

Searching for Alpha: Pairs Trading

Applying Machine Learning to Pairs Trading

- **Pair Trades 2.0** — We propose a novel pair trading strategy which selects historically correlated pairs that have diverged from their equilibrium and a model to predict the likelihood of mean reversion.
- **Timing Reversion** — We enhance the standard Pairs Trading framework by introducing a Machine Learning model to forecast reversion in the stock pair price spread. We show that this trigger significantly improves the entry and exit points of the strategy and filters out pairs that will not converge to their historical equilibrium.
- **How it works** — We screen for the top correlated pairs within GICS Industry groups. Among these, to open a position we require their spread to diverge by 2.5 std from the historical equilibrium and where the ML model forecasts future mean reversion. Similarly, we close a position if the pair price spread converges to its equilibrium or if the ML model forecasts further divergence.
- **Daily Monitor** — Active positions and new open/close pairs are monitored on a daily basis. For a list of the pairs currently selected please see [Citi Daily Pairs Report: Update - 25-Mar-2021](#)

To subscribe to the daily Pairs Monitor report, subscribe on Velocity or ask you sales contact.

Europe

Chris Montagu ^{AC}
+44-20-7986-3958
chris.montagu@citi.com

David T Chew
+44-20-7986-7698
david.chew@citi.com

Pier Procacci
+44-20-7986-4228
pier.procacci@citi.com

Josie Gerken
+44-20-7986-4060
josie.gerken@citi.com

Bhavik Bochar, CFA
+91-22-4277-5019
bhavik.k.bochar@citi.com

North America

Hong Li
+1-212-816-5062
hong.li@citi.com

See Appendix A-1 for Analyst Certification, Important Disclosures and non-US research analyst disclosures.

Citi Research is a division of Citigroup Global Markets Inc. (the "Firm"), which does and seeks to do business with companies covered in its research reports. As a result, investors should be aware that the Firm may have a conflict of interest that could affect the objectivity of this report. Investors should consider this report as only a single factor in making their investment decision. Certain products (not inconsistent with the author's published research) are available only on Citi's portals.

Executive Summary

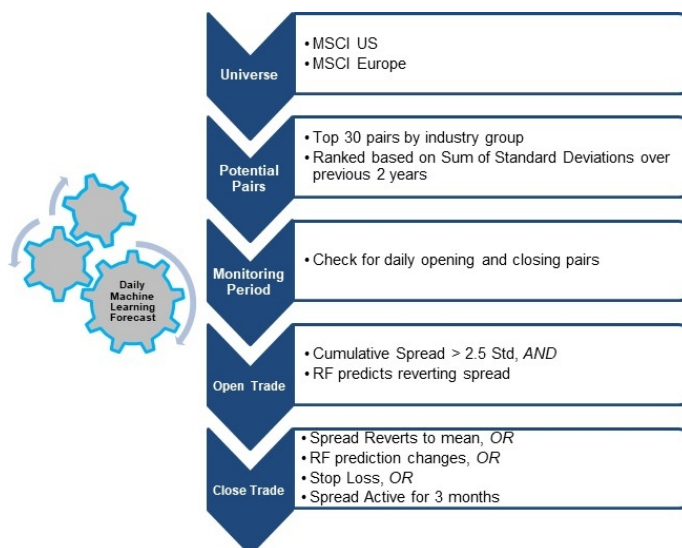
Pair trading is an investment strategy that seeks to identify two companies with similar characteristics and whose prices are currently trading outside of their historical range. Citi is not new to Pairs Trading having developed models across different regions over the past 20 years. Despite the theoretical underpinning and attractive historical returns, common belief is that the effectiveness of this strategy has reduced, making it less or not profitable in recent times. In this report, we combine the knowledge that we have accumulated over the years and combine it with Machine Learning to introduce our new pairs trading model covering the US and European markets.

The first part of the report is devoted to testing the 'standard' pairs trading approaches over recent market conditions, highlighting the role of some methodological choices often overlooked in practice. We found that simple approaches have delivered the best returns, but in recent times the efficacy has declined (after 2015) together with the number of profitable daily trades.

Having observed a decline in the risk-adjusted performance, we investigate the causes behind this phenomenon - we found two main reasons: 1. New Equilibria; and, 2. Timing. The standard pairs trading approaches do not take into account changes in fundamentals or macro drivers, which might affect the relative pricing and lead to a new long-term equilibrium. In addition, market participants have become increasingly efficient at tracking market deviation from the 'efficient pricing', leaving less opportunities to be exploited on a daily framework.

To tackle these issues, we propose a Random Forest model trained on a panel of fundamental, macro and technical data aiming at both modelling the mean-reversion pattern of stock pairs and changes in the stocks fundamentals, in the context of the overall macro environment. We find the machine learning based reversion signal significantly enhances performance by enforcing a stricter selection of possible pairs and improved entry and exit points of trades. The flow chart in Figure 1 provides a summary of the pair's selection process and the full set of open/close trading rules.

Figure 1. Pairs Strategy Flow Chart



Source: Citi Research

Introduction

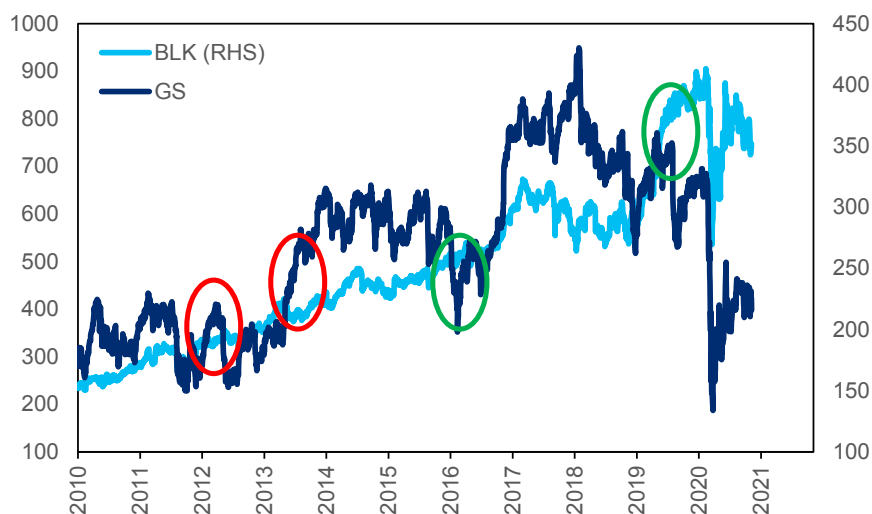
Pairs trading is a popular short-term trading strategy used by a variety of different investors in different context. Pairs trading, although very popular among hedge funds, can also be implemented by enhanced index funds and investors with quite tight tracking error mandates. Investors can fully replicate or track a large part of the index and do selective pair trades whenever there are opportunities. This strategy is not new, having being used by investment professionals and researched widely by academia for more than 30 years.

The concept of pairs trading is extremely intuitive: two securities with similar characteristics that tend to move together and whose relative prices form an equilibrium can only temporarily deviate from this equilibrium. Significant arbitrage opportunities can be present when such a deviation occurs - when the price spread (or whatever chosen measure) between the two securities widens, buy one stock, short, the other and reverse the trade when the two stocks return to their long-term relationship. Equilibrium relationships can be identified using relative valuation criteria or simply on the past price behaviour of securities.

As an example of the strategy, Figure 2 illustrates the pairs trading concept using two stocks, Goldman Sachs and Blackrock, showing the last 10 years of daily returns. The two stocks have closely tracked each other over the past decade, but in several instances, their prices have diverged for some time. This happened, for example, in 2012 and 2014 with GS outperforming BLK or in 2016 and recently in 2019 with BLK outperforming GS.

Assuming no changes in the underlying fundamentals, investors can expect the relationship to revert to its long-term equilibrium and thus profit from the divergence.

Figure 2. Example of Deviations from Long-term Equilibrium Relationship – GS vs BLK



Source: Citi Research

While the idea of pair trading is very intuitive, it is deeply rooted in the statistics literature and a great deal of academic research has been devoted to it, with different modelling approaches developed to describe this phenomenon.

Pairs Trading models essentially come down to two stages:

- 1. identifying the pairs universe – i.e. the stocks that ‘move together’;
- 2. defining a trading rule that triggers the buy/sell signals – i.e. when the stocks diverge, take a long/short position and unwind upon convergence.

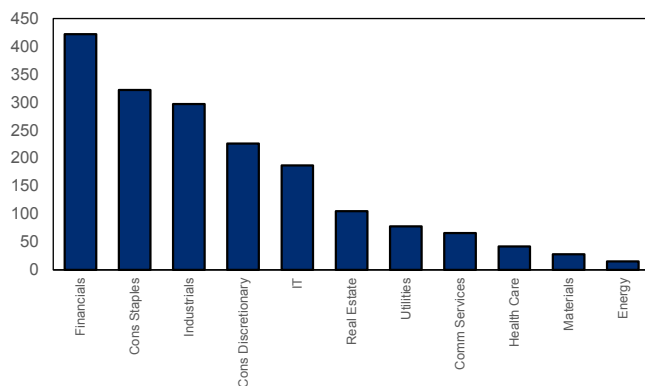
Modelling requires both of these steps to be parametrized in some way.

In this research, we review classic approaches to pairs trading strategies, investigating their (often-discussed) profitability in recent years. We then propose a novel approach to account for company fundamentals and the macro environment when modelling the stock pair mean reversion/price equilibrium.

Universe and Testing Environment

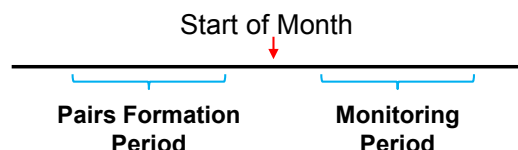
In this research, we focus our analysis on the US market and the investment universe that we utilize in the research is based on the constituents of MSCI US Index at the historical point of portfolio construction. At the start of each month, we consider all possible pairs within GICS industry groups. This provides a total of 1690 possible pairs to select from each month, with an average of 70 combinations for each industry group. Figure 3 shows the number of possible pairs combinations within industry groups aggregated across GICS sectors.

Figure 3. Possible Pairs by Sector



Source: Citi Research, MSCI

Figure 4. Formation and Execution Time Frames



Source: Citi Research, MSCI

We consider a period of 6 months - the ‘monitoring period’ - to execute the strategy using the parameters estimated in the previous 24 months, which we call the ‘formation period’. We run this process each month, without waiting six months for the current monitoring period to complete. As a result, we have six overlapping ‘portfolios’, with each portfolio associated with a trading period that has started in a different month. Lastly, in assessing the performance of the strategy, we equally weight all the active trades and assess the strategy performance on a daily basis.

Identifying Pairs

The first challenge in implementing this strategy is identifying stocks that have a 'relationship', i.e. stock prices tend to move together and exhibit mean reversion. We discuss and test two main approaches: the distance method and the Cointegration approach. Both these approaches are common within the investment management industry and finance literature. While other methods have been proposed (see, for example, Wei and Scheffer (2015)), in our view, the findings do not support the additional complexity in most of the cases. We therefore focus on the more traditional approaches to pairs trading strategies.

Distance Method

Distance based methods are the most intuitive, yet among the best performing approaches developed. These are based on the practical intuition of finding stocks whose prices 'move together'.

At the start of each month, we assess all possible pairs within industry groups and construct a normalized price series for each security over the previous two years (formation period). We then select the top 30 pairs that minimize the sum of squared deviations between their normalized price series. In addition, we also ensure that selected pairs have a positive correlation, although pairs that minimize the sum of squared deviations (SSD) within industries are almost surely positively correlated.

Cointegration

The pairs trading strategy may be justified within an equilibrium asset-pricing framework with non-stationary common factors like discussed in Bossaerts and Green (1989) and Jagannathan and Viswanathan (1988). For example, two stocks in the Energy sector could both be priced around the (non-stationary) oil price and, therefore, their spread would be stationary.

The idea is that if the price spread among two stocks fluctuates with common non-stationary factors, then the prices of the two stocks would be co-integrated and the pairs trading strategy applied to these stocks would generate a profit.

In essence, a pair is cointegrated if its price spread is stationary. To test for cointegration in practice, we follow the Engle and Granger (1987) approach. First, we estimated the relationship between the pairs running a simple regression of the form:

$$Stock_{1,t} = \beta Stock_{2,t} + u_t$$

We then test for the stationarity of the residual u_t calculating a standard ADF test (Dickey and Fuller (1979)). If u_t is stationary, then the two stocks are deemed to be cointegrated.

In defining the candidate pair of stocks based on cointegration, first, we sort all pairs based on their SSD as described above. Second, we test each pair with the smallest SSD for cointegration, using their cumulative return series in the formation period. Pairs that are not cointegrated are discarded. Pairs that are cointegrated are included in the universe.

Trading Rules

Having identified the universe of potential pairs (i.e. the pairs of stocks that show the highest degree of correlation within each industry), we need to define the trigger that signals the opening and closing of the pairs trade.

As we mentioned, over the years, the concept of pairs trading strategies has been studied widely and a large body of academic literature, as well as industry 'standards', are available. Most of these practices, however, are centered around techniques to identify pairs, with much less focus on the trading rules or parameters in which to trade the identified pairs.

In this section, we focus on classic trade signals, showing that the pairs universe selection is responsible for a great deal of the performance. However, we also highlight pitfalls related to the classic trading rules, laying the foundations for enhanced trading rules that we propose in the next section.

Classic Trading Triggers

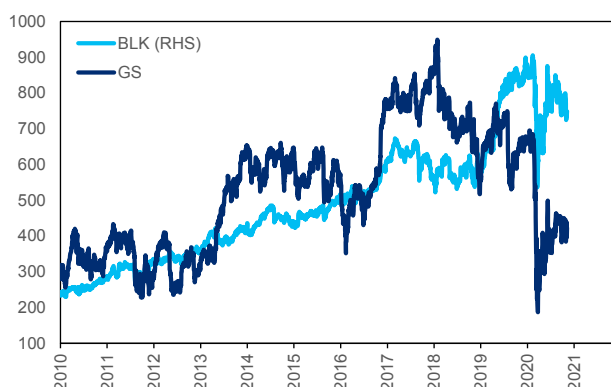
Consider two stocks that have historically been cointegrated. To profit from the pair of stocks, a long-short position is opened when the stock prices have diverged by a certain amount, and the position is closed when the prices have reverted.

Following practice, we base our rules for opening and closing positions on a standard deviation metric. We open a position in a pair when prices diverge by more than 2.5 historical standard deviations, as estimated during the pairs formation period. We unwind the position when the price spread metric crosses the mean again.

Figure 6 provides an example of this approach. The dark blue line in the chart is the cumulative normalized spread from the price series discussed in the introduction and reported in Figure 5 for convenience. The light blue line is the rolling cumulative average spread and the red dotted lines are the rolling ± 2.5 standard deviation bands.

