	0.04	0.90	0.06	0.04	3.72	539
ACROSS ALL PAIRS	0.008	0.02	9.30	0.06	0.073	0.00	8.78	0.05	0.88	0.08	0.03	4.09	11191

Notes: The table reports the results of the self-financing (columns 1 to 4) and beta-arbitrage (columns 5 to 8) pair trading strategies. For each strategy we report the average return and the average profits (if positive) or losses (if negative), whose statistical significance is tested based on the Newey-West heteroskedasticity and autocorrelation robust t-statistics (Newey & West, 1987). The symbols ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Columns 9 to 11 report the shares of trades closed due to the Spread reversion within the boundaries, due to option expiration and due to having reached the end of the trading period, respectively. The last two columns report the average number of days the trades remained opened, and the total number of trades observed. The results are reported by pairs of underlying indexes and refer to the trades triggered by the deviations of the spread estimated based on the regression where the Implied Volatility of the option written on the first underlying Index is used as X and the Implied Volatility of the option written on the second as Y.

4.4 Profitability drivers

We are interested in spotting the potential drivers of the profitability of index option pairs trading. To this end, we regress the observed returns of the pairs trades on the characteristics of both options involved in the trade, i.e. the one bought (long) and the one sold (short), and on the overall condition of the financial market at the moment the trades took place. All variables in the regression are measured at the moment the trade is closed.

The value of an option is function of several features, namely: moneyness, i.e. the closeness between option strike price and price of the underlying asset; time to maturity, i.e. the time left before expiration; the volatility of the underlying quotations; and, the interest rate. Since the latter two are (supposed to be) common across all options traded in the market, we focus on the time to maturity and the moneyness. The former is measured by the number of trading days left before the option expires. The value of the option increases with the time left to maturity, so the longer the maturity, the more (less) the chances of making a profit when a long (short) position is taken. We thus expect the profitability of the pair trading strategy to be positively associated with the maturity of the long option and negatively associated with the one of the sold option. As for moneyness, we focus on the strike-price ratio, $\left(\frac{K}{S}\right)$, which in our sample ranges in the interval [0.8 - 1.36] for the options sold and [0.85 - 1.62] for the ones bought, with mean and median in both cases approximately equal to 1.¹⁴ We classify each option as follows:

$$\begin{cases} ITM & \text{if } \left(\frac{K}{S}\right) < 0.98 \\ OTM & \text{if } \left(\frac{K}{S}\right) > 1.02 \\ ATM & \text{otherwise} \end{cases} \quad (4)$$

Where K is the strike of the option, S is the underlying price (at the time the transaction closes) and OTM , ITM , and ATM denote the option being out-of-the-money, in-the-money or at-the-money, respectively. Each trade involves two options, each of which at closure can be in each of the three conditions of moneyness, resulting in $3^2 = 9$ possible combinations. In the regression we thus include 8 dummies capturing all the possible combinations for the long and short options being, at the moment the trade is closed, at-the-money, in-the-money, or out-of-the-money (OTM_i), having the combination of both options being ATM as reference category.¹⁵ **Errore. L'origine riferimento non è stata trovata.** reports the distribution of the trades according to the moneyness of both options involved.

¹⁴ Notice that, even if the traded options are by construction both ATM when a position is opened, their moneyness might well have changed at the time the position is closed (which is the moment the variables in the regression refer to).

¹⁵ We also tried alternative classifications, using as thresholds for ITM/OTM the mean value $\pm 0.01, 0.03, 0.04$ and 0.05 and the results obtained (available upon request) remain qualitatively unchanged.

Table 3 - Self-financing strategy transactions, by moneyness of the options involved

Long leg	Short leg		
	IN	ATM	OUT
IN	1895	413	14
ATM	913	5793	518
OUT	28	289	1328

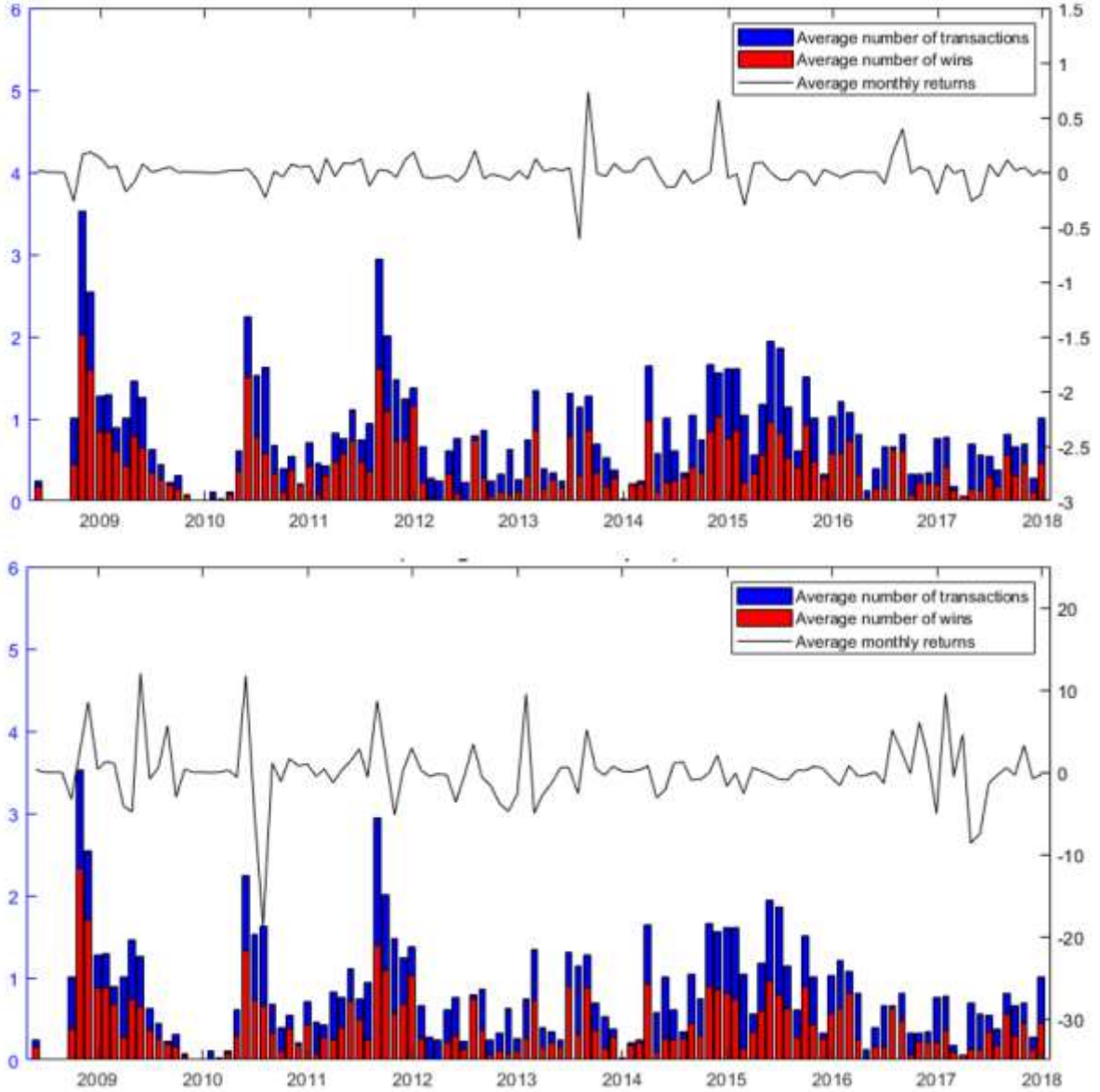
Notes: the table stratifies transactions based on the moneyness at the closure of the trade of each call option forming the pair, depending on the long or short positions taken on the asset.

In our empirical application, we work with call options, whose intrinsic value increases the more the underlying price is higher than the strike price (i.e. the more strike-price ratio is lower than 1). This means that the lower the strike-price ratio, the higher the chances of making a profit when a long position is taken on a call and, symmetrically, the higher the chances of losing if the call is sold. We thus expect the strategy returns to be positively related with the bought option being ITM and the sold option being OTM. By the same token, we expect the opposite this relation to be negative when short options are ITM and long options are OTM.

The profitability results of the implemented index option pair trading also shows a remarkable variability across time (see Figure 3)¹⁶. In order to assess if the profitability significantly varies along with periods of financial turbulence, we also include a dummy indicating if the trade is closed during one of the following crisis: the Financial Crisis (from October 2007 to May 2009) and the Chinese stock market turbulence (from June 2015 to June 2016).

¹⁶ The displayed results are obtained taking the average results, for each month of the trading period, of all the trades occurred across all pairs.

Figure 3 - Pairs trading (average) monthly results: trades, profitable trades and returns.



Average results across pairs of the trading strategies implemented over the sample from May 2008 to December 2017: average number of transactions per month, average number of wins per month (i.e. trades with positive final payoff) and average monthly returns. The top panel refers to the results of the self-financing strategy, while the bottom one refers to the results obtained with the beta-arbitrage strategy.

following model:

$$\begin{aligned}
 r_i = & \beta_0 + \beta_1 \tau_{i,short} + \beta_2 \tau_{i,long} + \\
 & \beta_3 ITM_{i,short} ITM_{i,long} + \beta_4 ITM_{i,short} ATM_{i,long} + \beta_5 ITM_{i,short} OTM_{i,long} + \\
 & \beta_6 OTM_{i,short} ITM_{i,long} + \beta_7 OTM_{i,short} ATM_{i,long} + \beta_8 OTM_{i,short} OTM_{i,long} + \\
 & \beta_9 ATM_{i,short} ITM_{i,long} + \beta_{10} ATM_{i,short} OTM_{i,long} + \beta_{11} Crisis_i + \epsilon_i
 \end{aligned} \tag{5}$$

where r_i is the return realized on the (self-financing or beta-arbitrage) pair trading strategy on trade i , and $\tau_{i,short}$ and $\tau_{i,long}$ are the time to maturity of the option sold and bought, respectively. The variables from $ITM_{i,short} ITM_{i,long}$ to $ATM_{i,short} OTM_{i,long}$ are dummies capturing the moneyness of the options involved in trade i (for instance, $ITM_{i,short} ITM_{i,long}$

takes value 1 if both options (long and short) involved in trade i are in-the-money at the moment the trade was closed, and 0 otherwise). Finally, $Crisis_i$ takes value 1 if trade i is closed during the Financial Crisis or Chinese stock market turbulence as indicated above, and 0 otherwise.