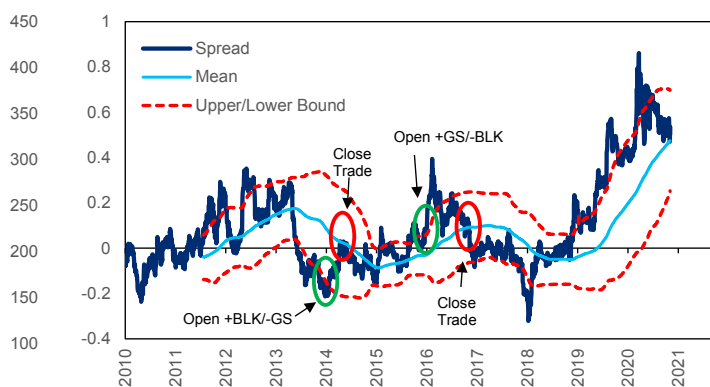
During the 10 years period that we show, the price spread remains relatively tight until 2019 and from there the spread crosses the upper bound frequently. Every time the spread breaks the upper or the lower bound, a position would be opened until convergence to the mean.

Figure 5. Pair Example



Source: Citi Research

Figure 6. Rolling Mean and Standard Deviation Bounds



Source: Citi Research

While the vast majority of open trades close within the first 20 trading days, a portion of the trades might take longer to revert/diverge. We discuss this behavior in detail in the next section, but for this reason, we allow positions to stay open for a maximum of three months. If the normalized prices do not cross the mean price spread metric, the position is closed and gains or losses are calculated at the end of the last trading day.

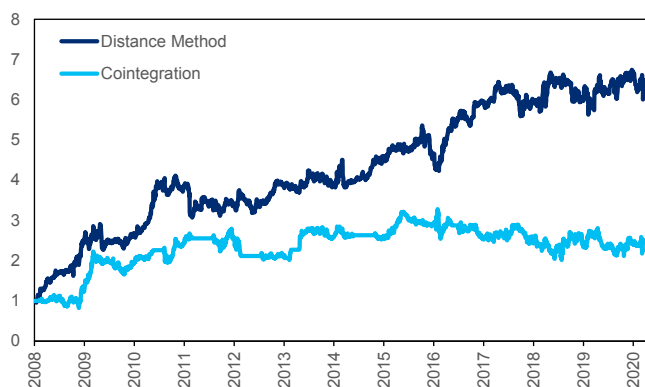
In addition to the standard deviation metric, we enforced a stop loss at a maximum loss of -25% on the (unweighted) trade. While this rule represents an empirical constraints that might somehow bias the statistical soundness of the research, this is undoubtedly a good practice and industry standard that we believe should be included in any arbitrage based strategy.

Performance

Following the test methodology described above and considering the pairs based on both the Distance and Cointegration methods, we evaluate the profitability of the strategy in the US market from 2008 to 2020.

Figure 7 and Figure 8 report the out of sample performance of both the Distance Based and Cointegration strategies when using the 2.5 standard deviation activation signal. Between the two strategies, it can be seen that the Distance method is far superior to the Cointegration method in our research setup, having both higher raw and risk adjusted returns. This is consistent with recent academic literature (see, for example, Rad et al. (2016)) which show a similar result.

Figure 7. Distance Method and Cointegration – Historical Performance



Source: Citi Research

Figure 8. Performance Summary Statistics

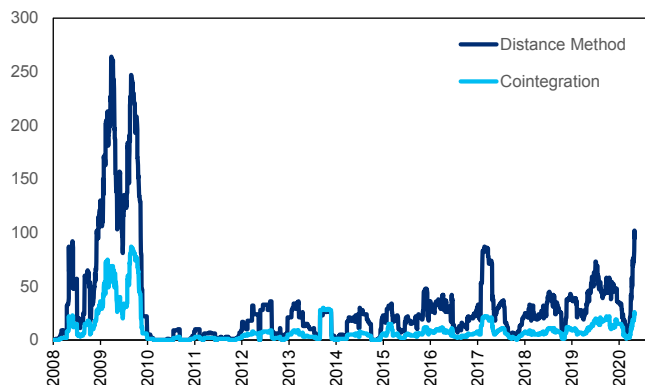
	Distance Method	Cointegration
Annualised Return	15.7%	6.5%
Annualised Volatility	19.2%	16.7%
IR	0.82	0.39
Min	-7.0%	-8.6%
Max	9.9%	8.7%

Source: Citi Research

Figure 7 also shows that the strategy delivered better performances during times of high volatility (e.g. 2008-2009, 2010-2011 and more recently 2019-2020). The intuition behind this result is that volatile markets tend to offer better opportunities to exploit spread diversions. This intuition is backed up by the number of active pairs traded through time as presented in Figure 9. While the number of potential pairs in our set-up stays constant (i.e. we only monitor the top 30 'closest' pairs), the number of opened positions is significantly higher during high volatility periods.

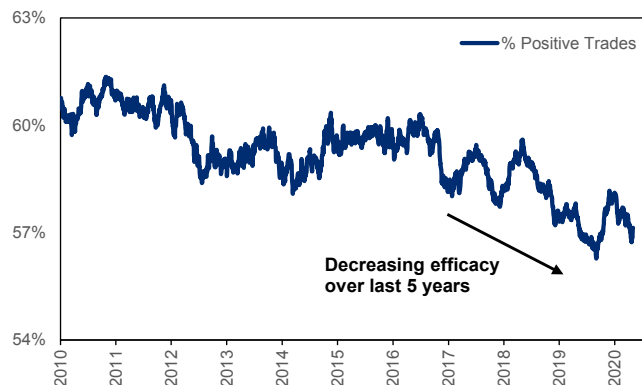
From Figure 9, 23 pairs were active on average each day in the period 2011-2018. This figure reached 250 in 2008 and 130 in 2020. The clear conclusion is that more stocks tend to deviate from their long-term equilibrium with other stocks during periods of high volatility, opening potential opportunities for mean reversion.

Figure 9. Number of Trades



Source: Citi Research

Figure 10. % of Positive Trades

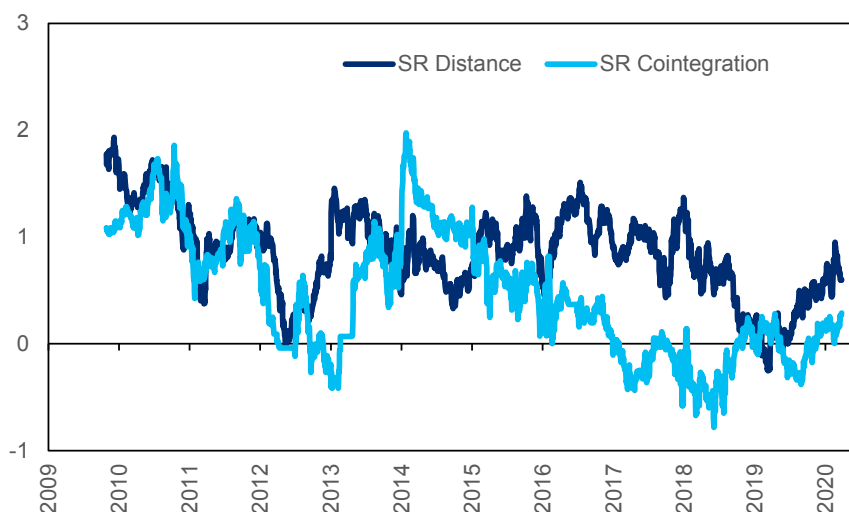


Source: Citi Research

The exposure to volatility is also shown by the rolling risk adjusted performances of the two strategies. Figure 11 shows the two-year rolling information ratio of both the Distance and Cointegration strategies. The period where the strategies suffered the most is between 2017 and 2019 similar to performance weakness in other quant strategies, and our result suggest that low volatility across the markets is the main driver of this underperformance.

The chart also reveals that, consistent with academic research, the profitability of the strategy has reduced over the last few years. This is further confirmed by the proportion of trades posting positive daily returns as shown in Figure 10. In the next section, we will examine in more detail the reasons for this decreased efficacy/performance and we propose a novel methodology to counter the strategy pitfalls.

Figure 11. 2Y Rolling Sharpe Ratio



Source: Citi Research

Alpha and Market Efficiency

To provide further perspective on the risk of the pairs trading strategies we have outlined, Figure 12 shows the estimated risk premia coefficients and the corresponding significance levels. As can be seen there are some significant risk exposures but of interest, particularly for the Distance strategy, is the highly significant positive alpha. This suggests that even after controlling for common risk factors, there is a significant alpha being generated for this strategy. Specific to the risk exposures, the table highlights a highly significant positive loading to the market. While pairs trades are delta neutral strategy, the positive exposure to the market is not a surprise given the exposure to volatility discussed above. Also not surprising is the highly significant negative loading to Price Momentum for both strategies. By construction, a pairs trading strategy is set to exploit short-term reversal patterns in prices that diverge from their long-term equilibrium.

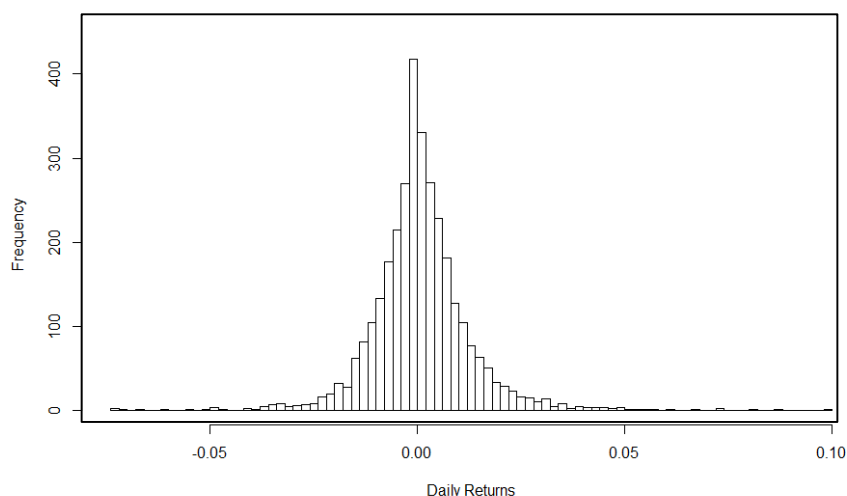
Figure 12. Styles Exposures

	Distance Method		Cointegration	
	Estimate	t stat	Estimate	t stat
(Intercept)	0.4%	3.01	0.1%	1.39
Market	11%	6.69	6%	2.99
Value	11%	1.97	0%	0.10
Price Mo	-16%	-4.52	-32%	-7.02
Size	12%	1.82	17%	2.11

Source: Citi Research

It is also worth emphasizing that, while trading individual pairs might generate exposure to tail risks (Gatev et al. 2006), when the strategy is implemented at a portfolio level the risk/return profile is significantly enhanced. Figure 13 illustrates this point through the distribution of daily returns of our strategy showing that the returns are balanced and exhibit positive skewness.

Figure 13. Daily Returns Distribution



Source: Citi Research

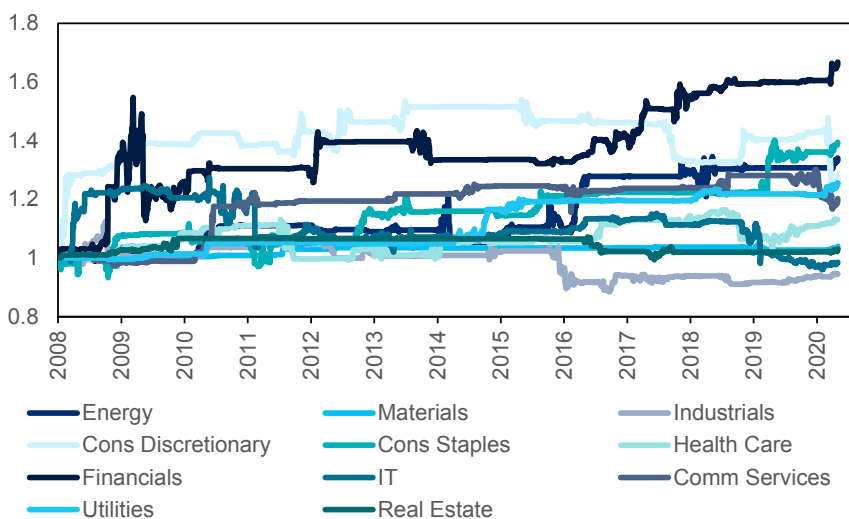
Sector Contribution

Our analysis and backtests are based on pairs that are identified within industry groups. This is done to restrict our universe to possible pairs that are more likely to

be cointegrated since stocks in the same industry can be expected to be exposed to similar fundamental and risk factors. It is interesting, therefore, to assess the performance contribution of each industry and how the contributions changed through time.

Figure 14 shows the cumulative performance of each industry group aggregated at a sector level to allow easier inspection. While some time varying patterns are observable, almost all sectors contributed positively to the performance of the strategy through time. The best contributor is the Financial sector, however, a great deal of this performance is generated in the 2008-2010 and 2016-2018 time periods. On the other hand, Industrials and Real Estate are the worst performers, although their performance is mostly due to significant losses posted in specific, short time periods.

Figure 14. Cumulative Performance by Sector



Source: Citi Research

Methodological Choices

Universe Selection

Having defined a measure of ‘closeness’ or relationship between stocks, a relevant parameter to be defined is the number of pairs to include in our ‘potential pairs’ universe: having ranked the pairs based on their sum of squared distances, how many pairs should we consider for trading? While it might seem a redundant question, Figure 15 shows that a large amount of performance depends upon it.

There is no consensus in literature and in many cases authors do not motivate their choice of how many pairs to trade. Also, optimizing this parameter would inevitably lead to biases or data snooping. Therefore, we have relied on balance and intuition and selected the top 30 pairs for each industry group. This is quite restrictive, but still provides an average universe of 750 ‘candidate’ pairs, which allows the model to exploit opportunities, particularly in periods of high volatility.

Lastly, it is worth highlighting that most authors in academia tend to be more restrictive. Gatev et. al (2006), for example, select only the top 20 overall pairs. Figure 15 shows that empirically, being restrictive with the number of possible pairs supports our intuition – the stronger the relationship between pairs, the higher the mean-reversion opportunity. We prefer to keep a balanced approach, maintaining a relatively large amount of stocks to monitor and to refine our trading signal (discussed in next chapter) rather than constrain the model too much.

Figure 15. Wealth Curve for Different Pairs Universes



Source: Citi Research

Monitoring Period

So far, in the research we have assumed a 6-month monitoring period before resetting the strategy parameters. In particular, at the beginning of each monitoring period we re-normalize the cumulative series, update the SSD and cointegration coefficients associated with each stock, so we can select a new set of candidate pairs and re-estimate the mean spread and standard deviation.

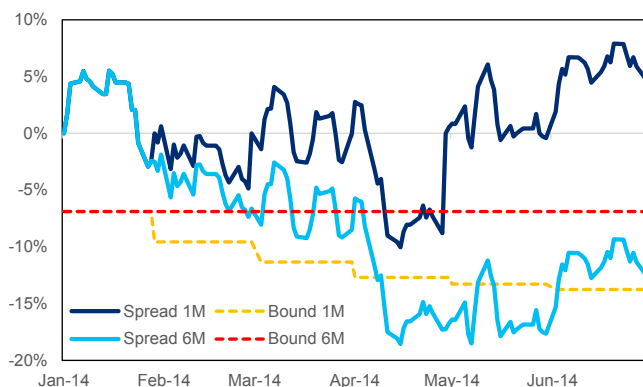
The implications of this choice are, indeed, very significant. Figure 16 provides an example of the implications of different training periods using again the spread between BLK and GS from Figure 2. The dark blue line shows what the cumulative spread and associated lower bound (yellow line) would look like with a 1-month monitoring period. At the beginning of each month, the spread would be rebased to zero and a new set of parameters would be estimated, leading the bounds/triggers to adapt much more dynamically.

With a six months monitoring period, instead, the cumulative spread (light blue line) can divergence even more before being rebased and the parameters do not allow the bounds (red dotted line) to adapt to recent moves. The monitoring period length is, therefore, a crucial component of the strategy. The idea underlying the pairs strategy is that we can exploit short term divergences from the long term equilibrium. The formation period and the monitoring period represent the definitions of 'short term' and 'long term'.

Figure 17 reports the performance of the strategy when different monitoring periods are considered, highlighting the significant impact of this choice or parameter. The best performance is achieved when considering a two months trading period, while a one-month trading period delivered the lowest return, possibly on the basis that this time period is too small for the mean reversion to occur.

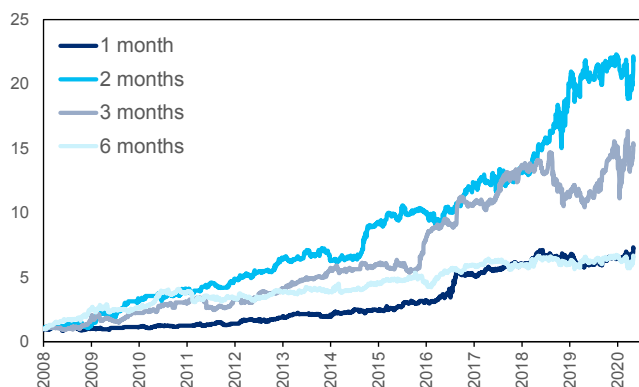
Similar to the universe selection, optimizing the monitoring period length would lead to biases. We rely, therefore, on common industry practice and relevant literature that suggests 6 months period is optimal.

Figure 16. Monitoring Periods Effects



Source: Citi Research

Figure 17. Wealth Curve for Different Monitoring Periods



Source: Citi Research

'Bad' Pairs and Relative Pricing

Pairs trading models have evolved throughout the years and many new techniques and approaches have been introduced as we touched on in the previous section. The vast majority of the innovations, however, focus on the identification of the pairs universe rather than the trading rules or managing the risk of the strategy. The fact that the prices of two securities move together, however, is not enough to qualify stocks as 'optimal' candidate pairs. What is central for this strategy to be successful is mean reversion.

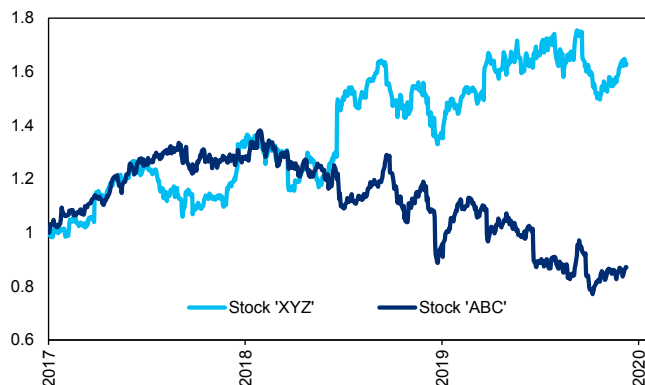
In some cases, there could be an important structural reason why the prices of two companies, having historically had a relationship, have now diverged from each other. This could be due to a corporate action in one or both companies, change in the fundamentals/macro drivers or any other reason that may lead to a new equilibrium preventing mean reversion of the price spread and, therefore, the profitability of the strategy. In other words, the historical cointegration (as pure statistical measure) of two stocks is not a guarantee of future mean reversion given a divergence in the price relationship.

An example of a theoretical 'bad' pair is illustrated in Figure 18. For this example, we are highlighting two stocks that are both constituents of the Consumer Services industry group – let's call them stock 'XYZ' and stock 'ABC'. This example also highlights the trade-off between pair selection and pair breadth. We stated before we are using the GICS level 2 Industry Groups as a way to quickly and easily group homogenous groups of stocks. By restricting the universe of potential pairs to sector groupings, we are able to make the assumption that many of the stock pairs within the grouping will be cointegrated because they should have similar fundamentals that underpin the relationship. The more homogenous the groups of stocks are, the more likely the stock pairs relationship will not only be statistically significant, but will also be fundamentally intuitive. The downside, however, is that the breadth of stocks in which to choose pairs and the opportunity of short-term deviations from a stock pair equilibrium will be in most cases lower. Therefore, the choice of how you split the universe into sub-universes to choose pairs from is important on a number of different levels.

Focusing back on stocks 'XYZ' and 'ABC', historically these stocks have formed a cointegrated pair within the Consumer Services industry group. Some may argue that despite being both Consumer Services companies, they are quite different – in our example, one is an online travel company, the other a restaurant company. Even if we go down a further level of GICS, both are still in the same industry – Hotel, Restaurants & Leisure. This highlights the tradeoff that we described before – if we had gone down another level to using sub-industries (where one is a constituent of Hotels Resorts & Cruise Lines, the other Restaurants) these stocks would not have had a chance to be selected as a pair despite having a statistically significant relationship. With that said, the price series of the two stocks have closely tracked each other for some time and their ADF statistic is well above the 3.5 significance level, meaning they are cointegrated – their prices exhibit a statistical relationship.

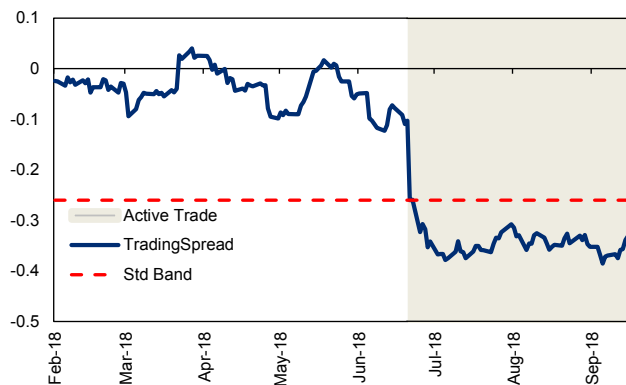
In our theoretical example, starting from May 2018, the stocks' prices started to diverge and their spread widened as shown in Figure 19. The cumulative spread metric crossed the 2.5 lower standard deviation bound in July 2018, triggering an entry point for a pair trade – sell 'ABC', buy 'XYZ'. However, as can be seen, despite the two stocks (prices) exhibiting a cointegrating relationship, after opening the trade, there has been no mean reversion in the price spread. The result being that the trade would be closed out at a loss.

Figure 18. 'Bad Pair' Example – Stock 'XYZ' and Stock 'ABC'



Source: Citi Research

Figure 19. Cumulative Spread and Action Point

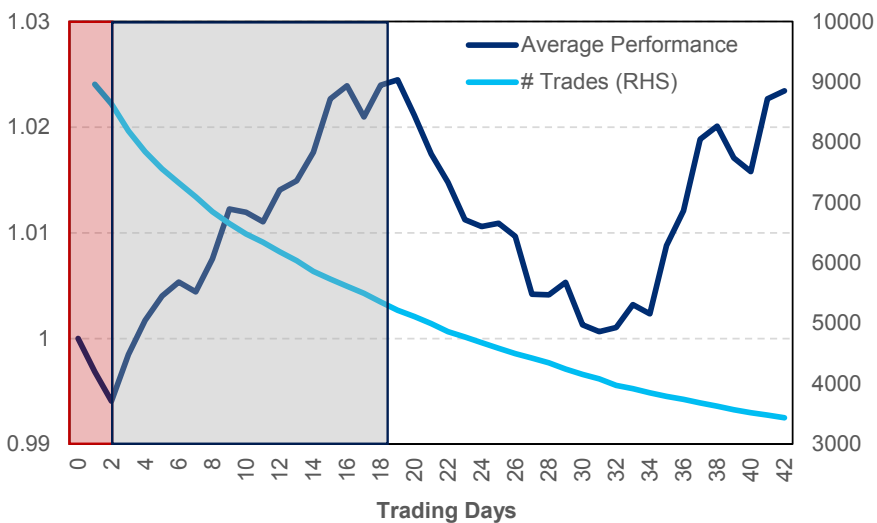


Source: Citi Research

The effects of these 'bad pairs' in the performance of our strategy are observable in Figure 20. To construct the chart, we have aligned all trades opened during our backtest across trading days, starting from their opening day. Our goal is to analyze their aggregate performance pattern.

The chart reports the cumulative average performance during each trading day overlaid with the proportion of trades that stayed open after each trading day.

Figure 20. Average Cumulative Performance by Trading Day



Source: Citi Research

Our first observation is that the pairs, on average, do not perform well during the first few days, meaning that the price spreads tend to further diverge after breaking the 2.5 standard deviations band. Secondly, most of the pairs do in fact revert toward their long-term equilibrium during the first 20 days from the opening of the positions and here most of the trades generate profits. However, around 50% of the trades remain open after such period. Of the remaining trades, a good portion close within the following 10 days generating losses (i.e. stop loss closes) and the remaining 30% generate, on average, profit by converging to their mean afterwards.

This suggests that for some stock pairs, once diverged, they can take quite some time to return to their equilibrium. Also and perhaps more interesting, some other pairs do not converge back to their historical mean but rather set into a new equilibrium, generating losses.

In the next section, we discuss the theory around pairs trading, searching for the common factors driving the 'Bad Pairs' and proposing a novel methodology to deal with this pitfall.

Machine Learning Triggers

The theory underpinning pairs trading strategies is based on the idea of relative pricing; two securities that are close substitutes for each other should theoretically have the same value and therefore the same price (scaled to share on issue). In our strategy, we use an algorithm to choose pairs based on the criterion that they have had the same or nearly the same state prices historically. We then trade pairs when their prices diverge, since in an efficient market their prices should be nearly identical.

Based on this, the profitability of pairs trading can be seen as the compensation for the disciplined investors taking advantage of the undisciplined over-reaction of the market and as such enforces efficiency. This is at least one possible – albeit behavioral – explanation for our results, which is consistent with Jegadeesh and Titman's (1995) finding that contrarian profits are in part due to over-reaction to company-specific information shocks rather than price reactions to common factors.

Over the last decade, however, market participants have become increasingly efficient at tracking market deviation from the 'efficient pricing', leaving less opportunities to be exploited on a daily framework. Moreover, in the classical pairs trading setting discussed so far, we are not taking into account changes in fundamentals or macro drivers which might affect the relative pricing of the pair and lead to a new long-term equilibrium.

While it is challenging to take into account stock specific events in our statistical framework, the data and the technology available today certainly allows us to include changes in the macro environment and in the stocks' fundamentals in the buy/sell signals.

In this section, we propose a novel methodology to enhance the typical trading triggers by both modelling the mean-reversion pattern of the pairs and by monitoring changes in the stocks fundamentals and overall macro environment. To achieve that, we have trained a Random Forest model using a panel approach with respect to our data. Our goal is to forecast whether a stock pair's price spread is going to mean revert and this model can be both a regression and a classification problem. In previous research ([Searching for Alpha: Machine Learning: Beyond Random Forest for Stock Selection](#)) we have shown that this is a significant choice and that, as it often happens, 'ensembling' the two methodologies can have advantages. We have tested, therefore, our model in both a regression and a classification setting and then the intersection of the two.

Random Forest Rules

We develop a rolling window model, using 10 years of daily observations to forecast the 15-day ahead spread. The model is re-trained only once a year, at the beginning of the year, and is then used to forecast the 15-day ahead price spread for each pair on a daily basis. We open a position in a pair when both the following conditions are met:

- Price spread diverges by more than 2.5 historical standard deviations; and,
- The 15-day ahead price spread is forecasted to revert toward its mean.¹

Similarly, we unwind the position when our model forecasts the 15-day ahead spread to diverge for two consecutive days.

We select a training set length of one year so that in out sample, the first training is conducted considering observations from January 2006 to December 2006. Given our daily time period, this offers approximately 250 time periods for approximately 1,700 pairs. Given the 88 explanatory variables considered (we discuss this further in the report), this amounts to more than 37 million training data points. Moreover, to keep our framework transparent and favoring simplicity over out-right performance, we keep the model's hyper-parameters constant through the testing period.

Data Selection

Our objective is twofold: 1. Modelling the mean-reversion pattern; and 2. Modelling the relationship between the changes in the price spread and changes in fundamentals and macro variables. To achieve this, we have designed a training set made up of three sets of data as illustrated in Figure 21.

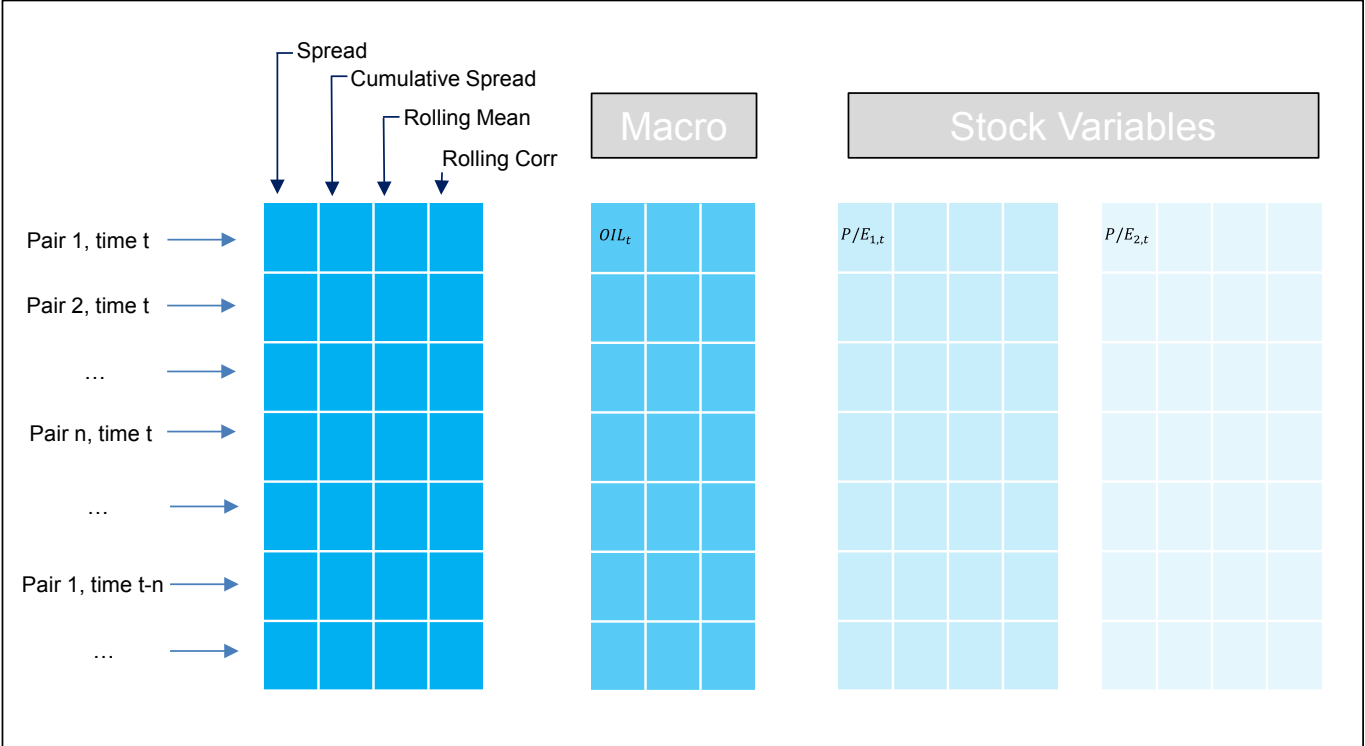
The first set of data includes daily observations on pair-specific variables. These are the daily spread, the cumulative spread, the rolling mean, standard deviation and correlation. The second set is a group of Macro/Technical indicators summarized Figure 33 in Appendix.