Table 4 reports the estimates of various specifications of regression model (5) for both the self-financing and the beta-arbitrage strategies returns, using the entire sample of the realized trades. In most of the cases, the returns turn out to be significantly associated to the time to maturity of both the options involved (the only exception being specification (4), in which the estimated effect for both maturities is not distinguishable from 0). Moreover, consistently with expectations, the strategy returns are negatively associated to the time to maturity of the option sold and positively related to the maturity of the option bought. Not surprisingly, the estimates for the two sides of the trade are quite similar in terms of magnitude, which is not surprising given the standardized maturities of the options used in the sample. As for moneyness, the estimated effect is largely significant in most model specifications and explains most of the variability of the returns. Besides, in line with expectations, the strategy returns are on average higher whenever the option sold is OTM and/or the option on which a long position is taken is ITM, while on average lower when the sold option is ITM and/or the option bought is OTM. Finally, the estimated effect for the dummy $Crisis_i$ suggests that the returns from pair trading strategy are significantly lower (and up to 5 percentage points lower) during periods of financial turbulence if compared to the entire sample average. Strikingly however, this difference is statistically significant only if referred to the extra-returns obtained applying the self-financing strategy.

Table 4 – Drivers of the pair-trading returns.

	Self-financing strategy				Beta-arbitrage strategy			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.04*** (0.00)	0.00 (0.70)	0.02*** (0.00)	0.01 (0.15)	-0.03 (0.96)	-0.27 (0.50)	-0.05 (0.89)	-0.90 (0.24)
$\tau_{i,short}$	-0.01*** (0.00)			0.00 (0.55)	-1.13*** (0.00)			-0.89*** (0.00)
$\tau_{i,long}$	0.01*** (0.00)			0.00 (0.54)	1.14*** (0.00)			0.92*** (0.00)
$ITM_{i,short}ITM_{i,long}$		0.02** (0.03)		0.03*** (0.00)		0.60 (0.46)		0.67 (0.42)
$ITM_{i,short}ATM_{i,long}$		-0.38*** (0.00)		-0.38*** (0.00)		-5.38*** (0.00)		-5.34*** (0.00)
$ITM_{i,short}OTM_{i,long}$		-1.05*** (0.00)		-1.07*** (0.00)		-25.34*** (0.00)		-18.60*** (0.00)
$OTM_{i,short}ITM_{i,long}$		0.73*** (0.00)		0.74*** (0.00)		5.57 (0.50)		6.01 (0.46)
$OTM_{i,short}ATM_{i,long}$		0.20*** (0.00)		0.20*** (0.00)		4.13*** (0.00)		4.18*** (0.00)
$OTM_{i,short}OTM_{i,long}$		0.02 (0.12)		0.03*** (0.00)		0.94 (0.31)		1.05 (0.28)
$ATM_{i,short}ITM_{i,long}$		0.77*** (0.00)		0.78*** (0.00)		13.49*** (0.00)		13.68*** (0.00)
$ATM_{i,short}OTM_{i,long}$		-0.15*** (0.00)		-0.14*** (0.00)		-2.29 (0.22)		-2.16 (0.24)
$Crisis_i$			-0.02*** (0.00)	-0.05*** (0.00)			0.43 (0.51)	-0.12 (0.86)
Ordinary R-squared	0.002	0.242	0.001	0.245	0.002	0.012	0.000	0.014

Num. of observations	11191	11191	11191	11191	11191	11191	11191	11191
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Notes: The table reports the regression estimates for four alternative model specifications of equation (5), with p-values in parenthesis. The dependent variable is the return obtained implementing the pairs trading (self-financing or beta-arbitrage) strategy. τ is the time to maturity. *ITM* is a dummy for the option being in-the-money, *ATM* is a dummy for the option begin at-the-money and *OTM* is a dummy for the option begin out-of-the-money, and they refer to both the option bought (long) and the option sold (short) in the transaction *i*. *Crisis* is a dummy taking value 1 if trade *i* closes during a period of financial turbulence. *significant at 10% level. **significant at 5% level. ***significant at 1% level.

In Table 5 – Drivers of the pair-trading returns: subsample of significantly positive returns.

we repeat the analysis of profitability drivers focusing on the trades that actually produced significantly positive returns only. Despite the remarkably reduced subsample, the results are overall similar to the previous analysis, with the only difference that now time to maturity is no longer significant in any of the model specifications. Notice however that in both Table 4 and Table 5 – Drivers of the pair-trading returns: subsample of significantly positive returns.

the variables considered are not able to fully explain the strategy performance. Since also the price of the underlying and options volatility play a central role in determining transactions payoffs, we can conclude that profitability of options pairs trading is affected by much more factors than in case of application to the stock market and this may be the reason behind the variability of our results.

Table 5 – Drivers of the pair-trading returns: subsample of significantly positive returns.

	Self-financing strategy				Beta-arbitrage strategy			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.07*** (0.00)	0.01 (0.37)	0.04*** (0.00)	0.04*** (0.00)	0.35 (0.34)	0.31 (0.15)	0.55*** (0.00)	0.05 (0.90)
$\tau_{i,short}$	-0.03* (0.09)			0.00 (0.87)	0.01 (0.65)			0.02 (0.29)
$\tau_{i,long}$	0.02 (0.12)			0.00 (0.82)	0.00 (0.00)			0.00 (0.00)
$ITM_{i,short}ITM_{i,long}$		0.07*** (0.00)		0.07*** (0.00)		0.34 (0.41)		0.43 (0.31)
$ITM_{i,short}ATM_{i,long}$		-0.31*** (0.00)		-0.32*** (0.00)		-1.94*** (0.00)		-2.00*** (0.00)
$ITM_{i,short}OTM_{i,long}$		-0.69*** (0.00)		-0.73*** (0.00)		0.00 (0.00)		0.00 (0.00)
$OTM_{i,short}ITM_{i,long}$		0.77*** (0.00)		0.77*** (0.00)		4.03 (0.29)		3.95 (0.30)
$OTM_{i,short}ATM_{i,long}$		0.20*** (0.00)		0.20*** (0.00)		1.79** (0.01)		1.68** (0.02)
$OTM_{i,short}OTM_{i,long}$		0.01 (0.40)		0.03* (0.05)		0.91** (0.03)		1.10** (0.01)
$ATM_{i,short}ITM_{i,long}$		0.71*** (0.00)		0.71*** (0.00)		2.53*** (0.00)		2.62*** (0.00)
$ATM_{i,short}OTM_{i,long}$		-0.12*** (0.00)		-0.11*** (0.00)		-1.23 (0.22)		-1.21 (0.23)
$Crisis_i$			-0.03*** (0.01)	-0.06*** (0.00)			-0.11 (0.73)	-0.38 (0.23)
Ordinary R-squared	0.004	0.212	0.001	0.217	0.000	0.030	0.000	0.032
Num. of observations	5132	5132	5132	5132	1366	1366	1366	1366

Notes: The table reports the regression estimates for four alternative model specifications of equation (5), with p-values in parenthesis. The dependent variable is the significantly positive return obtained implementing the pairs trading (self-financing or beta-arbitrage) strategy. τ is the time to maturity. *ITM* is a dummy for the option being in-the-money, *ATM* is a dummy for the

option begin at-the-money and *OTM* is a dummy for the option begin out-of-the-money, and they refer to both the option bought (long) and the option sold (short) in the transaction *i*. *Crisis* is a dummy taking value 1 if trade *i* closes during a period of financial turbulence. *significant at 10% level. **significant at 5% level. ***significant at 1% level.

5. Robustness

In this section we check the robustness of our results. We first apply a stricter definition of reversion to the equilibrium, by having the positions closed whenever the Spread converges back to exactly 0 (or at the end of the trading period or when the options reach maturity), rather than just reentering within the estimated $\pm 2\hat{\sigma}$ boundaries, as in equation (3). Then, we address the potential concern that the relationship between implied volatilities, which we use to estimate the long-run equilibrium, might not be directly extended to options prices.

5.1 Spread reaching the zero

A stricter definition of convergence to equilibrium is applied, by closing the trades when the *Spread* reverts to zero, rather than just re-entering the boundaries. The results obtained in terms of profitability are reported in Table 6. As the condition for closing the trade is now much more restrictive, the average life is now much longer (on average 13 days compared to the 4 observed in the previous application). Moreover, the percentages of transactions closed due to options' expiration or end of the trading period increase at the expense of a reduction in the closures coming from the *Spread's* convergence to zero. Nonetheless, the total number of trades is even nearly halved and the option pair trading arbitrage strategy does not produce significant positive expected returns. Our main conclusion that the pairs' trading strategy is not able to produce evidence against market efficiency remains thus unchanged. Similarly, the evidence concerning the profitability drivers, reported in Table 7 – Drivers of the pair-trading returns: closing when the Spread reaches 0.

, remains qualitatively unchanged with respect to our baseline results.

Table 6 – Results for the option pairs trading self-financing and beta-arbitrage strategies, by pairs of underlying indexes: closing when the Spread reaches 0.

	Self-financing strategy				Beta-arbitrage strategy returns				Closing			Average life (12)	Total number of trades (13)
	Average returns	NW stat	Average Profits (or losses)	NW stat	Average returns	NW stat	Average Profits (or losses)	NW stat	Convergence	Maturity	Trading period end		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)		
CAC40-DAX30	0.036	0.93			0.522	0.60			0.24	0.61	0.15	13.53	299
CAC40-ESTOX50	-0.040*	-1.81			-9.136**	-1.97			0.40	0.50	0.09	11.02	309
CAC40-FTSE100	-0.116**	-2.52			-2.084*	-1.94			0.45	0.43	0.13	11.83	336
CAC40-FTSEMIB	-0.009	-0.25			-0.480	-0.37			0.28	0.62	0.10	13.42	318
DAX30-CAC40	0.031	0.96			1.316	1.15			0.20	0.64	0.16	14.67	278
DAX30-ESTOX50	0.057*	1.94			5.137	1.03			0.28	0.60	0.12	13.77	309
DAX30-FTSE100	-0.137***	-2.60			-1.203	-0.29			0.17	0.68	0.15	14.89	353
DAX30-FTSEMIB	0.100*	1.80			-3.810	-0.78			0.20	0.66	0.14	13.75	319
ESTOX50-CAC40	-0.047*	-1.92			-4.643**	-2.44			0.33	0.56	0.11	12.29	300
ESTOX50-DAX30	0.079***	2.76			0.227	0.28			0.18	0.68	0.14	14.26	307
ESTOX50-FTSE100	-0.228***	-5.27			-1.935**	-2.00			0.33	0.55	0.12	12.88	312
ESTOX50-FTSEMIB	0.082**	2.11			0.519	0.74			0.28	0.60	0.12	13.30	354
FTSE100-CAC40	-0.037	-0.81			1.202	0.56			0.39	0.49	0.13	12.51	317
FTSE100-DAX30	-0.057	-1.27			-0.253	-0.17			0.16	0.69	0.15	15.04	386
FTSE100-ESTOX50	-0.193***	-3.65			-9.652	-1.64			0.34	0.55	0.11	12.76	318
FTSE100-FTSEMIB	-0.030	-0.44			-0.348	-0.12			0.21	0.66	0.13	13.64	343
FTSEMIB-CAC40	-0.017	-0.52			-0.699	-0.99			0.42	0.48	0.10	11.35	326
FTSEMIB-DAX30	0.094*	1.74			1.269	1.21			0.26	0.62	0.13	12.81	343
FTSEMIB-ESTOX50	0.109***	2.73			2.556*	1.73			0.47	0.44	0.10	10.53	402
FTSEMIB-FTSE100	-0.059	-0.82			0.983	0.26			0.31	0.56	0.13	11.92	311
ACROSS ALL PAIRS	-0.018	-0.02			-0.966	-0.02			0.29	0.58	0.13	13.00	6540