Lastly, the third group is a set of fundamental factors for each of the two stocks forming the pair. In essence, each row in the training set contains the same fundamental variables for both the stocks forming the pair. Figure 33 in the Appendix reports all the factors included.

The target or dependent variable to be forecasted is the 15-day ahead spread. In the regression setting this is the raw spread figure, while in the classification setting this is a binary outcome: 0 if the spread goes down, 1 if the spread goes up.

¹ In the 'ensemble' model we require both the forecasts from the RF regression and classification to predict a reversion in the spread

Figure 21. Training Set Structure



Source: Citi Research

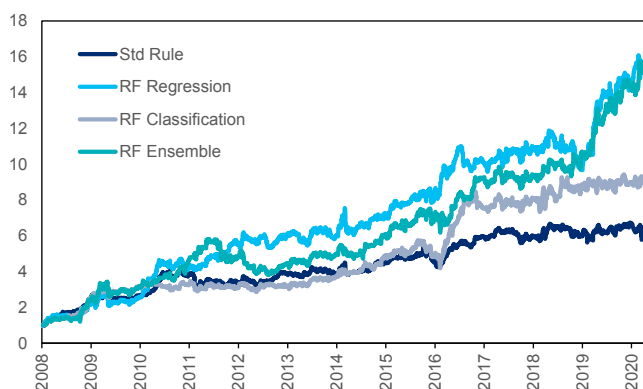
Consistent with our previous research on Random Forests, we neutralize the fundamental factor data for sector and country effects and rank factors such that each stock receives a score in the [0, 1] range, interpretable as the percentage of the universe which has a lower score than a particular stock. We have previously examined standardization techniques (see, for example, [Normalising for Style Factor Composites](#)) and concluded that ranking factors is robust to outliers while providing easy interpretability.

Testing and Performance

Figure 22 and Figure 23 report the performance metrics and wealth curves for the pairs trading strategy enhanced with the Random Forest (RF) predictions as compared to the classical Standard Deviation (Std) rule discussed in the previous sections. These results refer to the MSCI US universe, while in Figure 31 and Figure 32 in the Appendix we report the results for MSCI Europe,

Our first observation is that the Random Forest predictions significantly enhance the classical approach, with all Random Forest tests outperforming the Standard Deviation triggers. The regression approach posted the highest return, delivering an annualized 25% average return out-of-sample. The Ensemble model posted a lower standard deviation and a slightly higher Information Ratio.

Figure 22. Enhancing Pairs Trading Strategy – Wealth Curve



Source: Citi Research, MSCI

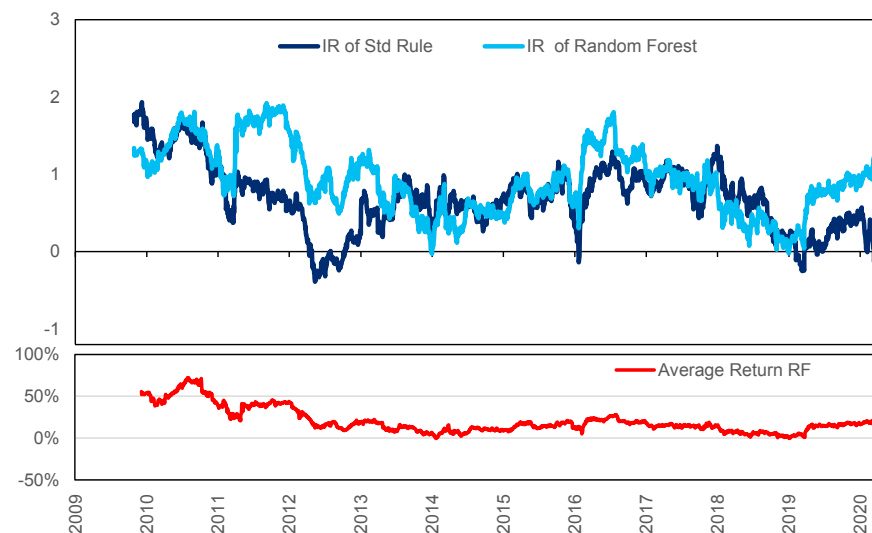
Figure 23. Performance Metrics

	Std Rule	RF Regression	RF Class.	RF Ensemble
Annualised Avg Return	14.7%	23.8%	19.0%	24.2%
Annualised Volatility	19.2%	23.9%	23.1%	23.1%
IR	0.76	1.00	0.82	1.05
Min	-7.0%	-8.3%	-8.8%	-7.4%
Max	9.9%	21.1%	17.4%	19.9%

Source: Citi Research, MSCI

While it is hard to identify 'the best model', having the Regression and the Ensemble models delivering a very similar performance and risk profile, we can conclude that in our testing sample and environment, the additional complexity of the ensemble model is probably not justified.

Figure 24. Rolling Information Ratios (IR) and Returns



Source: Citi Research

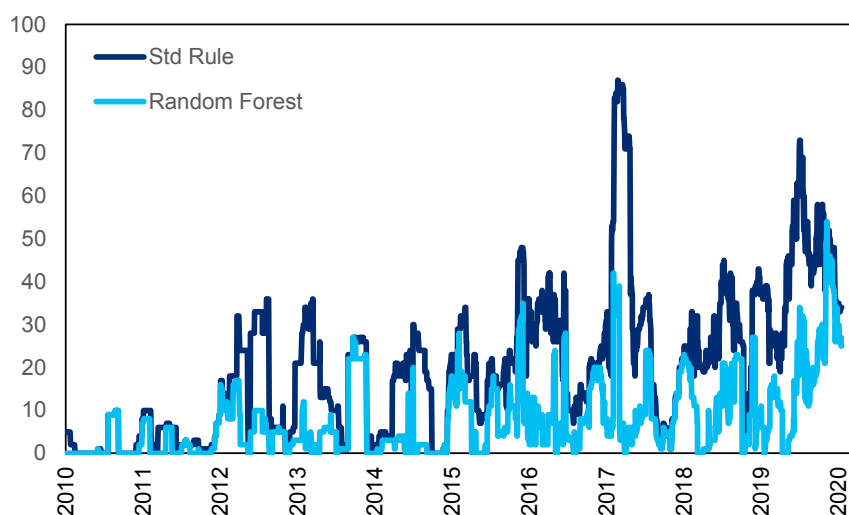
One last relevant observation is that the RF trigger algorithm enhances the strategy by not only boosting the overall returns, but also limiting the scenarios in which the classical trading strategy experiences a drag in performance, possibly from non-reverting pairs. Figure 24 supports this claim, showing that the 2-year rolling Information Ratios are mostly enhanced over the test period using the RF regression triggers, and particularly so in the 2011-2013 and 2018-2020 time frames, when the classical strategy suffered the most. Our interpretation is that this effect is particularly due to the influence of macro data included in Random Forest model. As discussed in previous section, the pairs opportunity set is highly dependent on the market environment (i.e. volatility). By including macro data in the Random Forest feature set, we allow our framework to take into account and mitigate the (negative) effects of the prevailing macro environment.

Implicit effects of Machine Learning Triggers

The motivation of this research is to enhance the pricing awareness of a classical pairs trading strategy with the goal of avoiding pairs, that while historically having a relationship (whether through SSD or cointegration), when deviating from their 'equilibrium', fail to converge, and in addition, improving the entry and exit points of the implementation.

We can indeed observe two effects of the machine learning (RF) rule as compared to the Std rule: 1. reducing the number of trades; and 2. reducing the average number of trading days, when a trade is opened. Figure 25 shows the number of active trades for each day in our backtest when using the RF Regression strategy as compared to the trading rules based on the STD/classical pairs strategy. It is clear that the RF rule acts as a filter, significantly reducing the pairs that are activated each day.

Figure 25. Number of Trades



Source: Citi Research

In addition, the gap between the RF and the Std rules is wider in presence of higher volatility, meaning that the RF rule is less sensitive to the market volatility. This is also reflected in the sensitivity of the strategy to the FF3 factors as shown in Figure 26. As opposed to the Std strategy, when the RF rule is introduced the strategy significantly reduces its loading to the market, other than improving the alpha generated both in magnitude and significance. This is compared to what we showed in Figure 12 where the loadings and tstats for the Std strategy, regardless of how the pair is selected, are 11% and 6.69 respectively.

Figure 26. Random Forest Pairs – Styles Exposures

	(Intercept)	Market	Value	Price Mo	Size
Estimate	0.7%	-2%	-1%	-20%	16%
t stat	3.33	-0.92	-0.30	-4.51	3.01

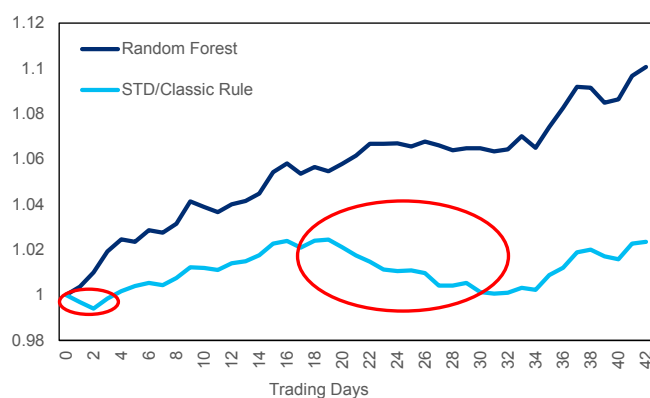
Source: Citi Research

Lastly, Figure 27 reports the cumulative average performance during each trading day compared to the basic (Std or classical) rule. The chart shows that the average losses posted by the Std rule during the first few days of trading and after day 20 are not experienced when the RF rule is used.

Figure 28 provides additional insights on how this is achieved. The chart reports the number of trades that stayed open after each trading day when using both the Std rule and the RF rule and the ratio of the two (red dotted line). Other than the significant filter operated by the RF rule (~4000 total trades versus 9000 trades with the classical trigger), the holding period of the trades tend to be much shorter. This is confirmed by the ratio of trades which reveals how, as the number of days increases, the number of trades that remained open with the ML rule diminish more than proportionally.

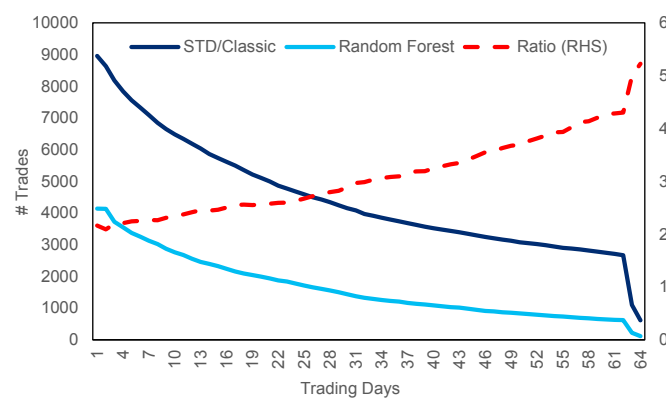
In essence, this means that the RF rule tends to close pairs sooner than the Std Rule. Overlaying this observation with the better average performance shown in Figure 27 leads us to the conclusion that the ML rule significantly enhanced the timing ability of the strategy.

Figure 27. Average Cumulative Return by Trade Day



Source: Citi Research

Figure 28. Number of Trades by Trading Day



Source: Citi Research

Where to get our Pair Trade Ideas

We check opening/closing positions and monitor active trades on a daily basis and we post open/close trade ideas on Citi Velocity. As an example, this is our first daily report: [Citi Daily Pairs Report: Update - 25-Mar-2021](#)

Typical output is shown in Figure 29. The table provides a snapshot of all trades that are currently active. It reports information on the long and short components forming each pair, the current price and mark-to-market of the position. On this last point, it provides the date in which the position has opened, the cumulative spread (since beginning of the monitoring period) when the pair was opened and its current level, and the return on the trade since inception.

Our model is based on daily close prices, therefore new positions are identified each morning, before market open. The first return on the new active pairs will be marked at close of the first day of trading.

Figure 29. Example of Open Pairs table

Open Trade: Long and Short names

Trade opening day

Cumulative spread when the trade has opened as of yesterday close

New trades identified before market open

Table 1: Current Open Pairs

	Long	Short	Long BBG Ticker	Short BBG Ticker	Long Price(USD)	Short Price(USD)	GICS Industry	Open Date	Opening Spread	Current Spread	Return Since Inception
Chart	CONS EDISON INC	PINNACLE WEST	ED US	PNW US	69.5	77.1	Utilities	22-Feb-21	-16.2%	-16.2%	
Chart	PLAINS GP HOLD-A	DIAMONDBACK ENER	PAGP US	FANG US	8.3	65.4	Energy	22-Feb-21	70.2%	140.3%	
Chart	HUNT (JB) TRANS	AMERCO	JBHT US	UHAL US	147.9	530.3	Transportation	22-Feb-21	37.0%	37.0%	
Chart	ADOBE INC	PAYPAL HOLDINGS	ADBE US	PYPL US	487.2	292.1	Software & Services	16-Feb-21	-30.9%	-31.1%	2.09%
Chart	CLOROX CO	ESTEE LAUDER	CLX US	EL US	191.5	288.0	Household & Personal Products	15-Feb-21	-42.4%	-40.0%	4.31%
Chart	VOYA FINANCIAL I	AMERICAN EXPRESS	VOYA US	AXP US	56.9	129.5	Diversified Financials	15-Feb-21	23.8%	19.3%	2.24%
Chart	AUTOZONE INC	BURLINGTON STORE	AZO US	BURL US	1212.3	267.0	Retailing	12-Feb-21	-30.3%	-50.6%	4.18%
Chart	CH ROBINSON	AMERCO	CHRW US	UHAL US	91.4	530.3	Transportation	12-Feb-21	48.6%	109.9%	-4.88%
Chart	HOME DEPOT INC	CARMAX INC	HD US	KMX US	282.9	120.8	Retailing	12-Feb-21	35.4%	30.0%	5.84%
Chart	DISCOVERY INC-C	DISCOVERY INC -	DISCK US	DISCA US	42.3	49.8	Media & Entertainment	12-Feb-21	4.6%	6.3%	-0.79%
Chart	UNDER ARMO-C	UNDER ARMOUR-A	UA US	UA-A US	18.7	22.6	Consumer Durables & Apparel	11-Feb-21	7.9%	8.4%	-0.72%
Chart	RENAISSANCE	AON PLC-CLASS A	RNR US	AON US	159.8	228.5	Insurance	10-Feb-21	24.3%	24.8%	-0.12%
Chart	LAS VEGAS SANDS	MGM RESORTS INTE	LVS US	MGM US	58.5	35.3	Consumer Services	8-Feb-21	-32.0%	-30.3%	4.51%
Chart	ANALOG DEVICES	MICRON TECH	ADI US	MU US	160.6	90.2	Semiconductors & Equipment	8-Feb-21	-37.1%	-78.2%	-3.43%
Chart	FACEBOOK INC-A	ALPHABET INC-A	F US	GOOGL US	269.9	2107.8	Media & Entertainment	8-Feb-21	32.8%	35.2%	0.04%
Chart	HARLEY-DAVIDSON	APTIV PLC	HOG US	APTIV US	35.6	151.4	Automobiles & Components	5-Feb-21	-38.2%	-34.5%	5.12%
Chart	BORGWARNER INC	LEAR CORP	BWA US	LEA US	43.7	163.6	Automobiles & Components	3-Feb-21	-30.1%	-30.3%	2.64%
Chart	HARLEY-DAVIDSON	GENERAL MOTORS C	HOG US	GM US	35.6	52.5	Automobiles & Components	3-Feb-21	-33.1%	-24.8%	7.43%
Chart	AMPHENOL CORP-A	TRIMBLE INC	APH US	TRMB US	65.7	73.3	Technology Hardware & Equipment	3-Feb-21	-27.1%	-26.0%	1.23%
Chart	HARLEY-DAVIDSON	FORD MOTOR CO	HOG US	F US	35.6	11.5	Automobiles & Components	3-Feb-21	30.0%	28.3%	0.43%

Link to the monitoring chart

Cumulative return on the Long minus Short since opening of the pair trade

Source: Citi Research. Note: this is provided as guide on how to read the report and should not be considered as a current investment view.

Lastly, the table includes a link to the monitoring chart for each open pair (other than all pairs closed within the last 30 days). An illustration of the chart is provided in Figure 30.

The monitoring chart consists of four panels. The left panels provide a visualization of the model parameters: the top-left panel reports the normalized prices series since the beginning of the monitoring period; and the bottom-left chart the corresponding cumulative spread and 2.5 standard deviation bands. The series are re-scaled and the standard deviation bands fixed at the beginning of the monitoring period.

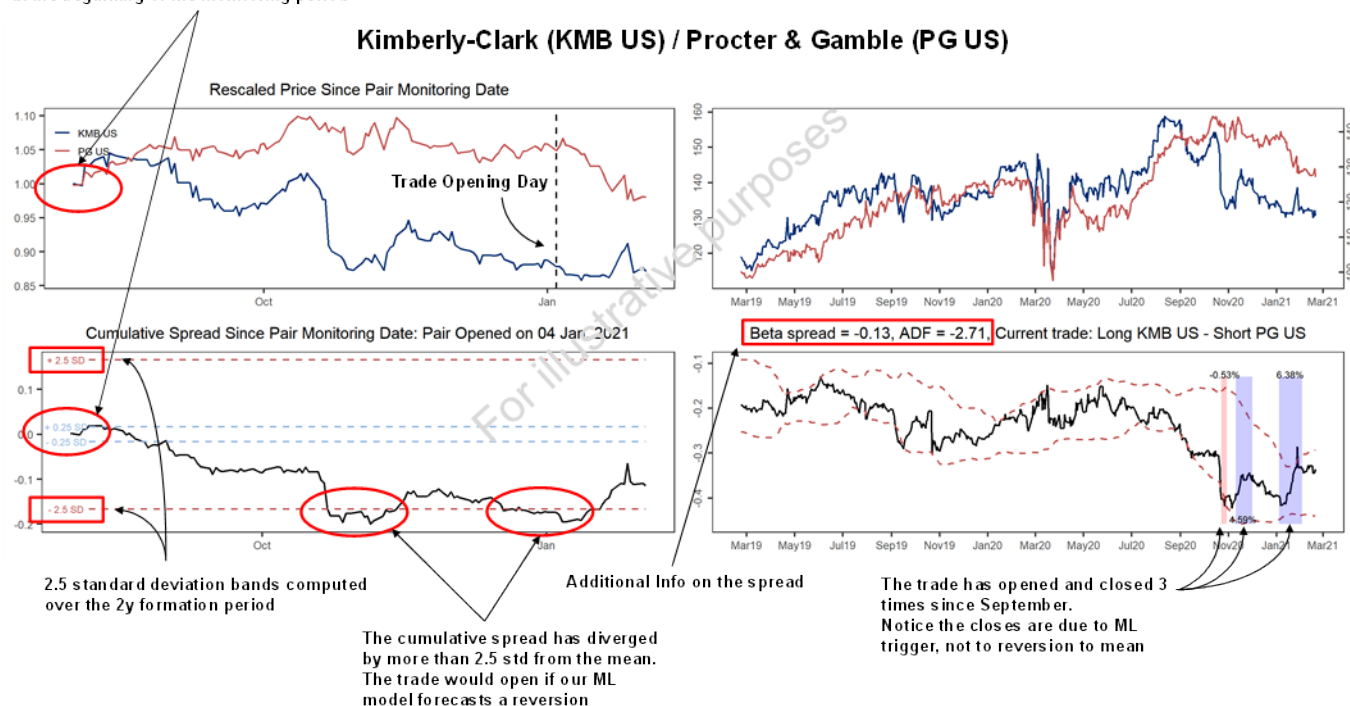
The right panels provide instead information on the historical relationship between the stocks forming the pair. The top-right panel reports the price series over the last 2 years in local currency while the bottom-right panel reports the corresponding spread and the rolling 2.5 standard deviation bands. On top of the panel, we report the beta spread (i.e. the difference in the beta to market of the two stocks) and the ADF test statistic. While we do not use this information in our model, we still believe it is relevant to check the relative exposure to the market and the historical reversion features of the spread.

The bottom-right panel also reports the any previous trade on the same pair opened over the last 2 years. In the example provided in Figure 30, the trade long KMB US and short PG US has opened three times since October 2020 and has delivered a total return of approximately 10.5%.

These trades also provide a good example of the triggers that we require to open and close the trade. For KMB/PG, the spread crossed the 2.5 standard deviation band for the first time on October the 3rd. Having our ML model forecasting a reversion in the spread, we opened the position. However, after a few days, the spread remained flat while the ML model changed its forecast causing the position to close. From the bottom left panel it is clear that, indeed, the spread continued to diverge until mid-November. Here the ML model forecasted a reversion and we opened again the trade leading to a +4.59% return. Notice that the trade was closed without the spread reverting to his mean due to the ML forecast. Similarly, the spread crossed the standard deviation band again in December, but our triggers signaled to open the trade only in January leading to a +6.38% return again without having the spread reverting to its mean.

Figure 30. Example of Specific Pair Monitoring charts

The price series and the spread are re-scaled at the beginning of the monitoring period



Source: Citi Research. Note: this is provided as guide on how to read the report and should not be considered as a current investment view.

Conclusions

In this research, we examine pairs trading strategies from a number of different angles in order to model the mean-reversion pattern in pairs of stocks and we propose a new framework to generate signals.

In the first Section, we review the basics of pairs trading and investigate the performance of standard strategies in recent years. We found that the strategy delivered good returns, but its efficacy has diminished over the last five to ten years.

The second section is devoted to advances in trading rules managing pairs trading strategies. We aim at improving the standard trading rules by both modelling the mean-reversion pattern of pairs and by monitoring changes in the stocks fundamentals and macro drivers. We fit a Random Forest using pairs related data, other than macro variables and stock specific fundamental data, for both the stocks involved in the trade.

We found the machine learning based rules to deliver significantly enhanced performances. We tested both a regression and a classification setting and an ensemble of the two and concluded that the regression random forest provides the best balance of performance and complexity.

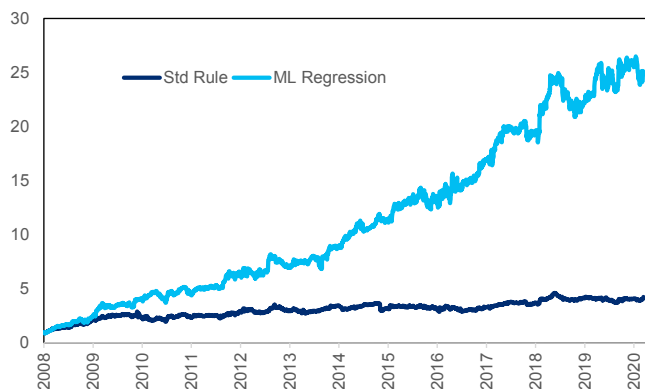
Lastly, we show that the outperformance delivered by the ML triggers is due to both a stricter selection of the pairs to act on and improved entry and exit points of the trades.

Appendix

Appendix A: Backtest Results for MSCI Europe

Figure 31 and Figure 32 report the performance metrics and wealth curves for our RF enhanced pairs trading strategy discussed in previous section when the MSCI Europe is used as starting universe. All results are in local currency.

Figure 31. Wealth Curve – Local Currency



Source: Citi Research

Figure 32. Performance Metrics

	Std Rule	RF Regression
Annualised Avg Return	14.0%	29.9%
Annualised Volatility	20.8%	23.2%
IR	0.67	1.29
Min	-7.0%	-7.5%
Max	14.2%	12.5%

Source: Citi Research

Appendix B: Full list of Factors used in RF Training

Figure 33. Random Forest Predictors

Macro / Technical Factors	Fundamental Factors	
Size Squared Returns	Earnings Yield (12 month Forward)	Earnings Yield (12 month Historical)
Price Mo Squared Returns	Cash Flow to Price	Dividend Yield
1M Returns	Book to Price	Sales to Price
RSI (14 days)	EBITDA to EV	Sales to EV
Volumes	Earnings Growth (12 month Forward)	S&P Growth-Value Score
Oil	1-Year Sales Growth	Long Term Earnings Growth
DXY	1-Year EPS Growth	1-Year DPS Growth
GSCI	3 Month Volatility Adj Price Trend	12 Month Volatility Adj Price Trend
JPY	First 11 Month Volatility Adj Price Trend	FCFY
VIX Index	1 Month Change in Earnings Forecasts	Earnings Revision
Credit Spread	Sales Revision	Cash Revision
Correlation	Equity to Debt	Earnings Stability
Dispersion	Beta against MSCI AC World	Beta against MSCI Country Index
	Earnings Certainty	ROE
	Net Profit Margin on Sales	Margin Growth
	Earnings Quality (Accruals)	Balance Sheet Quality (NOA)
	Market Capitalization (log)	Illiquidity Ratio
	6M Price Volatility	

Source: Citi Research

References

- Bogomolov, T., (2013). Pairs trading based on statistical variability of the spread process. *Quantitative Finance*, **13**(9), 1411-1430.
- Bossaerts, P. and Green, R. (1989). A General Equilibrium Model of Changing Risk Premia: Theory and Evidence. *Review of Financial Studies*, **2**, 467-493
- Dickey, D. A.; Fuller, W. A. (1979). Distribution of the Estimators for Autoregressive Time Series with a Unit Root. *Journal of the American Statistical Association*. **74** (366): 427–431
- Engle, R. and Granger, C. (1987). Co-integration and Error Correction: Representation, Estimation and Testing. *Econometrica*, **55**, 251-276.
- Fama, E. and French, K. (1996). Multifactor Explanations of Asset Pricing Anomalies. *Journal of Finance*, **51**, 131-155
- Gatev, E., Goetzmann, E.N. & Rouwenhorst, K.G. (2006). Pairs trading: Performance of a relative-value arbitrage rule. *Review of Financial Studies*, **19**(3), 797-827.
- Hastie, T., Tibshirani, R., & Friedman, J. (2008). *The Elements of Statistical Learning*. New York: Springer New York Inc.
- Jegadeesh, N. (1990). Evidence of Predictable Behavior of Security Returns. *Journal of Finance*, **45**, 881-898.
- Jegadeesh, N., and Titman, S. (1995). Overreaction, Delayed Reaction, and Contrarian Profits. *Review of Financial Studies*, **8**, 973-93
- Rad, H., Kwong, R., Low, Y. & Faff, R. (2016). The profitability of pairs trading strategies: distance, cointegration and copula methods, *Quantitative Finance*, **16**(10), 1541-1558
- Wei, G. N. F. and Scheffer (2015). Mixture pair-copula constructions. *Journal of Banking and Finance*, **54**, 175-191
- Zhang, T., & Johnson, R. (2014). Learning nonlinear functions using regularized greedy forest. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **5**(36).

Previously Published Research

Figure 34. Research Reports (since 2009)

Report	Date Published
Regime Modelling using Futures Positioning: Futures vs. Cash – A Distinct but Meaningful Relationship	09-Mar-2021
ESG Insights: The ESG 'Premium' – How does ESG compare to other Factors?	18-Feb-2021
Searching for Alpha: Asia Earnings Surprise – Predicting Asia Earnings Surprises	01-Feb-2021
ESG Insights: Where Machines do it Better – Inferred ESG Ratings Data	14-Jan-2021
Searching for Alpha: China A Alpha – Smoothing Price Momentum	30-Oct-2020
Under the Microscope: Overlapping Momentum	16-Oct-2020
Equity Markets Positioning Model – Introducing the EMP	14-Sep-2020
Searching for Alpha: Combining ESG and Risk Premia – A Double Screen Approach	11-Sep-2020
Searching for Alpha: Factoring Short Interest – Measuring and Profiting from Information in Shorts	8-Sep-2020
Searching for Alpha: Machine Learning – Attributing Higher-Order Interactions: SHAP Value as Factor Selection Criterion	28-May-2020
Searching for Alpha: Machine Learning – Leveraging Return Forecasts	28-Feb-2020
Searching for Alpha: China A Alpha – Sector-relative Value Is Powerful, Choose Sector Mappings Wisely	21-Feb-2020
Searching for Alpha: Machine Learning – Beyond Random Forests for Stock Selection	03-Oct-2019
Searching for Alpha: Earnings Surprise: Managing Expectations	23-Sep-2019
Searching for Alpha: Machine Learning – Interpreting Machine Learning Predictions	5-Mar-2019
Searching for Alpha: GAAP vs. Non-GAAP - Which Earnings does the Market Price?	7-Feb-2019
Searching for Alpha: Style Crowding in Asia - Getting Ahead of the Crowd	21-Nov-2018
Searching for Alpha: Earnings Surprise – Using Machine Learning to Forecast Earnings Surprises & Returns	17-Sep-2018
Searching for Alpha: The ESG Edge – A Step Forward	13-Sep-2018
Searching for Alpha: Machine Learning – Interacting Machine Learning and Factors	3-Sep-2018
Measuring the Crowded Trade: Introduction to our Crowding Composite for Individual Stocks	3-May-2018
Searching for Alpha: Profiting from Capex – Look to Capex Announcements	14-Mar-2018
Searching for Alpha: Tactical Style Rotation – Using Risk and Return to Manage Style Exposure	7-Sep-2017
Searching for Alpha: Big Data – Navigating New Alternative Datasets	10-Mar-2017
Searching for Alpha: Betting Against Accurate Beta	13-Feb-2017
Searching for Alpha: Competitive Advantage – Survival of the Fittest	19-Sep-2016
Searching for Alpha: Financial Strength Redux	9-Sep-2016
Searching for Alpha: Dynamic Style Weighting – Risk-Based Equity Style Allocation	14-Apr-2016
No Shorts Please: Long-Only Pure Style Portfolios	4-Mar-2016
Industry Alpha insights: Banks – One Size Does Not Fit All	18-Feb-2016
Under the Microscope: Stock Momentum Conflation	21-Sep-2015
Searching for Alpha: Macro Moves Markets	15-Sep-2015
Searching for Alpha: Style Performance, Trading Volumes and Investor Agreement	23-Mar-2015
World Radar Screen: Refining Our Global Search for Alpha	13-Mar-2015
Searching for Alpha: Networking with Analysts: Modelling Analyst Forecast Dependence	18-Feb-2015
The Rise of Low Risk Investing: Is it Getting Crowded Out There	01-Oct-2014
Under the Microscope: Five Innovations in Momentum Investing	27-Mar-2014
Searching for Alpha: Timing Price Momentum	07-Mar-2014
Equity Risk Premia Investing: A New Methodology For Monitoring Style Performance	27-Nov-2013
Stock Market Country Selection: Changes to a Well Established Model	23-Jul-2013
Searching for Alpha: Digging for Dividends – QUARI QUALity with A Reliable Income	02-Jul-2013
Global Theme Machine: An Objective Way of Identifying Attractive Investment Themes	24-Jun-2013
Searching for Alpha: Purifying Analyst Recommendations – Removing Beta to get to the Alpha	25-Mar-2013
Searching for Alpha: Tangible Benefits of Intangibles – Brand, Respect & Intellectual Capital	06-Nov-2012
Low-Risk Portfolio Strategies: Sharpe Ratio Maximisation and Multi-Asset Applications	09-Mar-2012
Macro Risk and Style Rotation: A Guide Rather than a Prescription	28-Feb-2012
Searching for Alpha: Accruals Volatility – A New Approach to Quality Investing	14-Sep-2011
Industry Alpha Insights: Four Approaches to Tactical Industry Selection	24-Aug-2011
Industry Alpha Insights: Quantifying Industry Specific Fundamentals	17-Mar-2011
Low-Risk Equity Portfolios: More than just Minimum Variance	18-Nov-2010
Under the Microscope: Measuring Systemic Risk – The Absorption Ratio	15-Nov-2010
Under the Microscope: Optionality in Valuation	14-Jun-2010
Searching for Alpha: Earnings Surprise – Still Profiting from Surprises	31-Mar-2010
Searching for Alpha: Optimising Style Rotation Strategies	15-Oct-2009