Notes: The table reports the results of the self-financing (columns 1 to 4) and beta-arbitrage (columns 5 to 8) pair trading strategies, whereby the trades close when the *Spread* reaches the zero level. For each strategy we report the average return and the average profits (if positive) or losses (if negative), whose statistical significance is tested based on the Newey-West heteroskedasticity and autocorrelation robust t-statistics (Newey & West, 1987). The symbols ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Columns 9 to 11 report the shares of trades closed due to the Spread reversion within the boundaries, due to option expiration and due to having reached the end of the trading period, respectively. The last two columns report the average number of days the trades remained opened, and the total number of trades observed. The results are reported by pairs of underlying indexes and refer to the trades triggered by the deviations of the spread estimated based on the regression where the Implied Volatility of the option written on the first underlying Index is used as X and the Implied Volatility of the option written on the second as Y.

Table 7 – Drivers of the pair-trading returns: closing when the Spread reaches 0.

	Self-financing strategy				Beta-arbitrage strategy			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.00 (0.88)	0.03** (0.04)	0.01 (0.31)	0.03** (0.04)	-1.82* (0.06)	-0.36 (0.80)	-1.24 (0.12)	-1.94 (0.24)
$\tau_{i,short}$	0.00 (0.72)			-0.01 (0.39)	-0.02 (0.99)			-0.12 (0.91)
$\tau_{i,long}$	0.00 (0.84)			0.01 (0.33)	0.10 (0.92)			0.24 (0.82)
$ITM_{i,short}ITM_{i,long}$		-0.11*** (0.00)		-0.10*** (0.00)		-4.42** (0.02)		-4.13** (0.03)
$ITM_{i,short}ATM_{i,long}$		-0.87*** (0.00)		-0.86*** (0.00)		-11.49*** (0.00)		-11.21*** (0.00)
$ITM_{i,short}OTM_{i,long}$		-1.23*** (0.00)		-1.22*** (0.00)		-7.01 (0.33)		-6.56 (0.36)
$OTM_{i,short}ITM_{i,long}$		0.98*** (0.00)		1.01*** (0.00)		18.67** (0.02)		19.09** (0.01)
$OTM_{i,short}ATM_{i,long}$		0.28*** (0.00)		0.29*** (0.00)		7.72** (0.03)		7.91** (0.02)
$OTM_{i,short}OTM_{i,long}$		-0.04** (0.04)		-0.02 (0.37)		0.48 (0.82)		0.41 (0.85)
$ATM_{i,short}ITM_{i,long}$		1.23*** (0.00)		1.23*** (0.00)		20.46*** (0.00)		21.17*** (0.00)
$ATM_{i,short}OTM_{i,long}$		-0.37*** (0.00)		-0.37*** (0.00)		-3.04 (0.37)		-3.05 (0.36)
$Crisis_i$			-0.11*** (0.00)	-0.09*** (0.00)			1.01 (0.51)	0.79 (0.62)
Ordinary R-squared	0.001	0.400	0.004	0.403	0.000	0.018	0.000	0.018
Num. of observations	6540	6540	6540	6540	6540	6540	6540	6540

Notes: The table reports the regression estimates for four alternative model specifications of equation (5), with p-values in parenthesis. The dependent variable is the return obtained implementing the pairs trading (self-financing or beta-arbitrage) strategy, closing the positions when the Spread reaches the value of 0. τ is the time to maturity. *ITM* is a dummy for the option being in-the-money, *ATM* is a dummy for the option begin at-the-money and *OTM* is a dummy for the option begin out-of-the-money, and they refer to both the option bought (long) and the option sold (short) in the transaction i . *Crisis* is a dummy taking value 1 if trade i closes during a period of financial turbulence. *significant at 10% level. **significant at 5% level. ***significant at 1% level.

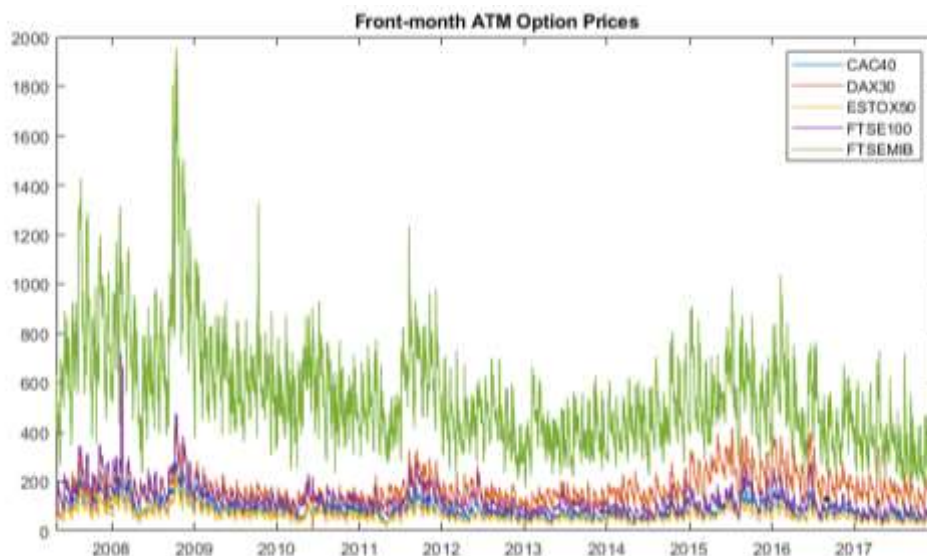
5.2 Spread estimated based on option prices

In our baseline analysis each potential mispricing of options is spotted based on a long-run relationship estimated on options' implied volatilities (rather than on underlying indexes' returns, as in Ammann and Herriger, 2002). Then, the statical arbitrage strategy is implemented on the options, using their prices to compute the final profits and returns. A potential concern with this approach might thus be that the long-run equilibrium relationship estimated on the implied volatilities might not directly translate to options prices. To address this concern we thus repeat the analysis estimating the long-run equilibrium relationship based on a(n artificially derived) time series of options prices (OP here on).

More specifically, for each underlying index the corresponding OP time series is obtained collecting, for each trading day, the price of the option that is at-the-money and front-month at that point in time. **Errore. L'origine riferimento non è stata trovata.** and Table 8 report a graphical representation and the main descriptive statistics of the OP time-series obtained. Despite the degree of correlation is generally lower compared to the series of the implied volatilities, the association is still relevant, ranging between 0.56 to as high as 0.95 (see Panel

B of Table 8). Moreover, as in the baseline case, the OP are still found stationary as confirmed by the Augmented Dickey-Fuller tests regardless of the specification used (see Panel C of Table 8).

Figure 4 – Option prices time-series of the daily one-month-maturity ATM option, by underlying index.



Front-month ATM call option prices series for each underlying Index (the series are constructed considering for each trading day the price of the option that is front-month and at-the-money at that point in time).

Table 8 - Descriptive statistics, correlation and ADF test: one-month ATM options prices, by underlying Index.

Panel A – Option Prices					
	CAC 40	DAX 30	ESTOX 50	FTSE 100	FTSE MIB
Mean	87.86	173.46	65.65	124.95	544.53
St. Deviation	280.72	451.80	243.50	718.12	1955.00
Min	21.61	0.10	16.50	24.84	173.00
Median	81.04	161.25	60.30	110.81	505.00
Max	35.79	61.64	27.34	59.74	217.10
Panel B – Correlation across Option Prices					
	CAC 40	DAX 30	ESTOX 50	FTSE 100	FTSE MIB
CAC 40	1	0.72	0.95	0.88	0.85
DAX 30		1	0.68	0.61	0.56
ESTOX 50			1	0.90	0.87
FTSE 100				1	0.83
FTSE MIB					1
Panel C – ADF tests on Option Prices					
	CAC 40	DAX 30	ESTOX 50	FTSE 100	FTSE MIB
ADF – with drift test statistics pvalue				0.0083	
ADF – with trend and drift test statistics pvalue					

Notes: The table reports the main descriptive statistics for the option prices time series obtained selecting, for each trading day, the price of the one-month maturity ATM call option (panel A), the Pearson Correlation Coefficient across the option

prices time series (panel B), and the t-statistics, and associated p-values, of the ADF test with drift only and with trend and drift run setting a maximum lag length equal to 15, by underlying Index.

The derived OP is then used to estimate the following OLS regression:

$$OP_{t,Y} = \gamma_0 + \gamma_1 OP_{t,X} + \varepsilon_t \quad (6)$$

where $OP_{t,Y}$ and $OP_{t,X}$ are the prices at day t of the 1-month maturity at-the-money option written on Index Y and X , respectively. Then, the Spread is computed as:

$$Spread_t = OP_{t,Y} - \hat{\gamma}_0 - \hat{\gamma}_1 OP_{t,X} \quad (7)$$

and, as above, the self-financing and the beta-arbitrage trading strategies are implemented whenever a mispricing is suspected, i.e. whenever the spread violates the condition as in equation (3), i.e. when $2\hat{\sigma} \geq Spread_t \geq -2\hat{\sigma}$.

The results obtained implementing both the self-financing and the beta-arbitrage strategies are reported in Table 10. The total number of transactions is almost unchanged, while the average life is halved, and again the reversion into the boundaries is by far the most common reason for a trade to be closed. In terms of returns, we again observe quite a high degree of variability among the pairs. For instance, when the self-financing strategy is implemented, option pairs trading is found to deliver significantly and positive returns in the majority of the cases (13 out of 20), even if within a much closer range: from a 1.4% (for the couple ESTOX50-CAC40) to a maximum of 7.3% (again, as above, for the couple involving the FTSEMIB and the DAX30). In the remaining cases, the strategy does not provide significant returns, and in 1 case (FTSE100-ESTOX50) it even leads to statistically significant negative excess returns. When the beta-arbitrage strategy is implemented, this single case of statistically significant negative return is confirmed, while the overall profitability is much reduced, as option pairs trading leads to significant returns in only 7 cases out of 20. Nonetheless, despite the high number of suspected mispricing, as signaled by the frequent trades, the average return across all pairs eventually obtained by both strategies is not statistically significant, thus supporting again the conclusion in favor of the index option market efficiency.

Table 9 – Results for the option pairs trading self-financing and beta-arbitrage strategies, by pairs of underlying indexes: spread estimated based on Option Prices.