Source: Citi Research

Citi Quant Research Team

Figure 35. Citi Quantitative Research Teams

For Informational Purposes Only

Global Quantitative Research

Europe

Chris Montagu ¹	+44-20-7986-3958	chris.montagu@citi.com
David Chew ¹	+44-20-7986-7698	david.chew@citi.com
Josie Gerken ¹	+44-20-7986-4060	josie.gerken@citi.com
Pier Procacci ¹	+44-20-7986-4228	pier.procacci@citi.com

North America

Hong Li ⁴	+1-212-816-5062	hong.li@citi.com
Jason Li ⁴	+1-212-816-6692	jason.li@citi.com
Tiffany Zhou ⁴	+1-212-816-9476	tiffany.zhou@citi.com
Richard Schlatter ⁴	+1-212-816 0591	richard.w.schlatter@citi.com

Asia

Chris Ma ²	+852-2501-2404	chris.ma@citi.com
Simon Jin ²	+852-2501-2444	simon.jin@citi.com
Yue Hin Pong ²	+852-2501-2449	yue.hin.pong@citi.com
Liz Dinh ³	+61-2-8225-4896	liz.dinh@citi.com
Rory Anderson ³	+61-2-8225-4808	rory.anderson@citi.com
Bhavik Bochar ⁴	+91-22-4277-5019	bhavik.k.bochar@citi.com

Multi-Asset

David Bieber ¹	+44-20-7986-4976	david.bieber@citi.com
Kim Jensen ¹	+44-20-7986-3284	kim.jensen@citi.com

1 Citigroup Global Markets Ltd; 2 Citigroup Global Markets Asia Limited; 3 Citigroup Pty Limited, 4 Citigroup Global Markets Inc., 5 Citigroup Global Markets India Private Limited

NON-US RESEARCH ANALYST DISCLOSURES: The non-US research analysts listed above (i.e., the research analysts listed above other than those identified as employed by Citigroup Global Markets Inc.) are not registered/qualified as research analysts with FINRA. Such research analysts may not be associated persons of the member organization and therefore may not be subject to the NYSE Rule 472 and NASD Rule 2711 restrictions on communications with a subject company, public appearances and trading securities held by a research analyst account. Unless indicated in Appendix A-1 of this document or any of the referenced documents, the analysts listed above have not contributed to this document or any of the referenced documents.

Appendix A-1

Analyst Certification

The research analysts primarily responsible for the preparation and content of this research report are either (i) designated by "AC" in the author block or (ii) listed in bold alongside content which is attributable to that analyst. If multiple AC analysts are designated in the author block, each analyst is certifying with respect to the entire research report other than (a) content attributable to another AC certifying analyst listed in bold alongside the content and (b) views expressed solely with respect to a specific issuer which are attributable to another AC certifying analyst identified in the price charts or rating history tables for that issuer shown below. Each of these analysts certify, with respect to the sections of the report for which they are responsible: (1) that the views expressed therein accurately reflect their personal views about each issuer and security referenced and were prepared in an independent manner, including with respect to Citigroup Global Markets Inc. and its affiliates; and (2) no part of the research analyst's compensation was, is, or will be, directly or indirectly, related to the specific recommendations or views expressed by that research analyst in this report.

IMPORTANT DISCLOSURES

Disclosure for investors in the Republic of Turkey: Under Capital Markets Law of Turkey (Law No: 6362), the investment information, comments and recommendations stated here, are not within the scope of investment advisory activity. Investment advisory service is provided in accordance with a contract of engagement on investment advisory concluded between brokerage houses, portfolio management companies, non-deposit banks and clients. Comments and recommendations stated here rely on the individual opinions of the ones providing these comments and recommendations. These opinions may not fit to your financial status, risk and return preferences. For this reason, to make an investment decision by relying solely to this information stated here may not bring about outcomes that fit your expectations. Furthermore, Citi Research is a division of Citigroup Global Markets Inc. (the "Firm"), which does and seeks to do business with companies and/or trades on securities covered in this research reports. As a result, investors should be aware that the Firm may have a conflict of interest that could affect the objectivity of this report, however investors should also note that the Firm has in place organisational and administrative arrangements to manage potential conflicts of interest of this nature.

Analysts' compensation is determined by Citi Research management and Citigroup's senior management and is based upon activities and services intended to benefit the investor clients of Citigroup Global Markets Inc. and its affiliates (the "Firm"). Compensation is not linked to specific transactions or recommendations. Like all Firm employees, analysts receive compensation that is impacted by overall Firm profitability which includes investment banking, sales and trading, and principal trading revenues. One factor in equity research analyst compensation is arranging corporate access events between institutional clients and the management teams of covered companies. Typically, company management is more likely to participate when the analyst has a positive view of the company.

For securities recommended in the Product in which the Firm is not a market maker, the Firm is a liquidity provider in the issuers' financial instruments and may act as principal in connection with such transactions. The Firm is a regular issuer of traded financial instruments linked to securities that may have been recommended in the Product. The Firm regularly trades in the securities of the issuer(s) discussed in the Product. The Firm may engage in securities transactions in a manner inconsistent with the Product and, with respect to securities covered by the Product, will buy or sell from customers on a principal basis.

Unless stated otherwise neither the Research Analyst nor any member of their team has viewed the material operations of the Companies for which an investment view has been provided within the past 12 months.

For important disclosures (including copies of historical disclosures) regarding the companies that are the subject of this Citi Research product ("the Product"), please contact Citi Research, 388 Greenwich Street, 30th Floor, New York, NY, 10013, Attention: Legal/Compliance [E6WYB6412478]. In addition, the same important disclosures, with the exception of the Valuation and Risk assessments and historical disclosures, are contained on the Firm's disclosure website at https://www.citivelocity.com/cvr/eppublic/citi_research_disclosures. Valuation and Risk assessments can be found in the text of the most recent research note/report regarding the subject company. Pursuant to the Market Abuse Regulation a history of all Citi Research recommendations published during the preceding 12-month period can be accessed via Citi Veloccity (<https://www.citivelocity.com/cv2>) or your standard distribution portal. Historical disclosures (for up to the past three years) will be provided upon request.

Citi Research Equity Ratings Distribution

Data current as of 31 Dec 2020	12 Month Rating			Catalyst Watch		
	Buy	Hold	Sell	Buy	Hold	Sell
Citi Research Global Fundamental Coverage	56%	34%	10%	24%	67%	9%
% of companies in each rating category that are investment banking clients	64%	64%	57%	68%	62%	67%
Citi Research Quantitative World Radar Screen Model Coverage	30%	40%	30%			
% of companies in each rating category that are investment banking clients	39%	34%	31%			
Citi Research Quantitative Latam Radar Screen Model Coverage	20%	60%	20%			
% of companies in each rating category that are investment banking clients	75%	72%	38%			
Citi Research Quantitative Asia Radar Screen Model Coverage	20%	60%	20%			
% of companies in each rating category that are investment banking clients	33%	29%	24%			
Citi Research Quantitative Australia Radar Screen Model Coverage	49%	0%	51%			
% of companies in each rating category that are investment banking clients	51%	0%	35%			

Guide to Citi Research Fundamental Research Investment Ratings:

Citi Research stock recommendations include an investment rating and an optional risk rating to highlight high risk stocks.

Risk rating takes into account both price volatility and fundamental criteria. Stocks will either have no risk rating or a High risk rating assigned.

Investment Ratings: Citi Research investment ratings are Buy, Neutral and Sell. Our ratings are a function of analyst expectations of expected total return

("ETR") and risk. ETR is the sum of the forecast price appreciation (or depreciation) plus the dividend yield for a stock within the next 12 months. The target price is based on a 12 month time horizon. The Investment rating definitions are: Buy (1) ETR of 15% or more or 25% or more for High risk stocks; and Sell (3) for negative ETR. Any covered stock not assigned a Buy or a Sell is a Neutral (2). For stocks rated Neutral (2), if an analyst believes that there are insufficient valuation drivers and/or investment catalysts to derive a positive or negative investment view, they may elect with the approval of Citi Research management not to assign a target price and, thus, not derive an ETR. Additionally, in certain circumstances Citi Research may suspend its rating and target price and place the stock "Under Review". "Under Review" status may be imposed when the rating has been suspended for (a) regulatory and/or internal policy reasons or (b) other exceptional circumstances (e.g. lack of information critical to the analyst's thesis) affecting the company and / or trading in the company's securities (e.g. trading suspension). In such situations, the rating and target price will show as "-" and "-" respectively in the rating history price chart. As soon as practically possible, the analyst will publish a note re-establishing a rating and investment thesis. Investment ratings are determined by the ranges described above at the time of initiation of coverage, a change in investment and/or risk rating, or a change in target price (subject to limited management discretion). At times, the expected total returns may fall outside of these ranges because of market price movements and/or other short-term volatility or trading patterns. Such interim deviations will be permitted but will become subject to review by Research Management. Your decision to buy or sell a security should be based upon your personal investment objectives and should be made only after evaluating the stock's expected performance and risk.

Catalyst Watch Upside/Downside calls:

Citi Research may also include a Catalyst Watch Upside or Downside call to highlight specific near-term catalysts or events impacting the company or the market that are expected to influence the share price over a specified period of 30 or 90 days. A Catalyst Watch Upside (Downside) call indicates that the analyst expects the share price to rise (fall) in absolute terms over the specified period. A Catalyst Watch Upside/Downside call will automatically expire at the end of the specified 30/90 day period; the analyst may also close a Catalyst Watch call prior to the end of the specified period in a published research note. A Catalyst Watch Upside or Downside call may be different from and does not affect a stock's fundamental equity rating, which reflects a longer-term total absolute return expectation. For purposes of FINRA ratings-distribution-disclosure rules, a Catalyst Watch Upside call corresponds to a buy recommendation and a Catalyst Watch Downside call corresponds to a sell recommendation. Any stock not assigned to a Catalyst Watch Upside or Catalyst Watch Downside call is considered Catalyst Watch Non-Rated (CWNR). For purposes of FINRA ratings-distribution-disclosure rules, we correspond CWNR to Hold in our ratings distribution table for our Catalyst Watch Upside/Downside rating system. However, we reiterate that we do not consider CWNR to be a recommendation. For all Catalyst Watch Upside/Downside calls, risk exists that the catalyst(s) and associated share-price movement will not materialize as expected.

Guide to Citi Research Quantitative Research Investment Ratings:

Citi Research Quantitative Research World Radar Screen recommendations are based on a globally consistent framework to measure relative value and momentum for a large number of stocks across global developed and emerging markets. Relative value and momentum rankings are equally weighted to produce a global attractiveness score for each stock. The scores are then ranked and put into deciles. A stock with a decile rating of 1 denotes an attractiveness score in the top 10% of the universe (most attractive). A stock with a decile rating of 10 denotes an attractiveness score in the bottom 10% of the universe (least attractive).

Citi Research Asia Quantitative Radar Screen model recommendations are based on a regionally consistent framework to measure relative value and momentum for a large number of stocks across regional developed and emerging markets. Relative value and momentum rankings are equally weighted to produce a global attractiveness score for each stock. The scores are then ranked and put into quintiles. A stock with a quintile rating of 1 denotes an attractiveness score in the top 20% of the universe (most attractive). A stock with a quintile rating of 5 denotes an attractiveness score in the bottom 20% of the universe (least attractive).

Citi Research Quantitative Research Latam Radar Screen recommendations are based on a globally consistent framework to measure relative value and momentum for a large number of stocks across markets in Latin America. Relative value and momentum rankings are equally weighted to produce a global attractiveness score for each stock. The scores are then ranked and put into quintiles. A stock with a quintile rating of 1 denotes an attractiveness score in the top 20% of the universe (most attractive). A stock with a quintile rating of 5 denotes an attractiveness score in the bottom 20% of the universe (least attractive).

Citi Research Australia Quantitative Radar Screen model recommendations are based on a robust framework to measure relative value and momentum for a large number of stocks across the Australian market. Stocks with a ranking of 1 denotes a stock that is above average in terms of both value and momentum relative to the stocks in the Australian market. A ranking of 10 denotes a stock that is below average in terms of both value and momentum relative to the stocks in the Australian market.

For purposes of FINRA ratings-distribution-disclosure rules, a Citi Research Quantitative World Radar Screen recommendation of (1), (2) or (3) most closely corresponds to a buy recommendation; a recommendation from this product group of (4), (5), (6) or (7) most closely corresponds to a hold recommendation; and a recommendation of (8), (9) or (10) most closely corresponds to a sell recommendation. An (NR) recommendation indicates that the stock is no longer in the screen.

For purposes of FINRA ratings-distribution-disclosure rules, a Citi Research Latam Radar Screen recommendation of (1) most closely corresponds to a buy recommendation; a recommendation of (2),(3) or (4) most closely corresponds to a hold recommendation; and a recommendation of (5) most closely corresponds to a sell recommendation. An (NR) recommendation indicates that the stock is no longer in the screen.

For purposes of FINRA ratings distribution disclosure rules, a Citi Research Asia Quantitative Radar Screen recommendation of (1) most closely corresponds to a buy recommendation; a Citi Research Asia Quantitative Radar Screen recommendation of (2), (3), (4) most closely corresponds to a hold recommendation; and a recommendation of (5) most closely corresponds to a sell recommendation. An (NR) recommendation indicates that the stock is no longer in the screen.