	Self-financing strategy returns			Beta-arbitrage strategy returns			Closing			Average life	Total number of trades
	Mean	Std	NW stat	Mean	Std	NW stat	Boundary	Maturity	Trading period end		
CAC40-DAX30	0.020	0.21	2.13**	0.250	1.77	2.84***	0.97	0.02	0.01	2.75	542
CAC40-ESTOX50	0.015	0.09	3.19***	0.050	0.40	2.77***	1.00	0.00	0.00	1.19	568
CAC40-FTSE100	0.016	0.20	2.01**	-0.636	22.49	-0.67	1.00	0.00	0.00	1.98	598
CAC40-FTSEMIB	0.064	0.20	7.45***	0.071	0.34	5.63***	1.00	0.00	0.00	1.28	664
DAX30-CAC40	0.004	0.20	0.46	-0.008	0.53	-0.30	0.98	0.02	0.01	2.75	448
DAX30-ESTOX50	0.007	0.20	0.64	0.086	0.57	2.84***	0.98	0.01	0.01	2.73	398
DAX30-FTSE100	0.001	0.34	0.07	-0.170	3.87	-1.22	0.97	0.02	0.01	2.34	517
DAX30-FTSEMIB	0.073	0.25	6.14***	0.106	0.47	4.60***	0.99	0.01	0.01	1.56	600
ESTOX50-CAC40	0.014	0.07	5.35***	0.131	0.74	4.65***	1.00	0.00	0.00	1.23	675
ESTOX50-DAX30	0.033	0.21	2.66***	0.070	5.63	0.34	0.98	0.01	0.01	2.83	513
ESTOX50-FTSE100	-0.004	0.24	-0.33	-0.036	0.81	-1.11	0.99	0.00	0.00	1.94	569
ESTOX50-FTSEMIB	0.069	0.20	7.06***	0.092	0.33	6.17***	1.00	0.00	0.00	1.31	603
FTSE100-CAC40	0.001	0.20	0.14	-0.036	0.58	-1.28	1.00	0.00	0.00	1.92	572
FTSE100-DAX30	0.000	0.34	0.00	-2.116	32.22	-1.50	0.98	0.01	0.01	2.84	581
FTSE100-ESTOX50	-0.034	0.25	-2.63***	-0.124	0.54	-4.85***	1.00	0.00	0.00	1.83	526
FTSE100-FTSEMIB	0.039	0.29	2.96***	0.046	0.52	2.04**	1.00	0.00	0.00	1.53	621
FTSEMIB-CAC40	0.053	0.24	6.08***	0.013	0.45	0.80	0.99	0.00	0.01	1.59	738
FTSEMIB-DAX30	0.062	0.25	7.21***	-0.001	0.37	-0.04	0.97	0.02	0.01	2.24	721
FTSEMIB-ESTOX50	0.058	0.19	7.25***	0.012	0.41	0.69	1.00	0.00	0.00	1.51	688
FTSEMIB-FTSE100	0.046	0.30	3.01***	0.006	0.38	0.31	0.98	0.02	0.01	2.04	579
ACROSS ALL PAIRS	0.029	0.23	0.11	-0.108	8.93	-0.01	0.99	0.01	0.00	1.92	11721

Notes: The table reports the results of the self-financing (columns 1 to 4) and beta-arbitrage (columns 5 to 8) pair trading strategies, whereby the *Spread* used to spot the mispricing is estimated based on option prices time series rather than on Implied Volatilities. For each strategy we report the average return and the average profits (if positive) or losses (if negative), whose statistical significance is tested based on the Newey-West heteroskedasticity and autocorrelation robust t-statistics (Newey & West, 1987). The symbols ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Columns 9 to 11 report the shares of trades closed due to the Spread reversion within the boundaries, due to option expiration and due to having reached the end of the trading period, respectively. The last two columns report the average number of days the trades remained opened, and the total number of trades observed. The results are reported by pairs of underlying indexes and refer to the trades triggered by the deviations of the spread estimated based on the regression where the Implied Volatility of the option written on the first underlying Index is used as X and the Implied Volatility of the option written on the second as Y.

The analysis of the profitability drivers produces results that are largely in line with our baseline methodologies, both in terms of parameters' signs and magnitude (**Errore. L'origine riferimento non è stata trovata.**). Time-to-maturity displays a marginal impact, as opposite to the moneyness of both the options involved in the trading. Again, the results prove that the returns are on average higher for those trades in which the long position is taken on an option that at the closure of the trade is in-the-money and the short position is taken on an option which is at-the-money. On the other hand, the combination leading to the worst outcome in terms of expected returns is the one entailing an option which at the end of the trade is in-the-money while the long position is on an option which is out-of-the-money. Again, with only one exception, the obtained returns are not remarkably different in periods of financial turbulence.

Table 10 – Drivers of the pair-trading returns when the spread is estimated based on Option Prices.

	Self-financing strategy				Beta-arbitrage strategy			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.05*** (0.00)	0.05*** (0.00)	0.03*** (0.00)	0.05*** (0.00)	0.34*** (0.00)	0.01 (0.67)	0.01 (0.72)	0.29*** (0.00)
$\tau_{i,short}$	0.00 (0.87)			0.00*** (0.00)	-0.01 (0.20)			0.00 (0.90)
$\tau_{i,long}$	0.00 (0.56)			0.00*** (0.01)	0.00 (0.81)			-0.01 (0.25)
$ITM_{i,short}ITM_{i,long}$		0.08*** (0.00)		0.07*** (0.00)		0.01 (0.88)		0.00 (0.98)
$ITM_{i,short}ATM_{i,long}$		-0.18*** (0.00)		-0.18*** (0.00)		-0.13 (0.13)		-0.16* (0.08)
$ITM_{i,short}OTM_{i,long}$		-0.65*** (0.00)		-0.69*** (0.00)		-1.04** (0.01)		-1.19*** (0.01)
$OTM_{i,short}ITM_{i,long}$		0.76*** (0.00)		0.76*** (0.00)		0.00 (0.00)		0.00 (0.00)
$OTM_{i,short}ATM_{i,long}$		0.09*** (0.00)		0.07*** (0.00)		0.11 (0.61)		0.06 (0.80)
$OTM_{i,short}OTM_{i,long}$		-0.02** (0.02)		-0.02** (0.02)		0.02 (0.84)		0.00 (0.98)
$ATM_{i,short}ITM_{i,long}$		0.40*** (0.00)		0.40*** (0.00)		1.49*** (0.00)		1.44*** (0.00)
$ATM_{i,short}OTM_{i,long}$		-0.13*** (0.00)		-0.13*** (0.00)		-0.01 (0.91)		0.02 (0.83)
$Crisis_i$			0.02*** (0.00)	0.00 (0.98)			0.06 (0.24)	0.02 (0.75)
Ordinary R-squared	0.000	0.182	0.002	0.183	0.003	0.014	0.000	0.016
Num. of observations	7706	7706	7706	7706	5499	5499	5499	5499

Notes: The table reports the regression estimates for the four alternative model specifications of equation (5). The dependent variable is the return obtained implementing the pairs trading (self-financing or beta-arbitrage) strategy, whereby the *Spread* used to spot the mispricing is estimated based on option prices time series rather than on Implied Volatilities. τ is the time to maturity. *ITM* is a dummy for the option being in-the-money, *ATM* is a dummy for the option begin at-the-money and *OTM* is a dummy for the option begin out-of-the-money, and they are defined for both the option bought (long) and the option sold (short) in the transaction. *Crisis* is a dummy for the trade's closure being in periods of crisis. *significant at 10% level. **significant at 5% level. ***significant at 1% level. The pValue is in parenthesis.

6. Conclusions

This paper represents the first attempt after Ammann and Herriger (2002) of testing the index options market efficiency by means a statistical arbitrage strategy, namely pair trading.

With respect to the above cited work a small variation is proposed, as the mean-reverting relationship aimed at identifying potential options' mispricing is estimated directly on the options' implied volatilities, rather than indirectly derived from the one estimated on underlying index returns. Significant deviations from this mean-reverting relationship between implied volatilities are observed (interpreted as signals of one option being not "correctly" priced with respect to the other), trigger a simple pair trading strategy, in which the relatively underpriced option is bought and contextually the relatively overpriced option is sold. The positions are then unwounded as soon as the mispricing signal re-enters within the significant boundaries. According to the Efficient Market Hypothesis, in efficient markets no arbitrage opportunity should arise and no systematical mispricing can be exploited. So, significant profits generated by this trading strategy would thus be interpreted as disproving the index option market efficiency.

Using data on one-month maturity ATM call options written on five European Indexes, over the 2007-2019 period, we find that arbitrage opportunities, despite frequent, are short-lived and mostly lead to non-significant profits, in both the self-financing strategy (in which the quantities traded in the two stocks are such that no initial capital investment is required) and in the beta-arbitrage (in which the quantities traded are a function of the regression slope estimates). Market forces are thus able to quickly identify and reabsorb potential mispricing, further confirmed by the fact that the average trade closes within 4 days. Consistently with previous works on European index option market (Capelle-Blancard and Chaudhury, 2001, Mitnik and Rieken, 2000, Cavallo and Mammola, 2000, and Brunetti and Torricelli, 2005), our final conclusion is in favor of index option market efficiency. Notice that all the results presented are computed without taking transaction costs into account. Their inclusion in fact is likely to further reduce the profitability of the strategies, so our conclusion about index option market efficiency is reached under the most conservative condition.

Investigating the main drivers of options' pair trading, we find that the realized returns are mostly driven by the monyness of both the options involved. Consistently with expectations, the strategy returns are on average higher whenever the option sold is OTM and/or the option on which a long position is taken is ITM, while on average lower when the sold option is ITM and/or the option bought is OTM. Besides, the returns from pair trading self-financing strategy are significantly lower (and up to 5 percentage points lower) during periods of financial turbulence if compared to the entire sample average.

Our results are proved to be robust to a stricter definition of reversion to the equilibrium, by having the positions closed whenever the estimated spread between implied volatilities converges back to exactly 0, rather than just reentering within the significance boundaries. Then, we address the potential concern that the relationship between implied volatilities, which we use to spot options mispricing, might not directly translate to options prices. We

thus repeat the analysis estimating the long-run equilibrium relationship based on the time series of options prices constructed collecting the price of the 1-month at-the-money option of each day. Also in this case, the results remain qualitatively unchanged.

Further investigations are needed on the application of pairs trading strategies to options market. To our knowledge, this is still an unexplored research field that could be able to contribute in verifying whether options market is efficient. For instance, an investigation in terms of risk factors of the observed profitability of options pair trading might be informative, as options characteristics are able to explain only a limited portion of the variability of observed returns. This, along with the enlargement of the investigation to other markets as well to options with different contract type, maturity and moneyness are left to further research.

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