For purposes of FINRA ratings-distribution-disclosure rules, a Citi Research Quantitative Research Australia Radar Screen recommendation of "attractive" (1) most closely corresponds to a buy recommendation. All other stocks in the sector are considered to be "unattractive" (10) which most closely corresponds to a sell recommendation. An (NR)/(0) recommendation indicates that the stock is no longer in the screen.

Recommendations are based on the relative attractiveness of a stock, thus can not be directly equated to buy, hold and sell categories. Accordingly, your decision to buy or sell a security should be based on your personal investment objectives and only after evaluating the stock's expected relative performance.

NON-US RESEARCH ANALYST DISCLOSURES

Non-US research analysts who have prepared this report (i.e., all research analysts listed below other than those identified as employed by Citigroup Global Markets Inc.) are not registered/qualified as research analysts with FINRA. Such research analysts may not be associated persons of the member organization and therefore may not be subject to the FINRA Rule 2241 restrictions on communications with a subject company, public appearances and trading securities held by a research analyst account. The legal entities employing the authors of this report are listed below (and their regulators are listed further herein):

Citigroup Global Markets Limited	Chris Montagu; David T Chew; Pier Procacci; Josie Gerken
Citigroup Global Markets India Private Limited	Bhavik Bochar, CFA
Citigroup Global Markets Inc.	Hong Li

OTHER DISCLOSURES

Any price(s) of instruments mentioned in recommendations are as of the prior day's market close on the primary market for the instrument, unless otherwise stated.

The completion and first dissemination of any recommendations made within this research report are as of the Eastern date-time displayed at the top of the Product. If the Product references views of other analysts then please refer to the price chart or rating history table for the date/time of completion and first dissemination with respect to that view.

Regulations in various jurisdictions require that where a recommendation differs from any of the author's previous recommendations concerning the same financial instrument or issuer that has been published during the preceding 12-month period that the change(s) and the date of that previous recommendation are indicated. For fundamental coverage please refer to the price chart or rating change history within this disclosure appendix or the issuer disclosure summary at https://www.citivelocity.com/cvr/eppublic/citi_research_disclosures.

Citi Research has implemented policies for identifying, considering and managing potential conflicts of interest arising as a result of publication or distribution of investment research. A description of these policies can be found at https://www.citivelocity.com/cvr/eppublic/citi_research_disclosures.

The proportion of all Citi Research research recommendations that were the equivalent to "Buy", "Hold", "Sell" at the end of each quarter over the prior 12 months (with the % of these that had received investment firm services from Citi in the prior 12 months shown in brackets) is as follows: Q4 2020 Buy 33% (69%), Hold 43% (60%), Sell 23% (54%), RV 0.6% (79%); Q3 2020 Buy 33% (69%), Hold 43% (63%), Sell 23% (58%), RV 0.7% (87%); Q2 2020 Buy 33% (68%), Hold 43% (62%), Sell 24% (60%), RV 0.7% (88%); Q1 2020 Buy 33% (68%), Hold 43% (60%), Sell 24% (57%), RV 0.6% (85%). For the purposes of disclosing recommendations other than for equity (whose definitions can be found in the corresponding disclosure sections), "Buy" means a positive directional trade idea; "Sell" means a negative directional trade idea; and "Relative Value" means any trade idea which does not have a clear direction to the investment strategy.

European regulations require a 5 year price history when past performance of a security is referenced. CitiVelocity's Charting Tool (https://www.citivelocity.com/cv2/#go/CHARTING_3_Equities) provides the facility to create customisable price charts including a five year option. This tool can be found in the Data & Analytics section under any of the asset class menus in CitiVelocity (<https://www.citivelocity.com/>). For further information contact CitiVelocity support (https://www.citivelocity.com/cv2/go/CLIENT_SUPPORT). The source for all referenced prices, unless otherwise stated, is DataCentral, which sources price information from Thomson Reuters. Past performance is not a guarantee or reliable indicator of future results. Forecasts are not a guarantee or reliable indicator of future performance.

Investors should always consider the investment objectives, risks, and charges and expenses of an ETF carefully before investing. The applicable prospectus and key investor information document (as applicable) for an ETF should contain this and other information about such ETF. It is important to read carefully any such prospectus before investing. Clients may obtain prospectuses and key investor information documents for ETFs from the applicable distributor or authorized participant, the exchange upon which an ETF is listed and/or from the applicable website of the applicable ETF issuer. The value of the investments and any accruing income may fall or rise. Any past performance, prediction or forecast is not indicative of future or likely performance. Any information on ETFs contained herein is provided strictly for illustrative purposes and should not be deemed an offer to sell or a solicitation of an offer to purchase units of any ETF either explicitly or implicitly. The opinions expressed are those of the authors and do not necessarily reflect the views of ETF issuers, any of their agents or their affiliates.

Citigroup Global Markets India Private Limited and/or its affiliates may have, from time to time, actual or beneficial ownership of 1% or more in the debt securities of the subject issuer.

Please be advised that pursuant to Executive Order 13959 of November 12, 2020 (the "Order"), U.S. persons are prohibited from investing in securities of any company determined by the United States Government to be a Communist Chinese military company as defined in the Order. This research is not intended to be used or relied upon in any way that could result in a violation of the Order. Investors are encouraged to rely upon their own legal counsel for advice on compliance with the Order and other economic sanctions programs administered and enforced by the Office of Foreign Assets Control of the U.S. Treasury Department.

This communication is directed at persons who are "Eligible Clients" as such term is defined in the Israeli Regulation of Investment Advice, Investment Marketing and Investment Portfolio Management law, 1995 (the "Advisory Law"). Within Israel, this communication is not intended for retail clients and Citi will not make such products or transactions available to retail clients. The presenter is not licensed as investment advisor or marketer by the Israeli Securities Authority ("ISA") and this communication does not constitute investment or marketing advice. The information contained herein may relate to matters that are not regulated by the ISA. Any securities which are the subject of this communication may not be offered or sold to any Israeli person except pursuant to an exemption from the Israeli public offering rules, including according to the Israeli Securities Law.

Citi Research generally disseminates its research to the Firm's global institutional and retail clients via both proprietary (e.g., Citi Velocity and Citi Personal Wealth Management) and non-proprietary electronic distribution platforms. Certain research may be disseminated only via the Firm's proprietary distribution platforms; however such research will not contain changes to earnings forecasts, target price, investment or risk rating or investment thesis or be otherwise inconsistent with the author's previously published research. Certain research is made available only to institutional investors to satisfy regulatory

requirements. Individual Citi Research analysts may also opt to circulate published research to one or more clients by email; such email distribution is discretionary and is done only after the research has been disseminated. The level and types of services provided by Citi Research analysts to clients may vary depending on various factors such as the client's individual preferences as to the frequency and manner of receiving communications from analysts, the client's risk profile and investment focus and perspective (e.g. market-wide, sector specific, long term, short-term etc.), the size and scope of the overall client relationship with the Firm and legal and regulatory constraints.

Pursuant to Comissão de Valores Mobiliários Rule 598 and ASIC Regulatory Guide 264, Citi is required to disclose whether a Citi related company or business has a commercial relationship with the subject company. Considering that Citi operates multiple businesses in more than 100 countries around the world, it is likely that Citi has a commercial relationship with the subject company.

Securities recommended, offered, or sold by the Firm: (i) are not insured by the Federal Deposit Insurance Corporation; (ii) are not deposits or other obligations of any insured depository institution (including Citibank); and (iii) are subject to investment risks, including the possible loss of the principal amount invested. The Product is for informational purposes only and is not intended as an offer or solicitation for the purchase or sale of a security. Any decision to purchase securities mentioned in the Product must take into account existing public information on such security or any registered prospectus. Although information has been obtained from and is based upon sources that the Firm believes to be reliable, we do not guarantee its accuracy and it may be incomplete and condensed. Note, however, that the Firm has taken all reasonable steps to determine the accuracy and completeness of the disclosures made in the Important Disclosures section of the Product. The Firm's research department has received assistance from the subject company(ies) referred to in this Product including, but not limited to, discussions with management of the subject company(ies). Firm policy prohibits research analysts from sending draft research to subject companies. However, it should be presumed that the author of the Product has had discussions with the subject company to ensure factual accuracy prior to publication. All opinions, projections and estimates constitute the judgment of the author as of the date of the Product and these, plus any other information contained in the Product, are subject to change without notice. Prices and availability of financial instruments also are subject to change without notice. Notwithstanding other departments within the Firm advising the companies discussed in this Product, information obtained in such role is not used in the preparation of the Product. Although Citi Research does not set a predetermined frequency for publication, if the Product is a fundamental equity or credit research report, it is the intention of Citi Research to provide research coverage of the covered issuers, including in response to news affecting the issuer. For non-fundamental research reports, Citi Research may not provide regular updates to the views, recommendations and facts included in the reports. Notwithstanding that Citi Research maintains coverage on, makes recommendations concerning or discusses issuers, Citi Research may be periodically restricted from referencing certain issuers due to legal or policy reasons. Where a component of a published trade idea is subject to a restriction, the trade idea will be removed from any list of open trade ideas included in the Product. Upon the lifting of the restriction, the trade idea will either be re-instated in the open trade ideas list if the analyst continues to support it or it will be officially closed. Citi Research may provide different research products and services to different classes of customers (for example, based upon long-term or short-term investment horizons) that may lead to differing conclusions or recommendations that could impact the price of a security contrary to the recommendations in the alternative research product, provided that each is consistent with the rating system for each respective product.

Investing in non-U.S. securities, including ADRs, may entail certain risks. The securities of non-U.S. issuers may not be registered with, nor be subject to the reporting requirements of the U.S. Securities and Exchange Commission. There may be limited information available on foreign securities. Foreign companies are generally not subject to uniform audit and reporting standards, practices and requirements comparable to those in the U.S. Securities of some foreign companies may be less liquid and their prices more volatile than securities of comparable U.S. companies. In addition, exchange rate movements may have an adverse effect on the value of an investment in a foreign stock and its corresponding dividend payment for U.S. investors. Net dividends to ADR investors are estimated, using withholding tax rates conventions, deemed accurate, but investors are urged to consult their tax advisor for exact dividend computations. Investors who have received the Product from the Firm may be prohibited in certain states or other jurisdictions from purchasing securities mentioned in the Product from the Firm. Please ask your Financial Consultant for additional details. Citigroup Global Markets Inc. takes responsibility for the Product in the United States. Any orders by US investors resulting from the information contained in the Product may be placed only through Citigroup Global Markets Inc.

Important Disclosures for Bell Potter Customers: Bell Potter is making this Product available to its clients pursuant to an agreement with Citigroup Global Markets Australia Pty Limited. Neither Citigroup Global Markets Australia Pty Limited nor any of its affiliates has made any determination as to the suitability of the information provided herein and clients should consult with their Bell Potter financial advisor before making any investment decision.

The Citigroup legal entity that takes responsibility for the production of the Product is the legal entity which the first named author is employed by.

The Product is made available in **Australia** through Citigroup Global Markets Australia Pty Limited. (ABN 64 003 114 832 and AFSL No. 240992), participant of the ASX Group and regulated by the Australian Securities & Investments Commission. Citigroup Centre, 2 Park Street, Sydney, NSW 2000. Citigroup Global Markets Australia Pty Limited is not an Authorised Deposit-Taking Institution under the Banking Act 1959, nor is it regulated by the Australian Prudential Regulation Authority. The Product is made available in Australia to Private Banking wholesale clients through Citigroup Pty Limited (ABN 88 004 325 080 and AFSL 238098). Citigroup Pty Limited provides all financial product advice to Australian Private Banking wholesale clients through bankers and relationship managers. If there is any doubt about the suitability of investments held in Citigroup Private Bank accounts, investors should contact the Citigroup Private Bank in Australia. Citigroup companies may compensate affiliates and their representatives for providing products and services to clients.

The Product is made available in **Brazil** by Citigroup Global Markets Brasil - CCTVM SA, which is regulated by CVM - Comissão de Valores Mobiliários ("CVM"), BACEN - Brazilian Central Bank, APIMEC - Associação dos Analistas e Profissionais de Investimento do Mercado de Capitais and ANBIMA - Associação Brasileira das Entidades dos Mercados Financeiro e de Capitais. Av. Paulista, 1111 - 14º andar(parte) - CEP: 01311920 - São Paulo - SP.

If the Product is being made available in certain provinces of **Canada** by Citigroup Global Markets (Canada) Inc. ("CGM Canada"), CGM Canada has approved the Product. Citigroup Place, 123 Front Street West, Suite 1100, Toronto, Ontario M5J 2M3.

This product is available in **Chile** through Banchile Corredores de Bolsa S.A., an indirect subsidiary of Citigroup Inc., which is regulated by the Superintendencia de Valores y Seguros. Agustinas 975, piso 2, Santiago, Chile.

The Product is made available in **Germany** by Citigroup Global Markets Europe AG ("CGME"), which is regulated by the German Federal Financial Supervisory Authority (Bundesanstalt für Finanzdienstleistungsaufsicht BaFin). CGME, Reuterweg 16, 60323 Frankfurt am Main.

Research which relates to "securities" (as defined in the Securities and Futures Ordinance (Cap. 571 of the Laws of Hong Kong)) is issued in **Hong Kong** by, or on behalf of, Citigroup Global Markets Asia Limited which takes full responsibility for its content. Citigroup Global Markets Asia Ltd. is regulated by Hong Kong Securities and Futures Commission. If the Research is made available through Citibank, N.A., Hong Kong Branch, for its clients in Citi Private Bank, it is made available by Citibank N.A. (organized under the laws of U.S. A. with limited liability), Champion Tower, 3 Garden Road, Hong Kong. Citibank N.A. is regulated by the Hong Kong Monetary Authority. Please contact your Private Banker in Citibank N.A., Hong Kong, Branch if you have any queries on or any matters arising from or in connection with this document.

The Product is made available in **India** by Citigroup Global Markets India Private Limited (CGM), which is regulated by the Securities and Exchange Board of India (SEBI), as a Research Analyst (SEBI Registration No. INH000000438). CGM is also actively involved in the business of merchant banking and stock brokerage in India, and is registered with SEBI in this regard. CGM's registered office is at 1202, 12th Floor, FIFC, G Block, Bandra Kurla Complex, Bandra East, Mumbai – 400098. CGM's Corporate Identity Number is U99999MH2000PTC126657, and its contact details are: Tel: +9102261759999 Fax: +9102261759961.

The Product is made available in **Indonesia** through PT Citigroup Securities Indonesia. 5/F, Citibank Tower, Bapindo Plaza, Jl. Jend. Sudirman Kav. 54-55, Jakarta 12190. Neither this Product nor any copy hereof may be distributed in Indonesia or to any Indonesian citizens wherever they are domiciled or to Indonesian residents except in compliance with applicable capital market laws and regulations. This Product is not an offer of securities in Indonesia. The securities referred to in this Product have not been registered with the Capital Market and Financial Institutions Supervisory Agency (BAPEPAM-LK) pursuant to relevant capital market laws and regulations, and may not be offered or sold within the territory of the Republic of Indonesia or to Indonesian citizens through a public offering or in circumstances which constitute an offer within the meaning of the Indonesian capital market laws and regulations.

The Product is made available in **Israel** through Citibank NA, regulated by the Bank of Israel and the Israeli Securities Authority. Citibank, N.A., Platinum Building, 21 Ha'arba'ah St, Tel Aviv, Israel.

The Product is made available in **Japan** by Citigroup Global Markets Japan Inc. ("CGMJ"), which is regulated by Financial Services Agency, Securities and Exchange Surveillance Commission, Japan Securities Dealers Association, Tokyo Stock Exchange and Osaka Securities Exchange. Otemachi Park Building, 1-1-1 Otemachi, Chiyoda-ku, Tokyo 100-8132 Japan. If the Product was distributed by SMBC Nikko Securities Inc. it is being so distributed under license. In the event that an error is found in an CGMJ research report, a revised version will be posted on the Firm's Citi Velocity website. If you have questions regarding Citi Velocity, please call (81 3) 6270-3019 for help.

The product is made available in the **Kingdom of Saudi Arabia** in accordance with Saudi laws through Citigroup Saudi Arabia, which is regulated by the Capital Market Authority (CMA) under CMA license (17184-31). 2239 Al Urubah Rd – Al Olaya Dist. Unit No. 18, Riyadh 12214 – 9597, Kingdom Of Saudi Arabia.

The Product is made available in **Korea** by Citigroup Global Markets Korea Securities Ltd., which is regulated by the Financial Services Commission, the Financial Supervisory Service and the Korea Financial Investment Association (KOFIA). Citibank Building, 39 Da-dong, Jung-gu, Seoul 100-180, Korea. KOFIA makes available registration information of research analysts on its website. Please visit the following website if you wish to find KOFIA registration information on research analysts of Citigroup Global Markets Korea Securities Ltd. <http://dis.kofia.or.kr/webssquare/index.jsp?w2xPath=/wq/fundMgr/DISFundMgrAnalystList.xml&divisionId=MDIS03002002000000&serviceId=SDIS03002002000>. The Product is made available in Korea by Citibank Korea Inc., which is regulated by the Financial Services Commission and the Financial Supervisory Service. Address is Citibank Building, 39 Da-dong, Jung-gu, Seoul 100-180, Korea. This research report is intended to be provided only to Professional Investors as defined in the Financial Investment Services and Capital Market Act and its Enforcement Decree in Korea.

The Product is made available in **Malaysia** by Citigroup Global Markets Malaysia Sdn Bhd (Company No. 460819-D) ("CGMM") to its clients and CGMM takes responsibility for its contents. CGMM is regulated by the Securities Commission of Malaysia. Please contact CGMM at Level 43 Menara Citibank, 165 Jalan Ampang, 50450 Kuala Lumpur, Malaysia in respect of any matters arising from, or in connection with, the Product.

The Product is made available in **Mexico** by Citibanamex Casa de Bolsa, S.A. De C. V., Casa de Bolsa, Integrante del Grupo Financiero Citibanamex which is a wholly owned subsidiary of Citigroup Inc. and is regulated by Comisión Nacional Bancaria y de Valores. Reforma 398, Col. Juárez, 06600 Mexico, D.F.

In **New Zealand** the Product is made available to 'wholesale clients' only as defined by s5C(1) of the Financial Advisers Act 2008 ('FAA') through Citigroup Global Markets Australia Pty Ltd (ABN 64 003 114 832 and AFSL No. 240992), an overseas financial adviser as defined by the FAA, participant of the ASX Group and regulated by the Australian Securities & Investments Commission. Citigroup Centre, 2 Park Street, Sydney, NSW 2000.

The Product is made available in **Pakistan** by Citibank N.A. Pakistan branch, which is regulated by the State Bank of Pakistan and Securities Exchange Commission, Pakistan. AWT Plaza, 1.1. Chundrigar Road, P.O. Box 4889, Karachi-74200.

The Product is made available in the **Philippines** through Citicorp Financial Services and Insurance Brokerage Philippines, Inc., which is regulated by the Philippines Securities and Exchange Commission. 20th Floor Citibank Square Bldg. The Product is made available in the Philippines through Citibank NA Philippines branch, Citibank Tower, 8741 Paseo De Roxas, Makati City, Manila. Citibank NA Philippines NA is regulated by The Bangko Sentral ng Pilipinas.

The Product is made available in **Poland** by Dom Maklerski Banku Handlowego SA an indirect subsidiary of Citigroup Inc., which is regulated by Komisja Nadzoru Finansowego. Dom Maklerski Banku Handlowego S.A. ul. Senatorska 16, 00-923 Warszawa.

The Product is made available in the **Russian Federation** through AO Citibank, which is licensed to carry out banking activities in the Russian Federation in accordance with the general banking license issued by the Central Bank of the Russian Federation and brokerage activities in accordance with the license issued by the Federal Service for Financial Markets. Neither the Product nor any information contained in the Product shall be considered as advertising the securities mentioned in this report within the territory of the Russian Federation or outside the Russian Federation. The Product does not constitute an appraisal within the meaning of the Federal Law of the Russian Federation of 29 July 1998 No. 135-FZ (as amended) On Appraisal Activities in the Russian Federation. 8-10 Gasheka Street, 125047 Moscow.

The Product is made available in **Singapore** through Citigroup Global Markets Singapore Pte. Ltd. ("CGMSPL"), a capital markets services license holder, and regulated by Monetary Authority of Singapore. Please contact CGMSPL at 8 Marina View, 21st Floor Asia Square Tower 1, Singapore 018960, in respect of any matters arising from, or in connection with, the analysis of this document. This report is intended for recipients who are accredited, expert and institutional investors as defined under the Securities and Futures Act (Cap. 289). The Product is made available by The Citigroup Private Bank in Singapore through Citibank, N.A., Singapore Branch, a licensed bank in Singapore that is regulated by Monetary Authority of Singapore. Please contact your Private Banker in Citibank N.A., Singapore Branch if you have any queries on or any matters arising from or in connection with this document. This report is intended for recipients who are accredited, expert and institutional investors as defined under the Securities and Futures Act (Cap. 289). This report is distributed in Singapore by Citibank Singapore Ltd ("CSL") to selected Citigold/Citigold Private Clients. CSL provides no independent research or analysis of the substance or in preparation of this report. Please contact your Citigold/Citigold Private Client Relationship Manager in CSL if you have any queries on or any matters arising from or in connection with this report. This report is intended for recipients who are accredited investors as defined under the Securities and Futures Act (Cap. 289).

Citigroup Global Markets (Pty) Ltd. is incorporated in the **Republic of South Africa** (company registration number 2000/025866/07) and its registered office is at 145 West Street, Sandton, 2196, Saxonwold. Citigroup Global Markets (Pty) Ltd. is regulated by JSE Securities Exchange South Africa, South African Reserve Bank and the Financial Services Board. The investments and services contained herein are not available to private customers in South Africa.

The Product is made available in the **Republic of China** through Citigroup Global Markets Taiwan Securities Company Ltd. ("CGMTS"), 14 and 15F, No. 1, Songzhi Road, Taipei 110, Taiwan, subject to the license scope and the applicable laws and regulations in the Republic of China. CGMTS is regulated by the Securities and Futures Bureau of the Financial Supervisory Commission of Taiwan, the Republic of China. No portion of the Product may be reproduced or quoted in the Republic of China by the press or any third parties [without the written authorization of CGMTS]. Pursuant to the applicable laws and regulations in the Republic of China, the recipient of the Product shall not take advantage of such Product to involve in any matters in which the recipient may have conflicts of interest. If the Product covers securities which are not allowed to be offered or traded in the Republic of China, neither the Product nor any information contained in the Product shall be considered as advertising the securities or making recommendation of the securities in the Republic of China. The Product is for informational purposes only and is not intended as an offer or solicitation for the purchase or sale of a security or financial products. Any decision to purchase securities or financial products mentioned in the Product must take into account existing public information on such security or the financial products or any registered prospectus.

The Product is made available in **Thailand** through Citicorp Securities (Thailand) Ltd., which is regulated by the Securities and Exchange Commission of Thailand. 399 Interchange 21 Building, 18th Floor, Sukhumvit Road, Klongtoey Nua, Wattana, Bangkok 10110, Thailand.

The Product is made available in **Turkey** through Citibank AS which is regulated by Capital Markets Board. Tekfen Tower, Eski Buyukdere Caddesi # 209 Kat 2B, 23294 Levent, Istanbul, Turkey.

In the **U.A.E**, these materials (the "Materials") are communicated by Citigroup Global Markets Limited, DIFC branch ("CGML"), an entity registered in the Dubai International Financial Center ("DIFC") and licensed and regulated by the Dubai Financial Services Authority ("DFSA") to Professional Clients and Market Counterparties only and should not be relied upon or distributed to Retail Clients. A distribution of the different Citi Research ratings distribution, in percentage terms for Investments in each sector covered is made available on request. Financial products and/or services to which the Materials relate will only be made available to Professional Clients and Market Counterparties.

The Product is made available in **United Kingdom** by Citigroup Global Markets Limited, which is authorised by the Prudential Regulation Authority ("PRA") and regulated by the Financial Conduct Authority ("FCA") and the PRA. This material may relate to investments or services of a person outside of the UK or to other matters which are not authorised by the PRA nor regulated by the FCA and the PRA and further details as to where this may be the case are available upon request in respect of this material. Citigroup Centre, Canada Square, Canary Wharf, London, E14 5LB.

The Product is made available in **United States** by Citigroup Global Markets Inc, which is a member of FINRA and registered with the US Securities and Exchange Commission. 388 Greenwich Street, New York, NY 10013.

Unless specified to the contrary, within EU Member States, the Product is made available by Citigroup Global Markets Europe AG ("CGME"), which is regulated by the German Federal Financial Supervisory Authority (Bundesanstalt für Finanzdienstleistungsaufsicht-BaFin).

The Product is not to be construed as providing investment services in any jurisdiction where the provision of such services would not be permitted. Subject to the nature and contents of the Product, the investments described therein are subject to fluctuations in price and/or value and investors may get back less than originally invested. Certain high-volatility investments can be subject to sudden and large falls in value that could equal or exceed the amount invested. Certain investments contained in the Product may have tax implications for private customers whereby levels and basis of taxation may be subject to change. If in doubt, investors should seek advice from a tax adviser. The Product does not purport to identify the nature of the specific market or other risks associated with a particular transaction. Advice in the Product is general and should not be construed as personal advice given it has been prepared without taking account of the objectives, financial situation or needs of any particular investor. Accordingly, investors should, before acting on the advice, consider the appropriateness of the advice, having regard to their objectives, financial situation and needs. Prior to acquiring any financial product, it is the client's responsibility to obtain the relevant offer document for the product and consider it before making a decision as to whether to purchase the product. Citi Research product may source data from dataCentral. dataCentral is a Citi Research proprietary database, which includes the Firm's estimates, data from company reports and feeds from Thomson Reuters. The source for all referenced prices, unless otherwise stated, is DataCentral. Past performance is not a guarantee or reliable indicator of future results. Forecasts are not a guarantee or reliable indicator of future performance. The printed and printable version of the research report may not include all the information (e.g., certain financial summary information and comparable company data) that is linked to the online version available on the Firm's proprietary electronic distribution platforms.

Card Insights. Where this report references Card Insights data, Card Insights consists of selected data from a subset of Citi's proprietary credit card transactions. Such data has undergone rigorous security protocols to keep all customer information confidential and secure; the data is highly aggregated and anonymized so that all unique customer identifiable information is removed from the data prior to receipt by the report's author or distribution to external parties. This data should be considered in the context of other economic indicators and publicly available information. Further, the selected data represents

only a subset of Citi's proprietary credit card transactions due to the selection methodology or other limitations and should not be considered as indicative or predictive of the past or future financial performance of Citi or its credit card business.

Where included in this report, MSCI sourced information is the exclusive property of Morgan Stanley Capital International Inc. (MSCI). Without prior written permission of MSCI, this information and any other MSCI intellectual property may not be reproduced, disseminated or used to create any financial products, including any indices. This information is provided on an "as is" basis. The user assumes the entire risk of any use made of this information. MSCI, its affiliates and any third party involved in, or related to, computing or compiling the information hereby expressly disclaim all warranties of originality, accuracy, completeness, merchantability or fitness for a particular purpose with respect to any of this information. Without limiting any of the foregoing, in no event shall MSCI, any of its affiliates or any third party involved in, or related to, computing or compiling the information have any liability for any damages of any kind. MSCI, Morgan Stanley Capital International and the MSCI indexes are services marks of MSCI and its affiliates. Part of this product may contain Sustainalytics proprietary information that may not be reproduced, used, disseminated, modified nor published in any manner without the express written consent of Sustainalytics. Sustainalytics, its affiliates and any third party involved in, or related to, computing or compiling the information hereby expressly disclaim all warranties of originality, accuracy, completeness, merchantability or fitness for a particular purpose with respect to any of this information. Any information attributed to Sustainalytics is provided solely for informational purposes and on its own should not be considered an offer to buy or sell a security. Neither Sustainalytics nor all its third-party suppliers provide investment advice (as defined in the applicable jurisdiction) or any other form of (financial) advice. The information is provided "as is" and, therefore Sustainalytics assumes no responsibility for errors or omissions. Sustainalytics cannot be held liable for damage arising from the use of this product or information contained herein in any manner whatsoever. Where data is attributed to Morningstar that data is © 2020 Morningstar, Inc. All Rights Reserved. That information: (1) is proprietary to Morningstar and/or its content providers; (2) may not be copied or distributed; and (3) is not warranted to be accurate, complete or timely. Neither Morningstar nor its content providers are responsible for any damages or losses arising from any use of this information.

The Firm accepts no liability whatsoever for the actions of third parties. The Product may provide the addresses of, or contain hyperlinks to, websites. Except to the extent to which the Product refers to website material of the Firm, the Firm has not reviewed the linked site. Equally, except to the extent to which the Product refers to website material of the Firm, the Firm takes no responsibility for, and makes no representations or warranties whatsoever as to, the data and information contained therein. Such address or hyperlink (including addresses or hyperlinks to website material of the Firm) is provided solely for your convenience and information and the content of the linked site does not in any way form part of this document. Accessing such website or following such link through the Product or the website of the Firm shall be at your own risk and the Firm shall have no liability arising out of, or in connection with, any such referenced website.

© 2021 Citigroup Global Markets Inc. Citi Research is a division of Citigroup Global Markets Inc. Citi and Citi with Arc Design are trademarks and service marks of Citigroup Inc. and its affiliates and are used and registered throughout the world. All rights reserved. The research data in this report are not intended to be used for the purpose of (a) determining the price of or amounts due in respect of (or to value) one or more financial products or instruments and/or (b) measuring or comparing the performance of, or defining the asset allocation of a financial product, a portfolio of financial instruments, or a collective investment undertaking, and any such use is strictly prohibited without the prior written consent of Citi Research. Any unauthorized use, duplication, redistribution or disclosure of this report (the "Product"), including, but not limited to, redistribution of the Product by electronic mail, posting of the Product on a website or page, and/or providing to a third party a link to the Product, is prohibited by law and will result in prosecution. The information contained in the Product is intended solely for the recipient and may not be further distributed by the recipient to any third party.

ADDITIONAL INFORMATION IS AVAILABLE UPON REQUEST